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Proceedings of the Ninth Biennial Southern Silvicultural Research Conference

Clemson, South Carolina
February 25-27, 1997

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One hundred seventeen papers, 3 abstracts, 2 poster summaries, and 1 summary address a range of issues affecting southern forests. Papers are grouped in several categories including tree improvement and nursery technology, site preparation, vegetation management, site classification, longleaf pine silviculture, nutrient dynamics, silvicultural systems, intermediate management, hardwood regeneration, pine and pine-hardwood regeneration, impacts of harvesting and site preparation, pine nutrition management, physiology, plant and structural diversity, growth and yield, stand development and dynamics, and measurement and research methods.

Proceedings of the Ninth Biennial Southern Silvicultural Research Conference

Edited by
Thomas A. Waldrop

Clemson, South Carolina
February 25-27, 1997

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PREFACE

The Ninth Biennial Southern Silvicultural Research Conference was held February 25-27, 1997 on the campus of Clemson University in Clemson, SC. This conference was the latest in a series of meetings designed to provide a forum for the exchange of research information among silviculturists and researchers in related areas, research coordination, review of research in progress, and new approaches or techniques of general interest. The conference consisted of four concurrent sessions over 2 days, a poster session, and two concurrent field tours on the third day. Presentations covered a wide array of topics related to silvics and silviculture. They emphasized research in pine, hardwood, and mixed-species forests. Field trips included (1) a view of over 40 years hardwood regeneration research at the Bent Creek Research and Demonstration Forest and (2) numerous topics related to management and research on the Clemson Experimental Forest. This was the largest conference of the series with 154 oral and poster presentations and 351 registered participants.

Sponsors of the conference included the Southern Research Station, Clemson University, the Society of American Foresters, the Southern Region of the National Association of Professional Forestry Schools and Colleges, the Southern Industrial Forestry Research Council, the National Hardwood Lumber Association, the Southern Group of State Foresters, the National Association of Consulting Foresters in America, the Historically Black Colleges and Universities Program, and the University of Arkansas, Monticello. Funding for many conference expenses was provided by the Southern Research Station, Clemson University, and Alabama A&M University. Each sponsor provided one or more representatives to the steering committee. This committee worked numerous hours to review abstracts that were submitted by authors, establish the program for oral and poster presentations, and make all necessary arrangements for the conference. Steering committee members included:

Southern Research Station, USDA Forest Service
- Jim Baker, Monticello, AR
- Eric Berg, Asheville, NC
- Boyd Edwards, Juliette, GA
- Jim Reaves, Asheville, NC
- Tom Waldrop, Clemson, SC

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National Association of Consulting Foresters of America
- Larry Reamer, Land Resources Inc., Clemson, SC

University of Arkansas, Monticello
- Brian Lockhart

A new feature of the Ninth Biennial Southern Silvicultural Research Conference was a partnership between the Southern Research Station and Clemson University to co-host this meeting. The Southern Research Station is grateful to Clemson University for their diligence in handling the fiscal responsibilities of this meeting. Special thanks go to Jeanne Campbell, Gladys Crawford, Steve Muzal, and Yvonne Scott for many hours of tedious work.

Special recognition is offered to the excellent panel of distinguished moderators that led each session. I am particularly grateful to Jackie Haymond, Vic Shelburne, and Tom Green who coordinated local arrangements, field trips, and the poster session, respectively.

Papers published in these proceedings were submitted by authors in electronic media. Editing was done to ensure a consistent format. Authors are responsible for content and accuracy of their individual papers.

Thomas A. Waldrop
Program Chair
Southern Research Station, Clemson, SC

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Tree Improvement and Nursery Technology

Moderator:

GEORGE R. ASKEW
Clemson University

EFFECTS OF TOP-PRUNING ON SURVIVAL OF SOUTHERN PINES AND HARDWOODS

David B. South'

Abstract-Two schools of thought exist regarding top-pruning bareroot seedlings. One school favors top-pruning due to the economic advantages. Top-pruning can reduce the production of cull seedlings (increase crop value) as well as increase the chance of survival after outplanting. Published studies suggest that top-pruning can increase overall survival of loblolly pine and longleaf pine by 7 and 13 percentage points, respectively. Pruning various hardwood species (mainly after lifting) increased average survival by 5 percentage points. The benefits of top-pruning appear greater when seedlings experience stress after planting and when non-pruned seedlings have low root-weight ratios (root dry weight/total seedling dry weight). On some droughty sites, a seedling with a 0.3 root-weight ratio might have a 26 percentage point higher chance of survival than a seedling with a 0.2 root weight ratio. In most studies with hardwoods or multinodal pine species, height growth is stimulated so that after 3 years in the field, pruned seedlings have caught up to the heights of non-pruned seedlings.

One school advises against top-pruning in the nursery. Some believe the concern for a balance between roots and shoots at planting has been greatly overemphasized. Others believe that top-pruning is not natural and that cutting the shoot will anthropomorphically hurl the seedling. A few believe top-pruning will result in forked trees at harvest (with the fork just above ground level). Those who advise against top-pruning tall seedlings usually do not give justifications that are based on economics or field performance.

INTRODUCTION

Nursery managers have been improving the "transplantability" of bare-root seedlings by top-pruning for over 300 years. John Evelyn (1679) gave a prescription for cutting oak *(Quercus* sp.) seedlings in the nursery to a height of 3 centimeters (cm). After resprouting, some growers applied a second pruning at a 15-cm height. Two hundred years later, Fuller (1884) reported that "All kinds of forest trees may be, and nearly all should be pruned at time of transplanting." Brisbin (1888) observed that many planting failures could be explained by not pruning enough. Fernow (1910) stated that "...pruning is to be done at the time of planting, when it is needful to restore the balance between the branch system and the root system, the latter often having been curtailed in the operation of transplanting the tree." Tourney (1916) stated that the more severely the root system is injured in lifting the trees, the greater the necessity for pruning the tops. Today, more than 90 percent of nursery managers in the Southern United States and Australia top-prune seedlings (Duryea 1986, Duryea and Boomsma 1992). Most managers apply this practice to improve the root-weight ratio[2] of both bare-root seedlings and rooted cuttings.

Even though it has been practiced for centuries, two schools of thought have evolved regarding top-pruning. Some believe that top-pruning is not beneficial and should never be practiced. Others believe top-pruning increases the chances of survival and increases crop value. This review paper summarizes top-pruning studies mainly from southern forest nurseries and was written in hopes of clarifying some of the differences in philosophy between the two schools.

METHODS

Published studies were compiled for loblolly pine (*Pinus taeda* L.), longleaf pine (*Pinus palustris* Mill.), slash pine *(Pinus elliottii* Englm.), eastern white pine (*Pinus strobus* L.) and various hardwood species. Eight unpublished studies on loblolly pine were also included. Survival data from these studies were used to develop three regression equations relating survival of pruned seedlings (Y) to survival of non-pruned seedlings (X).

RESULTS AND DISCUSSION

Effect on Survival

Survival of loblolly pine was increased by top-pruning (table 1). In tests where survival of non-pruned seedlings was high, there was little or no increase in the survival rate.

Table I-Overall effect of top-pruning on seedling survival of loblolly pine, longleaf pine, and hardwood species

		Survival rate	
Species	Number of tests	Pruned	Non-pruned
		..... *Percent*	
Loblolly pine	28	86	79
Longleaf pine	20	59	48
Hardwoods	17	90	85

[1] Professor, School of Forestry and Alabama Agricultural Experiment Station, Auburn University, AL 36849-5418.

[2] Root-weight ratio (RWR) is determined by dividing the dry weight of the root system by the dry weight of the total seedling. The term is inherently easier to comprehend than the root-shoot ratio. The RWR is also less confusing, since many practitioners believe the root-shoot ratio compares shoot height with taproot length.

However, as environmental stresses at the planting site increased, top-pruning increased the probability of survival ($Y = 16.9\ X^{0.375}$; $R^2 = 0.80$). On one piedmont site in Virginia, top-pruning increased seedling survival by 43 percentage points (Dierauf 1976). For this species an increase in survival may result, in part, from an increase in freeze tolerance (South and others 1993). For the 13 tests where survival of non-pruned seedlings was less than 80 percent, top-pruning increased survival by 16 percentage points.

For longleaf pine, pruning increased overall survival of seedlings by 11 percentage points (table 1). For the 16 comparisons showing a benefit to clipping needles, survival increased by 14 percentage points ($Y = 5.2\ X^{0.64}$; $R^2 = 0.90$). Wakeley (1954) warned against "close" pruning of longleaf needles and this might have accounted for the negative results reported by Derr (1963) who pruned needles back to 13 cm.

Top-pruning of eastern white pine had no effect on seedling survival (Dierauf 1997). Data from two studies with slash pine show no statistically significant effect of top-pruning on survival after outplanting (Barnett 1984, Duryea 1990).

Effects of top-pruning on hardwoods were previously reported (South 1996). Due to short heights (c 0.5 meter) and a high survival rate (>79 percent) of most non-pruned seedlings, top-pruning increased average survival by only 5 percentage points (table 1). Therefore, for hardwood seedlings less than 0.5 meters tall, there was no relationship between survival of pruned and non-pruned seedlings ($Y = 75.8 + 0.16X$; $R^2 = 0.05$). However, out of a total of 18 comparisons, only in three studies was the survival rate lower for top-pruned seedlings. There was a 17 percentage point increase in survival for six studies exhibiting a benefit from top-pruning (ranging from +3 to +42 percent).

Importance of Restoring the Balance Between Roots and Shoots

The increase in survival due to top-pruning results from planting seedlings with a higher root-weight ratio (RWR) (i.e., a better "balanced" seedling). A proper balance between roots and shoots is important for good survival of loblolly pine (Larsen and others 1986). At lifting in December, a RWR within the range of 0.27 to 0.35 is preferred to a ratio of less than 0.25 [initial survival = 157.6 + 64.7 ln (RWR); $R^2 = 0.541$. On some droughty sites, an increase in RWR from 0.2 to 0.3 could increase seedling survival by 26 percentage points. The main reason nursery managers top-prune bare-root seedlings is to improve the RWR.

Improper and Proper Top-pruning

Pruning is a general term that refers to any removal of the foliage, branches, terminal bud, or stem of seedlings. This often vague term includes both "proper" and "improper' pruning. Proper top-pruning meets the objectives of the nursery manager (which might include reducing seedling height at planting, increasing the RWR at planting, increasing seedling uniformity, increasing seed efficiency). Likewise, improper top-pruning fails to meet management objectives. As an example, in some cases a single top-pruning will fail to meet the objective of reducing heights of pines in the nursery (Mexal and Fisher 1984, Haack 1988, Blake and South 1991). When compared to non-pruned seedlings, taller, improperly top-pruned seedlings might exhibit lower outplanting survival (Blake and South 1991). However, proper top-pruning of southern pine seedlings (involving a series of clippings) can reduce seedling height at lifting and this can result in a dramatic increase in field survival (Dierauf 1976, South and Blake 1994). It is now accepted that single top-pruning of loblolly pine or slash pine in the month of August is "improper" since it will likely have no effect on increasing RWR in December. Multiple top-pruning (typically involving three or more clippings) as described by Dierauf (1997) is much more likely to meet management objectives. The first clipping is typically conducted about August 1 and cuts about 10 to 20 percent of the seedlings. The second clipping cuts about 50 percent of the seedlings and is conducted in the last week of August. The third clipping occurs in mid-September about 3 or 4 weeks later (cutting perhaps 33 percent of the seedlings). In years with unusually rapid growth after the equinox, a fourth clipping may be required.

The difference between "proper" and "improper" pruning of pine seedlings depends on the degree of pruning. In some situations, moderate top-pruning (reducing shoot height by 17 percent) can improve survival of loblolly pine by 20 percentage points. However, removal of one needle will have no effect on reducing seedling height and would not result in increased survival. Top-pruning only the terminal bud will have no effect on the root growth potential of loblolly pine (Williams and others 1988). On the other hand, removing the entire shoot (increasing the RWR to 100 percent) will likely kill a loblolly pine seedling. Even removing all but 10 cm of stem (above the root-collar) can greatly increase mortality. Removal of all foliage by hand (leaving an intact stem) will reduce survival of longleaf pine and slash pine (Wakeley 1954). Removing too much foliage will decrease survival since new root growth of pines depends on needle biomass. Therefore, conifer seedlings should not be top-pruned to such an extent as to reduce new root growth or to check shoot growth (Brisbin 1888). However, several hardwoods are quite tolerant of severe top-pruning, and planting of "stumps" is an accepted practice in many tropical countries. This agrees with Tourney (1916) who stated that "On the whole, broadleaved species withstand pruning better than conifers."

Reasons to Top-Prune

Reasons for and against top-pruning are listed in table 2. Individuals in favor of top-pruning usually are so for economic reasons. The primary economic justification for top-pruning in the nursery is to increase field survival. For example, a 10 percent increase in survival might be worth $40 to $50 per hectare (ha). Assuming seedlings in a hectare of nursery can be used to plant 1,000 ha of woodlands, increasing seedling survival by 10 percent on all planting sites would increase crop value by $40,000 to $50,000 per ha. Even when top-pruning increased survival

Table 2—Reasons for and against top-pruning of bare-root seedlings

Stated reasons for top-pruning
It increases the chance of survival.
It increases the root/weight ratio.
It increases crop value by increasing seed efficiency.
It increases seedling uniformity.
For some species, it increases freeze tolerance.
For some species, it increases initial growth after outplanting.
For some top-blights, it reduces the disease symptoms at lifting.
For some species, it reduces shipping costs.
For longleaf pine, it permits lateral root pruning.
For some hardwoods, it reduces injury to workers during lifting.
Top-pruning allows managers to fertilize and irrigate to produce large root systems.
Stated reasons against top-pruning
It is not natural.
The balance between root and shoot is not important for survival.
It causes a wound.
It increases seedling uniformity.
It alters seedling biochemistry.
It causes forked seedlings.
It makes culling of small seedlings difficult.
It might increase disease.
For some species, it reduces the probability of having a terminal bud at lifting.
Top-pruning is not needed when short seedlings with small diameters are produced by withholding fertilization and irrigation.

by 10 percent on only 5 percent of the sites, crop value would increase by $2,000 to $2,500 per ha. Either case would easily justify the cost of top-pruning (about $40 per ha per clipping).

Another economic justification for top-pruning involves increasing seed efficiency. Seed efficiency is defined as the number of plantable seedlings produced per pure live seed. When increasing seed efficiency, top-pruning has a dual benefit. First, multiple top-pruning reduces the number of tall seedlings that exceed the culling limit. In one case where seedlings were top-pruned only once, 77 percent of the crop exceeded a cull limit of 33 cm (Haack 1988). Reducing the number of tall seedlings can be a major economic benefit when tall seedlings end up on the culling room floor. Second, top-pruning tends to reduce the growth of the dominants in the seedbed and allows some of the smaller seedlings to grow into a plantable grade. For pines, this "release" effect occurs mainly when multiple top-pruning is practiced. For example, with one pruning the smaller diameter seedlings might be decreased by 2 percentage points (Mexal and Fisher 1984) but with two prunings, a decrease of 5 percentage points might result (Duryea 1990). Assuming 1.5 million seedlings could be produced without top-pruning, an additional 30,000 to 75,000 plantable seedlings would increase crop value by $1,000 to $2,500 per ha.

Improving outplanting survival will allow some organizations to lower target outplanting densities. Planting fewer trees will not only reduce regeneration costs but will also allow the best genotypes to be planted over more hectares. Nursery managers may also benefit from reduced lifting, culling, and shipping costs. Although safety is sometimes mentioned as a reason to top-prune hardwoods (due to a reduction in eye injuries during hand lifting), this is typically not a driving factor. However, seedling uniformity can be important. In some cases, a nursery with uniform nursery beds will attract and retain more customers. In years with a regional seedling surplus, this will convert to a distinct economic advantage.

An improvement in seedling growth after outplanting is often observed for top-pruned seedlings. Typically the increase in growth allows pruned seedlings to catch up to the heights of non-pruned seedlings at the end of two or three growing seasons (Zaczek and others 1997). For some oaks, the probability of achieving dominance in the canopy is increased by top-pruning (Johnson 1984). For some species, the top-pruning increases the rate of bud flushing and stimulates "free growth" (Colombo 1986). In a few cases, top-pruned seedlings after two growing seasons were taller than non-pruned seedlings (Smith and Johnson 1981, McCreary and Tecklin 1994). However, in one study with white pine, seedlings top-pruned twice were still 15 cm shorter than controls after three growing seasons (Dierauf and others 1995).

Reasons Not to Top-Prune

Students of the "no top-pruning" school can provide several reasons why nursery managers should not top-prune seedlings (table 2). Most of these reasons are not based on economics but are based on feelings instead. One reason given for not top-pruning is that it is not "natural." However, this is not entirely true since deer, moose, cattle, and rabbits often top-prune both pine and hardwood seedlings. The terminals of many pines are killed in nature by insects. In some areas, 50 percent of the terminal buds of conifers die after outplanting (Colombo 1986). Some believe a live terminal bud is important at time of planting. However, terminal bud abortion is a natural and common occurrence for many angiosperms.

A few believe top-pruning is bad in that it produces a uniform seedling crop. A uniform seedling crop makes it more difficult to cull the bottom 25 percent of the population. With pines and some hardwood species, top-pruning does increase the number of seedlings with forks (Dierauf 1997) and some customers do not like forked trees. However, forks at time of planting affect appearance rather than long-term growth or survival.

Some who advise against top-pruning claim the concern for a balance between roots and shoots has been greatly overemphasized. For example, Kormanik and others (1995) say that a RWR of 0.12 is typical in November and has not affected survival of loblolly pine. Some point to studies in Canada that show no relationship between survival and seedling balance (Racey and others 1983, Bernier and others 1995). A lack of a relationship can be expected when researchers obtain high outplanting survival. Researchers typically achieve higher survival rates than operational planting crews. However, a significant relationship is more likely when some seedlings die due to unfavorable environmental conditions.

Some fear that top-pruning will increase disease. Tourney (1916) was concerned about the introduction of disease since "every cut produces a wound through which spores of fungi may gain access..." As a result, he said, "as little pruning should be done as is necessary to maintain a proper balance between root and shoot." The concern about top-pruning increasing seedling diseases persists today. If some unidentified disease is observed late in the growing season, top-pruning is sometimes suspected of having increased susceptibility to the pathogen.

One year at the Ashe Nursery in Mississippi, brown spot needle blight *(Mycosphaerella dearnessii)* was observed after pruning longleaf pine (Kais 1978). Top-pruning in July and November spread infected needles over the nursery. Even so, periodic clipping of needles during the growing season is recommended as a means to reduce the incidence of brown spot in the nursery. Pruning avoids forming a dense mat of needles and allows a uniform application of fungicides. Some managers who grow longleaf pine apply fungicides both before and after clipping. For drill-sown longleaf, clipping allows managers to do a better job of lateral root pruning which increases survival.

Top-pruning will not increase fusiform rust (*Cronartium quercuum f. sp. fusiforme*) in the nursery since spore flight occurs several months before the first clipping in August. However, Stanley (1986) reported an increase in rust on 3-year-old trees that had been severely top-pruned in the nursery. It seems likely that top-pruning to a height of 10 to 15 cm in the nursery stimulated height growth (and succulent foliage mass) the year after planting. The increase in rust galls at age 3 likely resulted from infection during the year after outplanting (above the 15 cm height). Other management practices that increase seedling growth also increase fusiform rust; these include fertilization, soil cultivation, and use of herbicides for weed control.

Some are concerned that top-pruning in the nursery will affect wood quality when the tree is harvested after 30 years. A similar concern was expressed by Tourney (1928) who stated that "Poor bole form, particularly crookedness, is very commonly caused by damage to the leading shoot or to the terminal bud." He adds that "The loss of the terminal bud very frequently causes double top in pine, spruce, balsam fir and larch." He said the double top causes great loss in the quality of the timber. These statements could lead some to conclude that injury to the terminal bud in the nursery always results in a permanently crooked or forked tree. However, there are no published data to support this belief. Long-term top-pruning studies with oak *(Quercus sp.)* and yellow poplar *(Liriodendron tulipifera* L.) report no problems with tree form. For Monterey pine (*Pinus radiata* D. Don), a fork low to the ground does not affect average tracheid length, spiral-grain angle, average density, or late-wood ratio (Nicholls and Brown 1974). In fact, total volume can be slightly greater for a forked tree. A fork caused by pruning seedlings to a 25 cm height would not be higher than 25 cm from the ground (few pines exhibit permanent forks this close to the ground). Likewise, a fork 1 meter above the ground would not be caused by top-pruning a hardwood back to a 50 cm height in the nursery. Although top-pruning will cause some seedlings to be forked in the year after planting, this fork is ephemeral and certainly does not move up the stem as the tree ages. After the seedlings are outplanted and reach a height of 2 meters, most people cannot tell the difference between a top-pruned and non-pruned loblolly pine. Although a harvested tree with two stems originating 25 cm above ground will produce different amounts and quality of lumber, there are no data to show that top-pruning increases the frequency of these (low forked) trees in a plantation.

Scientific Method

At this point I will digress and touch briefly on the scientific method. The scientific process follows a pattern: define the problem; make observations and collect data; analyze data and form a generalization; formulate a null hypothesis; design a study to test the null hypothesis; draw conclusions; accurately report and publish results; reevaluate generalization. The null hypothesis is rejected only when data from a well-designed study can be used to reject the hypothesis. In the case of lumber quality, the null hypothesis can be stated as: top-pruning in the nursery has no effect on lumber quality. I know of no data from a top-pruning study that can be used to reject this hypothesis. Since researchers cannot prove a null hypothesis, it remains the responsibility of those who reject the null hypothesis (e.g., claim that top-pruning does affect wood quality) to publish data to support their claims. In other words, it is unscientific to reject a null hypothesis using only intuition and assumptions (no matter how often the intuition is accepted by the public).

CONCLUSIONS

A large number of research studies indicate that proper top-pruning is a beneficial nursery practice. It can benefit nursery managers by increasing both crop value and seedling uniformity. For the consumer or forest landowner, seedlings that have been properly top-pruned will have a higher RWR and a greater chance of survival. Proper top-pruning increases growth after planting so that after 3 years in the field, there typically is no difference in total height between non-pruned and top-pruned seedlings.

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EFFECT OF DENSITY AND SPACING ON SEEDLING UNIFORMITY IN A LOBLOLLY PINE NURSERY

Thomas A. Greene and John R. Britt[1]

Abstract-We conducted a nursery study to determine the effects of spacing and arrangement on size and uniformity (variance) of loblolly pine (*Pinus taeda* L.) seedlings. Three spacings and two arrangements were simulated. Sections of nursery bed were thinned to 170 and 200 seedlings per square meter by either removing seedlings within each drill or by a combination of removing seedlings from within drills and removing the third and sixth drills in the bed. A control, unthinned treatment (approximately 320 seedlings per square meter) was also included. Standard nursery practices, including top-pruning and root-pruning, were followed. On October 21, 1996, seedlings were lifted by drill, and the following measurements were made: shoot length, root length, and root collar diameter. Oven-dry biomass of roots and shoots were measured on a subsample from each drill. Data were subjected to analysis of variance to determine treatment differences in means of measured variables. The effect of drill on seedling variables was determined. A one-tailed F test was used to test the alternative hypothesis that the six-drill variances were smaller. Variances of seedling shoot dry weights, root dry weights, and total dry weights were significantly reduced in the six-drill treatments, compared with eight-drill culture at both seedbed densities. Seedling root collar diameters were significantly less variable in the six-drill culture than in the eight-drill culture at the higher density, but not at the lower density. We concluded that six-drill seedling beds significantly reduced variability in seedling size compared to conventional eight-drill beds.

INTRODUCTION

Seedling uniformity is a significant factor influencing the quality of seedlings in loblolly pine nursery operations. Seedlings with highly variable root collar diameters and weights are difficult to pack, inefficient to plant, and have larger percentages of culls. These factors are also strongly correlated with survival and growth of seedlings after planting. Seedling size has been shown to strongly influence post-planting survival and growth in loblolly pine (South 1992, Switzer and Nelson 1963). Producing seedlings with small, predictable ranges of these variables is an important goal of nursery management. As part of a larger seedling quality project, we devised an experiment to test the hypothesis that seedlings grown in three pairs of drills spaced at 15 centimeters (cm) within the pair and 30 cm between pairs would have less variable size distributions than those grown in eight drills spaced at 15 cm, but have similar mean seedling sizes. We tested this hypothesis at two densities and compared to an operational check.

METHODS AND MATERIALS

Research was conducted during the 1996 growing season at the John F. Sisley Nursery in Buena Vista, GA. Two densities and two arrangements were simulated by thinning within drills and by removing drills 3 and 6 (of 8 drills). On June 6, 1996, 1.5-meter long [1.9 square meter (m^2)] sections of nursery bed were thinned to 170 and 200 seedlings per m^2 by either removing seedlings within each drill or by a combination of removing seedlings from within drills and removing the third and sixth drills in the bed. Original drill spacing was 15 cm; spacing between drills 2 and 4 and between drills 5 and 7 after removal of drills 3 and 6 was 30 cm. A control, unthinned treatment (approximately 320 seedlings per m^2) was included as an operational check. Treatments were applied in three randomized complete blocks. All plots were installed on beds sown with a single, half-sibling family to control for genetic effects. Operational nursery practices including fertilization, top-pruning, and root-pruning were followed. A schedule of these treatments is presented in table 1.

Between October 21 and 25, 1996 all seedlings within the interior 60 cm of each plot were lifted, and the following measurements were made: shoot length, root length, and root collar diameter. Drill identity was maintained throughout the data collection. Oven-dry biomass of roots and shoots were determined on four, systematically selected seedlings from each drill in each plot. Separate means were calculated for each drill. The effect of drill on seedling

Table I-Cultural treatments followed at Sisley Nursery during 1996 growing season

Treatment	Rate	Date
Sowing	—	Apr. 9
Undercutting	—	Aug. 6
Undercutting	—	Sept. 19
Lateral root pruning	—	Aug. 21
Top clipping	—	July 23
Top clipping	—	Aug. 20
Top clipping	—	Sept. 25
Ammonium sulfate	22.5 kg/ha N	Jun. 3
10-10-10	14 kg/ha N	Jun. 19
Urea ammonium nitrate	28.1 kg/ha N	Jun. 24
Urea ammonium nitrate	28.1 kg/ha N	July 17
Urea ammonium nitrate	28.1 kg/ha N	Aug. 5
Ammonium sulfate	22.5 kg/ha N	Aug. 28
Urea ammonium nitrate	28.1 kg/ha N	Sept. 9
10-10-10	14 kg/ha N	Sept. 9

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variables was determined. Data were subjected to analysis of variance to determine treatment differences in means of measured variables. One-tailed F tests were done to test the alternative hypotheses that the six-drill treatments had lower overall root collar diameter (RCD), shoot dry weight, root dry weight, and seedling dry weight variances.

RESULTS

Treatment means are presented in table 2. Root collar diameter and seedling biomass were negatively related to bed density, as expected. Drill arrangement had no significant effect on seedling biomass within a density, and only a minor effect on root collar diameter at the lower density level. Shoot and root length varied significantly among treatments, but no clear patterns were evident. Magnitudes of the differences in shoot length were not considered biologically significant.

Seedling weight variance was significantly reduced by the six-drill treatment at both bed densities, and RCD variance was significantly reduced at the 200 seedlings per m^2 density but not at 170 seedlings per m^2. Both shoot dry weight and root dry weight variances were similarly affected by the treatments (table 3).

Table 2—Means[a] of seedling variables by treatment measured at the end of the 1996 growing season in the seedling density and spacing uniformity trial

	Treatment[b]				
Variable	8-320	6-200	8-200	6-170	8-170
Density, seedlings/m^2	319	199	202	167	170
Root collar dia., mm	4.3d	5.1c	5.0c	5.3b	5.4a
Seedling dry wt., g	4.0d	5.6bc	5.2c	6.0ab	6.3a
Shoot dry wt., g	3.3c	4.6b	4.3b	5.0a	5.2a
Root dry wt., g	0.7c	1 .0ab	0.9b	1 .0ab	l.la
Shoot/root wt. ratio	5.4a	4.7c	5.4a	5.2ab	4.9bc
Shoot length, cm	31.8b	32.0ab	32.1ab	31.2c	32.2a
Root length, cm	16.7c	18.1b	18.0b	18.1b	18.6a

[a] Means in the same row followed by the same letter are n.s.d. according to Duncan's multiple range test, $p<0.05$
[b] Treatments are designated by [number of drills]-[target density].

Table 3-Variances and F statistics for one-tailed F tests of homogeneity of variance in the seedling density and spacing uniformity trial[a]

Variable	Density (trees/m^2)	Variance: 8-drill	Variance: 6-drill	F	P>F
Root collar diameter	200	0.90	0.67	1.33	0.01
Root collar diameter	170	0.71	0.77	0.92	n.s.
Seedling dry weight	200	3.97	2.89	1.37	0.10
Seedling dry weight	170	5.18	3.32	1.56	0.05
Shoot dry weight	200	2.90	1.91	1.52	0.05
Shoot dry weight	170	3.52	2.42	1.46	0.05
Root dry weight	200	0.49	0.18	20.	0.01
Root dry weight	170	0.21	0.10	2.01	0.01

[a] Degrees of freedom for the F tests were 450/443 for root collar diameter at 200 seedlings per square meter, 379/371 for root collar diameter at 170 seedlings per square meter, and 95/71 for the other variables and densities.

DISCUSSION AND CONCLUSIONS

Significant reductions in the variability of seedling RCD and dry weight were achieved by growing the trees in six unequally spaced drills as compared with eight equally spaced drills. We attribute this effect to the reduction in the variability of the competitive environment encountered by each seedling. Each seedling has two types of competitors-those in the same drill and those in the adjacent drills. For the seedlings in the outer two drills, adjacent-drill competition is, of course, restricted to one side, while inner-drill seedlings face adjacent-drill competition on both sides. In the six-drill beds, adjacent-drill competition is reduced for the inner drill seedlings by removing drills 3 and 6. Although the competitive environment is not identical for inner and outer drills under the six-drill regime, it is much more similar.

We concluded from this study that it is possible to reduce within-bed seedling size variability without changing seedling size by manipulating seedling arrangement. Further research is needed to determine whether the six-drill arrangement will reduce seedling variability at higher bed densities.

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TOPWORKING GENETIC SELECTIONS TO REDUCE THE BREEDING CYCLE IN LOBLOLLY PINE

David L. Bramlett and Leon C. Burris[1]

Abstract-Genetic improvement of forest trees is a slow process because many tree species have long generation intervals. Even though forest geneticists can make early evaluations in progeny tests, the new genetic selections cannot be bred until adequate male and female strobili are produced on the selected genotypes. This time period is typically 4 to 6 years, or even longer, after the selections are grafted into a seed orchard or clone bank. The topworking procedure described reduces the generation interval in loblolly pine (*Pinus taeda* L.) and, thus, reduces the breeding cycle for the species. In this study, 200 selected scions from progeny tests were grafted into the crowns of reproductively mature loblolly pines in an operational seed orchard. One-half of the grafts were made in the upper crown and one-half were made in the lower crown. One year after grafting, 55 percent of the surviving topworked scions produced female strobili in the upper crown, and 33 percent of similar scions produced pollen in the lower crown. Two years after grafting, the total number of female cones was 875 on 96 live branches in the upper crowns. In the lower crowns, no female strobili were produced in either year but 91 percent of the live grafts produced pollen strobili 2 years after grafting. The number of pollen clusters on the surviving grafts in both the upper and lower crowns increased from 99 in year 1 to 1,394 in year 2. Topworking is an effective and inexpensive procedure and has the potential to greatly accelerate the tree improvement process by reducing the breeding cycle in loblolly pine.

INTRODUCTION

Tree improvement programs in loblolly pine (*Pinus taeda L.*) use a recurrent selection strategy in which new selections are made among individuals in the best performing families based on progeny field trials. Crosses among the selections evaluate the genetic performance of each selection and produce the next generation of pedigreed individuals for recurring selections. Plant breeders who work with annual crops can complete a breeding cycle in the growing season after selection. Unfortunately, this process is much slower in forest trees and is the major deterrent to accelerated breeding programs.

Once selections are made, vegetative propagation is used to move the genotype from the field site to a breeding orchard or clone bank location. After the genetic tests are completed, the best of the new selections are sent to a seed orchard. This process requires valuable time between selection and establishment in a seed orchard. Tree breeders seek to shorten the breeding cycle by reducing the generation interval, i.e., the time required to produce adequate pollen and female strobili and complete cross-pollinations among selected genotypes for genetic testing.

To reduce the generation interval in forest trees, indoor breeding facilities were developed. Large containers with grafted trees were grown in a high-ceiling greenhouse environment. Water stress and gibberellic acid induced the young grafts to produce both female and male clones to use in the breeding program (Greenwood and others 1986). Using this method, selection preceded seed production by at least 5 years.

Burris and others (1991) reduced indoor breeding schedule by 1 year when they applied flower inductive treatments in the same year as grafting. The breeding cycle could not be reduced further because pollen was unavailable on indoor-grown pines until 26 months after grafting. A surrogate pollen production method produced pollen in year 1 (Bramlett and others 1995). Scions from newly selected genotypes were grafted into the lower crown on heavy pollen-producing trees in a production seed orchard. Pollen strobili, present 13 months after grafting, provided adequate pollen for breeding four of five grafted genotypes.

Similar experiments produced female strobili on newly selected scions when grafted into the upper crown of seed orchard trees. Bramlett and Burris (1995) reported that scions from seedlings age 1 to 5 years produced female strobili 1 year after grafting into reproductively mature loblolly pines. This paper presents the results of second-year growth and flower initiation on scions grafted into the upper and lower crowns of reproductively mature loblolly pines.

MATERIALS AND METHODS

Scions were collected from trees that ranged in age from 1 to 5 years. Scions from each age class were part of a 12-clone, first-generation mix of trees used as a check lot in the Weyerhaeuser Company's progeny tests. Because the mix had an equal number of seedlings from each clone, each age class included similar but not identical genetic material. Individual trees selected for scion collection could not be identified by individual family, but the composite sample represented a minimum of 15 trees from the same genetic source. Scions from age classes 2 to 5 were collected from progeny test sites. Scions from age class 1 were collected from seedlings growing in a nursery bed.

Four clones were selected as receptor clones in the Weyerhaeuser Company's second-generation loblolly pine

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seed orchard at Lyons, GA. Good female and pollen strobili producers, these clones had been established in the seed orchard in 1984. The seed orchard is intensively managed by fertilizing, mowing, applying herbicides, and spraying for insect pests.

Scions were grafted in February 1994. The scion was prepared by removing all needles and making longitudinal cuts to form a wedge starting just below the terminal bud. Ten receptor (interstocks) branches were chosen, five in the upper crown and five in the lower crown. A longitudinal cut was made just below the terminal bud of each interstock branch, reaching into the pith area and continuing downward for another 3 to 4 inches. The prepared scion was inserted into this slit. After the left side of the scion cambium was matched with the cambium layer of the interstock, the scion was secured in place with a rubber budding strip. Hot wax (175 to 200 °F) was applied to the completed graft. Two to four weeks after new shoot growth emerged through the wax, the interstock branch tip and the rubber budding strip were removed.

A split-plot experimental design was used with the receptor clones considered blocks and scion age the treatment variable. An individual ramet of the receptor clone was the whole plot, and crown location was the split plot. Five individual branches were observations within the subplots. The receptor clone was considered a random variable, and treatment (age class) a fixed variable. Survival of scions, shoot elongation, and the number of female and pollen strobili in the upper and lower crown locations were recorded in March 1995 and 1996.

The data were analyzed using the SAS (SAS Institute, Cary, NC) procedure for mixed models. Contrasts were computed for all possible comparisons (10) of the five scion age classes for the upper and lower crown levels. For each response variable tested, mean separation was computed using the 5 percent level of probability for the comparison-wise error rate.

RESULTS AND DISCUSSION

The pronounced effect of crown location on shoot growth, observed in the first year after grafting, became even more evident in the second year after grafting. Surviving lower crown grafts increased in shoot length from an average of 5.4 inches to an average of 14.8 inches after the second growing season (table 1). Scions grafted in the upper crown produced branches that were much larger in both years. In year 1, shoot growth averaged 14.6 inches. In year 2, shoot length increased to an average of 33.0 inches. The crown location effect on shoot growth was statistically significant at the 0.01 level of probability in both the first and second year after grafting. Differences were not statistically significant among the mean values for shoot growth within age classes in either the upper or lower crowns.

The increased growth of grafted branches in the upper crowns also increased the number of second order branches and, subsequently, the number of potential flower producing locations. Although the total number of branches was not recorded in the second year, the upper crown grafts had much larger branches and a more complex branching order than lower crown grafts. Grafted scions in

Table 1 -Shoot growth on 1- to 5-year-old scions 2 years after grafting into mature loblolly pines

Receptor clone	Crown level	Scion age (years)					
		1	2	3	4	5	Mean
		Inches					
24	Lower	10.3	12.2	15.6	16.6	14.0	14.1
12		16.6	23.2	14.5	18.4	9.7	16.9
66		17.0	12.5	15.4	14.6	13.4	14.6
10		14.5	14.6	15.6	12.0	13.1	13.9
Mean[a]		15.0a	15.9a	15.3a	15.4a	12.8a	14.8
24	Upper	31.4	35.4	35.4	32.4	28.4	32.6
12		33.0	39.6	29.8	37.6	24.7	33.8
66		24.4	36.4	38.6	39.8	30.2	33.9
10		30.5	34.2	39.4	17.8	37.0	31.8
Mean[a]		29.8a	36.4a	36.1a	31.9a	30.7a	33.0

[a] Means followed by the same letter are not significantly different at the 0.05 level.

both the upper and lower crowns retained their juvenile foliar appearance in the second year. Needles on grafts were smaller in length and diameter than mature foliage of the interstock. Needles on grafts also showed differential dormant season coloration, with grafts having more yellow foliage, typical of juvenile trees. In addition, the dormant buds of grafted scions were smaller in diameter and length than comparative buds on the interstock, and the shoots of grafts elongated more growth cycles than similar branches on the interstocks.

Female Strobili Production

The number of female strobili produced in the upper crowns increased the second year after grafting. In the first year, 247 female strobili were initiated on the 96 live grafts. In the second year, 875 female strobili were produced on the grafts, averaging 9.1 strobili per live graft (table 2). Female strobili were not produced on any branches grafted in the lower crowns. This pattern reflects the normal distribution of female strobili within the crown of loblolly pine. The mean number of female strobili was significantly larger on 4-year-old scions than on 1 -year-old or 5-year-old scions. The observation that 4-year-old scions have more strobili than 5-year-old scions may be a result of different clonal material.

Pollen Clusters

One year after grafting, no pollen clusters were initiated on scions from 1 -year-old trees grafted in either the upper or lower crowns (Bramlett and Burris 1995). However, 2 years after grafting, scions from l-year-old seedlings produced pollen in both upper and lower crowns and scions from all other age classes produced abundant pollen (table 3). In the lower crowns, 88 percent of the live grafts produced pollen 2 years after grafting; in the upper crowns, 96 percent produced pollen. Pollen production dramatically increased in the upper crowns from year 1 with 43, to year 2 with 1,101 clusters or an average of 11.5 pollen clusters per live graft. This large increase probably resulted from the large increase in shoot growth of grafts in the upper crowns. Grafted branches averaged over 33 in. in length with many side shoots and multiple low order branches, which are optimum sites for pollen initiation. In addition, in the 2 years since grafting, the growth of the tree crowns has increased and the former upper crowns are now more correctly classified as midcrowns. The midcrown is within the zone of heavy pollen production on the seed orchard ramets used for interstocks. The difference in pollen production between the lower and upper crowns was statistically significant at the 0.01 level of probability. No statistical differences were noted among mean values for scion ages in the lower crowns. In the upper crowns, 4-year-old scions produced fewer pollen strobili than 2-, 3-, or 5-year-old scions. This result is probably an effect of the specific genotypes used in the study.

CONCLUSIONS AND IMPLICATIONS

Waiting an additional year after topworking new selections into mature loblolly pine crowns apparently increases the number of female strobili and pollen clusters for breeding. Even though this delay would add 1 year to the breeding schedule, fewer grafts would provide enough strobili to complete the breeding cycle.

The 350 percent increase in female strobili production is partly a result of selecting large primary branches for grafting. These branches continued to develop within the tree crowns and increase in size and number of female strobili per graft. These primary branches were also suitable for installing isolation bags for controlled pollination procedures. For efficient tree breeding, a relatively small number of topwork grafts could be made and controlled pollination could begin the second year after grafting. How many grafts are enough for each selection? Based on this study, approximately nine strobili were produced per living graft 2 years after grafting.

Table 2—Female strobili produced after 2 years from five grafts on 1- to 5-year-old scions grafted into the upper crown of mature loblolly pine (no female strobili were produced in the lower crown)

Receptor clone	Crown level	Scion age (years) 1	2	3	4	5	Total
		Numbers					
24	Upper	27	35	24	37	81	204
12		33	64	26	171	0	294
66		34	90	18	71	12	225
10		2	39	85	13	13	152
Mean[a]		24b	57 ab	38 ab	73 a	26b	219
Total		96	228	153	292	106	875

[a] Means followed by the same letter are not significantly different at the 0.05 level.

Therefore, 5 to 10 grafts for every anticipated cross in the mating design should provide adequate female strobili for breeding 2 years after grafting. Of course, grafting success is critical! In this study, 96 percent of attempted grafts were alive in the upper crowns 2 years after grafting; 91 percent in the lower crowns. These results may be exceptional but a success rate of 75 to 80 percent appears achievable. Grafting procedures are basically similar in the crowns and at ground level except for logistics. However, procedures to maintain hot wax in a bucket truck or aerial lift are required to maintain grafting efficiency and to minimize the time and expense of grafting.

These results give the tree breeder another option. If the breeder waits until the second year after grafting, both male and female strobili production increase dramatically. Thus, if the breeder waits until year 2, only a few grafts (5 to 10) in the upper and midcrowns may produce enough pollen and female flowers to complete each cross.

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Table 3-Total number of pollen clusters produced 2 years after grafting in the lower and upper crown of topworked, mature loblolly pines

Receptor clone	Crown level	Scion age (years) 1	2	3	4	5	Total
		Numbers					
24	Lower	2	8	15	23	10	58
12		17	9	17	28	5	76
66		1	19	22	25	21	88
10		4	19	14	21	13	71
Mean*		6a	14a	17a	24a	12a	73
Total		24	55	68	97	49	293
24	Upper	18	46	62	29	58	213
12		42	106	38	82	22	290
66		26	122	46	44	87	325
10		37	39	103	31	63	273
Mean[a]		31b	78ab	62ab	46b	58ab	275
Total		123	313	549	186	230	1101

[a] Means followed by the same letter are not significantly different at the 0.05 level.

Site Preparation

Moderator:

LARRY R. NELSON
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SITE PREPARATION TREATMENT IMPACT ON *PINUS TAEDA* AND *PINUS SEROTINA* VOLUME PRODUCTION IN A NORTH CAROLINA POCOSIN

Jerry L. Bettis, Sr.[1]

Abstract-Converting the pocosin landform to loblolly pine (*Pinus teada* L.) plantations has again received increased attention. However, the recent attention has not been geared toward the "wondrous yields of loblolly pine when planted on pocosin soils," but instead, what are the alternatives? Should we even be draining and converting this landform? One of the current difficulties in answering this question is our lack of information on pond pine (*Pinus serotina* Engelm.) productivity, whether grown naturally or in plantation. The results of this study show that maximum site preparation treatment (disk/burn and fertilization) yields the highest planted pine volume. However, this high volume is associated with pond pine and not loblolly pine, as might be expected. In almost all cases, loblolly pine produced higher average heights and diameters, and pond pine produced higher stocking levels. Fertilization increased planted pine diameter, height, and volume, as expected.

INTRODUCTION

Converting the pocosin landform to loblolly pine plantations has again received increased attention. However, recent attention has not been geared toward the high productivity of loblolly pine when planted on pocosin soils, but instead, what are the alternatives? Should we even be draining and converting this landform? One of the current difficulties in answering this question is our lack of information on pond pine productivity, whether grown naturally or in plantations.

Another difficulty in answering this question is that "model" pond pine stands, whether natural or planted, are rare if not nonexistent. However, it is accurate to say that a few isolated, suitable pond pine stands exist today. This study was conducted to determine the growth response and potential productivity of two pine species (loblolly and pond) growing in a low pocosin in eastern North Carolina.

METHODS

Three treatment combinations (site preparation, species, and fertilization) were allocated randomly by Teate (1967) in the original stand establishment. The block layout consists of five ditches dug east and west and two ditches dug north and south through the middle of a low, unaltered pocosin. The plantation of interest comprises a 25.91 hectare (ha) tract divided into four blocks.

The site preparation consists of four treatments: (1) control, (2) burn, (3) disk, and (4) disk/burn. Each of the four site preparation treatment plots was subdivided into four 0.4047-ha square subplots, and one-half of each subplot was randomly allocated to loblolly and pond pine plantings. The planting took place during March and April of 1963 on a 1.8 by 2.4 meter (m) spacing. Prior to planting, each 1-acre subplot was randomly selected for one of the following fertilizer treatments: (1) control-no fertilizer application; (2) lime at 12.35 tons per ha; (3) Calphos at 2.47 tons per ha; and (4) lime plus Calphos at the above rates. ("Calphos" is a mixture of calcium phosphate and kaolin, a colloidal phosphate.)

This study investigated the planted pine productivity and response to the nonfertilized (None) and Calphos or phosphate (P_2O_5) fertilization treatments across all four site preparation treatments.

Tree height and diameter were measured on trees in the two center rows in each control and phosphate 0.20 ha subplot. Data were tallied in each 6.47 ha block by species, fertilizer, and site preparation treatments.

ANALYSIS OF DATA

The loblolly and pond pines were analyzed for growth (volume, diameter, and height) by treatment combination. Three (inside bark and total height) volume equations are used in the planted pine analysis: (1) loblolly pine (volume $= 0.11691 + 0.00185 \times D^2Ht$); (2) pond pine 12.7 - 22.6 centimeters (cm) (volume $= -0.301238 + 0.002452 \times D^2Ht$); and (3) pond pine $\geq$ 22.86 cm (volume $= 0.088812 + 0.002374 \times D^2Ht$). The loblolly pine volume equation is designed for plantation grown wood (Burkhart 1977). The pond pine volume equations are designed for naturally grown wood[2], since no volume equation exists for pond pine grown in plantations. Pond pine volume for trees smaller than 12.7 cm was estimated using equation (2).

RESULTS AND DISCUSSION

The disk fertilized loblolly pine treatment yielded 38.21 cunits per ha (1 cunit = 100 cubic feet of solid wood). This volume is less than one-half that of a loblolly pine pocosin plantation receiving average silvicultural care (98.84 cunits per ha: author's experience after working 5 years in eastern North Carolina). The average height is only 57 percent of the expected value (28.32 m: author's experience), while the average diameter is slightly above that of the average pocosin loblolly pine plantation. These low values are due to loblolly pine's inability to compete and survive in an unbedded and unweeded environment. The low height is due to loblolly's inability to compete with the pocosin vegetation in an unweeded regime. The low volume is attributed to low height and stocking level.

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[2] Personal communication. 1994. N.O. Cost, U.S. Department of Agriculture, Forest Service, Southern Research Station, Asheville, NC.

Of the four disk treatments, the disk fertilized pond pine treatment stands out significantly with 1,003 stems per ha and 74.84 cunits per ha. This volume is acceptable though not equal to what is expected of a loblolly pine plantation receiving average silvicultural care when grown on pocosin soils. On a positive side, this productivity is only 24 percent below expectation of 98.84 cunits per ha. The surviving stocking level of 1,003 stems per ha is high, and the relatively high volume is related to stocking. The association of pond pine and pocosin vegetation resulted in a detriment to this stocking value. That is, too many trees survived, creating smaller stems with an average diameter of 20.8 cm. This treatment had the second highest volume productivity found in this study and, based upon the treatment regimes employed in this study, one would choose this treatment combination second to the disk/burn fertilized pond pine treatment when wood production is of primary concern.

Clearly, the disk nonfertilized loblolly pine treatment is a commercial failure with just 7.84 cunits per ha. This low volume is attributed to the low survival of 96 stems per ha. The disk nonfertilized pond pine treatment also has a comparatively low survival rate (662 stems per ha), though not as low as its loblolly counterpart. In the absence of fertilization, the competing vegetation grew much faster and shaded out many of the planted pine seedlings. With fertilization, it is clear that the surviving trees grew compartively much larger.

Since no fertilizer was added to the disk nonfertilized pond pine treatment and pond pine is the planted species, volume per hectare is not expected to be high, based on previous results, even though the stocking level is comparatively high at 662 trees per ha. However, the volume level is three times higher than that of the disk nonfertilized loblolly pine treatment at 20.77 cunits per ha. Still, this is an unacceptable productivity level for commercial forestry. The low volume is due to low stocking, and small average height and diameter. The average height and diameter are 11 m and 14 cm less than the expected value, respectively.

When the burn treatment combinations are considered, the pond pine combinations stand out, though the results are not highly significant. The burn fertilized loblolly pine treatment's planted pine volume per ha, 39.32 cunits, is less than one-half that of a pocosin loblolly pine plantation receiving average silvicultural care. The low productivity is due to loblolly pine's inability to survive and grow in the burn fertilized treatment. The pocosin vegetation resprouted quickly following the burn treatment, and its growth was boosted by the added fertilizer. The average diameter of loblolly pine for this treatment equals the expected value, at 24.8 cm, but the average height is considerably lower than that of the average pocosin loblolly pine plantation, at 13.5 m. The low average height is due to loblolly pine's inability to compete with the pocosin vegetation in the absence of severe site disturbance and fertilization.

The burn fertilized pond pine treatment's volume is 36.19 cunits per ha. This value is only 37 percent of what might be expected of a pocosin loblolly pine plantation receiving average silvicultural care. This low productivity, even though trees per ha are relatively high for this study, is due to relatively low stocking and pond pine's stature, i. e., greater tapering and short trees.

The burn nonfertilized loblolly pine treatment's volume is a commercial failure at 8.29 cunits per ha. Since loblolly pine didn't survive well in this study, it is not surprising to see such a low value in the absence of fertilization. This low volume is due to low stocking and poor height and diameter. The average height is 41 percent of the expected value of a pocosin loblolly pine plantation, and the average diameter is slightly lower than the average. The low average height and diameter are attributed to the lack of fertilization.

Because the planted stems per ha are high in the burn nonfettilized pond pine treatment, one would expect volume productivity to also be high. However, planted pond pine without supplemental fertilization grew at a slow pace, producing only 25.98 cunits per ha at age 29 years. Again, pond pine does not produce high volumes due to its stature. The average height and diameter are quite low, and the stems per ha are only 75 percent of the expected value at 657. The low diameter, stocking, and height are a function of the species and the absence of fertilization.

It has been shown that loblolly pine does not survive well with the pocosin lesser vegetation; therefore, the control fertilized loblolly pine treatment's low planted pine volume, 34.12 cunits per ha, is not surprising. The low productivity is due to a small number of surviving trees (227 stems per ha) and poor height growth (60 percent of the expected value). However, average diameter exceeds the expected value which is a function of the fertilization and low stocking level, while the low height is a function of the species.

Since there are more than 900 stems per ha in the control fertilized pond pine treatment, one would expect productivity to be relatively high. The volume for this treatment is 55.43 cunits per ha, a value that is 44 percent less than that of the average loblolly pine pocosin plantation. Again, the stature of pond pine, even with fertilization, prevents it from attaining volume levels comparable to that of a pocosin loblolly pine plantation receiving average silvicultural care. The average height and diameter are 16 m and 4.5 cm, respectively, less than the expected value. The low diameter is attributed to the relatively high stem count and the low height is attributed to the species.

The planted seedlings in the control nonfertilized loblolly pine treatment did not survive well, and the volume per ha is low at 10.20 cunits. This treatment has the lowest productivity of the four control treatment combinations, at one-tenth the volume of an average managed loblolly pine pocosin plantation. The average height and diameter are

16 m and 5.5 cm, respectively, less than the expected value. This low volume is due to the low stocking level of 227 stems per ha, while the low diameter and height are due to the lack of fertilization and weed control.

When considering the control nonfertilized pond pine treatment, one finds 17.00 cunits per ha, still another commercial failure attributed to the lack of fertilization, slightly low stocking, and the stature of pond pine-i.e., small diameter and short stems. The average height is more than 300 percent less than the expected value, and the average diameter is 66 percent less than the expected value.

These outstanding results, high in the case of pond pine and low in the case of loblolly pine, are attributed to: (1) pond pine's association with pocosin vegetation, (2) pocosin environment, (3) lack of fertilization, (4) lack of severe site alteration, and (5) genetics.

The disk/burn fertilized loblolly pine treatment's volume productivity of 58.96 cunits per ha is 66 percent of a loblolly pine pocosin plantation receiving average silvicultural care. This relatively high volume, though lower than the expectation, is due to accelerated growth resulting from the application of fertilizer and the drainage effects. The low volume level is attributed to the low stocking level, 437 stems per ha, which is one-half the expected value. The maximum site preparation disturbance (disk/burn) is offset by the stocking level. The average height is low at 17.7 m and the average diameter is slightly below the expectation at 27.9 cm. The low height is attributed to competition from the pocosin vegetation.

Contrary to expectation, the disk/burn fertilized pond pine treatment has the highest planted pine volume of any observed in this study, at 78.92 cunits per ha. This high volume productivity is 75 percent of that expected of a loblolly pine pocosin plantation receiving average silvicultural care. The treatment's productivity is high due to high planted pine survival: 1,228 trees per ha. This stocking level is about 40-50 percent higher than optimum for a plantation 29 years old.

Caution is warranted here, as volume per hectare is just one measure of forest productivity. Perhaps the most meaningful measure is product, since the value difference between pulpwood and gradewood is quite high. Alternatively, one can argue that thinning can be used to reduce this treatment's stocking level and create a desired product, i.e., a large average diameter. This, assumes that pond pine's wood quality and property are comparable to those of loblolly pine. The average height and diameter are much lower than the expected values. The low diameter is due to high stocking, while the low height is attributed to the species.

When the disk/burn nonfertilized loblolly pine treatment is considered, one finds another commercial failure with a volume of 23.47 cunits per ha. This level is only 25 percent of the expected value of an average managed pocosin loblolly pine plantation. The low volume is due to a low stocking level of 373 trees per ha and relatively poor growth. This treatment's planted pine survival is the lowest of the disk/burn combinations. The average height and diameter are much lower than the expected value. The low volume, stocking, height, and diameter are attributed to the lack of fertilization.

Because the stocking level is high in the disk/burn nonfertilized pond pine treatment, one would expect relatively high-volume productivity. However, this treatment produced 35.20 cunits per ha, a value that is only 36 percent of a pocosin loblolly pine plantation receiving average silvicultural care. The low volume is due to pond pine's stature and the lack of fertilization. The average height and diameter are 17 m and 8 cm, respectively, below the expected value. The low volume, height, and diameter are attributed to the lack of fertilization and high stocking level.

CONCLUSIONS

1. The disk/burn fertilized pond pine treatment has the highest planted pine volume productivity, and is recommended when wood production is the overwhelming consideration.
2. Pond pine has a "harmony or association" effect with pocosin lesser vegetation.
3. Planted pine volume and stem count increase in association with pond pine.
4. Loblolly pine has higher average heights and diameters than pond pine.
5. Fertilization increases planted pine diameter, height, and volume.

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SITE PREPARATION TECHNIQUES FOR ESTABLISHING MIXED PINE-HARDWOOD STANDS IN THE SOUTHERN APPALACHIANS

John A. Mullins, Edward R. Buckner, Thomas A. Waldrop, and Richard M. Evans'

Abstract-Following commercial clearcutting of an upland hardwood stand, four site preparation treatments (control, silvicultural clearcut, fell-and-burn, and brown-and-burn) were tested for establishing a mixed pine-hardwood stand. Half of each treatment plot was planted (20 by 20 foot spacing) with 1-O loblolly pine (*Pinus taeda* L.) and the other half with 2-O white pine (? *strobus* L.). After six growing seasons the resulting stands were composed of both natural regeneration (both hardwoods and pines) and planted pines. There were significant differences among the four site preparation treatments in numbers of naturally established stems per acre, and in the survival and growth of planted pines. Most of the differences were due to the use of fire, which reduced the number of hardwood stems, providing pines room to grow. Both the brown-and-burn and fell-and-burn treatments resulted in the establishment of a significant planted pine component, while the commercial and silvicultural clearcuts did not. The brown-and-burn treatment produced the best survival and growth of the planted pines and will likely develop into an understocked pine stand. At this time the fell-and-burn treatment has the best opportunity to develop into a mixed pine-hardwood stand.

INTRODUCTION

The inability to develop forest management strategies that are attractive to the nonindustrial, private forest landowner (NIPF) has been troublesome to forestry professionals for decades. Recurring reasons given by NIPF landowners for their failure to practice the more widely recommended forms of forest management are: (1) failure of these practices to maintain good wildlife habitat, (2) their dislike for the lack of diversity in pine plantation monocultures, and (3) their dislike of the clearcutting and conversion to short rotation management systems (pines) that are commonly recommended. Most NIPF landowners will not invest in forest regeneration (Alig and others 1990), yet would prefer to be growing a forest crop of some economic value. Failure to address these constraints is, to a large degree, the reason why the forestry profession has had little impact on NIPF landowners in Eastern North America.

These problems are most acute in upland forests that tend to be more droughty and less productive. Many of these sites are currently supporting low-quality forests due to repeated high grading, fires, and grazing. Pines are more marketable and tend to be more productive on these poorer, droughty sites than hardwoods. A strategy that will likely be attractive to NIPF landowners would be maintaining pines in mixtures with hardwoods to improve wildlife habitat with lower establishment inputs (planting with wider spacing, and less site preparation) than traditional monocultural procedures.

The initial problem that must be addressed in moving these forest lands toward some reasonable degree of productivity is the removal of low-quality trees from stands. In most cases this will be most effectively and efficiently done with a silvicultural clearcut. Once this low-quality material is removed, natural regeneration most often creates pure hardwood stands. Waldrop (1997) has found that a pine component can be introduced by planting pines with wide spacing after using various low-cost site preparation treatments.

METHODS

The study was conducted on the Oak Ridge Forestry Experiment Station, a unit of the University of Tennessee Agricultural Experiment Station. An upland hardwood stand on a south-facing slope was commercially clearcut; all sawtimber, pulpwood, and firewood [down to a diameter at breast height (d.b.h.) of 5 inches] was removed from the site. Twenty 1-acre, square plots were established within the harvest area. A randomized complete block design with five replications of the four site preparation treatments was used. The whole-plot treatments were: (1) control (commercial clearcut); (2) silvicultural clearcut; (3) brown-and-burn, (industry-type site-preparation method); and (4) fell-and-burn (Abercrombie and Sims 1986, Phillips and Abercrombie 1989).

In the spring following the commercial clearcut, all remaining trees taller than 6 feet were felled on plots receiving the silvicultural clearcut and the fell-and-burn treatments. The brown-and-burn plots were hand sprayed in midsummer (late July, early August), simulating a helicopter application of a tank mix consisting of 12 ounces Arsenal@, 2 quarts Roundup@, and 1 quart ionic surfactant in 10 gallons of water per acre.' The brown-and-burn and fell-and-burn treatment plots were burned on September 8 and 9, 1989. Each treatment plot was split in half with both loblolly pine (1-O stock) and half to white pine (2-O stock) planted to each subplot, respectively. The pines were planted in rows arranged perpendicular to the slope to eliminate a possible slope effect on species response. Each species subplot consisted of five rows 20 feet apart with trees in rows planted 20 feet apart. Pine seedlings were planted by hand using dibble bars.

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In September 1995, after six growing seasons, the following data were collected for all planted pines: (1) survival, (2) total height (nearest foot), and (3) d.b.h. (1/10 inch). For natural regeneration the data included the number of stems per acre by diameter class and species. Natural regeneration was sampled along two transects, 6.6 feet wide and 66 feet long (0.01 acre). Stems (the dominate stem in a clump) were tallied by species in 1-inch-diameter classes along the transect. Data were analyzed using a random block [split plot] model (Proc Mixed) (SAS 1996). Survival data were transformed using an arsin (SAS) transformation. Least square means were produced and compared using pairwise t-tests (P> .05).

RESULTS

Species Composition

Pre-harvest stand-The most abundant overstory trees in the preharvest stand were chestnut oak, white oak, yellow-poplar, and blackgum (see table 1 for scientific nomenclature). Sourwood, red maple, hickories, sugar maple, sassafras, southern red oak, post oak, black cherry, and shortleaf pine were minor overstory components (Andrews 1995). The understory consisted primarily of red maple, sourwood, blackgum, sassafras, and dogwood, (Andrews 1995). The preharvest stand was uniform in species mix and stocking across the study site.

Regenerating stand-Seven years after stand harvest, 27 hardwood and 3 conifer species were found regenerating naturally on the study site (table 1). The species mix was similar to that of the preharvest stand.

Table l-Species found on the study site seven growing seasons after harvest and site preparation

Common name	Scientific name[a]
Black cherry	*Prunus serotina* Ehrh.
Blackgum	*Nyssa sylvatica* Marsh
Black oak	*Quercus velutina* Lam.
Black walnut	*Juglans nigra* L.
Carolina buckthorn	*Rhamnus caroliniana* Walt.
Chestnut oak	*Quercus prinus* L.
Dogwood	*Cornus florida* L.
White ash	*Fraxinus americana* L.
Hickories[b]	*Carya* sp.
Eastern redcedar	*Juniperus virginiania* L.
Red maple	*Acer rubrum* L.
Sassafras	*Sassafras albidum (Nutt.) Nees*
Scarlet oak	*Quercus coccinea* Muenchh.
Sourwood	*Oxydendrum arboreum* (L.) DC.
Southern red oak	Quercus *falcata* Michx.
Sugar maple	*Acer saccharum* Marsh.
Shortleaf pine	*Pinus echinata* Mill
Serviceberry	*Amelanchier arborea* (Michx. f.) Fern.
Virginia pine	*Pinus virginiana* Mill.
White oak	*Quercus alba* l.
Yellow-poplar	*Liriodendron tulipifera* L.

Species with only one stem count per 40 plots; American chestnut, *Castanea dentata* Marsh; Cucumber magnolia, *Magnolia acuminata* L.; Eastern redbud, *Cercis canadensis* L.; Mimosa, *Albizia julibrissin* (Durazzini) Wild.; Paulownia, *Paulownia tomentosa* (Thunb.) Sieb.& Zucc. ex Steud.; Red mulberry, *Morus rubra* L.; Sweetgum, *Liquidambar styraciflua* L.
[a] Taxonomy follows Little(1988)
[b] Includes mockernut *(C. tomentosa* Nutt.), pignut (*C. glabra* (Mill.), and shagbark (C. *ovata* (Mill.) K. Koch.

Treatment Effects

Seven years after treatment, stem counts of potential overstory species differed significantly among treatments (table 2). The plots that were not burned (commercial clearcut and silvicultural clearcut) had significantly higher stem counts (3,573 and 4,186, respectively) than plots that were burned (fell-and-burn, 2,195; and brown-and-burn, 1,361). Stem counts for understory species followed the same pattern but the differences were not significant. Total stem counts for all species differed significantly among treatments (table 2).

While differences were not significant, the stem counts for the natural yellow pines seeding into the study area increased with the intensity of the site preparation treatments (table 2). Smooth sumac, which was not found in the original stand, was abundant in all regeneration plots.

Planted Pines

Survival-Survival differences between loblolly pine (45 percent) and white pine (52 percent) were not significant. Pine survival for the commercial clearcut (27 percent) and silvicultural clearcut (26 percent) did not differ significantly. However, survival in both of these treatment areas was significantly lower than in the two treatment areas that were burned (fell-and-burn, 68 percent; brown-and-burn, 72 percent). Survival for both planted pine species was similar among all treatments (table 3). Mortality of pine seedlings between 1 and 6 years of age was approximately five times greater for treatments that were not burned than that for treatments that were burned.

Height and diameter-After 6 years, overall growth of loblolly pine was significantly greater for both height (13.7 feet) and d.b.h. (2.4 inches) than was that of white pine (6.8 feet, and 0.8 inches) (table 3). Other studies in this area indicate that white pine has slow early height growth. These trees should catch up with the loblolly pine around 16 years of age (Thor and others 1979, Miller 1982). Height and d.b.h. growth on the four site preparation treatments followed the same response pattern as did survival. Height and d.b.h. for both loblolly and white pines in the treatments involving fire were significantly greater than in the unburned treatments (table 3).

CONCLUSIONS

The silvicultural clearcut resulted in more hardwood stems per acre than did the commercial clearcut. Neither of the clearcut treatments contained a pine component. The stands developing on those plots will be hardwood stands similar in species makeup to the preharvest stand.

Table 2—Stem counts of natural regeneration, six growing seasons after different site preparation methods

Species groups	CC	SC	FnB	BnB
	Site preparation treatments[a]			
	- - - - - - - - Stem counts per acre - - - - - - - -			
Potential overstory				
Yellow-poplar	1630	1014	717	682
Chestnut oak	690	872	50	40
Red maple	500	965	150	110
Blackgum	223	665	680	369
Hickory[b]	180	140	278	30
Sugar maple	150	70	30	0
Black cherry	90	250	70	0
White oak	10	30	10	0
Upland red oaks[c]	30	100	60	0
Subtotal	3573 a[d]	4156 a	2045 b	1231 b
Pines[e]	0	30	150	130
Understory	1984	2130	1554	627
Total	5557 ab	6316 a	3749 bc	1988 c

[a] (CC) commercial clearcut-all trees 5 inches and larger removed; (SC) silvicultural clearcut-all trees over 6 feet in height or taller felled; (FnB) fell-and-burn; and (BnB) brown-and-burn.
[b] Mockernut, pignut, and shagbark
[c] Black oak, scarlet oak, and southern red oak.
[d] Within each row, means not followed by the same letters differ significantly at P=.05.
[e] Shottleaf pine, and Virginia pine.

Table 3-Survival, height, and d.b.h. for loblolly pine and white pine after six growing seasons following establishment, using four different site preparation methods

Treatment	Survival	Height	D.b.h.
	Percent	*Feet*	*Inches*
Loblolly pine			
Brown-and-burn	68 a[a]	17.0 a	3.3 a
Fell-and-burn	63 a	15.9 a	2.9 a
Silvicultural[b]	23 b	10.8 b	1.9 b
Commercial[c]	2 b	11.2 b	1.7 b
White pine			
Brown-and-burn	76 a	9.8 a	1.3 a
Fell-and-burn	72 a	8.7 a	1.0 ab
Silvicultural[b]	30 b	4.7 b	0.4 b
Commercial[c]	27 b	4.1 b	0.4 b

[a] Means within each column not followed by the same letter differ significantly at P =.05.
[b] Silvicultural clearcut - all trees over 6 feet in height or taller felled.
[c] Commercial clearcut - all trees 5-inches and larger removed.

The use of fire increased both planted and natural pine establishment and growth. The increased intensity of the brown-and-burn treatment resulted in lower numbers of hardwood stems than did the fell-and-burn treatment. Several hardwood species (Carolina buckthorn, black cherry, sugar maple) were not present, and others (flowering dogwood and the hickories) were less frequent in plots treated with herbicides. The stand resulting from this treatment will result in an open pine stand with a minor hardwood component. The stand developing in the fell-and-burn treatment has established both a hardwood and pine component.

The fell-and-burn treatment offers the NIPF landowners an opportunity to increase the productivity of their forests by introducing a pine component in future stands. This is accomplished at a low cost and without reducing wildlife benefits.

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SITE PREPARATION METHODS AND THEIR IMPACTS ON TIMBER AND NONTIMBER VALUES OF FOREST STANDS

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Abstract-This study evaluated timber values and nontimber benefits of forest stands generated 15 years earlier using four site preparation methods in the Tuskegee National Forest. Timber values of the forest stands were assessed with yields predicted by the SE TWIGS model. Nontimber benefits were evaluated through the Contingent Valuation Method using 200 user interviews. Results indicate that the majority (62 percent) of users felt that the national forest should be managed for both timber and nontimber products. The soil-active herbicide method was projected to produce the highest timber value. For the nontimber benefits, the public seemed to prefer the forest stand without site preparation to those generated by the chainsaw felling, soil-active herbicide, or tree injection methods. When both timber and nontimber values are considered, the no-site-preparation method is the generally preferred alternative to best meet the desires of citizens with different or even conflicting preferences over timber and nontimber products.

INTRODUCTION

Silvicultural practices affect both timber and nontimber values of forest stands. Driven by public demand, national forests in the United States are required to be managed for "multiple uses" that include timber and nontimber uses. Understanding impacts of silvicultural treatments on timber and nontimber values is essential to (a) identifying preferred forest management strategies to meet the public's diverse demand, and (b) comprehensively assessing benefits and costs associated with forest management.

Effects of site preparation methods on timber yields and growth have been studied widely for different tree species and in various locations (Danger-field and Edwards 1991, Glover and Zutter 1993, Greene and Lowe 1992, Knowe and Stein 1995, Minore and Weatherly 1990, Pienaar and Rheney 1993a, 1993b, South and others 1995). However, studies on the effects of site preparation methods on nontimber values, particularly on both timber and nontimber values, are quite limited. This is partially due to the difficulty in assessing nontimber values. Unlike timber, most of the nontimber products from a forest are environmental goods. Markets for these goods do not exist; thus no price information on these goods is available.

This study was designed to investigate the impact of the four site preparation methods on the timber and nontimber values of the forest stands in the Tuskegee National Forest. The specific objectives were: (1) to predict/estimate the timber values of the forest stands treated with the four site preparation methods; (2) to assess the nontimber values of the forest stands; and (3) to rank the four site preparation methods in terms of both timber and nontimber values generated.

METHODS

The Tuskegee National Forest is located in Macon County, east-central Alabama, in the loam hills of the Hilly Coastal Plain Physiographic Province. Fifteen years ago, 16 1.2-acre research plots were established in a recently harvested stand. Only pines with diameter at breast height (d.b.h.) larger than 4 inches (in.) were harvested. Four site preparation methods were tested: (1) no site preparation, (2) chainsaw felling of all woody plants taller than 4 feet (ft), (3) herbicide tree injection with Pathway (picloram +2, 4-D) of both hardwoods and pines, and (4) soil-active herbicide (Velpar) applied in a spot-grid. Loblolly pine seedlings were planted on all plots using an 8 by 8 ft spacing. The experiment was a randomized complete block design with four replications of the four treatments. The site index (base 50 years) ranged from 76 to 95 for the four blocks.

Timber yields of the forest stands treated with the four site preparation methods were projected using the SE TWIGS Model Version 6.1 (Bolton and Meldahl 1990a, 1990b). This model was designed for uneven-aged stand projections. Three rotation lengths of 40, 70, and 100 years were used. No thinning was assumed in predicting timber yields. The volumes of sawtimber were measured in International 1/4-inch. The merchantable standards used were: 5 to 9 in. d.b.h. for pine pulpwood and >9 in. d.b.h. to 7 in. top for pine sawtimber. Because of the lack of a market for hardwood sawtimber, all hardwood timber yield was converted to pulpwood yield. A two-way analysis of variance was conducted to test whether treatment, age, and interaction between them had a significant impact on timber values. A Duncan multiple range test was also performed to compare the mean timber values yielded by the four site preparation treatments.

In addition to timber yields, the economic return from the timber production was also evaluated using the criteria of Net Present Value and Annual Equivalent Revenue. The mean yield for each treatment was used. The timber prices used in this analysis were $186 per mean board foot (MBF) for pine sawtimber, $21 per cord for pine pulpwood, and $10 per cord for hardwood pulpwood. The costs of the four site preparation methods were estimated based on current

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Forest Service contracts, Forest Farmer's 1995 Manual (Dubois and others 1995), and herbicide application costs from Miller and Glover (1995). These costs were zero for the no site preparation, $50 per acre for the chainsaw felling, $77.50 per acre for the tree injection, and $36.34 per acre for the soil-active herbicide, respectively. The seedling price was estimated to be $0.064 per seedling. And planting costs were $39.00 per acre for the no-site preparation and $37.90 per acre for the other treatments. No taxes or land rent were included in the economic analysis.

The nontimber benefits of the forest stands were evaluated by using the Contingent Valuation Method (Gan and others, in press; Hargrove and others, in press). This method induces respondents to release their preferences over a specific nonpriced good by directly asking them about the amount of their willingness to pay for the good (Cummings and others 1986, Mitchell and Carson 1989). Two hundred persons randomly selected from three counties surrounding or near the Tuskegee National Forest were interviewed by using a carefully designed survey questionnaire. These counties were Macon, Lee, and Montgomery. The interviewees were presented with four enlarged, color photographs that showed the 15-year old forest stands resulting from the four silvicultural treatments. They were asked to give their preferences and the dollar value that they were willing to pay for various nontimber benefits in each of the forest stands. The questions regarding willingness to pay were open-ended, i.e., no monetary value or range was suggested or indicated in the questionnaire. The interviewees were given no information on how the forest stands were generated. In other words, they were not told that chemicals were used in the tree injection and soil-active herbicide methods. Further, the respondents were informed that the management of the national forest was fully financed by taxes. The color photos used for the interviews were taken in April 1995. The interviews were conducted from April to December 1995 by seven trained interviewers.

A multiattribute assessment approach was used to rank the four site preparation methods in terms of the timber and nontimber values generated. This approach enables an individual to select among choices with different attributes (Keeney and Raiffa 1976). Usually, a weighted-additive utility function is used. For multiple attribute measures x_1, $x_2, \ldots, x_n$, the weighted-additive utility function can be specified as:

$$\mu(x_1, x_2, \ldots, x_n) = \sum_{i=1}^{n} w_i \mu_i(x_i) \qquad (1)$$

where

w_i is the weight for the ith attribute with $w_i \geq 0$ and $\sum_{i=1}^{n} w_i = 1$

One disadvantage of the weighted-additive utility function is that all the weights must be known a *priori.* The weights can be difficult to determine, particularly when many decision makers-in our case the taxpayers-who share different sets of weights, are involved. To overcome this problem, we used an algorithm developed by Kirkwood and Sarin (1985), which requires only partial information on the weights. This approach requires only the ordering of the importance of the attributes, not the exact values of the weights for the attributes. However, this approach also has its limitation. Using the partial information on the weights may result in the inability to distinguish the ranking of some alternatives.

The attributes considered in this study were timber and nontimber benefits. The site preparation methods were compared by using two sets of the parameters: (1) the ratios of the timber and nontimber values to the establishment costs of the forest stands, and (2) the Net Present Value of timber production and the nontimber value. Using the first set of parameters implies that the forest establishment costs are jointly borne by timber and nontimber production. When using the second set of parameters, we allocated all the establishment costs to timber production. Before applying the multiattribute assessment approach, the value of each attribute was transformed to an index value ranging from 0 to 10 to overcome the unit difference in the attributes. Then, the multiattribute algorithm was employed to find the efficient set of alternatives and to rank the alternatives.

RESULTS

Timber Value

In general, the test site preparation methods generated four distinctly different stand types. No site preparation with planting produced mixed uneven-aged stands with scattered older hardwoods. The application of the soil-active herbicide Velpar also yielded uneven-aged stands but with scattered older residual pines, due to the resistance of pine to this herbicide. Both chainsaw felling and tree injection yielded even-aged stands, with mostly resprouted hardwoods with felling and mostly pines with herbicide injection.

According to the projected average timber volumes, the soil-active herbicide will produce the highest volumes of sawtimber, followed by the tree injection, no-site preparation, and chainsaw felling methods for the 40-, 70-, and 100-year rotations. The soil-active herbicide method will also generate the highest timber value, whereas the chainsaw felling method will produce the lowest timber value at the 40-year rotation and the no-site-preparation method will have the lowest timber value at the 70- and 100-year rotations (table 1).

The overall F-value of the two-way (treatment and age) analysis of variance was 28.13 ($p=.0001$). Treatment and age were significant at $p=.0476$ and $p=.0001$, respectively. The interaction between treatment and age was not significant. A Duncan multiple range test ($p=.05$) showed that mean timber values yielded by soil-active herbicide and tree injection are not significantly different, and those resulting from tree injection, no-site preparation, and chainsaw felling are not significantly different, either. But soil-active herbicide produced significantly higher timber values than no-site preparation and chainsaw felling.

Table I-Average projected timber yield and value of the forest stands treated with different site preparation methods

Site preparation method	Sawtimber	Pine pulpwood	Hardwood pulpwood	Value
	Bd ft	...... Cords/ac	......	$
40-year rotation				
No-site preparation	9,369	8.5	5.0	1,971
Chainsaw felling	7,272	9.5	7.8	1,630
Tree Injection	9,654	12.2	4.2	2,094
Soil-active herbicide	11,938	10.9	1.6	2,465
70-year rotation				
No-site preparation	20,998	2.5	11.2	4,070
Chainsaw felling	20,615	1.7	20.6	4,076
Tree Injection	22,685	2.8	12.5	4,403
Soil-active herbicide	24,126	2.6	5.2	4,598
100-year rotation				
No-site preparation	24,803	0.1	13.7	4,760
Chainsaw felling	25,745	0.2	22.2	5,015
Tree injection	27,138	0.3	14.0	5,194
Soil-active herbicide	27,750	0.4	6.6	5,236

Economic returns from timber production are presented in table 2. Based on the Net Present Value or the Annual Equivalent Revenue from timber production at a 4-percent real discount rate, the soil-active herbicide method is most profitable at the 40-year rotation, while the no-site-preparation method is most profitable at the 70- and 100-year rotations.

Nontimber Value

The selected sociodemographic characteristics of the respondents resemble quite well those of the population in the three counties surrounding and near the Tuskegee National Forest. Some 63 percent of the respondents did not have college degrees, 35 percent had earned at least a bachelor's degree. The medial annual household income for the respondents was between $20,000 and $30,000. Approximately 60 percent of the respondents were employed, the rest of them were not in the labor force (including unemployed, youth, students, retired, etc.). Fifty-three percent of the interviewees were male and 47 percent were female. About 53 percent of the respondents lived within a radius of 25 miles from the Tuskegee National Forest.

About one-third of the 200 people interviewed had visited the Tuskegee National Forest. The major purposes for their visits were hiking/walking/cycling, picnicking, and camping, which accounted for more than 70 percent of the respondents who had visited the national forest.

Sixty-two percent of interviewees indicated that the national forest should be managed for both timber and nontimber products. Among the nontimber products identified, wildlife habitats, water protection, and hiking/walking/cycling were ranked as the top three most important nontimber benefits for the respondents. According to the respondents' preferences, timber was ranked the fifth most important product from the national forest.

The values (willingness to pay) of the nontimber products released by the respondents are presented in the following tabulation:

Site preparation method	Willingness to pay ($/person)
No-site preparation	158
Chainsaw felling	141
Tree injection	129
Soil-active herbicide	129

In terms of the total values of the nontimber benefits, the respondents valued the forest stands generated by the no-site-preparation method as the highest, followed by those resulting from chainsaw felling, tree injection, and soil-active herbicide.

Rankings of the Site Preparation Methods

Three scenarios were considered in ranking the site preparation methods. They were: (1) timber and nontimber values are equally important, (2) timber value is more important than nontimber value, and (3) nontimber value is more important than timber value. Rankings were done by using two sets of parameters: (1) the ratios of the timber and nontimber values to the forest establishment costs (table 3), and (2) the Net Present Value of timber production and the nontimber value (table 4).

Table 2—Net present value and annual equivalent revenue of timber production[a]

Rotation age	No-site preparation	Chainsaw felling	Tree injection	Soil-active herbicide
40 years	328/16.57[b]	208/1 0.51	227114.00	396119.99
70 years	179/7.64	130/5.57	124/5.29	177/7.59
100 years	1210.47	-32/-1.32	-56/-2.29	-14/-0.58

[a] No taxes or land rent were included, and a 4-percent discount rate was used.
[b] Net Present Value ($)/Annual Equivalent Revenue ($/yr).

Table 3-Rankings of the site preparation methods based on the ratios of the timber and nontimber values to the forest establishment costs

Site preparation method	$w_t = w_n$ [a]	$w_t >> w_n$ [b]	$w_t << w_n$ [c]
40-year rotation			
No-site preparation	1	1	1
Chainsaw felling	3	4	3
Tree injection	4	3	4
Soil-active herbicide	2	2	2
70-year rotation			
No-site preparation	1	1	1
Chainsaw felling	3	3	3
Tree injection	4	4	4
Soil-active herbicide	2	2	2
100-year rotation			
No-site preparation	1	1	1
Chainsaw felling	3	3	3
Tree injection	4	4	4
Soil-active herbicide	2	2	2

[a] Timber and nontimber values are equally important.
[b] Timber value is more important than nontimber value.
[c] Nontimber value is more important than timber value.

Table 4—Rankings of the site preparation methods based on the net present value of timber production at a 4-percent real discount rate and the nontimber value

Site preparation method	$w_t = w_n$ [a]	$w_t >> w_n$ [b]	$w_t << w_n$ [c]
40-year rotation			
No-site preparation	1	2	1
Chainsaw felling	4	4	2
Tree injection	3	3	4
Soil-active herbicide	2	1	3
70-year rotation			
No-site preparation	1	1	1
Chainsaw felling	3	3	2
Tree injection	4	4	4
Soil-active herbicide	2	2	3
100-year rotation			
No-site preparation	1	1	1
Chainsaw felling	2	3	2
Tree injection	4	4	4
Soil-active herbicide	3	2	3

[a] Timber and nontimber values are equally important.
[b] Timber value is more important than nontimber value.
[c] Nontimber value is more important than timber value.

When the ratios of the timber and nontimber values to the forest establishment costs are used as the parameters for ranking the site preparation methods, the most preferred method is no-site preparation for all of the three rotation lengths, regardless of the priority/preference over timber and nontimber values. This implies that the no-site-preparation method is the best alternative for groups with different or even conflicting preferences over timber and nontimber products. At the 70- and 100-year rotations, even the order of ranking of the four site preparation methods is the same across the three scenarios: (1) equal importance between timber and nontimber values, (2) more importance of timber value than nontimber value, and (3) less importance of timber value than nontimber value. In this case, the best alternative is no site preparation, followed by soil-active herbicide, chainsaw felling, and tree injection (table 4).

When the Net Present Value of timber production at a 4-percent real discount rate and the nontimber value are used for ranking, the best alternative is also the no-site-preparation method except the scenario in which timber value is more important than nontimber value at the 40-year rotation. In this scenario, the best site preparation method is soil-active herbicide, and no-site preparation is the second best alternative (table 4).

CONCLUSIONS AND DISCUSSION

The four site preparation methods affected the timber and nontimber values of the forest stands they generated differently. The soil-active herbicide method has the highest projected timber value at the 40-, 70-, and 100-year rotations, while the forest stand resulting from no-site preparation is most preferred by the respondents in terms of the nontimber benefits. This stand type is characterized as an uneven-aged mixed stand with mainly hardwoods. According to the Net Present Value (at a 4-percent real discount rate) of timber production only, the best site preparation alternative is the soil-active herbicide method at the 70- and 100-year rotations, and the no-site-preparation method at the 40-year rotation, respectively.

The respondents seemed to desire both timber and nontimber benefits from the Tuskegee National Forest. Sixty-two percent of the respondents felt that the national forest should be managed for both timber and nontimber products. When both timber and nontimber values are considered, the best site preparation method is no-site preparation except at the 40-year rotation, when all the establishment costs are borne by timber production and timber has higher priority than nontimber products. Therefore, in general, the no-site-preparation method is the alternative that can satisfy the goals of the groups with different preferences over timber and nontimber products.

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Vegetation Management

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EFFICACY OF DORMANT SEASON BASAL APPLICATIONS OF IMAZAPYR AND TRICLOPYR FOR CONTROLLING UNDESIRABLE WOODY STEMS

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Abstract-A total of 23 herbicide treatments were applied under the auspices of 3 separate projects to evaluate the efficacy of basal applications utilizing imazapyr and/or triclopyr on selected species. Seven species were treated at the study locations in Mississippi and six species were treated at study sites in South Carolina. Results indicated that imazapyr was effective as a basal treatment with the addition of triclopyr improving control on many species. The addition of Weedone 170 did not significantly improve control of species in this study. Increasing the rate of imazapyr or triclopyr did not consistently improve control, but the basal applications of these herbicides controlled species considered to be resistant to foliar applications of imazapyr.

INTRODUCTION

Timber stand improvement activities have been an integral component of forest management for decades. While the most common form of individual stem treatment used in forestry has been injection, the application of herbicides in basal sprays has been practiced for nearly 40 years. Basal applications have been used extensively for many years in right-of-way management, and forest managers have used the technique sparingly for a number of possible reasons.

Until 1979, (Clason 1991, Hendler and others 1987) 5-T was the principal herbicide used in basal applications. Since that time, triclopyr has been tested and the ester formulation has given excellent control of a number of species (Hendler and others 1987, Miller and Glover 1993, Warren 1982, Yeiser and others 1989). The primary focus of these studies has been on using basal applications for pine release, but Clason (1991) evaluated the use of this methodology for precommercial thinning of pines.

Studies evaluating the use of triclopyr as a "streamline" application (Burch and others 1987, Schutzman and Kidd 1987, Yeiser and Boyd 1989) demonstrated efficacies of different equipment and timing in basal applications. Later work explored the importance of different carriers in basal work (9).

Tank-mixing triclopyr with picloram has been shown to give excellent control (Hall and Hendler 1986). Also, imazapyr and triclopyr had been evaluated as streamline applications separately, but not as tank mixtures in one earlier study (Pancake and Miller 1990). Given that imazapyr and triclopyr were both effective in basal application for woody stem control, the purpose of this study was to evaluate combinations Chopper EC? and Garlon 4® on a variety of tree species.

MATERIALS AND METHODS

The overall study included the protocols for three separate projects which shall be referred to as Projects "A," "B," and "C." All three projects shared some protocols in that treated stems should be 1 to 4 inches (in.) diameter at breast height (d.b.h.), the lower 12 to 18 in. of stem would be treated, each stem would be flagged and tagged for identification purposes, applications were made during the dormant season, and all stems were evaluated at the end of the first and second growing seasons following application. For each treated stem, the herbicide mixture was applied until the bark was moistened, with care taken not to apply excessive amounts which would cause puddling at the root collar. Approximately 30 milliliters (ml) of solution were used per treated stem in the study, with Penevator Basal Oil used as the carrier.

The objective of Project "A" was to evaluate the efficacy of imazapyr/triclopyr tank mixtures on species known to be tolerant or resistant to foliar sprays of imazapyr. For that purpose, a fixed amount of Chopper EC was added to varying amounts of Garlon 4 with one treatment having Chopper EC with Weedone 170. An untreated check and Garlon 4 applied alone provided a basis for evaluations of the mixtures. Table 1 has a complete listing of treatments. A total of three species known to be "resistant" to imazapyr and three species deemed "susceptible" to imazapyr were treated under the auspices of this project at each study location (table 2).

Project "B" was designed to evaluate the addition of increasing amounts of Chopper EC to a fixed amount of Garlon 4. In this project, imazapyr was applied alone and with Weedone 170 to compare with an untreated check and Garlon 4 applied alone (table 3). The species used in this project are listed in table 4.

Project "C" was designed to evaluate the efficacy of reduced rates of Chopper EC mixed with varying amounts of Garlon 4. An untreated check was included to provide a basis for evaluation (table 5) and the species included in the study are listed in table 6.

All treatments for the three projects were installed at two study locations-near Clemson, SC, and near Starkville, MS. In South Carolina, all species were found at one location. In Mississippi, four sites were utilized in order to

[1] Mississippi State University, Mississippi State, MS; Clemson University, Clemson, SC; American Cyanamid Co., Frankfort, OH; American Cyanamid Co., Warner Robins, GA; and Mississippi State University, Mississippi State, MS (respectively).

Table l-Treatments used in Project "A"

Treatment number	Chopper EC	Garlon 4	Weedone 170	Oil
	Herbicide applied			
	Percent			
1	7.8	—	—	92.2
2	7.8	20	—	72.2
3	7.8	15	—	77.2
4	7.8	10	—	82.2
5	7.8	5	—	87.2
6	—	20	—	80.0
7	7.8	—	25.0	67.2
8	Untreated check			

Table 2-Species used in Project "A" and location

Resistant species	Location	Susceptible species	Location
Hackberry	MS	White oak	MS
Loblolly pine	MS	Green ash	MS
Eastern redcedar	MS	Boxelder	MS
Loblolly pine	SC	Black cherry	SC
Winged elm	SC	Red oak	SC
Black locust	MS	Dogwood	SC

Table 3-Treatments used in Project "B"

Treatment number	Chopper EC	Garlon 4	Weedone 170	Oil
	Herbicide applied			
	Percent			
1	1.56	20	—	78.44
2	3.125	20	—	76.875
3	4.70	20	—	75.30
4	6.25	20	—	73.75
5	7.80	20	—	72.20
6	—	20	—	80.0
7	7.80	—	25.0	67.20
8	7.80	—	—	92.20
9	Untreated check			

Table 4-Species used in Project "B" and location

Species	Location	Species	Location
White oak	MS	Red oak	SC
Sweetgum	MS	Black cherry	SC
Hickory	MS	Loblolly pine	SC
Loblolly pine	MS		

Table 5—Treatments used in Project "C"

Treatment number	Chopper EC	Garlon 4	Oil
	Herbicide applied		
	Percent		
1	1.56	5	93.44
2	1.56	10	88.44
3	1.56	15	83.44
4	3.125	5	91.875
5	3.125	10	86.875
6	3.125	15	81.875
7	4.70	5	90.30
8	4.70	10	85.30
9	4.70	15	80.30
10	Untreated check		

Table 6-Species used in Project "C" and location

Species	Location	Species	Location
White oak	MS	Black locust	SC
Hickory	MS	Winged elm	SC
Green ash	MS	Red oak	SC

obtain the desired species diversity. All four stands were on the Noxubee Wildlife Refuge and included a mixed pine-hardwood site, a bottomland hardwood site, an old field cedar succession site, and a pine natural regeneration site.

All treatments were applied with a CO_2-powered backpack sprayer with a 2-foot wand and full cone nozzle. Treatments were applied in February 1994 with evaluations completed in September 1994 and September 1995. During evaluation, each tree was classed as 1 of 10 codes ranging from "no injury" to "completely dead," and the percentage of crown reduction was recorded for all tagged trees.

Data were subjected to analysis of variance with Tukey's Test used to establish significance among the means. Percentages were analyzed following arc syne transformation. Overall, approximately 2,000 stems were tagged and evaluated in this study.

RESULTSANDDISCUSSION

To facilitate presentation of results, each project will be discussed separately. The species deemed "susceptible" in Project "A" included green ash, boxelder, white oak, red oak, black cherry, and dogwood. Overall, all treatments controlled all these species very well except white oak (table 7). It is unknown why the herbicide treatments were less effective on white oak, as that species is typically more susceptible than red oak. The Chopper/oil mixture gave crown reductions of 60 to 100 percent after 2 years depending on the species. If white oak is excluded, all other treatments resulted in at least 90 percent crown reductions, with most treatments resulting in a total kill of all stems. The addition of triclopyr did improve control significantly for green ash, boxelder, and red oak, but not for the other three species. The addition of Weedone 170 did not improve control, and increasing the amount of triclopyr did not improve control on these species.

For the species deemed "resistant" in Project "A," the addition of triclopyr significantly improved control for all species except Eastern redcedar (table 8). Tank mixtures of imazapyr and triclopyr killed all stems of hackberry, loblolly pine, and winged elm. Increasing the amount of triclopyr did not improve control except for black locust, and the addition of Weedone 170 did not improve control except for black locust. Overall, species that have demonstrated resistance to imazapyr foliar spray can be controlled by these basal applications with Eastern redcedar being the exception.

Table 7-Percentage of crown reduction after two growing seasons for susceptible species in Project "A"

Treatment number	Species[a] A	B	WO	C	D	RO
	Percent					
1	72	88	60	90	100	77
2	100	100	93	90	100	100
3	100	100	63	100	100	100
4	100	100	83	100	100	100
5	100	100	57	100	100	100
6	100	100	55	90	100	100
7	100	100	58	100	100	99
8	24	3	20	9	10	3

[a] A=ash, B=boxelder, WO=white oak, C=cherry, D=dogwood, RO=red oak.

Table 8-Percentage of crown reduction after two growing seasons for susceptible species in Project "A"

Treatment number	Species[a] RC	H	P	E	L	P
	Percent					
1	19	52	45	78	88	80
2	25	100	100	100	89	100
3	30	100	100	100	91	100
4	61	100	100	100	81	100
5	13	100	100	100	49	100
6	36	100	100	100	68	100
7	48	90	60	90	99	100
8	20	0	3	0	31	3

[a] RC=redcedar, H=hackberry, P=pine, E=elm, L=locust, P=pine.

In Project "B," increasing the amount of imazapyr did not improve control on white oak, hickory, sweetgum, black cherry, red oak, or loblolly pine (table 9). Once again, white oak was the most resistant of the species treated, but adequate control was obtained by all treatments except the imazapyr/oil and imazapyr/Weedone 170/oil combinations. Chopper alone provided excellent control of black cherry, red oak, and loblolly pine, but the addition of triclopyr was necessary to adequately control the other species in the project.

Table g-percentage of crown reduction after two growing seasons for susceptible species in Project "B"

Treatment number	Species[a] WO	K	S	C	RO	P
	Percent					
1	90	100	100	100	100	100
2	86	100	100	100	99	100
3	60	100	80	100	100	100
4	84	100	100	100	100	100
5	92	92	100	100	100	100
6	100	90	100	100	100	100
7	39	83	64	100	87	90
8	11	20	58	100	100	91
9	22	2	22	0	16	9

[a] WO=white oak, K=hickory, S=sweetgum, C=cherry, RO=red oak, P=pine. [a] RC=redcedar, H=hackberry, P=pine, E=elm, L=locust, P=pine.

Results from Project "C" paralleled Project "A" in that white oak demonstrated less response to treatments than the other six species involved. Only three of the nine herbicide mixtures provided adequate control of white oak (table 10). With the exception of white oak, the lowest rates of imazapyr and triclopyr (Treatment 1) resulted in 100 percent control of all species in the project. Increasing the rate of imazapyr and/or triclopyr therefore could not improve control on these species. Notable in the results were the responses of loblolly pine, winged elm, and black locust. All are considered "resistant" to imazapyr, and all were effectively controlled by the lower rates of Chopper and Garlon mixtures.

SUMMARY AND CONCLUSIONS

A compilation of the percentage of control obtained for all species in the three projects is found in table 11. Of the 13 species involved, only Eastern redcedar proved strongly resistant to these basal treatments. One treatment (#4 in Project "A") did provide 60 percent control, but the overall average of 33 percent control is less than desirable. White oak was consistent in the response in all three projects in that @ 70 percent control was obtained. The other 11 species treated all proved susceptible to various treatments in this study.

Examination of the responses to individual treatments revealed trends of interest. It was clearly demonstrated that imazapyr is effective as a basal treatment. Based on examination of the varying rates in the three projects, increasing the rate of imazapyr did not result in improved control on the species in this study. The addition of triclopyr to imazapyr improved control on many of the study species, but increasing the amount of triclopyr did not consistently improve control-an actual decrease in control occurred in some treatments. The addition of Weedone 170 did not consistently or significantly improve control of species in this study. Perhaps of greatest interest was the observation that basal applications using imazapyr controlled species considered "resistant" to foliar sprays of imazapyr. Eastern redcedar remained resistant to these basal treatments, but fire is effective on this species when used in forest management.

Table 1 O-Percentage of crown reduction after two growing seasons for susceptible species in Project "C"

Treatment number	Species[a] A	K	WO	P	E	L	RO
	Percent						
1	100	100	75	100	100	100	100
2	100	92	62	100	100	69	90
3	100	92	70	62	100	100	100
4	100	90	56	90	100	78	91
5	100	100	90	82	100	88	90
6	100	100	90	64	100	100	100
7	100	100	90	90	100	98	100
8	100	92	55	100	100	100	100
9	100	98	63	90	100	97	100
10	0	0	16	0	0	56	0

[a]A=ash, K=hickory, WO=white oak, P=pine, E=elm, L=locust, RO=red oak.

Table 1 I-Overall control after two growing seasons for species in the study (all treatments in all projects).

Species	Project "A"	"B"	"C"
	Percent		
Green ash	96		100
Boxelder	98		
White oak	67	70	72
Black cherry	96	100	
Dogwood	100		
Red oak	97	98	97
Sweetgum		88	
Hickory		86	96
Hackberry	92		
Loblolly pine	94	98	86
Winged elm	97		100
Black locust	81		92
Eastern redcedar	33		

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IMPACT OF HERBACEOUS WEED SUPPRESSION ON LOBLOLLY PINE SAWTIMBER ROTATIONS

Terry R. Clason[1]

Abstract-A study was initiated in 1957 to determine the long-term effect of herbaceous weed competition on growth and development of loblolly pine. Seedlings were planted at a density of 1,200 trees per acre (TPA) and three weed suppression treatments were applied: no weed suppression (Check), 1 year of weed suppression (1YS), and 2 years of weed suppression (2YS). By age 20, pine stocking density was similar for all treatments averaging 850 TPA. 2YS means merchantable volume was 2,940 cubic feet per acre (ft^3/acre), which exceeded Check and 1YS mean volumes by 540 and 260 ft^3/acre. Between ages 20 and 39, all treatment plots were thinned to similar pine stocking densities at ages 20, 25, and 34. The residual stand stocking densities for the respective ages were 225, 100, and 50 TPA. Total merchantable volume at age 39 averaged 4,400, 4,600, and 4,840 ft^3/acre for the Check, 1YS, and 2YS treatments, respectively merchantable volume growth from age 20 to age 39 did not differ among treatments, averaging 1,980 ft^3/acre. Early herbaceous weed competition did impact the wood yield distribution among products. At age 39, respective product volume yields for the Check, 1YS, and 2YS treatments were pulpwood 1,530, 1,410, and 1,400 ft^3/acre; chip-n-saw 850, 1,270, and 1,410 ft^3/acre, and sawtimber 2,020, 1,940, and 2,030 ft^3/acre. Check summed chip-n-saw and sawtimber volume was 340 and 570 ft^3/acre less than 1YS and 2YS treatment volume totals. The highest internal rate of return for all treatments occurred at age 34, and was 5.9, 6.3, and 6.6 percent for the Check, 1YS, and 2YS, respectively.

INTRODUCTION

Initial growth and development of loblolly pine (*Pinus taeda* L.) plantations can be improved by limiting the negative impact of herbaceous weed competition. Herbaceous weed suppression during the first growing season improves survival rate (Metcalf 1986) and increases height and diameter growth (Clason 1984, Miller and others 1987). Seedling growth responses attributed to herbaceous vegetation control increased merchantable volume yields 128 percent in 1 O-year-old loblolly plantations (Creighton and others 1986). Although a positive response to weed suppression is discernible in sapling-size plantations, the long-term effect on plantation growth and yield is not known.

In a loblolly pine plantation established as a planting site fumigation study, Hansbrough and others (1964) found seedling growth differences between treatments. By age 6, seedling height and diameter growth on a methyl bromide treatment exceeded the control treatment by 4.5 feet (ft) and 0.9 inches (in.). Seedling growth differentials were attributed to herbicidal activity of methyl bromide because weed and grass growth was suppressed for 2 years after treatment. Since tree growth was measured periodically between ages 6 and 39, a substantial data set was created for tracking long-term treatment growth and development patterns. Therefore, this data set will be used to examine efficacy of herbaceous weed suppression on plantation growth and development for rotation ages of 20, 25, 30, 34, and 39.

METHODS AND PROCEDURES

A study was initiated in 1957 to determine effects of planting site fumigation on growth and development of loblolly pine. The experimental area was an old field 4 acres in size having Shubuta and Savannah fine sandy loam soils and a site index of 64 ft at age 25. Prior to planting seedlings, the area, which had been withdrawn from cultivation for many years, was cleared and then disked several times to eliminate encroaching woody vegetation. Seedlings were planted at a spacing of 6 by 6 feet on 0.1 -acre plots. Treatments included: no weed suppression (Check), 1 year of weed suppression (1YS), and 2 years of weed suppression (2YS). Soil fumigates used for treating the weed suppression plots were 1,3-dichloropropene-1 , 2-chloropropane for the 1 YS treatment and 98 percent methyl bromide + 2 percent chloropicrin for the 2YS treatments. Fumigation treatments were allowed to dissipate for 1 month prior to planting. Measurement plots, consisting of 6 rows with 10 seedlings, were designated in the center of each treatment plot. Seedling mortality was observed monthly during the first growing season and annually thereafter. Diameter at breast height (d.b.h.) and height growth were measured annually through age IO, and at ages 14, 17, 20, 25, 30, 34, and 39. Between ages 20 and 39, all treatment plots were thinned at ages 20, 25, and 34 to residual densities of 225, 100, and 50 TPA, respectively. Pine merchantable volume was computed to a 3.0-inch inside bark diameter using a pooled equation reported by Van Deusen and others (1981) and sawtimber volume (Doyle Scale) was determined from sawtimber cubic foot volume using a published conversion factor (Williams and Hopkins, 1968). All growth data were analyzed with ANOVA procedures.

RESULTS

Plantation Growth

Merchantable volume growth differences were detected among treatments at age 20 (table 1). Although 2YS treatment stocking density was 80 and 60 TPA less than the Check and 1YS treatments at age 20, 2YS treatment

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Table 1—Mean stand growth attributes by treatment from ages 20 to 39.

Treatment	Stocking density	D.b.h.[a]	Height	Basal area	Merchantable volume: Total	Pulpwood	C-N-S[b]	Sawtimber
	TPA[c]	*In.*	*Ft.*	*Ft²/acre*	-------- *Ft³/acre*		--------	*Bd. ft./acre*[d]
Age 20 standing								
Check	901	5.7	47	155	2,400	1,560	840	—
1 year sup	881	5.9	48	167	2,680	1,500	1,150	80
2 year sup	821	6.3	49	175	2,940	1,470	1,430	100
Age 20 harvest								
Check	691	5.2	45	97	1,350	1,350	—	—
1 year sup	625	5.6	46	105	1,520	1,200	320	—
2 year sup	588	5.8	47	107	1,620	1,150	470	—
Age 20 residual								
Check	232	7.1	48	63	1,050	210	840	—
1 year sup	256	6.9	50	67	1,160	300	830	80
2 year sup	233	7.6	52	74	1,320	320	960	100
Age 25 standing								
Check	222	8.1	59	73	1,530	230	1,150	350
1 year sup	245	8.0	60	78	1,670	260	1,230	470
2 year sup	227	8.6	63	81	1,790	280	1,190	830
Age 25 harvest								
Check	127	7.7	57	32	630	130	500	—
1 year sup	154	7.4	59	38	770	160	610	—
2 year sup	134	8.2	60	37	780	190	590	—
Age 25 residual								
Check	95	8.8	62	41	900	100	650	350
1 year sup	91	8.8	64	40	900	100	620	470
2 year sup	93	9.3	65	44	1,010	90	600	830
Age 30 standing								
Check	95	10.4	65	56	1,300	70	500	1,980
1 year sup	91	10.4	65	54	1,290	70	460	2,140
2 year sup	93	10.7	67	59	1,430	70	470	2,580
Age 34 standing								
Check	95	11.9	70	74	1,830	60	400	4,310
1 year sup	91	11.8	70	71	1,780	60	400	4,230
2 year sup	93	12.0	71	75	1,930	60	390	5,020
Age 34 harvest								
Check	39	11.0	69	26	630	30	190	1,180
1 year sup	40	10.9	70	26	660	30	200	1,220
2 year sup	46	10.8	69	30	750	40	230	1,420
Age 34 residual								
Check	56	12.4	70	48	1,200	30	210	3,130
1 year sup	51	12.5	70	45	1,120	30	200	3,010
2 year sup	48	13.3	73	45	1,180	20	160	3,600
Age 39 standing								
Check	56	14.7	75	67	1,790	20	160	6,400
1 year sup	51	15.1	74	63	1,650	20	140	6,130
2 year sup	48	15.7	75	64	1,690	20	120	6,660

[a] Diameter at breast height.
[b] Chip-n-saw.
[c] Trees per acre.
[d] Doyle Scale.

merchantable volume was significantly greater than, the other two treatments. The growth differentials for the check and 1 YS treatments were 540 and 260 cubic feet per acre (ft^3/acre), respectively. Between ages 20 and 39, treatment merchantable volume growth did not differ and averaged 1,940 ft^3 /acre. Periodic merchantable volume growth between thinning interventions did not differ among treatments. Mean volume growth from ages 20 to 25, ages 25 to 34, and ages 34 to 39 was 490, 900, and 550 ft^3 /acre. Thus, at each rotation age, 2YS merchantable volume yield exceeded the check yield by 500 ft^3 /acre.

Herbaceous weed treatment had a significant impact on product volume distribution. Pulpwood and chip-n-saw (C-N-S) volumes at age 20 were similar to total pulpwood and C-N-S volumes at age 39 (table 1). Pulpwood volume did not differ among treatments at either age, averaging 1,500 and 1,450 ft^3 /acre at ages 20 and 39. 2YS C-N-S volume was significantly greater than the Check at both ages. Respective treatment volumes at ages 20 and 39 were 840 and 1,430 ft^3 /acre, and 850 and 1,41 0 ft^3 /acre. Although 1YS and 2YS treatment had some sawtimber volume at age 20, sawtimber ingrowth did not begin until age 25. By age 39, sawtimber volume growth averaged 2,000 ft^3 /acre for all treatments. However, total lumber volumes (board foot, Doyle Scale) differed among treatments with Check, 1YS, and 2YS averaging 7,580, 7,350, and 8,080 board feet (bd. ft.) per acre, respectively.

Crop Tree Growth

At age 20, the equivalent of 50 crop TPA was identified on each treatment plot using d.b.h., tree form, and spatial position as selection criteria. Age 20 treatment crop tree d.b.h., height, and basal area differed significantly among treatments (table 2). Mean 1YS and 2YS treatment d.b.h., height, and basal area exceeded the Check by 0.5 inches, 3 feet, and .046 ft^2, respectively. Except for height, which averaged 75 feet for all treatments, 2YS crop tree total

Table 2-Mean crop tree growth attributes by treatment from age 20 to 39

Treatment	Stocking density	D.b.h.[a]	Height	Basal area	Merchantable volume: Total	Pulpwood	C-N-S[b]	Sawtimber
	TPA[c]	*In.*	*Ft.*	*F f*	*Ft^3*			
Age 20								
Check	50	7.8	56	0.337	6.685	1.175	5.510	—
1 year sup	50	8.2	57	0.374	7.621	2.166	5.455	1.062
2 year sup	48	8.4	59	0.392	8.184	2.111	6.073	1.030
Age 25								
Check	50	9.3	64	0.473	10.668	0.965	7.429	2.274
1 year sup	50	9.5	66	0.495	11.525	0.970	7.109	3.447
2 year sup	48	9.9	66	0.544	12.703	0.878	6.223	5.603
Age 30								
Check	50	11.0	66	0.667	15.685	0.707	4.171	10.807
1 year sup	50	11.1	68	0.679	16.476	0.722	4.232	11.521
2 year sup	48	11.6	69	0.743	18.141	0.656	3.989	13.496
Age 34								
Check	50	12.4	70	0.848	21.114	0.586	3.706	16.822
1 year sup	50	12.5	70	0.865	21.666	0.579	3.800	17.286
2 year sup	48	13.3	73	0.972	25.419	0.526	3.432	21.461
Age 39								
Check	50	14.7	75	1.192	31.638	0.424	2.877	28.336
1 year sup	50	15.1	74	1.258	33.058	0.401	2.726	29.931
2 year sup	48	15.7	75	1.360	36.333	0.374	2.557	33.354

[a] Diameter at breast height.
[b] Chip-n-saw.
[c] Trees per acre.
[d] Doyle Scale.

growth between ages 20 and 39 surpassed both the Check and 1YS treatments. Mean crop tree d.b.h., basal area, merchantable volume, and sawtimber volume growth differentials between the 2YS and the other two treatments were 0.4 inches, 0.1 ft^2, 2.95 ft^3, and 3.72 ft^3, respectively. Periodic tree basal area growth between thinning interventions differed among treatments. Mean basal area growth for the Check, 1YS, and 2YS treatments from ages 20 to 25, ages 25 to 34, and ages 34 to 39 was 0.136, 0.121, and 0.152 ft^2; 0.375, 0.370, and 0.428 ft^2; and 0.344, 0.393, and 0.388 ft^2, respectively. Crop trees on the 2YS treatment plots performed better after thinning than crop trees on the Check or 1 YS treatment plots.

Financial Comparisons

The long-term financial impact of herbaceous weed suppression was evaluated by comparing the treatment internal rates of return (IRR) for rotation ages of 20, 25, 30, 34, and 39. Cost and revenue data were standardized for all treatments. Cost data obtained from Dubois and others (1995) included aerial site preparation with a burn: $96.00 per acre; planting 1,200 TPA: $111.60 per acre; aerially applied herbaceous weed suppression: $36.00 per acre; thinning preparation: $16.00 per acre; and annual tax and administration cost: $3.50 per acre. A land value of $300.00 per acre was added as a rotation establishment cost. Revenue data obtained from Odom and Frey (1995) included pulpwood: $0.28 per ft^3; C-N-S: $0.99 per ft^3; and sawtimber: $0.361 per bd. ft. (Doyle Scale). A land value of $300 per acre was added at the end of the rotation as a revenue. All timber revenue was computed as the highest valued product.

For each rotation age, the IRR was directly related to the intensity of herbaceous weed suppression (table 3). Since treatment pulpwood and sawtimber volumes were similar for all rotation ages, treatment revenue differences were attributed to the C-N-S volume differentials detected at age 20. Under the conditions of this study, 1YS and 2YS treatment optimum rotation was 34 years; the IRR for the respective treatments were 6.35 and 6.58 percent. The financial results could have been altered by shortening the 2YS treatment rotations, thinning before age 20, or using a lower planting density.

Table 3-Treatment internal rate of return by rotation age.

	Rotation age				
Treatment	20	25	30	34	36
	Percent				
Check	5.30	5.40	5.50	5.88	5.89
1 year sup	5.98	6.10	6.14	6.35	6.12
2 year sup	6.41	6.33	6.34	6.58	6.24

CONCLUSIONS

Two years of herbaceous weed suppression had a positive impact on plantation growth and development for rotation ages of 20, 25, 30, 34, and 39.

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COMPETITION CONTROL FOR HARDWOOD PLANTATION ESTABLISHMENT

A.W. Ezell and A.L. Catchot, Jr.'

Abstract-Sulfometuron methyl was applied at both pre-emergent and postemergent timings in newly established oak and ash plantings. Species involved in the study include cherrybark oak, Nuttall oak, Shumard oak, water oak, willow oak, white oak, and green ash. Treatments were evaluated for both competition control and crop tolerance. First-year survival for treated and untreated areas was also evaluated for all species. Results indicate that effective competition control can be obtained with over-the-top treatments in hardwood plantations. No crop damage was exhibited in any of the pre-emergent treatments. However, postfoliation application resulted in foliar necrosis on some species and complete mortality for white oak. Overall, first-year survival for all species was increased by approximately 12 percent.

INTRODUCTION

For years, interest in managing and regenerating desirable species of hardwoods has been increasing. Paramount to that subject area has been the concern over cost-effective oak regeneration practices. Thousands of acres were artificially regenerated to hardwoods under the auspices of the Conservation Reserve Program with highly variable results. In many cases, the direct seeding efforts were failures in terms of establishment, and though planted seedlings have higher establishment rates, survival is often much lower than desirable. While a number of factors will directly affect the survival of hardwood planting, especially seedling quality and planting job quality, control of competing vegetation is a major concern, especially in areas of established herbaceous cover. Miller (1993) published a comprehensive overview of all the herbicides that were appropriate for oak culture. While pre-plant and directed spray applications are necessary components of different regeneration strategies, it was the focus of the current work to evaluate postplant, over-the-top applications of a suitable product. The prime candidate for such an application is sulfometuron methyl, which is labeled for such use when applied prior to bud break of the oak.

Rhodenbaugh and Yeiser (1994) reported tolerance of eight hardwood species to pre-plant and postplant (pre-budbreak) Oust® application. Decreases in survival and increases in injury were attributed to site factors other than Oust@ treatment for all oak species except cherrybark.

OBJECTIVE

The objectives of the study were as follows:

- To evaluate competition control efficacy of pre-emergent applications of Oust@ in an abandoned agricultural planting site.
- To evaluate any first-year survival differences in oak species planted in treated vs. untreated plots.
- To evaluate the effect of postfoliation applications of sulfometuron methyl to selected oak species.

MATERIALS AND METHODS

A total of six oak species and green ash were planted on an abandoned agricultural site approximately 6 miles north of Starkville, MS. Species included in the study included cherrybark oak, Nuttall oak, Shumard Oak, water oak, willow oak, white oak, and green ash. A complete listing of the common and scientific names follows:

Common name	Scientific name
Cherrybark oak	*Quercus pagoda* Raf.
Nuttall oak	*Q. nuttallii* Palmer
Shumard oak	*Q. shumardii* Buckl
Water oak	*Q. nigra* L.
Willow oak	*Q. phellos* L.
White oak	*Q. alba* L.
Green ash	*Fraxinus pennsylvanica* marsh.

The site had been out of cultivation for 4 years and herbaceous vegetation completely covered the planting area. All seedlings were planted in January 1996.

In early March, two rates of Oust@ [2 ounces (oz.) per acre and 4 oz per acre] were applied over the top of the planted seedlings. Three replications of each rate were completed for each species in this pre-emergent application in a completely randomized block design. All spraying was completed with a CO, powered backpack sprayer with a hand held wand, a TK 2.5 floodjet nozzle, and a total spray volume of 20 gallons (gal) per acre. The planted row served as the center for the 6-foot band application. All treatments were evaluated at 14 days after treatment (DAT), 30 DAT, 60 DAT, and 90 DAT intervals for both crop tree damage and competition control. In December 1996, first-year survival was recorded.

In late April, after all trees were fully foliated, Oust@ was applied over the top of cherrybark oak, Nuttall oak, Shumard Oak, white oak, and green ash at a rate of 2 oz. per acre. These plots were evaluated at 30 DAT and 60 DAT for crop tree damage and in December 1996, for first-year survival. While not part of the original project protocol or labeled application, the availability of seedlings provided an opportunity to gain insight into the perennial question regarding postfoliation applications. Competition control in treated areas was assessed as a percentage of clear ground in 5-percent increments. Crop tree injury was evaluated as a percentage of foliar necrosis, and all foliage

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was examined for chlorosis. Percentage measurements were subjected to arc syne transformation prior to analysis of the variance.

RESULTS AND DISCUSSION

Both rates of herbicide gave excellent competition control for 60 DAT. No significant difference for control was observed until 90 DAT, when the 4 oz. rate demonstrated a greater residual effect; but at that time, the 2 oz. rate plots averaged 30 to 35 percent clear (see table 1). Overall, the treatments yielded good broadleaf control with the problem species being broomsedge and selected *Panicum.*

Crop Tree Tolerance (Pre-emergent)

No injury was noted on any seedlings resulting from herbicide application. Overall, the seedlings appeared thrifty, foliated fully, and established.

Crop Tree Tolerance (Postfoliation spray)

Species demonstrated different tolerance when evaluated 30 DAT. The cherrybark oak had no visible necrosis and any possible chlorosis was extremely slight. Nuttall and Shumard oaks both exhibited leaf margin necrosis across the crown, but new leaves continued to form and the trees continued to grow. Green ash response varied by the position of the apical leader in relation to the spray. If the herbicide was totally over the top of the seedling, leaf burn, necrosis, and leaf mortality were much more extensive than on the stems that had received spray only on lower crown positions. Damage ranged from 20 to 80 percent leaf burn. White oak exhibited a consistent response in that all stems were dead in the treatment plot.

Survival

First-year survival was very consistent across all replications (treatments) for all species (see table 2). All species had greater than 83-percent survival at the end of the first growing season in the treated plots. No significant survival difference was found in any comparison of herbicide application rate. Even through the 4 oz. rate provided greater residual control, the 2 oz. rate was sufficient on this site for establishment. By comparison, the untreated plots averaged 60 to 70 percent survival, which gave an overall increase of ≥13 percent survival to seedlings with competition control in this study. We fully expect species/site suitability to affect impact survival and growth in coming years as is normal with hardwood plantations. In what could be indicative of the future of this planting, a screening trial was completed on these same species of oak and ash 5 years ago on this site. While Nuttall oak and green ash have the highest 5-year survival rate (92 to 87 percent, respectively), all species exhibit @20 percent greater survival in plots receiving herbicide treatments than those in untreated areas.

Table I- Percentage of clear ground in Oust@ field trial treatment plots by evaluation time (average of all replications)

Herbicide rate	Time of evaluation (days after treatment) 14	30	60	90	120
2 oz./acre	100	100	87	33	20
4 oz./acre	100	100	93	63	52
Untreated	93	67	10	5	5

Table 2-First year survival in Oust@ pre-emergent application study (average all reps)

Species	Herbicide rate	Survival
	Oz. per acre	*Percent*
Cherrybark	2	85
	4	87
Nuttall	2	90
	4	92
Shumard	2	87
	4	87
White	2	83
	4	87
Water	2	87
	4	90
Willow	2	85
	4	88
Untreated (all species)	—	60-70

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DOES PARAQUAT CAUSE STEM SWELLINGS IN FIRST-YEAR COTTONWOOD SAPLINGS?

Theodor D. Leininger and Curtis S. McCasland[1]

Abstract-This study was prompted by the occurrence, in 1995, of stem swellings on about 80 to 90 percent of all first-year shoots of eastern cottonwood (*Populus deltoides* J. Bartam ex Marsh.) after an application of paraquat to control weeds in a 65-hectare plantation near Fitler, MS. Paraquat was applied in spring and summer 1996, respectively, to the bases of two different sets of first-year cottonwood saplings at 0, 0.25, 0.5, 1 .0, and 2.0 times the normal rate used for weed control to determine a dose-response relationship for paraquat and the occurrence of stem swellings. The occurrence of swellings 2, 3, and 4 months after the spring treatment was positively related to paraquat dose. Swellings occurred less often, and only at the 1 .O and 2.0 rates, after the summer treatment. Sapling survival was related to paraquat dose for the spring application ranging from 97 percent in the control group to 18 percent for saplings treated with the 2.0 rate. Paraquat dose did not affect sapling survival after the summer application. Four months after the spring treatment, stem diameters of saplings treated with 1 .O and 2.0 rates were 67 and 38 percent, respectively, of those of the control saplings. Stem heights showed similar responses. Summer treatments had little effect on diameters and heights of saplings. Use of paraquat to control weeds in first-year cottonwood plantations should include provisions to reduce or eliminate contact with green stem tissues.

INTRODUCTION

In mid-June 1995, an estimated 80 to 90 percent of all first-year shoots of cottonwood (*Populus deltoides* J. Bartam ex Marsh.) in a 65-hectare (ha) plantation near Fitler, MS, exhibited 10- to 15-centimeter (cm) long swellings located 3 to 10 cm above the attachment of the shoot to the cutting. The swellings were 2 to 2.5 times the normal stem diameter and were fusiform in shape. During cultivation in mid-June, an estimated 15 to 20 percent of the shoots broke just below the swellings where the stems were brittle. Swellings first appeared in mid-May following an application of paraquat to stem bases in early May to control weeds. The spray rig used in this application was not set up to shield stem bases from being sprayed. Cottonwood clones from Fitler and Stoneville, MS, and one of Texas origin, were affected. No effort was made to determine differences in cottonwood clones in manifesting the swellings. Paraquat damage was evident as black, sunken, oval lesions measuring about 0.5 cm by 1 .O cm on portions of the shoots above the swellings. Various causes for the swellings were considered including insects, diseases, weather, and chemical drift from nearby farms, but none of these provided a satisfactory explanation. Although the evidence was circumstantial, swellings appeared related to the application of paraquat.

Subsequent discussions with other plant pathologists and herbicide specialists revealed similar injuries on branches of loblolly pines exposed to paraquat spray drift, and on cotton from an incorrect application of paraquat. Paraquat is a contact herbicide which is absorbed quickly by green plant tissue where it reacts with the photosynthetic process producing free radicals; these destroy plant cells and membranes and cause the death of tissues within hours (Rice 1992). A hypothesis emerged which held that young, green phloem and bark tissues were killed by paraquat, thereby removing the conduit for photosynthates to be transported to roots. Photosynthates accumulated in stems distal to the dead tissue, thereby causing swellings and brashness. This phenomenon is known in woody ornamental production as "wire-tag disease," in which case a physical barrier (e.g., a wire tag) cuts into the phloem restricting the downward movement of photosynthates. Swellings occurred less frequently on first-year cottonwood saplings treated with paraquat in August 1995, presumably after bark tissue was more mature.

Paraquat was used by the grower, under the "trees and vines" section of the Federal label, to control weeds in first-year cottonwood plantations for several years before these swellings occurred. It was an important management tool because it was the only broad-spectrum herbicide that effectively controlled early-summer annual weeds, such as morning-glory (*Convolvulus* L. spp.), ragweed (*Ambrosia* L. spp.), pigweed (*Amaranthus* spp. L.), cocklebur (*Xanthium* L. spp.), *Sesbania* Scop. spp., and primrose (*Primula* L. spp.) at a low cost while posing a minimal risk to cottonwood health. Paraquat was not applied to sapling bases to control weeds during 1996 because of concern over the occurrence of these stem swellings. To address the growers' concern, this study was done to determine the concentration of paraquat at which bark and phloem were killed, thereby causing photosynthates to accrete as swellings on lower stems of first-year cottonwood saplings. A second objective was to determine whether swellings on first-year cottonwood saplings could be avoided by applying paraquat later in the season after bark tissue had become more mature.

This research also addresses an area of wider concern within the forestry community, that of having useful chemicals to control annual and perennial weeds in hardwood plantations. Commercial hardwood interests are more and more considering plantations as one key to meeting increased demands for hardwood fiber, and are looking to researchers to address questions of feasibility

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(Anonymous 1996). It is likely that more studies like this will need to be done to meet the needs of hardwood plantation growers in the private, as well as public, sectors.

METHODS

Experimental Design and Approach

The cottonwood saplings used in this study were planted as cuttings in December 1995. In February 1996, a tank mix of oxyfluorfen [80 ounce per acre] and paraquat [I quart per acre] was sprayed in 6-foot bands down the rows and over the top of the dormant cuttings. Weeds growing between rows were controlled using a disc harrow before paraquat was applied to the bases of saplings. Two times during the growing season after treatments were installed, a disc harrow was used for weed control. The disc harrow was driven between rows in one direction and then again between rows at a 90-degree angle to the first pass. These conditions replicated, as nearly as possible, the cultural conditions to which the 1995 saplings were exposed.

Treatments were set up as a two-way factorial in a randomized complete block design with 10 (two applications x five dose levels) factor-level combinations in each of three blocks. Applications of 0, 0.25, 0.5, 1, and 2 times the grower's normal operational rate of paraquat (24 ounces per acre as 37 percent paraquat dichloride a.i.) were made to the bases of first-year cottonwood saplings on June 17 (spring) and August 19 (summer) 1996. The control (0) treatment contained only the nonionic surfactant in water that was used to apply the paraquat. Paraquat was applied using a modified, conventional, farm spray rig outfitted with two 8004 flat-fan nozzles on both sides of each row of saplings. Two rows were sprayed simultaneously using a tractor speed of 4.8 miles per hour (mph) and a tank pressure of 10.5 pounds per square inch (psi) adjusted to produce relatively large droplets and avoid drift.

Each treatment was applied to 50 saplings, in 2 adjacent rows of 25 saplings each, planted in a 12 foot by 12 foot spacing. There was a total of 1,500 saplings on 5 acres. The study occupied about 12 acres, including buffers around treated areas, within a 100-acre plantation of first-year cottonwood saplings. Saplings were half-sib, first generation, improved clonal material that originated from Mississippi or Texas. It was not possible to determine clonal responses to paraquat because no record was kept of which clones were planted in the study area. The soil of the study area was of the Sharkey series.

Biological Measurements

Initial heights of saplings in the spring treatments were measured 8 days after spraying. The presence or absence of swellings was recorded on the dominant shoot of each sapling. Stem diameters were measured 10 cm above the ground. The widest diameter of each recorded swelling was measured. Weed control around each sapling was measured by estimating the percentage of area covered by weeds in a 0.5 square meter (m^2) plot centered around the sapling base. Sapling heights from the ground to the tip of the dominant leader were recorded, as were the occurrence of swellings, swelling diameters, stem diameters, percentage of weed cover, and survival for each sapling at 1 -month intervals following spring and summer applications. Data were taken until October 17, 2 months after the summer treatments. Biological measurement data were analyzed using a three-way analysis of variance procedure.

RESULTS AND DISCUSSION

Swelling Occurrence and Paraquat Dose

One month (July) after the spring application of paraquat, swellings occurred on 27 (or 7 percent) of the surviving saplings (fig. 1). Swellings occurred on saplings in all four paraquat treatments; no swellings were recorded on control saplings. At 2, 3, and 4 months after the spring application of paraquat, there was a clear response to dose expressed as percentages of swellings on paraquat-treated saplings. The total number of swellings on surviving saplings was about the same in July and August, but decreased in September and October. These decreases were due to diameter growth over time which tended to obscure swellings measured previously on some saplings. The percentages of saplings with swellings recorded after the spring treatment (2 to 27 percent) were less than the estimated 80 to 90 percent of saplings with swellings in 1995. One month (September) after the summer application of paraquat, there were swellings on six (or 1 percent) of the surviving saplings treated at the 1 .O (n=2) and 2.0 (n=4) rates. No swellings were recorded on saplings in 0, 0.25, or 0.5 treatments. In October, one sapling exposed to the 1 .O rate and nine saplings exposed to the 2.0 rate were the only saplings with swellings resulting from the summer treatments. These data address

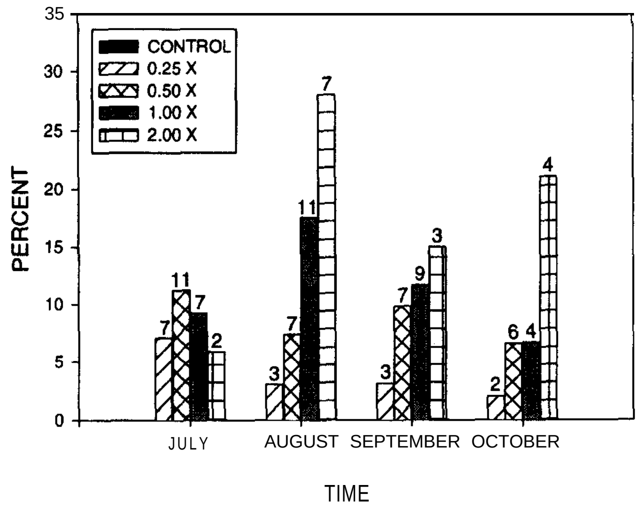

Figure I-Percentages of first-year cottonwood saplings with stem swellings caused by damage to bark tissue following the applications of various doses of paraquat on June 17. Swelling occurrences were assessed at 1 -month intervals. The number above each percentage bar is the actual number of swellings counted for that treatment. Doses are based on a 1 .O rate of 24 ounces per acre.

the first objective of the study by showing that paraquat, even at the 0.25 rate, caused swellings on first-year cottonwood saplings. Further, they show a relationship between paraquat dose and the occurrence of swellings. These data also address the second objective of the study since the occurrences of swellings were less when paraquat was applied 2 months later in the summer (August) after bark tissues were more mature than during the spring application (June).

While the occurrence of swellings was related to dosage, the diameters of swellings generally were not related to dosage in either season, with the exception of saplings treated with the 2.0 rate. In 12 of 14 cases, swelling diameters at the 2.0 rate were less than those at other rates. It appeared that tissue damage was so severe at the 2.0 rate that overall sapling growth, including swelling size, was affected.

Sapling Survival and Paraquat Dose

Sapling survival following the spring application was affected by paraquat dose and ranged from 97 percent for control saplings to 18 percent for saplings treated with the 2.0 rate (fig. 2). This dosage response was inversely related to sapling heights measured 8 days after application (fig. 3). The 2.0 rate of paraquat killed all saplings less than or equal to 0.4 meters (m) tall, whereas the 0.25 rate killed saplings 0.15 m or less. Those differences were statistically significant. Paraquat dose had little effect on sapling survival after the summer application with near 100 percent survival for saplings in control and paraquat treatments (fig. 2). Factors that probably were important in the dose response and height inverse relationship following the spring treatments included spray application height, spray drift height, and the relative response of bark tissues to various paraquat doses. The near total survival following the summer

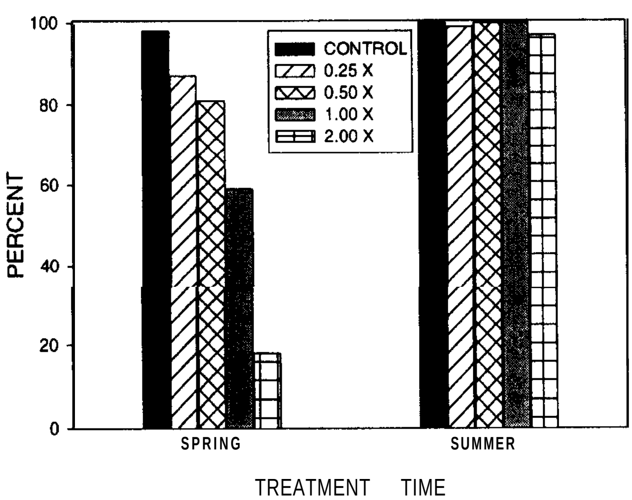

Figure 2-Percent survival of first-year cottonwood saplings evaluated 1 month after the application of various doses of paraquat on June 17 (spring), and 1 month after the application of the same doses of paraquat on August 19 (summer). Doses are based on a 1 .0 rate of 24 ounces per acre.

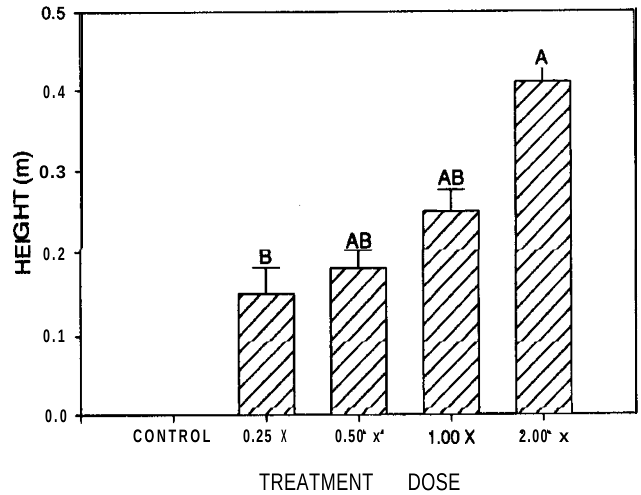

Figure 3-Average heights and standard errors of first-year cottonwood saplings killed by paraquat of various doses. Doses are based on a 1 .O rate of 24 ounces per acre. Different letters above bars indicate different heights, at P=0.5, tested by Tukey's W Procedure.

application indicated the difference in bark tissue maturity, and thus relative susceptibility to paraquat damage, between the groups of saplings treated in spring and summer.

Stem Heights and Diameters and Paraquat Dose

Average heights of saplings treated in June and measured 3 months later decreased in response to increasing paraquat dose (fig. 4). Saplings not treated with paraquat

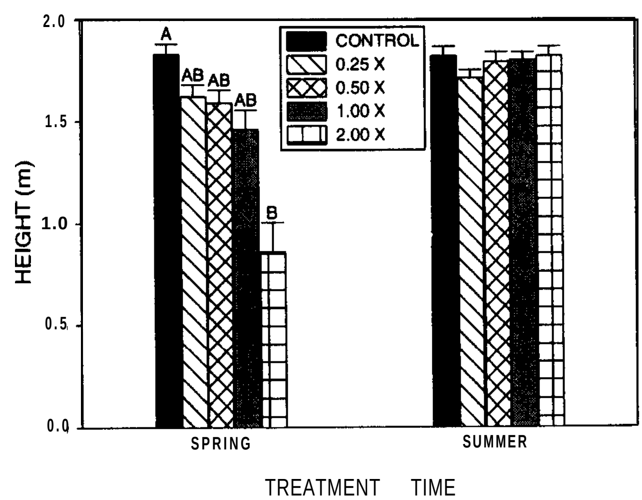

Figure 4—Average stem heights and standard errors of first-year cottonwood saplings measured in mid-September resulting from application of various doses of paraquat on June 17 (spring), or application of the same doses of paraquat on August 19 (summer). Doses are based on a 1 .O rate of 24 ounces per acre. Different letters above bars indicate different heights, at P=0.5, tested by Tukey's W Procedure.

were taller, on average, than saplings treated with the 1 .O and 2.0 rates of paraquat, but were not significantly taller than those treated with the 0.25 and 0.5 rates. There were no treatment differences among average heights of saplings treated in August and measured 1 month later (fig. 4). Average heights of all summer-treated saplings were approximately equal to average heights of spring-treated control saplings. Stem diameters of saplings treated in June and measured 3 months later also decreased as paraquat dose increased (fig. 5). Average stem diameters of control saplings were greater than those of saplings treated with the 1 .O and 2.0 rates of paraquat, but were not statistically different than diameters of saplings treated with the 0.25 and 0.5 rates. The smaller average diameter of saplings treated with the 0.25 rate compared with that of control saplings and saplings treated with the 1 .O rate, following the summer application, is explained best by experimental error. This same trend, though not statistically significant, occurred for stem heights following the summer application (fig. 4). Nonetheless, the average diameter of all summer-treated saplings was approximately equal to the average diameter of spring-treated control saplings.

The losses of growth apparent in stem height and diameter data indicate that there is some risk in applying paraquat for weed control before cottonwood sapling bark tissues have matured enough to not be damaged by the herbicide. In this study, the degree of maturation of bark tissues that protected saplings from paraquat damage occurred in the 2 months between the spring (June 17) and summer (August 19) applications. This time period is likely to vary depending on phenology and genetics. For example, the onset of spring was late in 1996 in comparison to the previous year when the first application of paraquat occurred in mid-May. In general, it would be inadvisable to use paraquat around the bases of first-year cottonwood saplings during spring and early summer. Applications made in mid- to late summer are less likely to cause damage to bark tissues. Stem height and diameter data of spring-treated saplings also suggested a threshold of damage starting with the 1.0 rate. Certainly at the 2.0 rate, paraquat damage was severe enough to reduce even the diameters of swellings. September measurements of stem heights (fig. 6) and diameters (fig. 7) of saplings treated in spring were less, at all four paraquat dosage levels, than their counterparts treated in summer; there were no differences between untreated controls. These spring-summer comparisons suggest that a damage threshold occurred at the 0.25 rate.

Weed Control and Paraquat Dose

Higher doses of paraquat tended to decrease the percentage of weed cover around sapling bases (fig. 8). Although paraquat was sprayed once for the spring treatment, the same dose-related trends in weed cover occurred at 1, 2, 3, and 4 months after spraying. The same trend occurred for percentage of weed cover after summer treatments. Although not specifically documented, it was apparent that different species of weeds were present around sapling bases during the various measurement times. This is evidenced somewhat by the increased weed cover measured in September and October compared to that measured for July and August following the spring treatments. The initial removal of weeds by paraquat may have given saplings time to occupy sites and maintain dominance over annual weeds well after the applications.

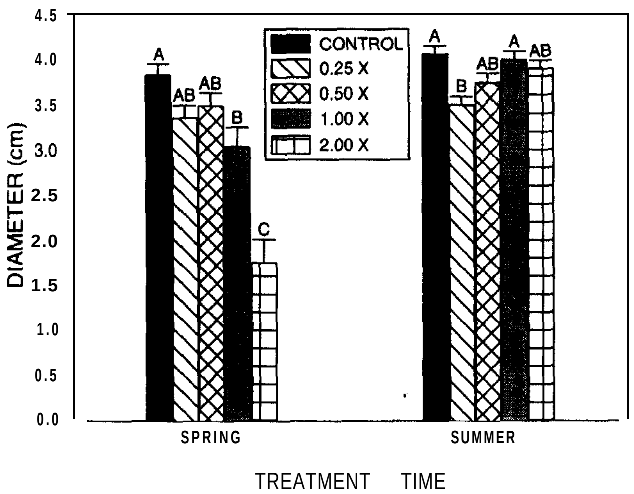

Figure 5-Average stem diameters and standard errors of first-year cottonwood saplings measured in mid-September resulting from application of various doses of paraquat on June 17 (spring), or application of the same doses of paraquat on August 19 (summer). Doses are based on a 1 .O rate of 24 ounces per acre. Different letters above bars indicate different diameters, at P=0.5, tested by Tukey's W Procedure.

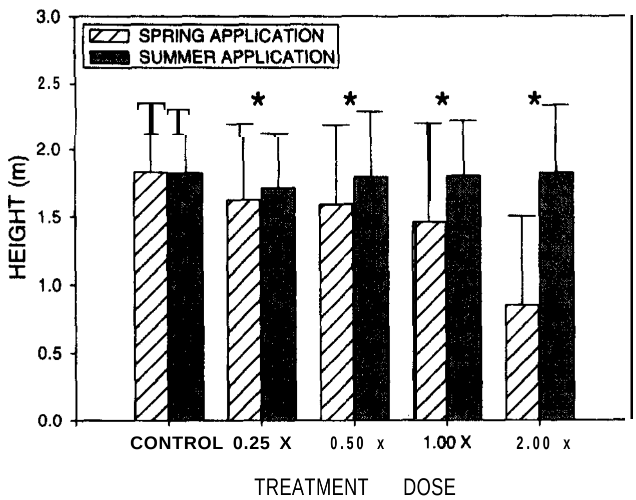

Figure 6-Comparisons between average stem heights, with standard errors, of first-year cottonwood saplings measured in mid-September following either spring or summer applications of various doses of paraquat. Doses are based on a 1 .O rate of 24 ounces per acre. Asterisks indicate different heights between application times, at P=0.5, tested by Tukey's W Procedure.

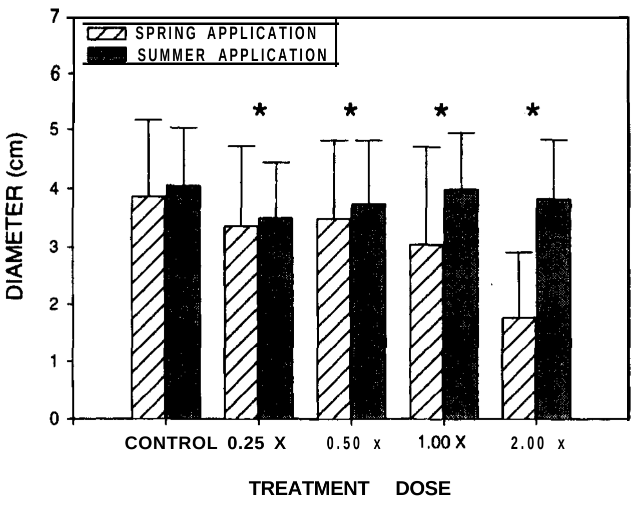

Figure 7-Comparisons between average stem diameters, with standard errors, of first-year cottonwood saplings measured in mid-September following either spring or summer application of various doses of paraquat. Doses are based on a 1 .0 rate of 24 ounces per acre. Asterisks indicate different heights between application times, at P=0.5, tested by Tukey's W Procedure.

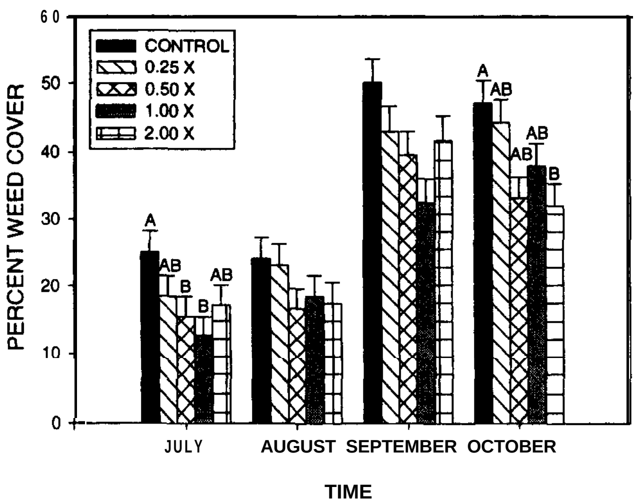

Figure 8-Weed control around the bases of first-year cottonwood saplings, measured by percentage of weed cover (with s.e.m.) within a 0.5 m2 plot, following the application of various doses of paraquat on June 17. Weed cover was assessed at l-month intervals. Doses are based on a 1 .O rate of 24 ounces per acre. Different letters above bars indicate different percentages of weed cover, at P=0.5, tested by Tukey's W Procedure on arc sine-transformed data.

CONCLUSIONS

This study showed that applications of paraquat at 6 oz/ac, the 0.25 x operational rate, caused necrosis of cottonwood bark tissue and stem swellings. Also at this dose, sapling survival was less than for untreated controls, and heights and diameters of saplings treated in June were less than those of saplings treated in August. Higher doses of paraquat increased these effects. Therefore it is inadvisable to apply paraquat around the bases of first-year cottonwood saplings to control weeds before bark tissues have matured enough to be resistant to paraquat damage-probably sometime after mid-summer. Otherwise, sapling mortality or loss of growth is likely to occur. Mechanical cultivation may be all that is needed for weed control since these data do not show any benefit to growth from paraquat applications. Further, a spray rig modified to shield stem bases from the herbicide should be used to apply paraquat. Eastern cottonwood is the fastest-growing commercially important tree species in North America (Cooper and Van Haverbeke 1990), and as such has the innate capacity to recover quickly from injury. Considering the rapid regrowth inherent to the species, cottonwood plantation managers should weigh the advantages of chemical control of annual weeds early in the growing season against the disadvantages of potential decreases in survival and growth in the first year. Additional controlled experiments and documentation of growth beyond the first year could address these issues. These findings should be useful to other commercial, private, and government growers interested in controlling annual weeds in first-year cottonwood plantations, and in reforestation efforts in which cottonwood is planted alone or intermixed with other species.

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COMPARISON OF SOIL BIOASSAY RESPONSES OF LOBLOLLY PINE SEEDLINGS WITH SOIL CHROMATOGRAPHY RESULTS FOR CONVENTIONAL AND CONTROLLED RELEASE HERBICIDES

Craig L. Ramsey, Glenn Wehtje, Harold Walker, Dean Gjerstad, and David South'

Abstract-The duration of herbaceous weed control is dependent on the rate of active ingredient dissipation in the upper soil layers. Controlled release carriers have the potential to maintain the herbicide-soil concentrations at effective "crop safe/weed toxic" levels over extended periods of time. Greenhouse bioassays were used to determine the dose-response of loblolly pine *Pinus taeda L.* and several weed species to a range of hexazinone and sulfometuron soil concentrations. Preliminary results are also reported for the release rates and soil mobility of the commercial, liquid formulation of hexazinone.

INTRODUCTION

The primary factor that determines the duration of herbaceous weed control in pine plantations is the degree of soil activity that can be achieved after a herbicide application. The magnitude of soil activity depends on the inherent properties of the selected herbicide, a host of environmental conditions, and numerous application factors. The soil half-life of a herbicide provides an estimate of the first order dissipation rate of the active ingredients under a specific set of conditions. The half-life of the herbicide-soil concentrations determines the length of time that the active ingredient levels remain within the effective dose range necessary for effective weed control (Cheng 1990).

Forest managers generally seek to achieve both minimal pine seedling injury and optimal weed control when prescribing herbaceous weed control rates. This goal is possible if the soil active herbicide level is maintained between the Toxic Dose (TD_{50}) soil concentration for the crop species and the Effective Dose (ED_{50}) soil concentration needed for most of the weed species (Schreiber and others 1987). Managers usually have to balance the desired level of weed control with the level of pine injury they can tolerate, when they apply single-dose, season-long herbicide applications. Reliance on nature's "regulation" of herbicide-soil concentrations, through first order dissipation, can lead to disappointing results due to erratic or extreme rainfall events, extremes in soil pH or percentage of organic matter, or voracious soil microbes. In addition to maintaining a "crop-safe/weed-toxic" soil concentration range, the spatial movement of the soil-herbicide solution should be restricted, as much as possible, to the upper weed root-zone layer.

Controlled-release herbicide carriers have the potential to both (1) maintain ED,, herbicide-soil concentrations over a season-long time period, and (2) reduce the active ingredient movement out of the weed root zone (Wilkens 1995). The herbicide release rate is controlled by rainfall events and/or surface erosion of the granule. The periodic release of active ingredients somewhat balances the ongoing soil losses to leaching and chemical or biological degradation.

A leaching study with Starch-Encapsulated (SE) atrazine found that 99 percent of the SE formulation was retained in the top 5 centimeters (cm) of the soil column. In contrast, the commercial liquid formulation retained only 18 percent of the active ingredients in the top 5 cm (Fleming and others 1992). Another leaching study with Alginate-Encapsulated (AE) alachlor found that only 4 percent of the AE alachlor was leached from the top 5 cm of soil. The standard liquid treatment, however, leached 33 percent of its active ingredients out of the top 5 cm of the soil column after 420 ml of $CaCL_2$ was leached through the column (Johnson and Pepperman 1996).

The goal of this research project is to improve herbaceous weed control for forest pine plantations through the use of after-market carriers that act as controlled release matrices. The project consists of three separate studies. The first study involves the determination of the TD,, and ED,, herbicide-soil concentrations for loblolly pine seedlings and several weed species. The second phase of the project investigates the active ingredient release rates and soil mobility from several matrices after three leaching events on thin layer soil chromatography plates. The third study is a field evaluation of the effectiveness and duration of weed control and pine safety for several of the controlled release carriers. The results from the greenhouse bioassay study, along with preliminary results from the chromatography study, are presented in this paper.

METHODS

The greenhouse bioassay studies were conducted to determine the dose-response of loblolly pine seedlings and three weed species, broadleaf signalgrass *Brachiaria platyphylla,* sicklepod *Senna obtusifolia,* and tall morning glory *Ipomoea purpurea* to soil applied hexazinone and sulfometuron. The studies were completely randomized with six single container replications of each treatment. The hexazinone and sulfometuron studies consisted of six and five soil concentrations, respectively. Both bioassays were conducted over a 2-month time period. The hexazinone study was conducted twice, the first on August 8, 1996, and the second on October 28, 1996.

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The bioassay soil was collected near Auburn, AL. The soil series is a Uchee loamy sand, classified as a loamy, siliceous, thermic, Arenic Hapludult. The particle sizes were 90 percent sand, 7 percent silt, and 3 percent clay, and the percentage of organic matter was 0.88 percent. The soil had a bulk density of 1.32 grams per cubic centimeter (g/cm^3), a pH of 4.8, a field capacity of .11 kilograms per kilogram (kg/kg) and a CEC of 3 cmol. The soil was collected only from the top 20 cm of the soil profile. The soil was air dried, thoroughly mixed, and passed through a 2 millimeter (mm) screen. Planting containers were filled with 1 kg of soil.

The pine soil concentrations for hexazinone were 0.0, 0.2, 0.4, 0.6, 0.8, and 1 .O mg active ingredient (ai) kg-‘. The weed soil concentrations for hexazinone were 0.0, 0.1, 0.15, 0.2, 0.25, 0.3, and 0.35 mg ai kg-‘. The pine soil concentrations for sulfometuron were 0.0, 0.01, 0.05, 0.1, and 0.5, mg ai kg^{-1}. The weed soil concentrations for sulfometuron were 0.0, 0.001, 0.005, 0.01, 0.05, 0.1, 0.5, 1 .0, 5.0, and 10.0 mg ai kg^{-1}. Each herbicide treatment was diluted in 110 ml of tap water to ensure that the initial soil moisture was at field capacity for each container. Pine seedlings or weed seeds were planted, or sown, as the pre-mixed soil was added to the containers. The loblolly pine seedlings were collected the day before planting from a forest company field nursery. The pine seedlings were 4 months old, with an average weight of 8.6 g for the first study, and 6 months old, with an average weight of 30.1 g for the second study. Each seedling was weighed before planting. Broadleaf signalgrass and sicklepod were sown together in a single container for each herbicide treatment.

Weed control assessments were expressed as percent mortality. Each pine seedling was root washed and weighed on a green weight basis. Differences in fresh weight biomass growth for each soil concentration were calculated by subtracting the initial seedling weights from the final weights. The treatment means for percent weed mortality and pine seedling biomass growth were used to estimate the ED,, and TD,, soil concentration levels for hexazinone and sulfometuron herbicides. These soil concentration estimates will then be used as target goals for the second phase of this project.

The laboratory study involving the kinetic rate of active ingredient release from various matrices combined soil thin-layer chromatography with liquid scintillation techniques. The same soil used for the bioassay study was also used in this study. Controlled release materials, such as crosslinked polyacrylamides, activated charcoal, newspaper fluff, and methylated seed oil will eventually be loaded with radiolabeled hexazinone or sulfometuron using acetone solvent. The preliminary results reported here include only the initial trial for the standard, suspension concentrate formulation of hexazinone, Velpar-L. The liquid formulation trial included three replications of three leaching events, i.e., three plates were leached once, another three plates were leached twice, and the last three plates were leached three times.

Modified plexiglass plates were used to hold the controlled release granules on the soil plates. The soil dimensions on the plates were 90 by 280 mm, with a uniform thickness of 2 mm. Each plate received 60 microliter (l) of radiolabeled hexazinone solution, approximately 2 cm up from the bottom of the soil plate. The hexazinone dose per plate was 1.43 mg of active ingredients. This rate is equivalent to approximately 6.9 pounds (lb) a.i. per acre. The plates were then placed in a water bath with paper wicks to ensure adequate air saturation. The covered baths were individually monitored, and removed as each wetting front reached the 27 cm mark on the plate. Each plate was then oven dried at a low, nonvolatilizing temperature before it was leached again, or set aside for soil counting. After completing each set of leaching cycles, the plates were divided into 27 soil samples, each 1 cm wide. The soil samples were then radio-counted according to the liquid scintillation techniques described by Corbin and Swisher (1986).

RESULTS AND DISCUSSION

The bioassay results for the first hexazinone study involving pine seedling injury are given in figure 1. The horizontal bars in the figure represent the treatment mean, and the vertical bars represent the standard errors. There was a negative, linear reduction in biomass growth for the pine seedlings as the soil concentration increased. Two of the treatment means are labeled with the equivalent active ingredient rate per acre; given that the soil has a bulk density of 1.32 g per cm^3 and the herbicide is uniformly distributed in the top 12 cm of soil.

The two exceptions to this linear trend were the highest hexazinone rates of 0.8 and 1 .O parts per million (ppm). This can be partially explained by the method used to estimate the "growth" for seedling mortality. All of the dead trees were

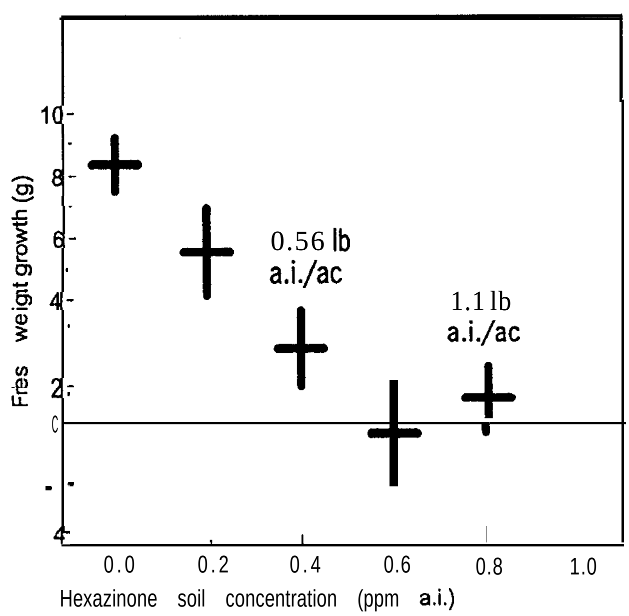

Figure l-Dose-response of loblolly pine seedlings to hexazinone, 2 months after treatment.

assigned a growth rate of zero. All of the seedlings with the 1 .0 ppm hexazinone treatment were dead at the end of the 2-month study. Thus, the mean for the 1 .0 ppm treatment was zero, with no vertical standard error bar. Pine seedlings may have a negative growth over time if the metabolism rate exceeds the photosynthetic rate, as shown by the 0.8 ppm treatment. Also, both of the standard errors for the 0.6 and 0.8 ppm treatments include zero growth rate.

This trial reveals that any soil concentration of hexazinone above the zero level will reduce pine growth. Approximately 3 g of growth is lost for each 0.2 ppm increment increase in hexazinone soil concentration, over the 2-month period. How much seedling growth loss can be tolerated in order to gain effective weed control is still an open question. The TD,, level for the pine seedlings is between the soil concentrations of 0.6 and 0.8 ppm (w\w). The TD_{100} is 1 .O ppm for the seedlings.

Figure 2 shows the dose-response of germinating signalgrass and tall morning glory to the seven hexazinone treatments, 2 months after treatment (MAT). There is a positive trend between percent weed control and increasing hexazinone soil concentrations. The minimal ED,, for control of these two weed species is between 0.2 and 0.3 ppm (w\w). The ED,,, for these species is between 0.3 and 0.35 ppm.

The margin of soil concentration safety between the TD,, for pine seedlings, 0.6 ppm, and the minimal ED_{50} for effective weed control, 0.3 ppm, is quite narrow. This indicates that the selectivity of hexazinone is restricted for pine seedlings. These results also suggest that hexazinone selectivity is based primarily on spatial patterns in soil concentrations.

Figure 3 shows the dose-response of pine seedlings to five soil concentrations of sulfometuron. There is a general, negative, linear decrease in pine fresh weight growth as sulfometuron soil concentrations increase. Two of the treatment means are labeled with the equivalent active ingredient rate per acre; given that the soil has a bulk density of 1.32 g per cm^3 and the herbicide is uniformly distributed in the top 12 cm of soil. There was no pine mortality over the 2-month period. However, there was an average fresh weight growth loss of 6.6 g per seedling between the soil concentrations of 0.0 and 0.5 ppm, 2 MAT. For every sulfometuron rate increase above 0.01 ppm, there was an average loss of 1.65 g of fresh weight growth. The TD,, cannot be estimated for sulfometuron, given the soil concentration range used in this trial. However, pine growth losses can be minimized by reducing the target herbicide-soil concentrations down to the ED,, or ED,,, weed control soil concentrations.

Figure 4 shows the dose-response of germinating sicklepod to sulfometuron, 2 MAT. There is a positive trend between percent weed control and increasing sulfometuron soil concentrations. The minimal ED,, for control of sicklepod is between 0.005 and 0.05 ppm (w\w). The ED,,, soil concentration is greater than, or equal to, 0.05 ppm.

The results from this trial indicate that sulfometuron is very selective for loblolly pine seedlings. Given the study conditions of uniform herbicide-soil concentrations, and a single germinating summer annual weed, there is a wide

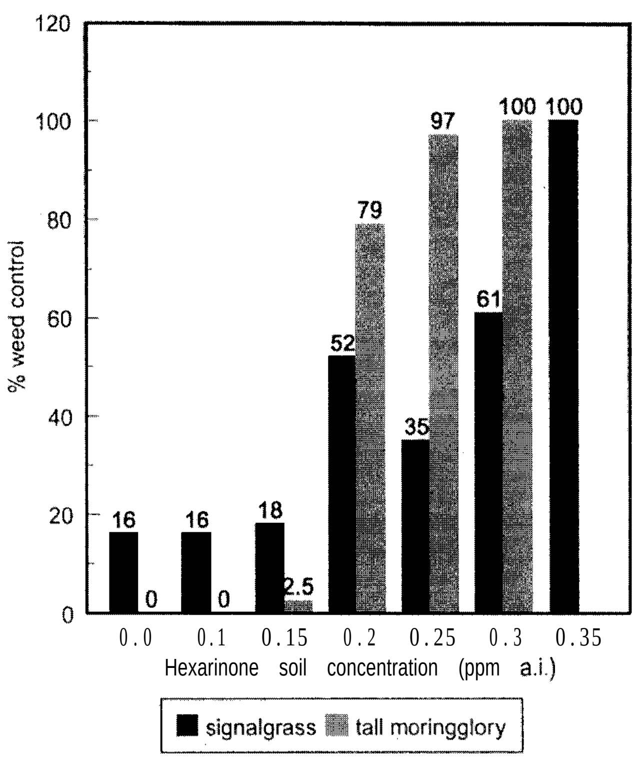

Figure 2—Dose-response of signalgrass and tall morning glory to hexazinone, 2 months after treatment.

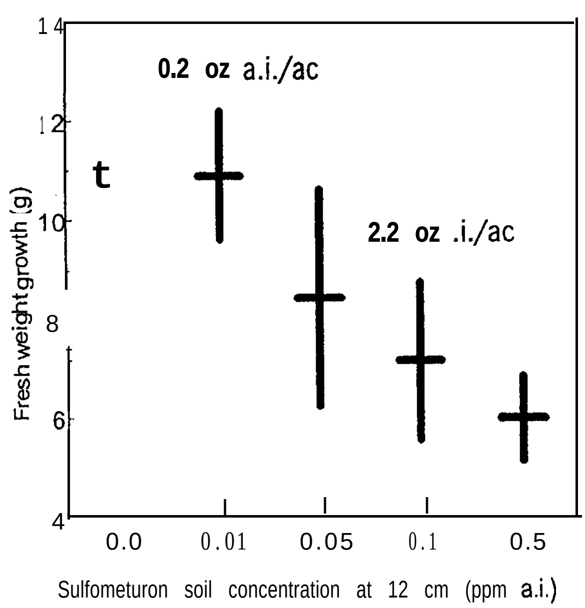

Figure 3-Dose-response of loblolly pine seedlings to sulfometuron, 2 months after treatment.

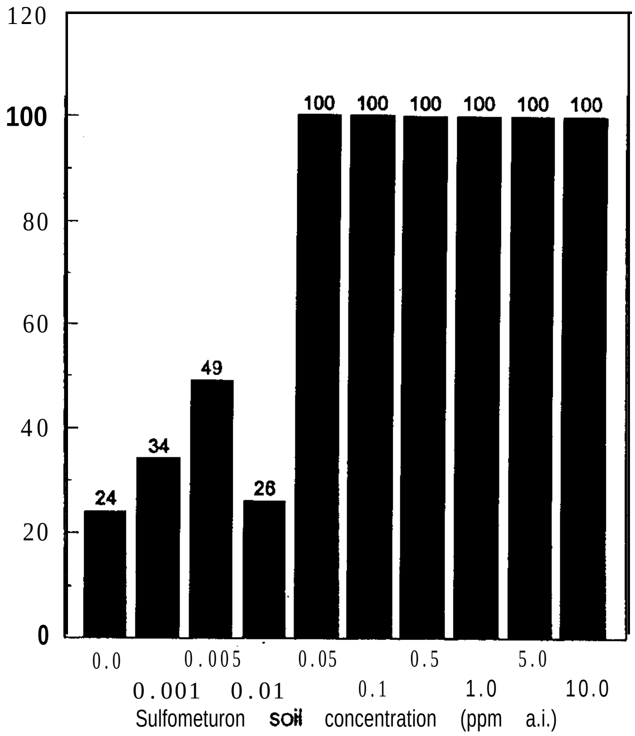

Figure 4-Dose-response of sicklepod to sulfometuron, 2 months after treatment.

margin of safety between the toxic dose level for pines and the effective dose level needed for weed control.

The results from these studies provide the TD,, and ED,, soil concentrations needed to set target release rates for the controlled-release carriers. Caution should be taken when interpreting these results. Soils with high cation exchange capacities, or organic matter content, will require higher dose rates due to high adsorption rates. Hard-to-control weed species will also require higher dose rates. In addition, the spatial patterns in soil concentrations due to active ingredient mass movement need to be taken into consideration, at least for hexazinone applications.

Figure 5 shows the preliminary, nonreplicated results for the first leaching cycle of the liquid formulation of hexazinone. The y axis of the graph is representative of the soil profile. The first bar represents the surface soil concentration, and the last bar represents the soil concentration 18 cm deep in the soil. After the first leaching event, 83 percent of the active ingredients remained in the top 12 cm of soil.

Figure 6 shows the hexazinone leaching results for a thin layer chromotography (TLC) plate receiving three separate bath cycles. Most of the active ingredients had been transported out of the weed root zone. Only 21 percent of the hexazinone remained in the top 12 cm of the soil profile. The soil retained an average of 4.4 ppm in the top 12 cm after the first leaching cycle. The third leaching cycle, however, retained an average of only 1 .O ppm in the top 12 cm of soil. These results show that the hexazinone

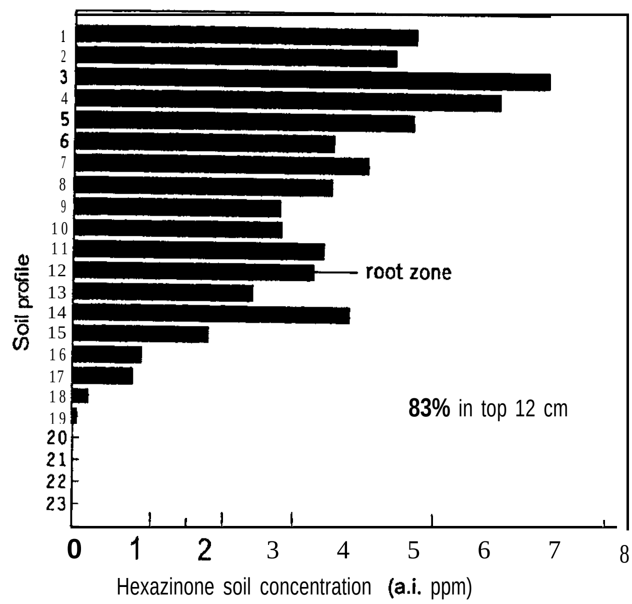

Figure 5—Hexazinone soil concentrations after the first leaching cycle.

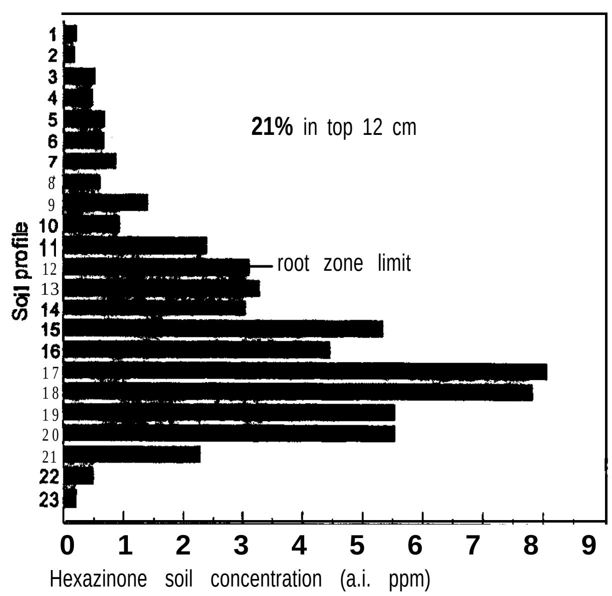

Figure 6—Hexazinone soil concentrations after the third leaching cycle.

soil concentration is reduced by 25 percent in the top 12 cm of soil, after three leaching cycles.

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Site Classification

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YELLOW-POPLAR SITE INDEX AND SOIL PROPERTIES IN THE PISGAH NATIONAL FOREST

W. Henry McNab[1]

Abstract-The relationship of site index (SI) of yellow-poplar (*Liriodendron tulipifera* L.) to soil series and soil physical and chemical properties was studied in a small area of mountainous terrain in western North Carolina. Site index ranged from 26.4 meters (m) to 38.7 m on 39 sample plots. Average SI of stands on Brevard soils (29.6 m) was significantly lower than that of stands on Tusquitee (33.2 m) or Haywood soils (33.5 m). Site index was correlated mainly with humic matter and bulk density. Regression models using age and bulk density as independent variables explained 50 percent of the variation in stand height at age 50. Residuals of models in which SI was the dependent variable were highly correlated with stand age. Models based on stand height at age 50 were always superior to those based on SI. Soil properties explained only a moderate proportion of variation in total height, and this suggests that other factors, such as topography and climate, may also be important determinants of site quality.

INTRODUCTION

Site index (St-total tree height at a specified age, usually 50 years) has been used to express productivity of forest sites for many commercial tree species since the 1920's. Determination and use of SI are not completely straightforward. Biased curve construction methods (Beck and Trousdell 1973), influence of stand density (Eigel and others 1982, Ike and Huppuch 1968), and sample tree selection (Lloyd and Jones 1983) can present problems. Despite these problems, SI is widely used as an expression of site quality because of its ease of application and interpretation. Site index is seemingly well suited for use in evaluation of sites dominated by yellow-poplar because this species is generally shade intolerant, displays apical dominance during early to middle ages, and occurs in even-aged stands.

Site index has long been presented in association with soil map units to provide information on forest productivity and suitable tree species. Ike and Huppuch (1968) found that yellow-poplar height was correlated with groups of soil series in north Georgia. Eigel and others (1982) reported that yellow-poplar site quality was correlated with several soil series in eastern Kentucky, but Phillips (1966) found little association of SI with soil series in New Jersey. Also, VanLear and Hosner (1967) found that yellow-poplar SI did not differ from soil mapping unit to soil mapping unit for five such mapping units in southwest Virginia. Most researchers have found that soil taxons have not accounted effectively for variation in yellow-poplar SI.

The influence of environmental factors on SI of yellow-poplar has been evaluated in various soil-site studies. Prediction models based on soil, topographic, and climatic variables have been developed (Auten 1945, Brown and Marquard 1988, Ike and Huppuch 1968, Munn and Vimmerstedt 1980, Smalley 1964, Tryon and others 1960). Usually, yellow-poplar growth is correlated mostly with soil and topographic properties that affect moisture availability during the growing season, and somewhat with factors that influence nutrient availability. In most cases the proportion of SI variation explained is moderate, between 50 and 75 percent. A problem with most soil-site relationships is lack of validation with independent data sets (Broadfoot 1969).

Because the results of studies of soils and SI have often been inconclusive, and have sometimes been contradictory, additional study of the factors affecting site quality is desirable. The purpose of this exploratory study was to evaluate the relative importance of specific soil variables that affect site quality for yellow-poplar, and to test for correlations between soil taxonomic units and yellow-poplar SI.

THE STUDY AREA

The study was conducted in the Pisgah Mountains of western North Carolina, near Asheville. Geologic formations of this region consist of highly metamorphosed Precambrian muscovite and biotite schist and gneisses, and occasional Devonian granitic outcrops. Local relief ranges from gently rolling hills to steep mountain slopes. Surficial geologic deposits consist of Holocene and Wisconsin loamy colluvium 2 to 5 meters (m) thick. Soils are mostly relatively deep [>100 centimeters (cm)], have a loam surface texture, are well drained, are fine to coarse in texture, and acidic. Dystrochrepts are typically present on moderate to steep slopes and Ultisols are present in low elevation intermountain basins where soils have formed in residuum. Mean annual temperature averages 13 °C. and mean monthly temperature ranges from 2 "C. in January to 22 °C. in July. Annual precipitation averages 120 cm in low-elevation mountain valleys but increases with altitude.

Over 100 arborescent species are indigenous to this region. Oaks (*Quercus* sp.) dominate dry slope and ridge sites at elevations below about 1500 m. Moist lower slopes and cove forests are dominated by mesophytic species such as yellow-poplar. Conifers may be present also.

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METHODS

Plots used in this study were originally established in the early 1960's for study of growth and yield of yellow-poplar (Beck and Della-Bianca 1970). Thirty-nine quarter-acre (0.10 hectare) plots in the Pisgah Mountains were selected for use in the present study. These were clustered in two groups: (1) 19 plots in the Bent Creek Experimental Forest, situated at an elevation of 830 m about 16 kilometers (km) south of Asheville (N35°30'00", W82°37'30"), and (2) 20 plots in Mince Cove (N35°22'30", W82°40'00"), about 8 km west of Bent Creek Experimental Forest, at the same average elevation. Most plots are on cove landforms, have northeast to southeast aspects, and have slope gradients between 20 and 40 percent. Beck's (1962) curves were used to determine SI for each plot when the original study was installed, and the SI's were reported in the establishment report (On file, Bent Creek Experimental Forest).

A soil scientist classified the soils on each plot to the series taxonomic unit during the summer of 1983. Soils were described in detail by subhorizon to a maximum depth of about 140 cm, which on most plots included the entire A-horizon and much of the B-horizon. Depth to each visible change of texture and color within each horizon was measured and composite samples were collected for determination of physical and chemical soil properties. Analysis was done by the North Carolina Soils Test Laboratory for: (1) humic matter (HM) (percent), (2) bulk density (BD) (grams per cm^3), (3) P (milligrams per cubic decimeter), (4) K (millequivalents per 100 cm^3), (5) Ca (millequivalents per 100 cm^3), (6) Mg (millequivalents per 100 cm^3), (7) Na (millequivalents per 100 cm^3), (8) cation exchange capacity (CEC) (millequivalents per 100 cm^3), (9) acidity factors (AF) (millequivalents per 100 cm^3), and (10) pH (log H-ion concentration). Three other soil properties were derived: (11) total bases (TB) (sum of Ca, Mg, K, Na), (12) total cations (TC) (calculated as TB+AF), and (13) base saturation (BS) (percent) (calculated as (TB/TC)*100). Concentrations of soil chemicals and values for physical properties were weighted by thickness of each subhorizon to approximate a value for the whole horizon. Values for the A and B horizons were weighted by the thicknesses of the horizons to characterize the solum. Although pH is expressed on a logarithmic scale, it was treated as a nonlogarithmic variable.

Simple relationships between soil properties and site quality were examined by plotting, correlation, and simple regression models. Site index was used as the dependent variable in one model to account for variation in height associated with age, thereby allowing maximum emphasis on the relative importance of soil properties. However, because SI curves are themselves predictions based on models, a more direct accounting of the importance of soil variables was made by expressing height at age 50 (HT50) as the dependent variable in the second regression model.

Separate regression analyses were made using soil variables for each horizon and the solum for (1) all series combined, and (2) individual series, where adequate replications were available. A dummy variable was used to account for differences in site quality associated with the two locations. Simple correlation coefficients (r) were used to evaluate the relationships between dependent and independent variables. Analysis of variance was used to test for significant differences in mean SI among series. Scheffe's test at the 0.05 level was used to separate means by soil series. Data were analyzed by stepwise regression using combination forward and backward methods for inclusion of variables in the model that produced the largest coefficients of determination (r^2). The level of significance for inclusion of variables in the model was $p<0.10$. All analyses were made using SAS (SAS Institute 1985).

RESULTS AND DISCUSSION

Average stand age was 53.5 (±11.9 standard deviation) years; average height was 32.8 (±3.3) m; and SI averaged 29.6 (+2.3) m. Initial analyses indicated no significant effect of group locations on SI.

Soil Series

The 39 sample plots were situated on soils representing 6 taxonomic series (table 1). All series were well drained, relatively deep (greater than 100 cm), and had loam surface texture and mesic temperature regime. Brevard and Watauga series have clay accumulation in the B

Table l-Number (N) of plots sampled, site index (SI), site type, and taxonomic class by six soil series for yellow-poplar stands in western North Carolina

Series	N	Si[a] (range)	Site	Taxonomic class
Ashe	1	33.7 (-)	Slope	Typic Dystrochrepts
Brevard	6	29.6 (26.7-32.7)	Bench	Typic Hapludults
Haywood	8	33.5 (28.9-38.7)	Slope	Cumulic Haplumbrepts
Porters	1	32.3 (-)	Slope	Umbric Dystrochrepts
Tusquitee	22	33.2 (26.4-38.3)	Cove	Umbric Dystrochrepts
Watauga	1	34.2 (-)	Slope	Typic Hapludults

[a]In meters, base 50 years.

horizon. Only three series (Brevard, Haywood, and Tusquitee) were represented by an adequate sample size (three or more plots) for testing mean differences in SI. Scheffe's test indicated that mean SI of Brevard (29.6±3.6 m) was significantly lower than mean SI of Haywood (33.5±3.6 m) or Tusquitee (33.2±2.9 m) and that mean SI of Haywood was not significantly different from mean SI of Tusquitee. The range of SI was least for Brevard (6.0 m) and greatest for Tusquitee (11.9 m).

Site index was correlated with relatively few properties in each soil series (table 2). Humic matter and Bulk density were most consistently correlated with SI. Many soil properties were significantly correlated with other soil properties. Correlated properties included humic matter and bulk density (r=-0.62), and CEC and Bulk density (r=-0.48). For Tusquitee, SI was correlated with only one variable: Humic matter of the solum.

The insensitivity of SI to soil series in my study is similar to that reported for other locations in the Southern Appalachians. Ike and Huppuch (1968) found a range of 35 feet (10.7 m) in SI for eight soil series, but differences in SI were only at the extremes. VanLear and Hosner (1967) reported a lack of significant correlation between SI and soil series and suggested that classification criteria for taxonomic units are more important for agricultural crops than for trees. Also, individual soil series can be described rather broadly, and broadness of description could allow excessive variation in site quality within series. Although this study revealed that yellow-poplar SI for the Brevard series differed significantly from that for other series, this finding is of limited usefulness because areas of Brevard soils are small and restricted to floodplain terraces. The fact that SI is about identical for Haywood and Tusquitee is surprising because these series differ considerably in thickness of A-horizon, which is typically correlated with site quality for yellow-poplar and other species. Shortly after this study was concluded, the Tusquitee taxon was subdivided into two series (the new series is Tuckasegee), and this subdivision may reduce the broad range of soil properties associated with Tusquitee.[2]

Soil Properties

Descriptive statistics for soil fertility factors summarized in table 2 are presented by individual cations for Tusquitee and all series in table 3. Ca accounts for about half or more of all cations in the A and B horizons and in the solum; Na is the least common cation. Acidity factors (mostly H and Al) are relatively constant among all soil layers for Tusquitee and all series. Site index was not significantly correlated with level of any cations for the Tusquitee series or for the pooled series data sets. The range of cation levels found on the study plots with Tusquitee soils nearly equaled the range reported by the Natural Resources Conservation Service that characterizes this series[3].

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[2] Personal communication. 1997. Sara A. Browning, Assistant Ranger, Nantahala National Forest, 90 Sloan Road, Franklin, NC 28734.

[3] Unpublished Natural Resource Conservation Service regional data for Tusquitee and Tuckasegee series were combined to approximate the Tusquitee series recognized in 1983 and resulted in a range of CEC for the A horizon of 3.1-20.0 millequivalents per 100 cubic centimeters and 1.2-4.9 millequivalents per 100 cubic centimeters for the B horizon. In this study, CEC ranges for Tusquitee soils were 3.1-14.7 and 2.2-5.2 millequivalents per 100 cubic centimeters for the A- and B- horizons, respectively.

Table 2-Mean soil properties[a] and correlation with site index[b] by series and horizon for yellow-poplar stands sampled in western North Carolina

Series	Hzn	Thk	TB	CEC	BS	HM	pH	P	BD
Brevard	A	15	4.1*	6.3	56	1.1*	5.5*	2.3	0.9
	B	114*	1.4	2.8	45	0.2	5.2	0.9	1.1*
	Solum	129*	1.7*	3.2	46	0.3	5.3*	1.1	1.1*
Haywood	A	55	3.3	6.3	41	2.4*	5.3	2.7	0.8
	B[c]	92*	0.9	4.0*	20	1.2*	4.9	2.3	1.0
	Solum	147*	1.6	4.7*	26	1.8*	5.1	2.6	0.9*
Tusquitee	A	23	3.5	6.5	45	1.9	5.4	2.8	0.9
	B	108	1.0	3.4	29	0.7	5.1	1.3	1.0
	Solum	131	1.5	3.9	32	0.9*	5.2	1.5	1.0
All	A	28	3.7	6.5	48	1.8*	5.4	2.8	0.9
	B	103	1.1	3.5*	31	0.7*	5.1	1.4	1.0*
	Solum	131	1.6	4.0*	34	0.9*	5.2	1.7	1.0*

[a] Soil property abbreviations and units of measure: Hzn=horizon, Thk=thickness (cm), TB=total bases ($meq/100cm^3$), CEC=cation exchange capacity ($meq/100cm^3$), BS=base saturation (pct), HM=humic matter (pct), BD=bulk density (g/cm^3).
[b] *Indicates significant ($p<0.1$) correlation with site index.
[c] No B horizon measured on one plot where A horizon >140 cm.

Table 3-Means and ranges of selected chemical properties of the A and B horizons of Tusquitee and all soil series for yellow-poplar stands in western North Carolina

Soil property[a]	Tusquitee (n=22) Mean	Tusquitee (n=22) Range	All series (n=39) Mean	All series (n=39) Range
A horizon				
Thickness	23.2	15.2-45.7	28.0	10.2-l 39.7
Ca	2.54	0.10-11.4	2.62	0.10-11.4
Mg	0.78	0.10-2.18	0.86	0.10-2.18
K	0.20	0.06-0.44	0.21	0.06-0.48
Na	0.01	0.00-0.03	0.01	0.00-0.03
TB	3.52	b	3.70	b
AF	2.94	b	2.79	b
CEC	6.46	b	6.49	b
BS	54	b	57	b
B horizon				
Thickness	108.3	86.4-124.5	102.7	58.4-i 24.5
Ca	0.50	0.1 O-2.04	0.51	0.1 O-2.04
Mg	0.39	0.08-l .01	0.44	0.08-l .62
K	0.14	0.04-0.29	0.41	0.03-0.36
Na	0.01	0.00-0.03	0.01	0.00-0.20
TB	1.04	b	1.11	b
AF	2.40	b	2.36	b
CEC	3.44	b	3.47	b
BS	30	b	32	b

[a] Soil property abbreviations and units of measure: Thickness in cm, Cations (Ca, Mg, K, Na) in meq/1 00cm^3, TB=total bases (meq/1 00cm^3), AF=acidity factors (meq/l 00cm^3), CEC=cation exchange capacity (meq/100cm^3), BS=base saturation (pct).
[b] Range not determined.

Regression analysis of SI as a function of soil properties was done using all series pooled (39 plots) and for Tusquitee, the only series with adequate sample size (22 plots). The best regression model for all series combined predicted SI as a function of Humic matter alone, but variation explained was low (r^2= 0.28). Examination of residuals around the regression revealed a highly significant correlation of SI with stand age (r=-0.64). When age was included in the regression the total proportion of variation explained increased (r^2=0.50), but variation explained by bulk density, the only significant soil variable, was low (r^2=0.18). For Tusquitee samples, age explained a significant proportion of variation in SI (r^2=0.37), but no soil variables entered the model. The Tusquitee series appears to be intermediate to the Brevard and Haywood series in many soil characteristics, but characteristics of the three series overlap considerably. Comparison of data upon which the model for all series is based suggests that data for the Brevard and Haywood series, with respectively higher and lower bulk densities than Tusquitee, account for the significance of the relationship between SI and bulk density (fig. 1).

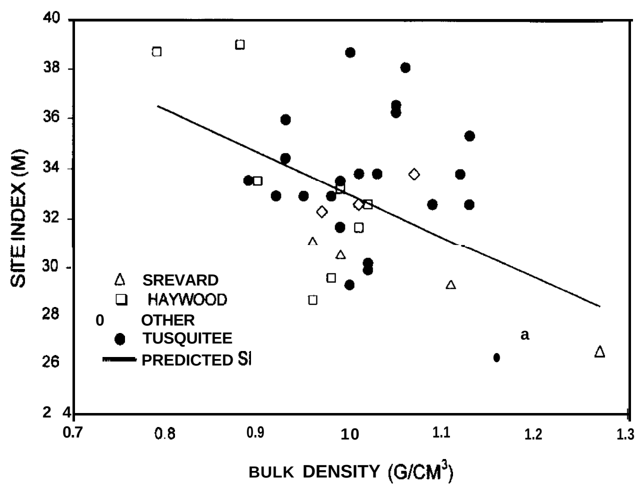

Figure l-Actual and predicted site index in relation to solum bulk density and soil series for yellow-poplar stands in western North Carolina.

Results using HT50 as the dependent variable in multivariate models indicated that stand age accounted for most variation (table 4). Bulk density was the most important soil variable for models of the B horizon and solum. Horizon thickness was also related to HT50, but explained little variation. For models based on Tusquitee series, stand age was the only significant variable. Although HT50 is a more appropriate dependent variable to use for predicting yellow-poplar site quality, the model accounted for about the same proportion of variation as SI.

Results of this study suggest that height of yellow-poplar is more a function of soil physical properties than of soil fertility. Many researchers have reached similar conclusions about the importance of variables that influence the soil moisture regime (Auten 1945, Hay and others 1987, Phillips 1966, Schomaker 1958, Smalley 1964). Fertilization studies conducted on poor sites indicate that yellow-poplar responds in height and diameter to increased N, P, and K (Finn and White 1966, Schomaker and Rudolph 1964), but response is generally less on good sites (Hay and others 1987, McAlpine 1959). Loftus (1971) reported that development of yellow-poplar root systems may be sensitive to Ca, particularly in the B horizon where increased acidity reduces potential availability of this cation. Ca levels in this study were somewhat above those reported by Loftus for Hartsells soils in Tennessee and were not significantly related to SI. However, the level of some soil cations could be influenced by decomposition of yellow-poplar litter because foliage of this species is high in Ca and Mg (Cotrufo 1977). Soils in the present study, represented mainly by Tusquitee, appeared to provide minimum requirements for moderate but not exceptional height growth.

The overall lack of association between soil cations and height of yellow-poplar is consistent with findings of Schomaker and Rudolph (1964). Schomaker and Rudolph (1964) found no correlation between growth of yellow-poplar and soil cation levels in a 25-year-old plantation in Michigan, but relationships between growth and levels Of nutrients in foliage and litter were highly significant. Finn and White (1966) and Gilmore and others (1968) also found high correlations between levels of nutrients in foliage and yellow-poplar growth. Heiberg and White (1956) state that foliar analysis provides a direct assessment of soil nutrients available and used by trees for growth compared to indirect evaluation based on soil analysis.

Other environmental variables in addition to those associated with soils must be considered when predicting growth of yellow-poplar in the Southern Appalachians. Topographic variables have an important influence on availability of moisture (Ike and Huppuch 1968) and may influence transpiration and respiration, length of growing season, and other factors related to tree growth but not expressed by soil properties. Climatic variables are also correlated with yellow-poplar growth (Beck 1985, Tryon and Myers 1952). As Smalley (1964) suggests, growth response of yellow-poplar to environmental factors is complex and a number of compensating and interrelated site factors are likely to be important.

In summary, even though wide ranges of SI and soil characteristics were included in this study, soil series or soil characteristics appear to be of limited usefulness for predicting site quality for yellow-poplar. The few soil variables that were significantly related to yellow-poplar SI suggest that variables affecting soil moisture regime are more important than those affecting soil fertility. More study-and especially study that includes topographic variables, samples in soil series other than Tusquitee, and nutrient analysis of foliar samples-is needed to determine the actual value of soil characteristics as predictors of site quality for yellow-poplar.

ACKNOWLEDGMENT

Donald E. Beck, retired Research Forester, USDA Forest Service, Bent Creek Experimental Forest, was responsible for the design and field implementation of this study.

Table 4-Partial and total correlation of significant regression variables[a] with total height at age 50 years for yellow-poplar stands on Tusquitee and all soil series in western North Carolina

Soil series	Horizon	Variable 1	Variable 2	Variable 3	Total
		Variable (r^2)			
Tusquitee	A	Age(0.47)	-		0.47
	B	Age(0.47)	-		0.47
	Solum	Age(0.47)	-		0.47
All series	A	Age(0.34)	TH(0.08)	PH(0.07)	0.49
	B	Age(0.32)	BD(0.15)	TH(0.03)	0.50
	Solum	Age(0.32)	BD(0.18)	-	0.50

[a] Age=stand age (years), TH=thickness of soil layer (cm), BD=bulk density (g/cm^3), PH=pH.

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BOTTOMLAND HARDWOOD CLASSIFICATION FOR USE IN WILDLIFE MANAGEMENT PLANNING

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Abstract-A bottomland hardwood classification system for use in wildlife management planning in the Lower Mississippi Alluvial Valley was developed and has specific implications as a practical and flexible means of identifying and delineating habitats based on characteristics meaningful to a broad range of native wildlife species. Classification methods were developed and evaluated on Twin Oaks and Mahannah Wildlife Management Areas north of Vicksburg, MS. Subsequently, maps were created using a geographical information system and have been used for management planning. A review of this classification and mapping process is provided and offers insight into opportunities and limitations with use of any similar system in this or other forest types or geographical regions.

INTRODUCTION

Increasingly, land managers are obligated to include, and Often to prioritize, wildlife management objectives when managing forested land. Successful incorporation of wildlife objectives into forest management planning requires that managers know the types and distribution of existing wildlife habitat as it relates to wildlife species of interest. Historically, classification of forest characteristics has been limited to identifying stand types as they relate to timber production objectives. Recent efforts to identify forest characteristics for use in wildlife management planning have emphasized the development of more intensive, and often species-specific, habitat evaluation systems such as habitat suitability indices. Though clearly valuable to some managers, these often laborious and costly systems may not be practical or economical for managers without primary wildlife management objectives or with limited financial and professional resources.

Furthermore, no system has previously been developed to classify bottomland hardwood forest habitats for use in managing a broad range of native wildlife species. Though work has been done to develop a more comprehensive system to evaluate wildlife communities and habitats for bottomland hardwood forests, at the initiation of this project no other system was completed or published and it remained unclear whether any of the ongoing work addressed the need for a system that is practical for use by managers with the aforementioned limited resources. Therefore, a need existed to develop a system that, while limiting the need for labor and professional resources, would allow managers to identify bottomland hardwood forest habitats meaningful to a broad range of native wildlife species.

Subsequently, a project was initiated by the College of Forest Resources at Mississippi State University in cooperation with the U.S. Army Corps of Engineers (COE) and the Mississippi Department of Wildlife, Fisheries and Parks to develop a forest management plan for Twin Oaks and Mahannah Wildlife Management Areas. These two areas, located north of Vicksburg, MS, in the Lower Mississippi Alluvial Valley, were purchased by the COE for mitigation of habitat losses during the construction of the Tennessee-Tombigbee Waterway and were to be managed for "maximum sustained public recreational opportunities for consumptive and non-consumptive users" (U.S. Army Corps of Engineers 1994). For managers to create and implement a forest management plan to meet these objectives, existing forest conditions had to be identified, described, and mapped in detail.

This need offered an opportunity to evaluate a bottomland hardwood classification system for use in wildlife management planning. Thus, a classification system was developed to provide a practical means of obtaining and mapping habitat information meaningful to a wide range of native wildlife species. This system was then implemented and evaluated for use in wildlife management planning on Twin Oaks and Mahannah.

METHODS

Though the system developed for this project is designed for use in the bottomland hardwood forests on Twin Oaks and Mahannah, the process of classification offers insight into using similar systems in other forest types or geographical regions. The process is as follows: (1) design the classification system by determining variables to be classified and establishing categories for each variable; (2) define stands on aerial photographs by delineating differences in classification; (3) verify and describe stands by classifying variables in the field; (4) create stand maps using final classifications; and (5) incorporate into a geographical information system (GIS).

Classification System

The classification system is divided into two sections (fig. 1). The first section includes "definitive variables" and the second section "auxiliary variables." Definitive variables define stand boundaries and stand type, whereas auxiliary variables further describe the stand.

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. Definitive variables

1. Cover class
   - (1) Forested land
   - (2) Nonforested land

2. Inundation
   - (1) Uncontrolled
   - (2) Controlled

3. Main canopy species association
   - (1) Red oaks, sweetgum, (sweet pecan)
   - (2) Elm, ash, sugarberry
   - (3) Red oaks, overcup, (elm/ash/sugarberry)
   - (4) Overcup, ash, bitter pecan
   - (5) Pure red oak
   - (6) Pure sweetgum

4. Average size class of main canopy stems
   - (1) Regeneration
   - (2) Sapling
   - (3) Pole
   - (4) Small sawtimber
   - (5) Large sawtimber
   - (6) Veterans

5. Main canopy density
   - (1) Sparse
   - (2) Normal
   - (3) Dense

6. Residuals
   - (1) Without residuals
   - (2) With residuals

II. Auxiliary variables

7. Vertical stratification
   - (1) Main canopy only
   - (2) With understory
   - (3) With midstory
   - (4) With mid- and understory

6. Topographical position
   - (1) Ridge
   - (2) Flat
   - (3) Slough

9. Presence of ground flora
   - (1) Sparse
   - (2) Moderate
   - (3) Heavy

10. Woody debris coverage
   - (1) None
   - (2) 1 to 5 percent
   - (3) 6 to 10 percent
   - (4) Greater than 10 percent

Figure I-Forest classification variables for Twin Oaks Wildlife Management Area, Sharkey County, MS.

Any variable can be included in the second section of the system but, as will be discussed later, any definitive variable must be readily identifiable on aerial photographs. In fact, any variable that can be directly or indirectly classified on aerial photographs should first be included as a definitive variable even if it is likely to be changed to an auxiliary variable later. By so doing, initial stands are divided as finely as possible and can always be merged later if needed.

Practical implementation of this system requires that all variables, whether definitive or auxiliary, be easily recognizable and classifiable. Physical characteristics of the forest, as is pointed out by Smith (1990), commonly meet these criteria. However, easily recognized characteristics are not necessarily easily classified and, therefore, care must be taken to define, for each variable, classes (or categories) that are meaningful, but practical.

Because any one species of wildlife may perceive a specific forest characteristic with finer or coarser resolution than another species, it is not practical to define categories based on its meaning to every species. It is practical, however, to define categories that can be readily identified by managers and yet still provide some indication of habitat suitability for most native wildlife. Also, starting with too many classes may require changes later but, again, it is easier to merge two separate stands than it is to divide one existing stand.

Though it may seem more logical to order variables by their importance within the system, any one characteristic could be the most important, or not important at all, to any given wildlife species of concern. For this reason, it is actually more practical to order variables by their relative ease in delineating and classifying. For example, it is easier to determine whether a stand is forested or nonforested than to determine its species association (fig. 1).

Aerial Imagery

Delineating stands on aerial imagery is a commonly used stratification technique to reduce sample size (Avery and Berlin 1992) and allows for more accurate boundary definition than could be accomplished in the field. Color infrared photographs taken during spring greenup or during fall drawdown provide excellent species distinction. At an approximate scale of 1:12,000, good quality photographs contain enough detail to classify all defining variables while still providing an aerial view wide enough to delineate entire stands on a single frame. Images are viewed in stereo and a change in any one of the definitive variables constitutes the delineation of a separate stand.

Field Classification

Using the stands defined and classified on aerial photography, the next step of this process is to verify classification and further describe stands with auxiliary variables. Sampling and measuring classified variables may assure accurate classification, or simple observation may provide sufficient verification when time or funding is limited (assuming variables can be easily identified and classified).

Auxiliary variables are not a part of stand delineation on aerial imagery, but rather are classified in the field. As previously discussed, auxiliary variables can be added at any time without changing stand boundaries or type. Classification of these variables simply allows a previously defined stand to be described in any amount of detail deemed important for management planning. Again, classification of auxiliary variables may be achieved by sampling and measuring or by observation only.

Mapping

Options for the form of the final map range from blueprint style, hand-drafted maps to comprehensive GIS's. For this project, geographically corrected stand maps were digitized with Arc/Info (ESRI 1992a) to establish a GIS for both study areas. The resulting data were then transferred to Arc/View (ESRI 1992b) and merged with database files containing stand classifications. Finally, a color coded map was created for each variable or combination of variables needed.

RESULTS AND DISCUSSION

Though development of a classification process was the objective of this project, this process was implemented on two study areas and, therefore, has been evaluated in some respects. Results and discussion of this evaluation will be presented in the same order as methods.

Classification System

Figure 1 represents the classification system used for describing habitat conditions on Twin Oaks. This was the first system developed and, with minor modifications, it allowed for what appears to be a relatively comprehensive, broad-based description of existing forest habitat conditions. However, when this system and its variables were applied on Mahannah, moderate modifications were necessary to achieve a similar description of habitat conditions. Though these modifications required additional resources, the process was still valid and the system was still practical to implement. It appears that with appropriate modifications to certain variables and their respective classes, and the addition of any pertinent auxiliary variables, this classification and mapping process can be used in other forest types and geographical regions.

Aerial Imagery

Though practical and accurate classification would not be possible without the information gained from aerial photographs, there appear to be three major limiting factors associated with this step of the classification process. These factors are summarized as follows: (1) acquisition of usable photographs, (2) opportunities to work with skilled photographic interpreters in a cooperative environment, and (3) practical limitations as to what variables can be used to define and delineate stands.

Acquisition of quality aerial photographs was limited by the availability of skilled aerial photographers and weather conditions during ideal greenup or drawdown periods. Though acceptable 1:24,000 spring color infrared photos already existed for Twin Oaks, no such images were found for Mahannah. Contracting a capable aerial photographer to photograph Mahannah during ideal periods with clear weather proved to be difficult.

Once all photographs were finally obtained, skilled photographic interpreters were readily available through the Mississippi Remote Sensing Lab at Mississippi State University. These resources, however, may not be as readily available elsewhere and, thus, may limit opportunities to successfully implement this process.

Assuming acquisition of good-quality photography and availability of skilled interpreters pose no problem, a limitation to this step of the process still exists in that even the most experienced photographic interpreter cannot classify on aerial photographs every variable that may be important to managers. It therefore stands to reason that a definitive variable must be directly or indirectly classifiable on aerial photography. Nonetheless, any variable deemed essential can be included as an auxiliary variable to describe the defined stand.

As for photographic requirements for this project, early-to-mid-April or early-to-mid-October appear to be best for ideal color signatures. Though a scale of 1:6,000 may have provided the best detail for interpretation, the increased chance of delineating entire stands on one frame and the lower cost of power frames made 1:12,000 an effective scale for this study. It was also noted that even with 1:12,000 scale images, some frames did not contain enough visible landmarks to allow for stand location on the ground.

Field Classification

As mentioned previously, verifying classifications in the field could potentially include sampling and measuring variables, or observation alone may offer sufficient assurance of accurate classifications if all variables can be readily identified and classified. While it does not necessarily require more professional knowledge to accurately classify variables by observation than to sample and measure those same variables, classifying by observation may, in fact, require a better understanding of the ecology common to the forest type being classified. Without quantitative measurements of certain forest characteristics or an in depth understanding of forest ecology, confidence in the accuracy of stand classifications is likely to be low.

Mapping

Because the time and economical requirements of this classification process are crucial to its usefulness, and because the choice of final map form can be relatively inexpensive or expensive, it is helpful that the choice of final map form is last in this process. Given that the GIS created for this project ultimately provides an efficient means for evaluating potential habitat alterations, adding other geographically referenced information, and identifying stands that contain unique habitat characteristics, creation of a GIS appears to be a useful and practical choice for final maps if sufficient time and funding remain after classification and verification are complete.

CONCLUSIONS

This classification system and process appear to provide information meaningful in managing bottomland hardwood forests for a wide range of native wildlife species and was relatively practical to implement. However, because this was an initial evaluation of the process, a need still exists to quantify the meaningfulness of the classified variables to native wildlife species and to determine whether this process has any real economical and practical advantage over more intense and quantitative habitat evaluation systems. It may be that the professional resources required for acquisition and interpretation of aerial photography, and the cost of creating final maps, negate any advantage to using this process instead of existing habitat evaluation systems.

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LANDSCAPE ECOSYSTEM CLASSIFICATION FOR THE MOUNTAIN HIGHLANDS OF THE CHEROKEE NATIONAL FOREST

Benjamin E. West and John C. Rennie[1]

Abstract-A landscape ecosystem classification (LED) was developed for the 26,100- hectare (ha) Mountain Highlands section [610 to 1660 meters (m) in elevation] of the Tellico Ranger District, Cherokee National Forest, Tennessee. Vegetation, soils, and landform data were obtained from 90 0.04-ha plots located in stands representing late successional stages. Indirect ordination was used to distinguish site units (plots with similar vegetation), followed by stepwise discriminant analysis to determine those environmental variables that contributed most to the classification of the vegetation. A technique of direct ordination, detrended canonical correspondence analysis, was also used to identify site types from vegetation, soils, and landform.

Five ecological site units were identified and found to be recurring across the landscape. These were: (1) yellow pine/mixed oak forest, (2) mixed oak/red maple forest, (3) cove hardwoods/mixed mesophytic forest, (4) eastern hemlock/yellow birch forest, and (5) beech forest. Each site unit represents an array of site types which are identifiable combinations of landform and soil features, associated with discrete vegetation communities. A four-variable model consisting of elevation, aspect, slope position, and A horizon depth accurately predicted site unit membership more than 60 percent of the time. For the purposes of developing a management strategy, elevation and aspect appear to be sufficient for predicting the distribution of site units across the landscape of the Mountain Highlands. Using a geographic information system (GIS), an ecosystem map was developed for the Mountain Highlands based on elevation and aspect.

INTRODUCTION

Natural resource managers are being asked to manage a wider range of natural resources, to meet broader and more diverse objectives, and to accomplish this with fewer financial resources. To achieve this, they will need new tools and techniques. Landscape ecosystem classification (LED) offers one approach to management that meets these criteria.

Development of an LED is generally completed in four phases (Jones and Lloyd 1993): Phase l-identifying vegetation types (site units) from late successional stages; Phase 2—determining seral vegetation stages associated with each site unit; Phase 3-mapping site units; and Phase 4-developing management strategies. The actual classification of ecosystems across the landscape is based on specific vegetation, soils, and landform characteristics. The advantage of LED models is that once a model for a particular landscape has been developed, it is possible to predict vegetation types from the more permanent features of its landform and soil characteristics.

This study is part of similar LED research being conducted throughout the Blue Ridge province of the Southern Appalachians by the USDA Forest Service and coordinated by Henry McNab of the Bent Creek Experimental and Demonstration Forest. The overall research effort includes 11 sites in Virginia, North and South Carolina, Georgia, and Tennessee.

STUDY SITE

This study represents Phase 1 of an LED for the Mountain Highlands section of the Tellico Ranger District in the Cherokee National Forest, Tennessee (fig. 1). Previous work (Yoke 1994, Yoke and Rennie 1996) defined two geographic sections of the district based on homogenous geological groups. These were then related to elevation for field use. The Foothill section coincides with the Walden Creek geologic group and ranges in elevation from 305 to 610 meters (m) (Yoke 1994). The Mountain Highlands section coincides with the Great Smoky group and occurs above an elevation of 610 m.

The Mountain Highlands section consists of approximately 26,100 hectares (ha) in Monroe County, TN. Temperatures range from 2 to 8 degrees cooler than the mean annual temperature for the rest of the county (13 “C.). Annual rainfall is about 191 centimeters (USDA 1981). All of the soils are classified as Inceptisols with the main subgroups including Typic and Umbric Dystrochrepts, and Typic Haplumbrepts (Scott ND).

Human activity in the Mountain Highlands section has been long and varied. Early use by Native Americans (about 10,000 years ago) was primarily for hunting and impacts from human occupation were likely minimal (Bass 1977). With the more permanent settlement patterns associated with the introduction of agriculture, clearing of the forest occurred and use of fire became more extensive (Chapman 1985). Logging in the higher elevations and on the steeper slopes of the Mountain Highlands was not widespread until after the turn of the 20th century (Weals 1991).

METHODS

Field Methods

With the assistance of personnel from the Tellico Ranger District, mature stands more than 75 years old were

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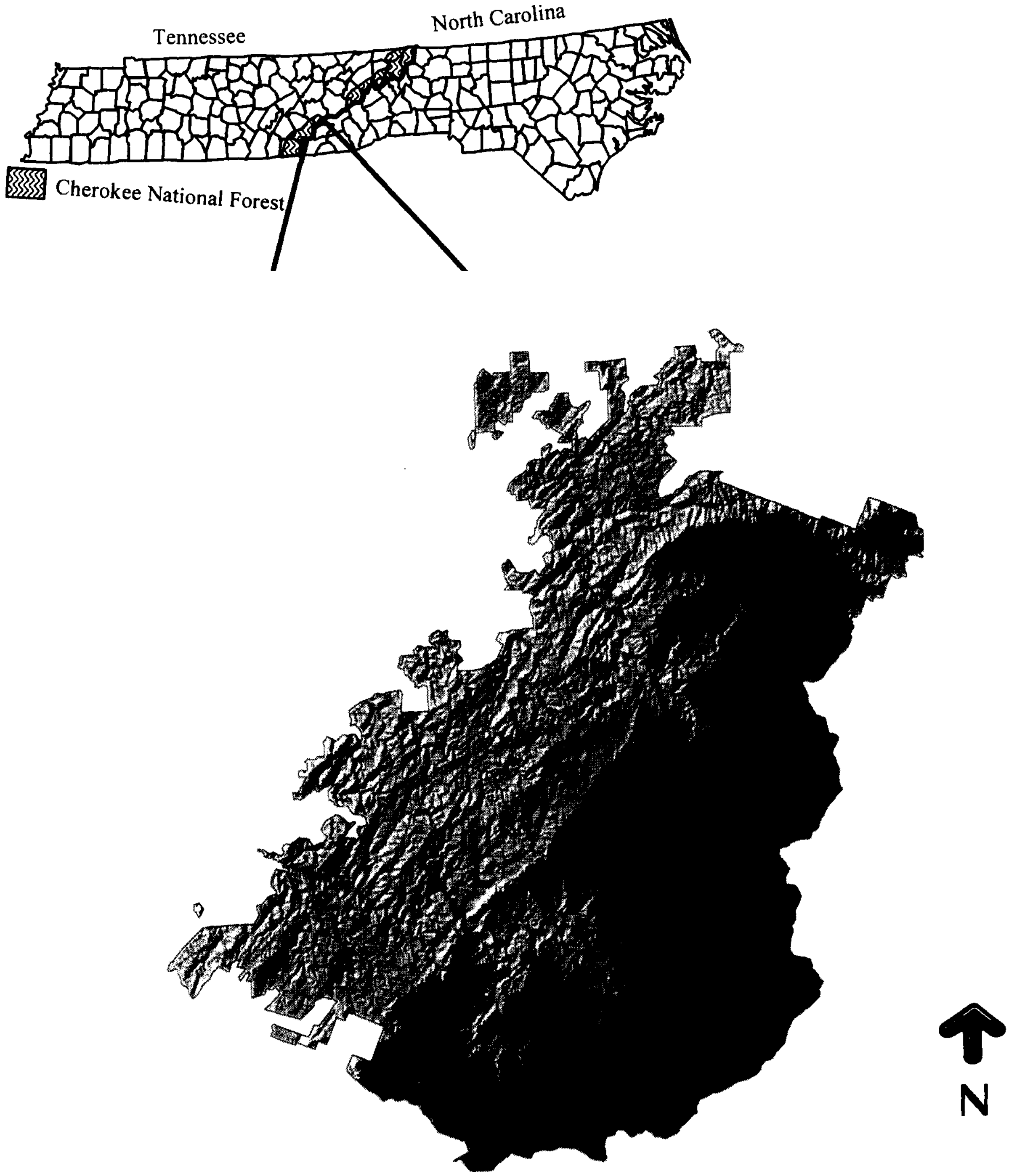

Figure l-Location of Tellico Ranger District, Cherokee National Forest, Tennessee. Dark area represents the Mountain Highlands section (areas above 610 meters in elevation).

identified. A matrix of aspect (north-facing and south-facing slopes) and slope type (ridges, upper, middle, and lower side slopes, and coves) was used to distribute plots over as much of the vegetation and environmental conditions as possible. Data were collected only in stands with few signs of disturbance, based on ground observations.

Vegetation, soils, and landform data were obtained from 90 stands representing late successional stages. Vegetation was sampled in four strata: trees, saplings and shrubs, regeneration, and herbs and vines. In each stand, a set of nested plots was established (fig. 2) with measurements being taken to estimate coverage and density by species for each stratum. Soil variables, determined from a soil pit within the 0.04-ha plot, included: humus thickness, A horizon thickness, and solum thickness. Topographic variables were: aspect, slope angle, slope position, landform index (McNab 1993), terrain shape index (McNab

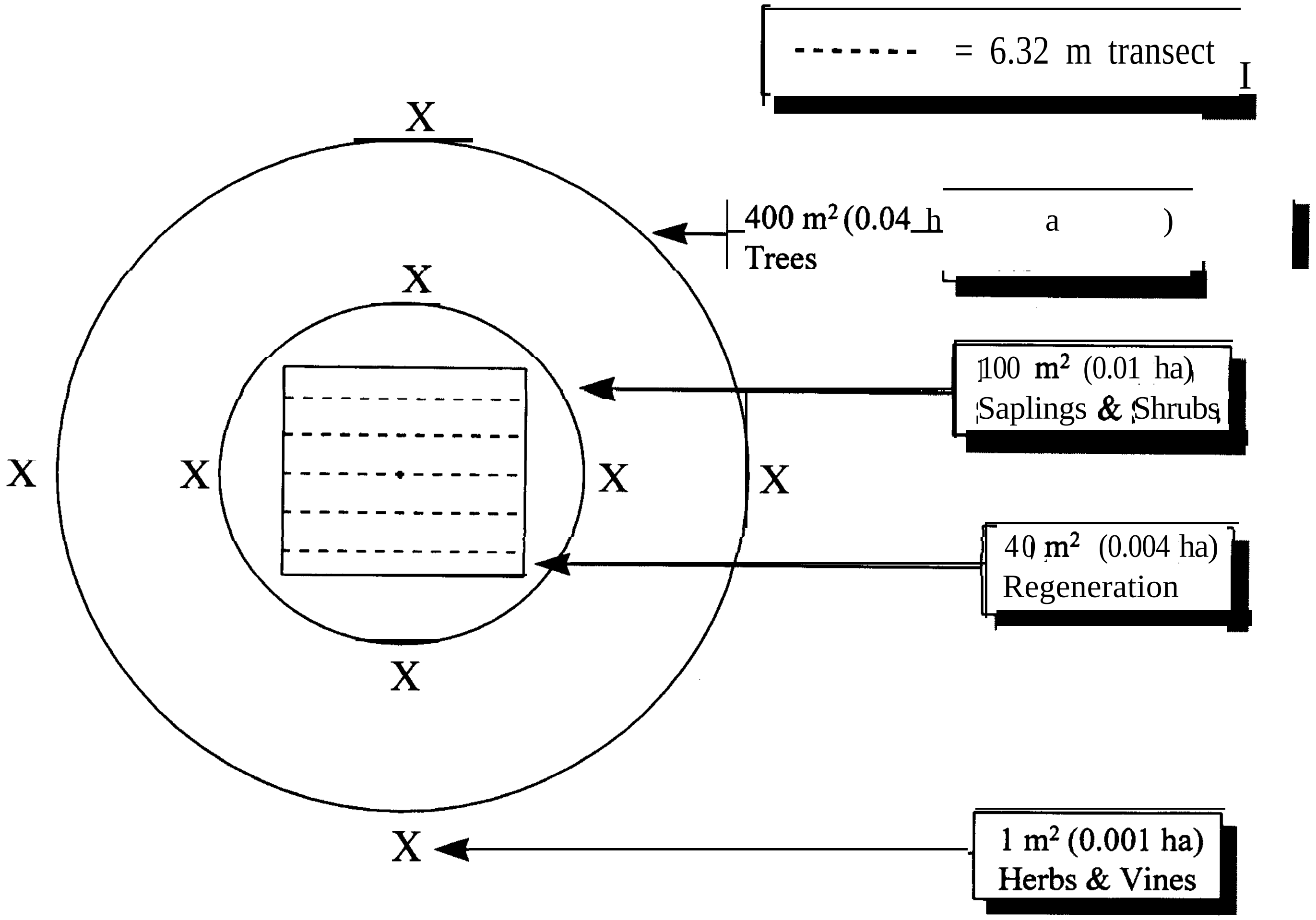

Figure 2-Arrangement and sizes of plots used to sample vegetation.

1989), and elevation. Aspect was transformed from degrees to a linear scale ranging from 0 for southwest aspects to 2 for northeast aspects (Beers and others. 1966).

Data Analysis

Vegetation data were summarized by species and stratum in terms of percent cover and density of the plot area. Importance Value (IV) 200 (relative coverage + relative density) was calculated for all strata except the herbaceous stratum, where IV 100 (relative coverage) was used. A data matrix based on these importance values was composed of 294 species and 90 plots.

Two techniques of indirect ordination were used to distinguish site units, i.e., plots with similar vegetation: polythetic divisive classification using TWINSPAN (Hill 1979a) and detrended correspondence analysis (DCA) using DECORANA (Hill 1979b). Stepwise discriminant analysis (SWDA) was then used to determine those environmental variables that contributed most to the classification of the vegetation. Combinations of topographic and soil variables were used to predict site unit membership for each plot with cross-validation of the discriminant analysis.

Direct ordination with detrended canonical correspondence analysis (DCCA) using CANOCO (ter Braak 1987) was also used to identify site types from vegetation, soils, and landform. Results of the direct and indirect gradient analyses were compared and evaluated for prediction of site units. A model to predict site units from soil and topographic variables was developed with particular concern for its use on the ground by natural resource management personnel.

RESULTS AND DISCUSSION

DCA ordination using DECORANA and TWINSPAN classification of the vegetation data resulted in the identification of five recurring ecological site units. These were: (1) yellow pine/mixed oak forest, (2) mixed oak/red maple forest, (3) cove hardwoods/mixed mesophytic forest, (4) eastern hemlock/yellow birch forest, and (5) beech forest. Figure 3 shows the clustering of plots from DECORANA in ordination space. In this figure, site units are represented by numbers and were derived using the TWINSPAN classification. Axis 1 and Axis 2 represent hypothetical environmental gradients. Because indirect ordination of the plots and species is not constrained by environmental variables, Axis 1 and Axis 2 in figure 3

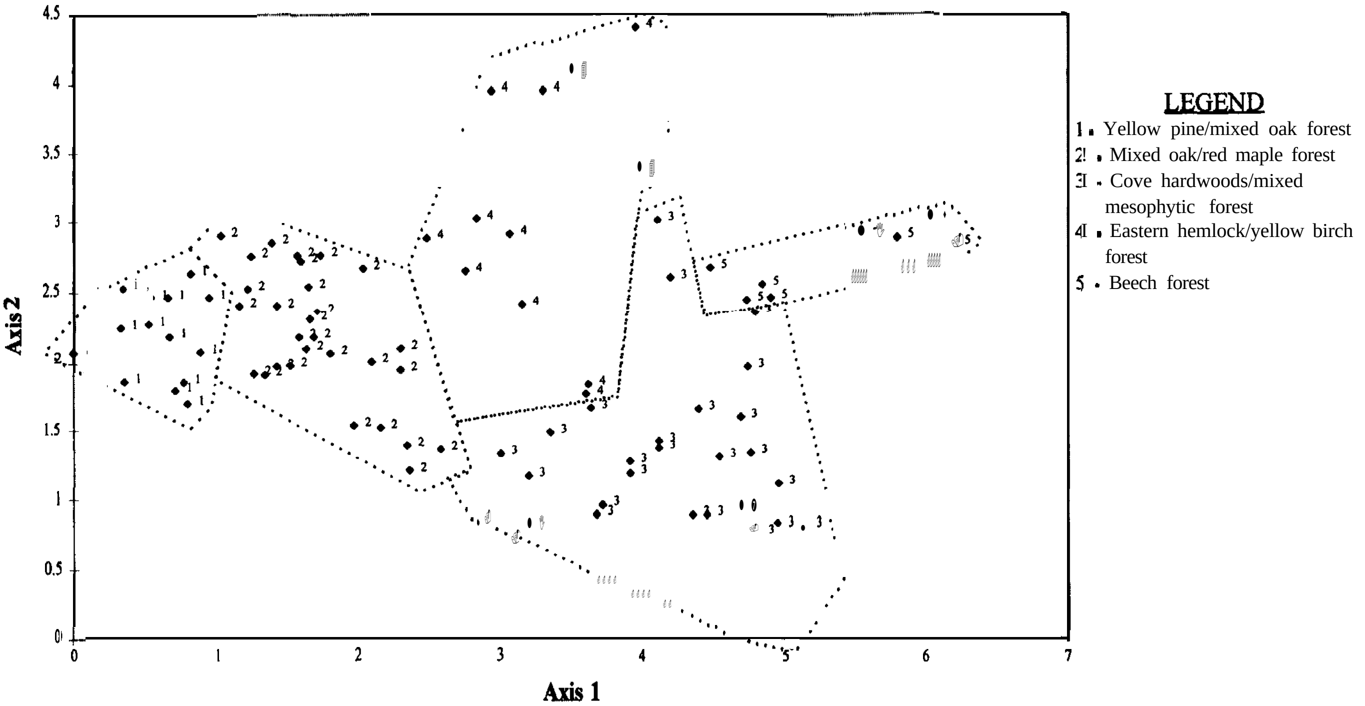

Figure 3-DCA ordination of ninety plots using DECORANA. Numbers represent TWINSPAN derived site units. Units of axes are standard deviations. Lines are subjectively drawn to show site unit membership.

remain unlabeled. Assignment of a particular environmental variable(s) to those axes occurs after stepwise discriminant analysis.

To determine the relationship between vegetation, soils, and landform, a SWDA was performed using the nine environmental variables and the site units designated by DECORANA and TWINSPAN. Six soil and topographic variables were determined to be significant at the 0.15 level (table 1). Elevation appears to be the most important variable in discriminating between site units, accounting for more than 54 percent of species variation, followed by slope position and aspect based on R^2 values.

Table I-Significant variables identified through stepwise discriminant analysis from nine environmental variables and five site units (significance level for entry and retention = 0.15)

Variable	R^2	Prob.>F
Elevation	0.547	4.0×10^{-13}
Slope position	0.359	3.0×10^{-7}
Aspect	0.340	9.0×10^{-7}
A horizon depth	0.280	2.0×10^{-5}
Solum depth	0.193	1.7×10^{-3}
Humus depth	0.167	5.2 x 10”

Cross-validation of the environmental variables selected by SWDA was performed to determine how successfully the variables could be used in combination to predict membership in the five site units. Results are shown in the tabulation below:

Variables	Correct classification
	- - Percent - -
Elevation and slope position	56
Elevation and aspect	55
Elevation, slope position, and aspect	55
Elevation, slope position, aspect, and A horizon depth	60
Elevation, slope position, aspect, A horizon depth, solum depth, and humus depth	41

Little improvement in classification resulted from using more than two variables. However, a four-variable model consisting of elevation, slope position, aspect, and A horizon depth, predicted site unit membership the best (60 percent).

DCCA combines indirect ordination (DCA) and multiple regression. The resulting ordination (fig. 4) represents the variation in species composition over the plots as can be explained by the environmental variables. Similar patterns of variation in plot distribution resulted from DCCA (fig. 4) as from DCA (fig. 3). However, there was greater overlap

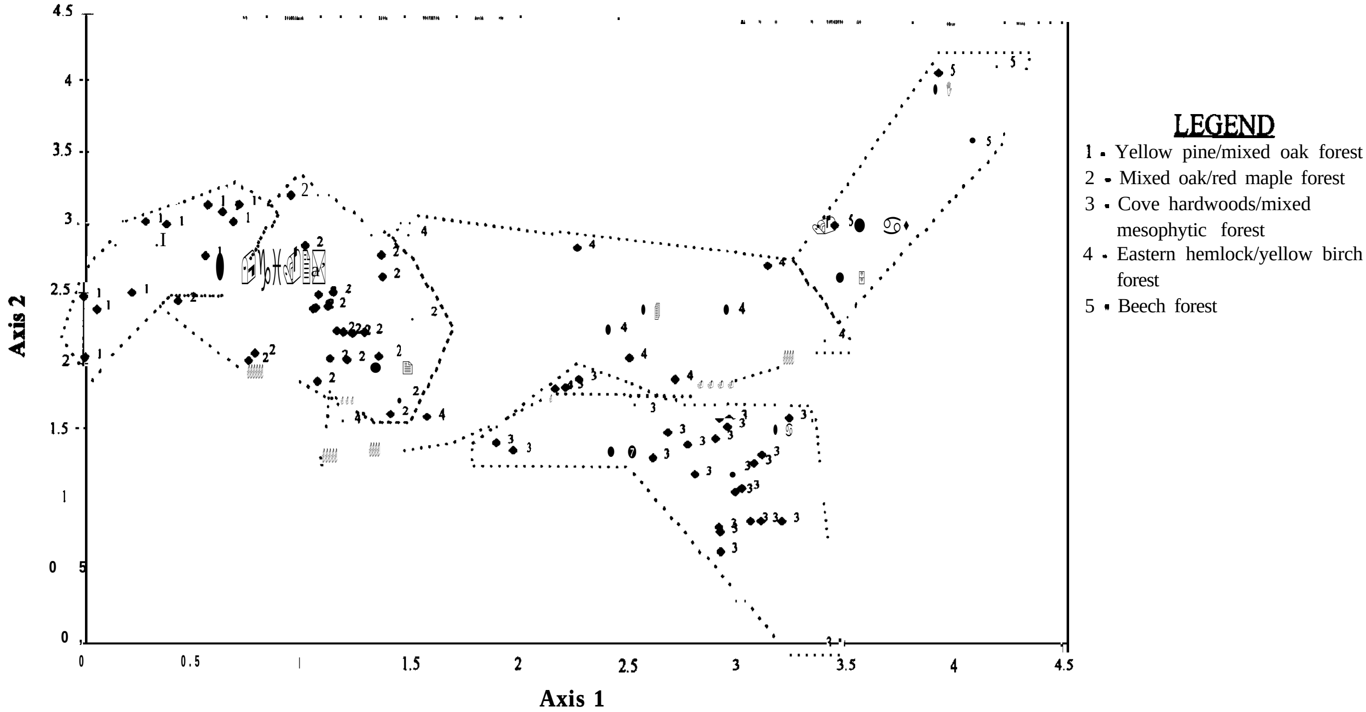

Figure 4—DCCA ordination of 90 plots using CANOCO. Numbers represent TWINSPAN derived site units. Units of axes are standard deviations. Lines are subjectively drawn to show site unit membership.

of site units with DCCA, especially for Site Unit 4. The spread of Site Unit 4 agreed with the cross-validation results from the discriminant analysis, which showed low predictive ability for Site Unit 4.

The correlation coefficients of environmental variables with the two axes (table 2) indicate that aspect (Axis 1) and elevation (Axis 2) are the most important predictors of vegetation distribution. An important part of the output from CANOCO is the creation of biplots of the vegetation ordination and the environmental variables. Figure 5 displays graphically the correlation results from table 2—

Table 2-Correlation coefficients between environmental variables and species ordination axes from direct ordination (DCCA)

Variable	Axis 1	Axis 2
Aspect	0.48	-0.54
Elevation	0.39	0.59
A horizon depth	0.32	-0.15
Landform index	0.22	-0.37
Slope position	-0.18	0.40
Solum depth	0.17	0.13
Humus depth	0.14	0.18
Slope	-0.09	0.17
Terrain shape index	0.08	-0.04

DCCA ordination of plots and environmental variables. The environmental variables are represented by arrows or vectors. The directions and relative lengths of the arrows convey the most meaningful information. The angle between an arrow and each axis is a representation of its degree of correlation with the axis, and the vector length indicates the strength of the correlation (ter Braak 1987). In addition, it can be inferred from figure 5 that Site Unit 5 is located at the highest elevations, and Site Unit 3 is located in areas with the highest transformed aspect (northeast-facing slopes). Similar trends can be interpreted for the other environmental variables.

Similar studies in the Southern Appalachians have found vegetation distribution to be related to different combinations of elevation and landform features. Whittaker's (1956) monograph on the vegetation of the Great Smoky Mountains concluded that moisture, as defined by the interaction of elevation, topographic shape, and slope aspect, was the primary environmental variable that determined the vegetation present at a given site. Golden (1974) concluded that vegetation pattern in the Great Smoky Mountains appeared to be most directly related to elevation and topography. Callaway and others (1987), Gattis (1992), and Yoke (1994) all reached similar conclusions. Each study identified slightly different combinations of topographic variables that were the best predictors of vegetation occurrence and productivity differences across the Southern Appalachian landscape. Overall, however, elevation was consistently the most important environmental variable. This research obtained similar

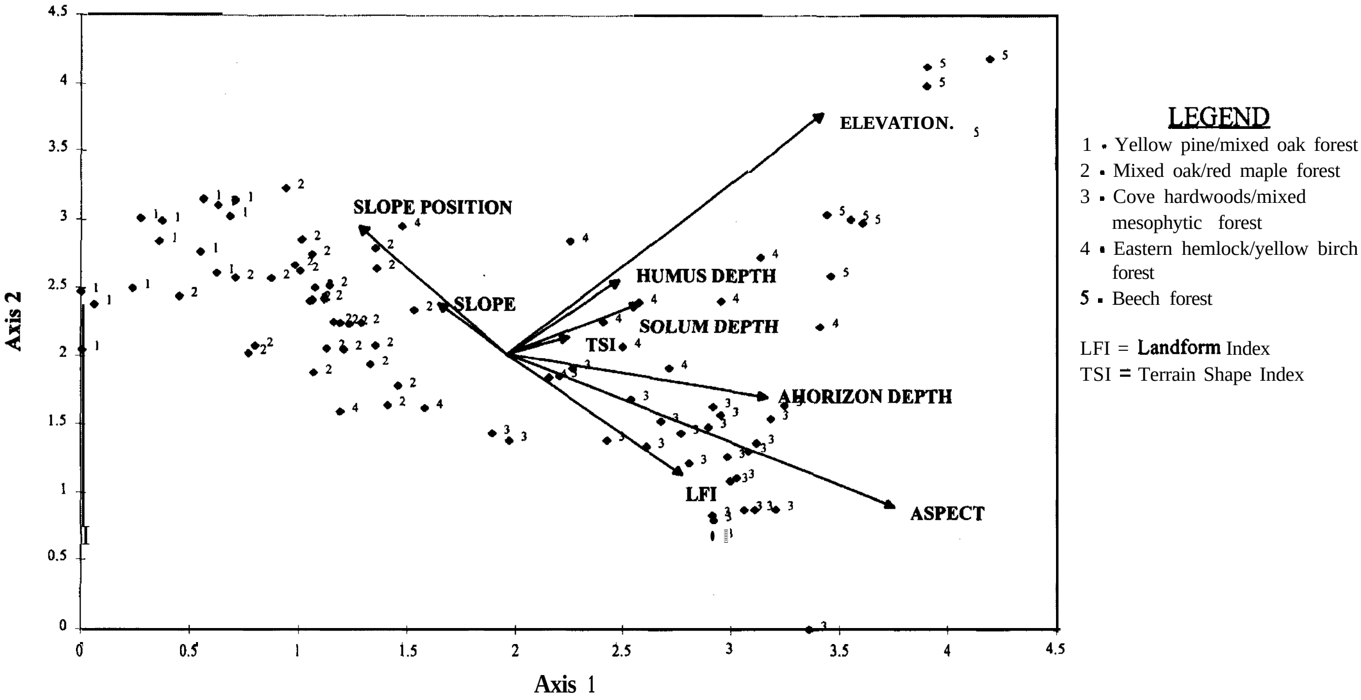

Figure 5—DCCA ordination of 90 plots and significant environmental variables (arrows) using CANOCO. Units of axes are standard deviations.

results. In addition, the five site units identified in this study were consistent with plant community types described by these other studies.

Based on the results of the DCA, SWDA, and DCCA, a two-variable model (fig. 6) was developed for use by natural resource managers working in the Mountain

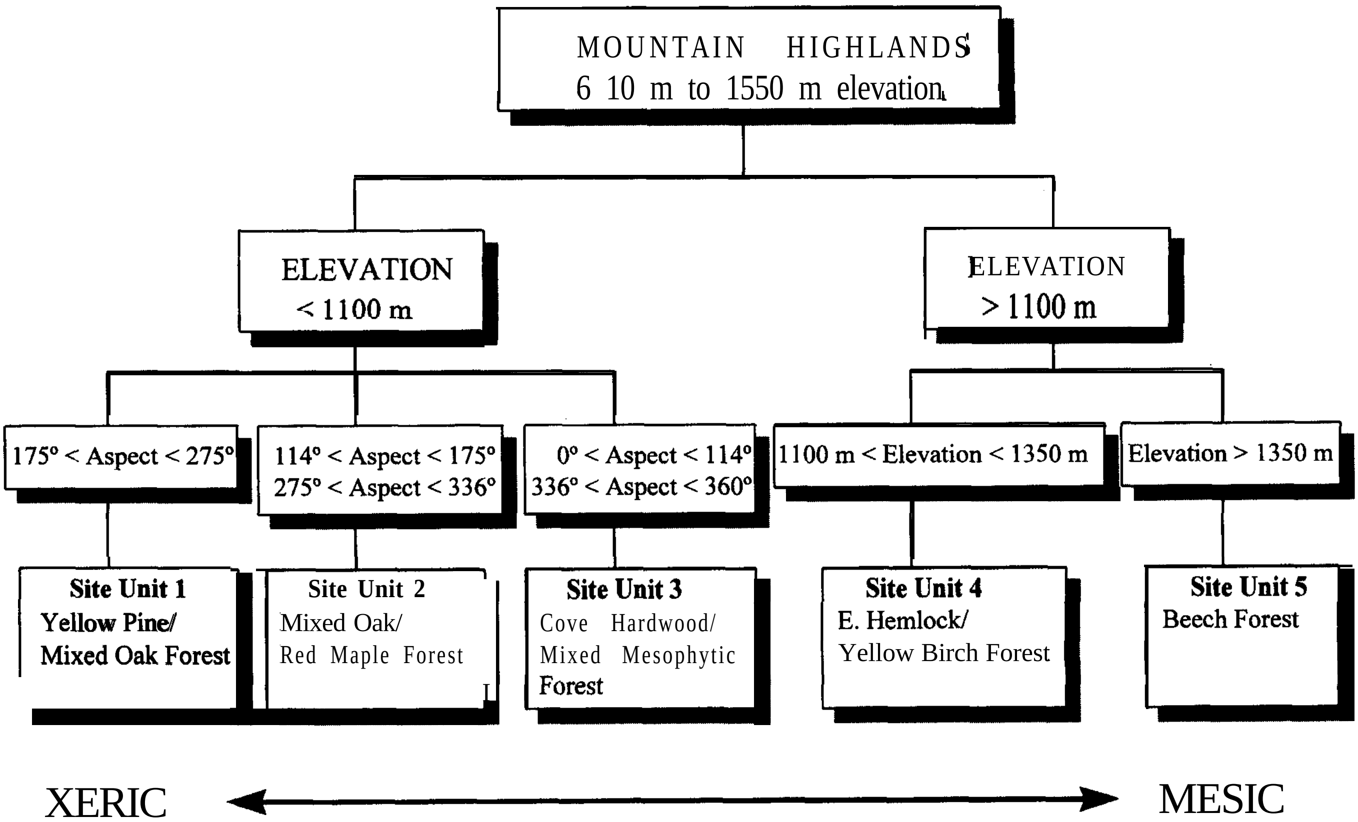

Figure 6—Landscape ecosystem classification model for the Mountain Highlands of the Tellico Ranger District, Cherokee National Forest, Tennessee.

Highlands section. Elevation and aspect were selected because they appear to be sufficient for predicting the distribution of site units across the landscape of the Mountain Highlands, and because of their ease of use both in the field and in creating ecosystem maps with a GIS. An ecosystem map of the Mountain Highlands section was created using the model shown in figure 6 and a GIS; however, it is not shown due to graphical limitations.

ACKNOWLEDGMENT

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PRELIMINARY ECOLOGICAL LAND CLASSIFICATION OF THE CHAUGA RIDGES REGION OF SOUTH CAROLINA

Curtis J. Hutto, Victor B. Shelburne, and Steven M. Jones'

Abstract-An ecological method of integrated multifactor land classification was applied in the Chauga Ridges region, a subregion of the Blue Ridge Physiographic province, in northwest South Carolina. Phase I sampling involved measuring 61 reference plots in undisturbed late-successional upland hardwood stands. Four distinct site units were identified using ordination, cluster analysis, discriminant function analysis, and canonical correspondence analysis. Using cross-validation of a discriminant function, a combination of five environmental features (landform index, weighted terrain shape index, slope position, root mat thickness, and distance-to-bottom) identified site units with an accuracy rate of 78 percent. A predictive Geographic Information System (GIS) model using spatial variables only (landform index, terrain shape index, slope position, distance-to-bottom, transformed aspect, and slope gradient) was also developed which identified site units with a success rate of 76 percent.

INTRODUCTION

Landscape Ecosystem Classification (LEC) is an integrated, multifactor, ecological classification system that is relatively new to the Southeastern United States. Although many approaches to classification are in use today (Bailey and others 1978), not all are designed to quantitatively assess the interrelationships of ecosystem components. Single-component classifications of soil only, vegetation only, or landform only ignore the complex relationship evident between plants and their environment. The LEC approach provides a taxonomic separation of sites within a hierarchical framework, and allows the model user to identify ecologically similar areas without the use of vegetation.

Managing forests on an ecosystem basis is a necessity for the development of a supporting framework used to sustain desirable landscape attributes. An ecological classification is one that expresses the interrelationships between plants and soil, plants and landform, and soil and landform. These reciprocal interactions between biota and the physical environment serve to define the concept of the ecosystem as a unit of management. Landscape ecosystem classification uses undisturbed late-successional reference stands to assess the plant community as a type of phytometer that expresses the combined forces of physiography and soils. Using an array of multivariate techniques, a model is constructed that will identify complex environmental gradients, and break out ecologically similar areas which will recur across the landscape.

The objectives of this study were to complete Phases I to III of an LEC for the Chauga Ridges region of the Blue Ridge Physiographic povince (Myers and others 1986). This paper will focus on Phase I, which expresses spatial variability in the landscape, and involved locating and sampling undisturbed reference stands to identify discriminating soil and landform variables. These were then used to develop the discriminant functions unique to each ecological site unit.

STUDY AREA

The study was conducted in northwest South Carolina, within the southern half of the Andrew Pickens Ranger District, Sumter National Forest, Oconee County. This area (approximately 38,000 acres) is bounded on the north by the higher elevations and steeper, broken topography of the Blue Ridge Mountain province (Myers and others 1986). To the south and east lies the Blue Ridge escarpment, which rises abruptly more than 650 feet above the Piedmont Foothills Region near the towns of Walhalla and Westminster, SC. The area is drained by the Chauga River and the Chattooga River, which also forms the western boundary.

Representative topography includes short, steep slopes formed by the dissection through biotite schist, phyllite, and horneblende gneiss parent materials from first- and second-order tributaries of the Chauga and Chattooga Rivers. Other geologic substrates consist of granitic and mylonitic gneiss, amphibolites, and scattered carbonate areas (Hatcher 1969). The study area is roughly bisected by the Brevard Fault Zone, a narrow belt of low-grade metamorphic rocks that marks the southeastern edge of the Blue Ridge Belt from northern North Carolina to northwestern Alabama (Reed and others 1970). Elevation ranges from about 900 feet to slightly over 1800 feet above mean sea level. Roughly 75 percent of the study area is mapped as the Evard soil series, and classified as a fine-loamy, oxidic, mesic Typic Hapludult. These reddish upland soils occupy most slope categories, have a solum thickness of 21 to 40 inches, and an argillic horizon that is 12 to 28 inches thick (USDA Soil Conservation Service 1985).

The climate of the area is mild, and is one of transition between the cooler, moist conditions of the Blue Ridge and the warmer, drier climate of the Piedmont. Mean July high temperature ranges from 75 to 77 "F., with a mean January low temperature of about 30 "F. Mean annual rainfall is

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about 62 inches and is fairly evenly distributed throughout the year, with the exception of a slightly drier period in the fall. Forest vegetation is dominated by mesic mixed hardwood forest and oak-hickory forest, with the many species of oaks most abundant on dry to intermediate sites. Shortleaf pine (*Pinus echinata*) is the most abundant coniferous species, although eastern white pine (*P. strobus*) and eastern hemlock (*Tsuga canadensis*) are also common.

METHODS

Sampling

Completion of Phase I of this study involved locating relatively undisturbed late-successional stands for sampling. Selected stands were those that showed little signs of vegetation or soil disturbance, and showed characteristic signs of mature forest or old-growth structure, such as large flat crowns or high levels of coarse woody debris. Stand age was also a determining factor; stands greater than 100 years old were searched out and evaluated for the above conditions.

Sixty-one late-successional stands were sampled using the Braun-Blanquet subjective selection system described above, with an attempt to distribute the plots equally throughout the different landscape positions. To insure ecological uniformity within each plot, site factors such as aspect, slope gradient, topographic position, and exposure were required to be consistent. Plot centers were located as close as possible to the center of a uniform stand area, and circular nested plots of 0.10 acre and 0.25 acre were marked on the ground. Diameter at breast height (d.b.h.) in l-inch classes, and frequency by species were recorded for saplings (1 .O inch d.b.h. to 4.9 inches d.b.h.) within the smaller plot. Diameter at breast height in 2-inch classes, and frequency by species were recorded for trees (5.0 inches d.b.h. and greater) within the larger plot. Vines, shrubs, herbs, and seedlings greater than 1 foot tall were also tallied and recorded by species within the larger plot, using Braun-Blanquet coverage classes.

Soil and physical variables were also collected at each plot. Soil variables included thickness of the B horizon (BTH), clay content of the B horizon (BCL), root mat thickness (RM), solum depth, and particle size distribution of the A and B horizons. Soil samples and data were collected systematically by spacing three auger holes along the contour, with the center auger hole at plot center and the outer two near the plot perimeter. These samples were then analyzed in the laboratory for particle size distribution. Soil chemical properties of previous LEC studies in the Southern Appalachians have been shown to be weak discriminators (Moffat 1993, Gattis and others 1993) and thus were not assessed.

Landform variables were also recorded from plot center. These measurements consisted of landform index (LFI) and terrain shape index (TSI), as developed by McNab (1993 and 1989, respectively), slope gradient (SG), slope position (SP), aspect (TASP), and slope distance to the nearest drain (DTB). Terrain shape index was multiplied by slope position to form a variable called weighted terrain shape index (WTSI). Aspect was transformed by the sine method of Beers and others (1966). Large LFI values indicate a higher degree of radiant energy protection from surrounding slopes. Large positive TSI readings indicate concave landform conditions for the plot, while negative readings are associated with drier, convex conditions. Slope position was recorded as a percentage on a relative sliding scale, with ridges classed as 0 percent and stream bottoms representing 100 percent. Importance value 200 (relative basal area + relative frequency/2) was used as a measure of tree and sapling abundance. These values, along with the coverage class midpoints for the herbs, vines, shrubs, and seedlings, were converted to a presence/absence structure and used for the vegetation analysis.

Data Analysis

For each plot, vegetation data were summarized for each species by canopy class. Members of the same species in different canopy layers were treated as separate "pseudospecies." Data were analyzed using a series of multivariate techniques. Using indirect gradient analysis, species abundance and plot data were initially organized and displayed in multidimensional space using the ordination technique of Detrended Correspondence Analysis (DECORANA, Hill 1979a). The distances between plot locations on the graph relate the relative degree of similarity or difference (fig. 1). A numerical method of polythetic divisive classification was then performed on the main matrix for vegetation data using two-way indicator species analysis (TWINSPAN, Hill 1979b). This is a subjective classification, and allows the investigator to draw a separation between the groups identified in the initial ordination of plots.

Significant separation between groups was then tested using discriminant function analysis of the 16 environmental variables collected (SAS Institute 1985). The initial goal was to develop a single model using physical variables that were cost-effective and relatively easy to measure in the field, and which could be integrated into a GIS predictive algorithm. We felt that soil variables could not be accurately assessed from existing digital information, and thus developed two models, each consisting of a unique suite of variables.

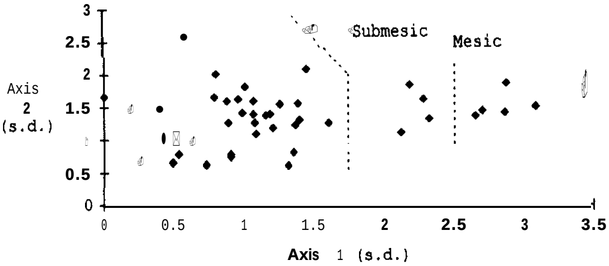

Figure l-Initial ordination of late-successional plots for the Chauga Ridges region.

Canonical correspondence analysis (CCA) was then applied to the main matrix of vegetation data, along with the secondary matrix of environmental data. We used the CANOCO program developed by ter Braak (1988). CCA is a method of direct gradient analysis which integrates linear regression and ordination to reveal relationships between plant communities and physical variables.

RESULTS

After deleting outlier plots and those thought to be successional, the primary data matrix consisted of 49 late-successional plots with 245 species and pseudospecies. The ordination procedure arranged the plots on a moisture gradient (axis 1) that showed a beta diversity of 3.5 standard deviations. Plots with low LFI and TSI scores (high exposure and convex microsites, respectively) expressed xeric soil moisture conditions, and tended to be distributed near the graph origin. Initial cluster analysis showed three groups that could be delineated (fig. 1). After deleting the two groups on the moist end of the gradient, ordination and cluster analyses were again performed; beta diversity decreased to 2.5 standard deviations and two more groups were separated (fig. 2). The species associations in each group were reviewed and labeled as mesic, submesic, intermediate, and xeric. Nearly 75 percent of the sites were classified as intermediate in soil moisture.

The primary and secondary matrices were then subjected to CCA, providing a validation source from physical variables for the ordination and cluster analysis performed previously. The first two axes were found to account for 74 percent of the variation in the species-environment relationship. Landform index and SP had the strongest correlation with Axis 1 ($r=0.86$ and 0.62 respectively), while SG had the highest correlation with Axis 2 ($r=0.65$). Another important output from CCA is the species-environment biplot (fig. 3). The arrow for each environmental variable points in the direction of maximum change for that variable across the diagram, and its length is proportional to the rate of change in this direction. Environmental variables with long arrows are more strongly correlated with the nearest ordination axis than are those with shorter arrows, and have a greater influence on the patterns of community variation as shown in the ordination diagram. Thus, landform index can be seen to have a high association with the moisture gradient of Axis 1. Transformed aspect, BCL, and BTH show relatively short

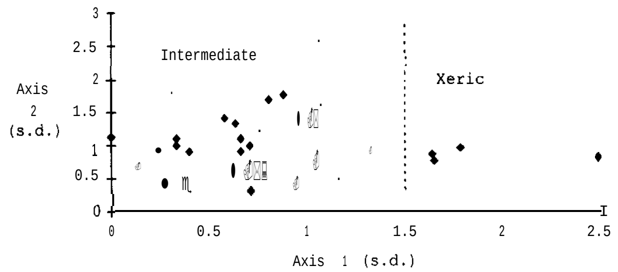

Figure 2-Second ordination after removal of mesic and submesic groups.

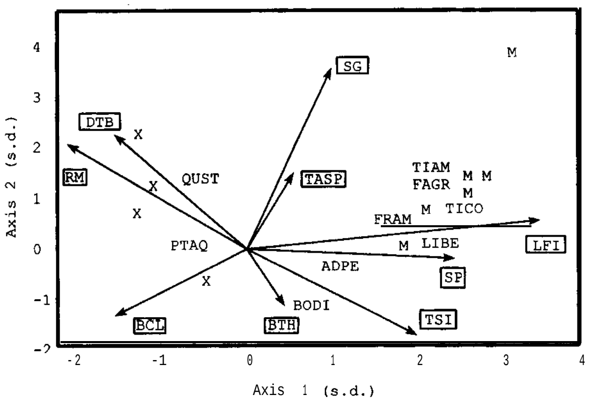

Figure 3-Environmental biplot from canonical correspondence analysis. M=mesic plot, X=xeric plot. TIAM= *Tilia americana*, FAGR=*Fagus grandifolia*, TICO=*Tiarella cordifolia*, FRAM=*Fraxinus americana*, LIBE=*Lindera benzoin*, BODI=*Botrychium dissectum*, ADPE=*Adiantum pedatum*, PTAQ=*Pteridium aquilinum*, QUST=*Quercus stellata*.

arrows, and as such are relegated to a minor discriminating role in influencing plant community variation. Ordinal species locations can also be projected onto each environmental arrow, and those that are near to or beyond the tip of the arrow will be most positively correlated with and influenced by that physical factor. *Pteridium aquilinum* and *Quercus stellata* are most strongly influenced by DTB and RM, respectively, while distributions of *Tiarella cordifolia* and *Fagus grandifolia* are controlled mostly by LFI.

Discriminant function analysis was then used to identify discriminating soil and landform variables that could be used to accurately predict site unit membership at the 0.20 significance level (table 1). The field model (LFI, WTSI, SP, RM, and DTB) classified accurately at 78 percent, while the model intended for GIS use had a classification success rate of 76 percent. As root mat type and thickness is sensitive to site disturbance (Pritchett and Fisher 1987), the field model is intended for use in undisturbed areas. The GIS model consists of spatial variables only (LFI, TSI, SP, DTB, TASP, SG) that can be built into GIS algorithms for predicting site unit membership. These models have yet to be validated by field measurements.

DESCRIPTION OF ECOLOGICAL UNITS

Xeric

With only four of the reference plots classified as xeric, these sites represent a small fraction of the land area in the Chauga Ridges region. The frequency of disturbance is greater on dry ridges, and in this area of steep, short slopes, topographic uniformity is rare on xeric sites. These units are characterized by low LFI readings (<0.24), indicating high exposure. Restricted rates of forest floor decomposition led to the development of a more humus type. Late-successional stands were dominated by *Quercus coccinea* and *Q. alba* in the overstory, along with

Table I-Mean values of environmental variables by ecological site unit for the Chauga Ridges region

Environmental variable	Site unit			
	Xeric	Intermediate	Submesic	Mesic
Landform index	0.17	0.21	0.42	0.49
Slope position (pct)	45	38	97	a9
Terrain shape index	-0.05	0.002	0.22	0.08
B horizon thickness (in)	32	22	44	25
B horizon clay (pct)	21	24	20	13
Root mat thickness (in)	1.40	0.92	0.20	0.31
Dist. to bottom (ft)	325	139	27	72
Slope gradient (pct)	39	37	25	61
Transformed aspect	1.06	0.92	0.93	1.60

scattered residuals of *Pinus echinata,* and *Vaccinium vacillans* and *Pteridium aquilinum* in the understory. *Carya glabra* and *Carya tomentosa* were also components of the overstory, with *Oxydendrum arboreum* common in the sapling layer. The herbaceous layer was very depauperate, with *V. vacillans* often comprising 70 to 80 percent of the ground cover. Soil properties were variable, with subsurface clay content ranging from 20 to 35 percent.

Intermediate

We estimated that this site unit occupied about three-quarters of the study area. Landscape positions typically were mid- lower slopes of southerly aspect or mid-slope positions with northerly or easterly aspects. Exclusive species in the overstory included *Nyssa sylvatica, Q. prinus,* and *Q. velutina.,* in association with *Q. alba, I? echinata,* and *C. glabra.* Flowering dogwood (*Cornus florida*) dominated the sapling strata and appeared to reach maximum development on these sites, often in association with *Styrax americana.* Although there were no exclusive species in the understory, common herbaceous associates included *Polystichum achrostichiodes, Collinsonia verticillata, Dioscorea villosa, Smilacena racemosa, Goodyera pubescens,* and *Chimaphila maculata.*

Submesic

These lower slope sites were most strongly influenced by concave microsite conditions, indicating soil moisture accumulation. The influence of aspect is overshadowed by degree of protection/exposure and TSI. Colluvial accumulation of coarse-textured materials produced 8- to 16-inch sandy loam surface horizons with sandy loam to clay loam subsurface horizons. There were no exclusive upper canopy dominants on submesic sites, but *Q. rubra, Fraxinus americana, C. tomentosa,* and *Q. alba* were the most common associates, with *Liriodendron tulipifera* found in scattered canopy openings. *Hydrangea arborescens* and *Calycanthus floridus* were the preferential species in the shrub layer. These communities had the highest level of herbaceous species richness of all ecological units, with an average of 20 species per plot. *Botrychium dissectum* was the only exclusive herbaceous species, and it was often found with *Sanguinaria canadensis, Sanicula canadensis, Thalictrum thalictroides, Lysimachia quadrifolia,* and *Bohemaria cylindrica.*

Mesic

Fagus grandifolia and *Tilia americana* dominated these lower slope sites, with five of six plots occupying northeast aspects. These cool and moist sites were found in highly protected coves (LFI > 0.37) on steep slopes of 43 to 94 percent. Soil epipedons were usually dark (< 3 value and chroma), but were not thick enough to be classified as umbric. Humus layer was very thin to nonexistent, indicating rapid breakdown and incorporation of organic materials by soil microbes. Soils were relatively young and largely of colluvial origin, with low subsurface clay contents of 7 to 19 percent. Occasional stems of *F. americana, Q. alba, T. canadensis, L. tulipifera,* and *Magnolia fraseri* were common associates in the overstory. Within the sapling and shrub layers, *Lindera benzoin* and *Leucothoe axillaris* were exclusive species restricted to these sites. A lush herbaceous layer was largely composed of *Cimicifuga racemosa, Tiarella cordifolia, Caulophyllum thalictroides, Geranium maculatum, Polystichum acrostichoides, Thelypteris noveboracensis* and *Hepatica acutiloba.*

SUMMARY AND CONCLUSIONS

The landscape ecosystem approach was used in the Chauga Ridges region to classify areas of the recurring landscape that express similar ecological attributes. By using a multifactor approach that integrates soil and landform variables as the driving force behind plant community variation, we were able to assess the nature of the study area as transitional between the Piedmont and Blue Ridge Physiographic provinces. Four multivariate analytical techniques were used to quantify the separation of four distinct ecological site units at the lowest level of classification heirarchy. A field model has been developed in addition to the GIS model, and is based on landform measurements that take 3 to 5 minutes per sample to measure.

Landform was found to have the strongest influence on plant community variation, with soil attributes playing a minor role. In this respect the Chauga Ridges region is similar to its northeastern neighbor, the Blue Ridge Mountains region. However, much of the vegetation is more closely aligned with species associations of the Piedmont province. This may indicate the true transitional nature of the Chauga Ridges region.

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Longleaf Pine Silviculture

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ECOLOGICAL LAND CLASSIFICATION OF LONGLEAF PINE ECOSYSTEMS IN THE SOUTHERN LOAM HILLS OF SOUTH ALABAMA

Robert E. Carter, Jr., Mark D. MacKenzie, and Dean H. Gjerstad[1]

Abstract-A landscape scale classification of ecosystems was undertaken on the Conecuh National Forest and Solon Dixon Forestry Education Center in south Alabama. Following the USDA Forest Service National Hierarchical Framework of Ecological Units, the three landtype associations in the study area were the Pine Hills, Dougherty Plain, and Wet Pine Flatwoods. The major environmental variables distinguishing the landtype associations were landform index, A horizon depth, B horizon depth, drainage class, A horizon P, percent B horizon clay, and percent B horizon silt. By interrelating vegetation, soils, and landform variables, two to four landtypes were identified in each landtype association along a moisture gradient from mesic to xeric. The diagnostic variables in the Pine Hills were landform index, slope, B horizon depth, B horizon N, A horizon fine sand, and A horizon silt. Dougherty Plain diagnostic variables included depth to mottling, B horizon fine sand, and A horizon Ca. In the Wet Pine Flatwoods, the diagnostic variables were slope, water table presence within 203 cm of the surface, depth to mottling, percent B horizon clay, and drainage class. Diagnostic species also were identified for each landtype.

INTRODUCTION

A key step of natural resource management is the delineation of land units that are similar relative to type, structure, and productivity of vegetation. Ecological Land Classification (ELC) accomplishes this by simultaneously interrelating vegetation, soils, and landform variables (Barnes and others 1982). This reveals diagnostic vegetation, soil, and landform variables that can be used to classify land into its appropriate land unit. Following the USDA Forest Service hierarchical framework of ecological units, the land units are termed Landtype Associations (LTAs) and Landtypes (LTs). LTAs are delineated on the basis of hydrology, geology, and topography, while LTs are delineated primarily on the basis of vegetation, soils, and landform.[2]

The ELC approach was applied in the uplands of the Southern Loam Hills of south Alabama in order to identify LTAs and LTs. The Southern Loam Hills are part of the longleaf pine *(Pinus palustris)* belt that extends from Virginia to Texas (Wahlenberg 1946). It previously covered 24 million hectares (ha) (Croker 1990) but presently occupies 1.5 million ha (Kelley and Bechtold 1990). Although there have been numerous descriptions of the vegetation and soils of longleaf pine ecosystems (Marks and Harcombe 1981, Pessin 1933, Gilliam and others 1993), few studies have attempted to identify and describe the large scale variation in the structure of the ecosystems.[3] Restoration and management of longleaf pine ecosystems are hindered by these deficiencies in information. This research addresses the present deficiencies in information pertaining to the structure of longleaf pine ecosystems in the Southern Loam Hills by (1) delineating ecosystems, (2) determining the soil and landform variables related to the ecosystems, and (3) producing discriminant functions for predicting ecosystems based on soil and landform variables.

METHODS

The study area was the Conecuh National Forest and Solon Dixon Forestry Education Center. This represented an area of approximately 36,450 ha; however, floodplains and bays were excluded from the study. The area is located in the Southern Loam Hills Subsection of the Lower Coastal Plain and Flatwoods Section of the Outer Coastal Plain Mixed Forest Province (McNab and Avers 1994).

One hundred eighteen circular 0.04-ha plots were established throughout the study area. Vegetation, soils, and landform variables were sampled at each plot. Vegetation strata sampled were trees, saplings, seedlings, shrubs and vines, and herbs. The d.b.h. cm was sampled for trees and saplings, while the frequency of seedlings and herbs was determined from four 1 by 10 meter subplots. With the vegetation data, relative importance values were calculated. Soil variables sampled were the depth of the A and B horizons, depth to the argillic horizon, depth to mottling, depth to the water table, Oe and Oi horizon thickness, and drainage class. Soil samples were collected for later analysis that included soil texture determination, total N and C percent, and P, K, Ca, and Mg in parts per million. The landform variables included landform index, terrain shape index (McNab 1991), slope gradient, and aspect.

Using species importance values, land units were determined through a combination of ordination and cluster analysis. The ordination method employed was canonical correspondence analysis (CCA) (ter Braak 1987). CCA utilizes a combination of species importance values and environmental variables to arrange sample units (plots) along axes (Jongman and others 1995). This results in vegetatively similar plots clustering together and dissimilar plots separating. Cluster analysis was performed using TWINSPAN (Hill 1979). This program uses species

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[2] USDA Forest Service. 1993. National hierarchical framework of ecological units. Draft report.

[3] Palik, B.J.; Mitchell, R.J.; Kirkman, L.K.; Michener, W.K. 1995. Structure and function of the longleaf pine ecosystem: review and synthesis. Draft report. On file with: Joseph W. Jones Ecological Center, Newton, GA.

importance values to divide the plots into successively smaller clusters of similar vegetation. Ordination was used in conjunction with cluster analysis to avoid subjectivity in delineating land units.

Once land units were delineated, stepwise discriminant analysis was used to determine which environmental variables were related to the vegetation (diagnostic variables) and to create discriminant functions (SAS Institute 1990). The ability of each discriminant function to correctly classify land units was tested with resubstitution and crossvalidation (SAS Institute 1990).

RESULTS

Through ordination and cluster analysis, nine landscape scale LTs were identified in the uplands of the Southern Loam Hills within three LTAs. The LTAs had previously been identified by the USDA Forest Service based on hydrology, geology, and topography.[4] They are the Pine Hills, Dougherty Plain, and Wet Pine Flatwoods. These LTAs were found to be valid with significant differences in the vegetation, soils, and landform. The diagnostic soil and landform variables ($p \leq 0.10$ level) were A horizon depth, B horizon depth, drainage class, A horizon P, percent B horizon clay, and percent B horizon silt. This combination of variables was significant ($p \leq 0.10$ level). The success rate of classifying the LTAs with discriminant functions and the diagnostic variables was determined by resubstitution (SAS Institute 1990). It resulted in rates of 84, 78, and 88 percent for the Pine Hills, Dougherty Plain, and Wet Pine Flatwoods, respectively.

Pine Hills Landtypes

Within the Pine Hills LTA, three LTs were identified along a gradient from xeric to intermediate. The discriminating landform and soil variables ($p \leq 0.10$ level) were landform index, slope, B horizon depth, percent B horizon N, percent A horizon fine sand, and percent A horizon silt. The classification success rate with resubstitution was 91, 67, and 92 percent for the xeric, subxeric, and intermediate LTs, respectively.

The vegetation of the intermediate LT was a longleaf pine-shiny blueberry (*Vaccinium myrsinites*)-meadow beauty (*Rhexia alifanus*) type. The overstory was dominated by *Pinus palustris,* while the sapling stratum was sparse. The seedling layer consisted of *V. myrsinites* and *Gaylussacia dumosa.* The herbaceous layer was rich and consisted of *Pityopsis graminifolia, R. alifanus, Carphephorus odoratissimus,* and *Pteridium aquilinum* (table 1).

The vegetation of the subxeric LT was a longleaf pine-post oak (*Quercus stellata*)-winged sumac (*Rhus copallina*) type. The tree stratum was similar to that of xeric sites with *Pinus palustris, Comus florida,* and *Q. falcata.* The sapling layer was sparse with no dominant species. The seedling stratum consisted of *Q. falcata, Rhus copallina, Q. stellata, V. myrsinies, V. corymbosum, V. arboreum,* and *Q. hemisphaerica.* The most common herbaceous species were *Smilax glauca* and *Pteridium aquilinum* (table 1).

The xerii LT vegetation was a longieaf pine-bluejack oak (*Q. incana*)-morning glory (*Ipomoea* sp.) type. The overstory was dominated by *Pinus palustris, Q. falcata,* and *Comus florida.* Q. *laevis* was not common and was only found on xeric sites. The sapling layer was sparse with *Q. margaretta* the only common species. The seedling stratum was a mixture of *Q. incana, Q. margaretta, Q. falcata, Q. hemisphaerica,* and *V. arboreum.* The herbaceous layer included *Ipomoea* spp., *Stylisma humistrata, Smilax glauca, Pteridium aquilinum,* and *Carphephorus odoratissimus* (table 1).

Dougherty Plain Landtypes

Within the Dougherty Plain LTA, two LTs were identified along a gradient from xeric to intermediate. The unique species of the Dougherty Plain LTA include *Aristida stricta*

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[4] USDA Forest Service. 1995. Land type associations: Conecuh National Forest. Draft report.

Table I-Vegetative types, diagnostic species, and diagnostic variabfes #or the Pine Hills Landtypes

Landtype	Intermediate	Subxeric	Xeric
Vegetative type	Longleaf pine-shiny blueberry-meadow-beauty	Longleaf pine-post oak-winged sumac	Longleaf pine bluejack oak-morning glory
Diagnostic species	*Vaccinium myrsinites*	*Quercus stellata*	*Quercus margaretta*
	Gaylussacia dumosa	*Rhus copallina*	*Comus florida*
	Pteridium aquilinum	*Quercus falcata*	*Quercus incana*
	Pityopsis graminifolia	*Vaccinium myrsinites*	*Stylisma humistrata*
	Rhexia alifanus	*Pteridium aquilinum*	*Ipomoea* spp.
Diagnostic variables:	Landform index, slope, B horizon depth, percent A horizon silt, percent A horizon fine sand, and percent B horizon nitrogen		

and *Q. virginiana.* The diagnostic physical variables ($p \leq$ 0.10 level) were depth to mottling, percent B horizon fine sand, and A horizon Ca. The overall classification success rate based on resubstitution and cross-validation was 91 and 86 percent for the xeric and intermediate LTs, respectively.

The vegetation of the intermediate LT was a longleaf pine-highbush blueberry *(V. corymbosum)*-pinweed *(Lechea minor)* type. The overstory was dominated by *Pinus palustris,* while the sapling stratum was sparse. Species common in the seedling layer were *Q. falcata, V. arboreum, Diospyros virginiana, V. corymbosum, G. dumosa,* and *Comus florida.* The herbaceous stratum was dominated by *Lechea minor, Crotolaria purshii, Oxalis comiculata, Danthonia sericea, Smilax glauca, Silphium compositum,* and *Elephantopus tomenfosus* (table 2).

The vegetation of the xeric LT was a longleaf pine-common persimmon *(Diospyros virginiana)*-elephant's foot *(E. tomentosus)* type. The overstory was dominated by *Pinus palustris.* The sapling layer was sparse, while the seedlings were numerous. Common seedlings included *Q. incana, Q. virginiana, Q. falcata, Diospyros virginiana, R. copallina, V. corymbosum, V. arboreum, Comus florida,* and *G. dumosa.* Common herbaceous species were *E tomentosus, Gelsemium sempervirens, Vitis rotundifolia, Stylosanthes biflora, Aristida stricta,* and *Hibiscus aculeatus* (table 2).

Wet Pine Flatwoods Landtypes

The Wet Pine Flatwoods had vegetation and soil characteristics unique in the study area. The most distinctive characteristic was the presence of the water table within 203 cm of the surface in 69 percent of the plots. Vegetation unique to this LTA included *Aristida stricta, Clethra alnifolia, Drosera brevifolia,* and *Pinus elliottii.*

In the Wet F'ine Flatwoods, four LTs were identified along an environmental gradient from xeric to bogs. The significant environmental variables ($p < 0.10$ level) were slope, water table presence within 203 cm of the surface, depth to mottling, percent B horizon clay, and drainage class. The overall success rates of classification ($p \leq$ 0.10 level) for both resubstitution and cross-validation were 80, 100, 83, and 78 percent for xeric, intermediate, mesic, and bog LTs, respectively.

The vegetation of the bogs was a slash pine-longleaf pine-sweet pepperbush (Clethra *alnifolia)* type. The overstory dominance was equally shared by *Pinus palustris* and ı? *elliottii.* The sapling layer was sparse with no dominant species. The seedling stratum was dominated by *Clethra alnifolia, V. myrsinites, V. stamineum,* and *Gaylussacia mosieri.* The common herbaceous species included *Rhexia alifanus, Drosera brevifolia, Smilax glauca, Carphephorus odorafissimus,* and *Aristida stricta* (table 3).

The vegetation of mesic LT was a longleaf pine-slash pine *(P. elliottii)*-deerberry type. The overstory was dominated by *Pinus elliottii* and *P. palustris.* No saplings were common, and the seedling layer was dominated by a few species. The species included *V. stamineum, Acer rubrum, Aronia arbutifolia,* and *Gaylussacia mosieri.* Common herbaceous species were *Aristida stricta, Carphephorus odoratissimus, Arundinaria gigantea, Rhexia alifanus, Smilax glauca,* and *Drosera brevifolia* (table 3).

The vegetation of the intermediate LT was a longleaf pine-deerberry *(V. stamineum)-hibiscus (Hibiscus aculeatus)* type. The overstory was dominated by *Pinus palustris* and *Pinus elliottii.* The sapling stratum was sparse, while the seedling stratum was rich. Seedling species included *V. stamineum, Symplocos finctoria, Q. hemisphaerica, V. myrsinites, Clethra alnifolia,* and *Prunus umbellate.* Among the common herbaceous species were *H. aculeatus, Aristida stricta, Smilax glauca, L. minor,* and *Parthenocissus quinquefolia* (table 3).

On xeric sites, the vegetation was a longleaf pine-common persimmon-wild sarsaparilla *(Smilax glauca)* type, with the overstory dominated by *Pinus palustris.* The sapling layer was sparse, but the seedling layer was rich. Common seedlings included *Clethra alnifolia, Rhus copallina, Q. falcata, Diospyros virginiana, Symplocos tinctoria, V. myrsinites,* and *Q. hemisphaerica.* Common herbaceous species included *H. aculeatus, Smilax glauca,* and *Aristida stricta* (table 3).

Table 2—Vegetative types, diagnostic species, and diagnostic variables for the Dougherty Plain Landtypes

Landtype	Intermediate	Xeric
Vegetative type	Longleaf pine-highbush blueberry-pinweed	Longleaf pine-common persimmon-elephant's foot
Diagnostic species	*Vaccinium corymbosum*	*Diospyros virginiana*
	Lechea minor	*Gelsemium sempervirens*
	Danthonia sericea	*Quercus virginiana*
	Oxalis comiculata	*Q. incana*
	Crotolaria purshii	*Elephantopus tomentosus*
Diagnostic variables:	Depth to mottling, percent B horizon fine, fine sand, and A horizon Ca	

Table 3-Vegetative types, diagnostic species, and diagnostic variables for the Pine Hills Landtypes and Wet Pine Flatwoods Landtypes

Landtype	Bogs	Mesic	intermediate	Xeric
Vegetative type	Slash pine-longleaf pine-sweet pepperbush	Slash pine-longleaf pine-deerberry	Longleaf pine-deerberry-hibiscus	Longleaf pine-common persimmon-wild sarsaparilla
Diagnostic species	*Pinus elliottii* *Clethra alnifolia* *Gaylussacia mosieri* *Rhexia alifanus* *Drosera brevifolia*	*Pinus elliottii* *Vaccinium stamineum* *Acer rubrum* *Drosera brevifolia* *Arundinaria gigantea*	*Vaccinium stamineum* *Symplocos tinctoria* *Hibiscus aculeatus* *Lechea minor* *Prunus umbellata*	*Diospyros virginiana* *Rhus copallina* *Quercus falcata* *Hibiscus aculea tus* *Smilax glauca*
Diagnostic variables:	Slope, depth to mottling, B horizon clay, variables presence of water table, and drainage class			

DISCUSSION

Within each LTA, two to four LTs were identified along an environmental gradient from xeric to mesic. The discriminant functions derived through the ELC process will aid in the recognition of ecological site units within the Southern Loam Hills. Due to the integrated nature of ELC, it will not only improve productivity predictions, but it also has implications for wildlife and endangered species management, regeneration techniques, harvesting, pest damage susceptibility, and successional pathways. As forest lands require more intensive and innovative management techniques, ELC can provide the detailed information necessary for making appropriate decisions. It is hoped that this ecological classification will provide a framework suitable for the management activities and potential restoration efforts of the USDA Forest Service. The information provided by ELC can be integrated into a Geographic Information System (GIS) to further improve natural resource management.

During the summer of 1996, an additional 180 plots were sampled. With these data, the seral vegetation of the LTs will be identified, and portions of the Conecuh National Forest will be mapped through GIS. These analyses are currently in progress.

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APPENDIX

Scientific names[a] and authorities:

Acer rubrum L.
Aristida stricta Michx.
Aronia arbutifolia (L.) Ell.
Arundinaria gigantea (Walt.) Muhl.
Carphephorus odoratissimus (Gmel.) Herb.
Clethra alnifolia L.
Cornus florida L.
Crotolaria purshii DC.
Danthonia sericea Nutt.
Drosera brevifolia Pursh
Elephantopus tomentosus L.
Diospyros virginiana L.
Gaylussacia dumosa (Andrz.) T. & G.
G. mosieri Small
Gelsemium sempervirens (L.) Ait. F.
Hibiscus aculeatus
Ipomea spp. L.
Lechea minor L.
Oxalis comiculata L.
Parthenocissus quinquefolia (L.) Planch.
Pinus elliottii Engelm.
P. palustris Mill.
Pityopsis graminifolia (Michx.) Nuff.
Prunus umbellate Ell.
Pteridium aquilinum (L.) Kuhn
Quercus falcata Michx.
Q. hemisphaerica Bark.
Q. incana Bartr.
Q. laevis Walt.
Q. margaretta Ashe
Q. stellata, Wang.
Q. virginiana Mill.
Rhexia alifanus Walt.
Rhus copallina L.
Silphium compositum Michx.
Smilax glauca Walt.
Stylisma humistrata (Walt.) Chapm.
Stylosanthes biflora (L.) BSP
Symplocos Victoria L.
Vaccinium arboreum Marsh.
V. corymbosum Ait.
V. myrsinites Lam.
V. stamineum L.
Vitis rotundifolia Michx.

[a] Nomenclature follows Clewell (1985) and Radford and others (1968).

PLANT COMMUNITIES IN SELECTED LONGLEAF PINE LANDSCAPES ON THE CATAHOULA RANGER DISTRICT, KISATCHIE NATIONAL FOREST, LOUISIANA

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Abstract-In Grant Parish, Louisiana, increases in overstory basal area, canopy cover, and development of understory woody plants reduced productivity of herbaceous plants in longleaf pine (*Pinus palustris* Mill.) stands that were managed with fire. Still, the herbaceous plant community can reestablish itself on properly managed upland longleaf pine sites in the West Gulf Region. Management efforts were considered most successful where pinehill bluestem [*Schizachyrium scoparium var. divergens* (Hack.) Gould] is the dominant herbaceous plant. The lack of oak (Quercus spp.) and hickory (*Carya* spp.) regeneration on more mesic sites was worrisome. Use of nested subplots was the best method for monitoring herbaceous vegetation.

INTRODUCTION

Fire was essential for the formation of many southern pine ecosystems. Today, failure to use prescribed fire in upland longleaf pine landscapes results in encroachment by, hardwood trees and shrubs and the loss of native pine and herbaceous vegetation. For example, in Alabama over 90 percent of the green biomass on the forest floor of young unburned longleaf pine stands is woody vegetation, while in periodically burned stands, less than 50 percent of the green biomass on the forest floor is woody vegetation (Boyer 1995). This woody vegetation can form a closed midstory that reduces species richness and productivity of the herbaceous plant community (unpublished field notes).

Only about 5 percent of the pine forest lands in Louisiana is publicly owned (Vissage and others 1992). Given the limited acreage, it makes sense to manage these lands for rare and endangered species, old growth characteristics, and other things that may be beyond the management capability of private landowners. As public lands are managed for these other attributes, monitoring becomes necessary for both legal and practical reasons.

In January 1993, the Kisatchie National Forest and the Southern Research Station began monitoring the effects of operational-scale burning in longleaf pine forests on overstory and midstory trees and shrubs and understory vegetation. In addition, research studies on the Catahoula Ranger District (RD) have provided useful information about the effects of fire. We are reporting on the fire effects from operational-scale bums done on two Ecosystem Management Project (EMP) sites and will compare those results to research findings.

SITES

All sites are on the Catahoula RD, Kisatchie National Forest, Grant Parish, LA. Elevations of the sites range from 53 to 76 meters (m). These sites are within the historical range of the upland longleaf pine forest type of the humid temperate, subtropical, outer coastal plain mixed forest, and are located in the coastal plains and flatwoods Western Gulf Ecoregion of the Southern United States (McNab and Avers 1994). The mean January and July temperatures are 10 and 28 °C, respectively (Louisiana Office of State Climatology 1995). Yearly precipitation averages 143 centimeters (cm) and growing-season precipitation averages 82 cm. The growing season is more than 200 days long; it usually begins before or during early March and ends because of dry weather in October.

The two research sites are as follows:

RES1 : The site is a slightly sloping upland of Metcalf (Aquic Glossudal@ and Cadeville (Albaquic Hapludal@ very fine sandy loams. An existing stand [7,450 stems per hectare (ha)] of 6-year-old lobiolly pine (*Pinus taeda* L.) was clearcut and the debris burned before 0.093-ha study plots were established. For the next 11 years, woody vegetation was controlled by biennial burning and by severing of all woody and blackberry (*Rubus* spp.) stems over 1 m tall. Over the next decade, a pasture of native woody and herbaceous plants became reestablished. We are using data from plots burned biennially in early May from 1962 through 1992.

RES2: The stand is a 17-ha longleaf pine shelterwood with reserves on a gently rolling upland of Ruston and Smithdale (Typic Paleudults) sandy loam soils. The shelterwood was established in 1968 when the initial preparatory cut left a residual basal area of 8.4 m^2 per ha. A seed-tree cut in 1975 left 6.9 m^2 per ha of basal area. The seed trees have been reserved for the management of red-cockaded woodpecker (*Picoides borealis)* habitat. The stand has been prescribed burned 11 times from 1969 through May 1993. Burns were during all seasons of the year.

The two EMP sites are as follows:

EMPL: The stand is a 188-ha longleaf pine forest on a Ruston, Smithdale, and Malbis (Plinthic Paleudult) sandy loam and loamy sand gently rolling upland. The two most recent prescribed bums were in 1990 and

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February 1993. Backing and striphead fires were employed.

EMP2: The stand is a 99-ha longleaf pine forest on a Ruston and Smithdale sandy loam and loamy sand gently rolling upland. The three most recent prescribed burns were in 1990, July 1993, and May 1995. Backing and flank fires were employed.

PROCEDURES

On RES1, total current-year herbaceous production was determined in February 1994 by clipping the aboveground foliage on 12 systematically located 0.22-m^2 subplots located within each 0.04-ha plot. Dry matter production (oven-dried at 80 °C for at least 24 hours) was determined after the samples were subdivided into six taxa: pinehill bluestem; other bluestems-mostly broomsedge *(Andropogon virginicus* L.), Elliott's bluestem *(A. elliottii* Chapm.), big bluestem *(A. gerardii* Vitm.), and slender bluestem (S. *tenerum* Nees); longleaf uniota [Chasmanthium sessiliflorum (Poir) Yates]; other grasses—mostly switchgrass *(Panicum virgatum* L.), yellow indiangrass [*Sorghastrum avenaceum* (Michx.) Nash],, low panicums *(Dichanthelium* spp), lovegrass *(fragrostis* spp.), and threeawn *(Aristida* spp.).; grasslikes-mostly nutrush (Scleria spp.), sedge (Carex spp.), flatsedge *(Cyperus* spp.), spikesedge *(Eleocharis* spp.), rush *(Juncus* spp.), and beakrush *(Rhynchospora* spp.); and forbs. In March 1994, all woody, blackberry, and vine stems were counted and heights and crown spreads estimated on five systematically located 40-m^2 subplots.

On RES2, EMP1, and EMP2, 0.04-ha plots were established for measuring heights and d.b.h. of the overstory and midstory trees. There were 16 ptots on the uplands in RES2 and 10 plots on both EMP1 and EMP2. Inventories were made in May 1996 on EMP1 and EMP2 and in July 1996 on RES2.

Within each 0.04-ha plot, five 4-m^2 subplots were systematically established for identifying and counting understory woody stems, blackberry stems, and vines and for measuring heights and crown cover of the woody and blackberry stems. This brush was inventoried in April 1995 on EMP2, in August 1995 on EMP1, and in August 1996 on RES2.

On RES2, five lines of 20 0.22-m^2 subplots were placed at equal distances apart across the site for inventorying herbaceous plant species. The lines were spaced 80 m apart and the subplots were spaced 16 m apart in each line. Only 86 of the 100 subplots fell on the upland soils. The remaining 14 subplots were in the Guyton (Typic Glossaqual) drainages and were not used. All herbaceous plants with root collars in the subplots were inventoried in July 1996. After the inventories, the herbaceous plants in the subplots were clipped to groundtine to determine dry matter production.

Twelve 100-point transacts were permanently located on both EMP1 and EMP2. These were used to inventory herbaceous plants. Each transect was 30 m long and readings were made every 30 cm. Readings were made through a circular loop 2 cm in diameter. The loop was held about 30 cm from the eye and 60 cm above the ground. All herbaceous plants seen through the loop were recorded. Readings were made in April 1995 on EMP2 and in August 1995 on EMP1. In September 1995, current-year herbaceous vegetation was clipped to groundline within seven, 0.22-m^2 subplots adjacent to each transect to determine dry matter production on both EMP1 and EMP2.

RESULTS AND DISCUSSION

Overstory and Midstory Vegetation

On RES2, EMP1, and EMP2 total stocking and basal area ranged from 54 to 279 stems per ha and 8.0 to 24.4 m^2 per ha (table 1). Canopy cover was too sparse to measure accurately on RES2 but averaged 67 percent on EMP1 and EMP2. Longleaf pine dominated the overstory on all sites

Table l-Number and basal area of overstory and midstory trees and shrubs and the percentage of the stand in longleaf pine (*Pinus palustris* Mill.)

Stands[a]	Number of stems/ha		Basal area (m^2/ha)			
	Total	Longleaf pine	Total	Longleaf pine	Longteaf pine	Total canopy cover
					Percent	Percent
RES2—shelterwood with reserves	54	48	8.01	7.67	96	- -[b]
EMPl—forest	279	124	24.36	19.85	81	77
EMP2—forest	210	153	24.40	21.89	90	57

[a] RES1 had no overstory or midstory vegetation.
[b] No data for this sparse overstory.

and made up from 81 to 96 percent of the total basal area. These three stands were classed as pure longleaf pine based on basal area (Ford-Robertson 1971).

More species of overstory and midstory trees and shrubs occurred on EMP1 and EMP2 than on RES2. Species other than longleaf pine represented a greater portion of the stand basal area on EMP1 and EMP2 than on RES2 (table 1).

-EMP1 had nine common overstot-y and midstory species: longleaf pine, mockernut hickory [*Carya tomentosa* (Poir) Nut-t.], flowering dogwood (*Cornus florida* L.), sweetgum (*Liquidambar styraciflua* L.), loblolly pine, southern red oak (*Q. falcata* Michx.), post oak (*Q. stellata* Wangenh.), black oak (Q. *velutina* Lam.), and sassafras [*Sassafras albidum* (Nutt.) Nees]. The common species on EMP2 were longleaf pine, mockernut hickory, blackgum (*Nyssa sylvatica* Marsh.), lobloily pine, southern red oak, blackjack oak (*Q. marilandica* Muenchh.), post oak, and black oak. On RES2, the common species were longleaf pine, sweetgum, southern red oak, and post oak.

Common Understory Woody Plants

Excluding blackberry, there were 16 tree, 15 shrub, and 15 vine species on EMP1, and 12 tree, 15 shrub, and 12 vine species on EMP2. Excluding pine seedlings, there were 60,100 tree, shrub, and blackberry stems per ha on EMP1, and 74,100 per ha on EMP2 (table 2). Height of this brush averaged 0.8 m on EMP1 and 0.5 m on EMP2. Vines numbered 86,600 per ha on EMP2 and 71,100 per ha on EMP1.

Excluding blackberry, there were six tree, nine shrub, and five vine species on RES2 and three tree, six shrub, and three vine species on RES1. Excluding pine seedlings, there were 24,500 tree, shrub, and blackberry stems per ha on RES2, and 9,700 per ha on RES1 (table 2). Vines numbered 27,800 per ha on RES2 and 4,900 per ha on RES1 .

The number of longleaf pine seedlings in the grass stage ranged from none on RES1 to 260,000 per ha 21 months after burning on EMP2. The number of loblolly pine seedlings ranged from 150 per ha 30 months after burning on RES2 to 9,300 per ha on EMP2. However, these small pine seedlings failed to develop because of the presence of overstory trees on RES2, EMP1, and EMP2 or because of continual cutting on RES1. While each successive burn reduced the number of pine seedlings, the population recovered between burns. This cycle should continue until there is either a natural disturbance or a change in management.

Tree species common in the understory were red maple (*Acer rubrum* L.), flowering dogwood, sweetgum, blackgum, black cherry (*Prunus serotina* Ehrh.), southern red oak, post oak, and sassafras, although the stocking and average height of these species varied among sites (table *2).* Red maple was not in the overstory on RES2, EMP1, and EMP2. However, red maple is susceptible to fire, and it may be being curtailed by burning on these upland sites (Haywood 1995).

Other hardwoods are also susceptible to fire (Chen and others 1975). Prescribed burning kills back the tops of hardwood stems but the root system is affected less (Silker 1961). This results in an increase in stem numbers, but the regrowth is smaller. However, continual burning-especially on an annual or biennial basis-eventually reduces the numbers and vigor of woody stems (Lotti 1956, Chen and others 1975).

On both EMP1 and EMP2, the overstory species not well represented in the understory were mockernut hickory, black oak, and blackjack oak. On RES2, the overstory species not well represented in the understory was post oak. Thus, it appears that oaks and hickories are not completely regenerating.

Shrub taxa in the understory included American beautyberry (*Callicarpa americans* L.), southern bayberry or waxmyrtle (*Myrica cerifera* L.), shining sumac (*Rhus copalina* L.), blackberry, tree sparkleberry (*Vaccinium arboreum* Marsh.), and other blueberries (*Vaccinium* spp.) (table 2). Common vine taxa in the understory were rattanvine [*Berchemia scandens* (Hill) K. Koch], Carolina jessamine [*Gelsemium sempervirens* (L.) Ait. f.], Japanese honeysuckle (*Lonicera japonica* Thunb.), dewberry (*Rubus trivia/is* Michx.), greenbrier (*Smilax* spp.), poison oak [*Toxicodendron toxicarium* (Salisb.) Gillis], and grape (*Vifis* spp.). Vines were most plentiful on EMP1 and EMP2, and numbers of vines varied from 4,900 per ha on RES1 to 86,600 per ha on EMP2.

Common Herbaceous Plants

On all four sites, the most well-distributed plants were pinehill bluestem, low panicurns, swamp sunflower (*Helianthus angustifolius* L.), grassleaf goldaster [*Heterotheca graminifolia* (Michx.) Shinners], and bracken fern [*Pferidium aquilinum var. pseudocaudatum* (Clute) Heller].

The total frequency of occurrence for all herbaceous vegetation was 30 percent on EMP1 and 74 percent on EMP2. The total current-year herbaceous production was 452 kilograms (kg) per ha on EMP1 and 753 kg per ha on EMP2.

On RES2, the total frequency of occurrence for all herbaceous vegetation was 805 percent. This high frequency of occurrence resulted partly from use of 0.22-m* subplots, whereas a 2-cm loop was used on EMP1 and EMP2. However, total current-year herbaceous production was 1,859 kg per ha on RES2. So, the plant cover was more abundant where overstory stocking was less, however the measurements were taken. No data on frequency of occurrence were collected on RES1 , but total current-year herbaceous production was 3,204 kg per ha. Of this total, 79 percent was in grasses, 6 percent in grasslikes, and 15 percent in forbs.

Common Grasses

There were 19, 26, and 18 taxa of grasses commonly found on RES2, EMP1, and EMP2, respectively. The

Table 2—Number of stems per hectare and average height (ht) in meters of the principal understory trees, shrubs, and blackberry, excluding longleaf and loblolly pine, and number of principal vines per hectare; cover types are pasture of native plants (RES1), longleaf shelterwood with reserves (RES2), and longleaf forests (EMP1 and EMP2)

Taxa	Stands							
	RES1		RES2		EMP1		EMP2	
	Stems	Ht	Stems	Ht	Stems	Ht	Stems	Ht
Trees								
Acer rubrum red maple	—[a]	—	1,077	1.8	346	1.3	2,323	0.8
Cornus florida flowering dogwood	—	—	—	—	2,768	0.7	9,933	0.6
Liquidambar styraciflua sweetgum	1,235	0.8	2,308	1.2	1,433	1.6	148	0.3
Nyssa sylvatica blackgum	—	—	—	—	297	0.6	2,372	1.1
Prunus serotina black cherry	—	—	—	—	939	2.1	1,631	0.9
Quercus falcata southern red oak	2,140	0.4	4,769	0.8	2,125	0.7	1,631	0.6
Q. stellata post oak	—	—	—	—	198	0.3	8,896	0.5
Sassafras albidum sassafras	—	—	769	0.3	2,817	0.6	4,893	0.8
Shrubs and blackberry								
Callicarpa americana American beautyberry	—	—	308	0.6	5,387	1.4	3,805	1.2
Myrica cerifera southern bayberry	3,292	0.8	154	1.1	9,489	0.7	7,611	0.3
Rhus copallina shining sumac	165	0.8	3,077	0.6	3,212	0.9	6,820	0.5
Rubus spp. blackberry	329	0.3	4,154	0.3	19,719	0.9	9,390	0.4
Vaccinium arboreum tree sparkleberry	1,152	0.4	2,615	0.3	544	0.7	1,631	0.6
V. virgatum, elliottii, and *stamineum* other blueberries	—	—	3,230	0.4	6,870	0.6	6,374	0.2
All trees and shrubs[b]	9,712	0.6	24,462	0.6	60,146	0.8	74,130	0.5
Vines[c]								
Berchemia scandens rattanvine	—		—		10,724		395	
Gelsemium sempervirens Carolina jessamine	4,115		2,923		15,963		10,625	
Lonicera japonica Japanese honeysuckle	—		—		297		17,989	
Rubus trivialis dewberry	—		11,538		9,340		26,588	
Smilax bona-nox, glauca rotundifolia, and *smallii* greenbrier	741		3,539		6,030		13,690	
Toxicodendron toxicarium poison oak	—		9,846		14,282		9,093	
Vitis rotundifolia and *aestivalis* grape	—		—		5,634		5,337	
All vines[b]	4,856		27,846		71,117		86,632	

[a] Taxon was not present.

[b] Number of stems for all trees and shrubs may also include numbers for taxa not reported in the table.

[c] Vine heights were not measured.

grasses that occurred most frequently were pinehill bluestem and low panicums on RES2 and EMP2 and pinehill bluestem and big bluestem on EMP1 (table 3). Spreading panicum (*Panicum anceps* Michx.) was also common on these three sites. On RES1, pinehill bluestem made up 58 percent, other bluestems 14 percent, and all of the other grasses 7 percent of the total current-year herbaceous production.

Other Herbaceous Plants

The grasslike plant most common on all uplands was nutrush. There were 22, 9, and 22 species or genera of composites on RES2, EMP1, and EMP2, respectively. The composite most common on these three uplands was grassleaf goldaster. Swamp sunflower was common on RES1, RES2, and EMP2. Both of these species are indicators of well-developed herbaceous plant communities.

Legumes numbered 19, 8, and 14 species or genera on RES2, EMP1 , and EMP2, respectively. The frequency of occurrence of the legumes averaged only 2 percent on EMP1 and EMP2, but was 176 percent on RES2. We believe that the method of sampling was a factor in the

Table 3-Grass taxa with frequency of occurrence exceeding either 4 percent on RES2 or 1 percent on EMP1 and EMP2; data on frequency of occurrence were not taken on RES1 . Cover types are longleaf shelterwood with reserves (RES2) and longleaf forests (EMP1 and EMP2)

	Stands		
Taxa	RES2[a]	EMP1	EMP2
	-------- Percent --------		
Andropogon gerardii big bluestem	1.16	2.67	0.75
A. subtenuis fineleaf bluestem	4.65	—[b]	—
Aristida purpurascens arrowfeather threeawn	23.26	0.08	1.25
Chasmanthium laxum and *C. sessiliflorum* spike and longleaf uniola	—	2.25	2.00
Dichanthelium spp. low panicums	79.07	1.50	12.67
Eragrostis elliotti and E. spectabilis Elliott and purple lovegrasses	4.65	0.25	0.08
Gymnopogon ambiguus bearded skeletongrass	18.60	0.17	1.42
Muhlenbergia expansa cutover muhly	4.65	0.08	—
Panicum anceps spreading panicum	3.49	1.83	1 .00
P. virgatum switchgrass	2.33	1.67	—
Schizachyrium scoparium var. *divergens* pinehill bluestem	95.35	7.58	8.08
S. tenerum slender bluestem	12.79	—	—
Sporobolus junceus pineywoods dropseed	4.65	0.17	—
All grasses[c]	270.94	21.40	30.82

[a] The frequencies of occurrence on RES2 are high partly because the sampling area was a 0.22-m^2 subplot rather than the 2-cm-diameter loop used on EMP1 and EMP2.
[b] Taxon was not present.
[c] Frequency of occurrence for all grasses may include frequencies for taxa not reported in table.

difference in legume frequency among sites. On RES2, the legumes that occurred most frequently were showy partridgepea (*Cassia fasiculata* Michx.), littleleaf tickclover [*Desmodium ciliare* (Muhl.) DC.], erect milkpea [*Galactia erecta* (Walt.) Vail], catclaw sensitivebrier (*Schrankia uncinata* Willd.), pencilflower [*Stylosanthes biflora* (L.) BSP.], and Virginia tephrosia [*Tephrosia virginiana* (L.) Pers.].

These findings suggest that it was better to use 9.22-m' subplots than the transect method when inventorying herbaceous plant species. Future work should use a nested subplot technique as recommended by the North Carolina Vegetation Survey.[2]

The other forbs numbered 26, 10, and 18 species or genera on RES2, EMP 1, and EMP2, respectively. Texas dutchmanspipe (*Aristolochia reticulate* Nutt.) occurred most frequently on RES2, narrowleaf mountainmint (*Pycnanthemum tenuifolium* Schrad.) occurred most frequently on EMP1, and flowering spurge (*Euphorbia corollata* L.) occurred most frequently on EMP2. Bracken fern represented 97 percent of the total fern population on RES2, EMP1, and EMP2.

Effects of the Overstory on Herbaceous Vegetation

The amount of current-year herbaceous production on each site was partly associated with overstory and midstory basal area, canopy cover, and number and size of understory trees and shrubs. EMP1 had the greatest canopy cover, the tallest understory vegetation, and the least current-year herbaceous production. RES1 had no overstory, the fewest understory woody stems, and the greatest herbaceous production.

Continual prescribed burning can be used to reduce understory woody vegetation beneath forest canopies over a number of years, and this may increase herbage production (Lotti 1956, Silker 1961, Chen and others 1975). However, as a pine canopy closes, shading by the overstory and competition for water and nutrients still limit herbaceous production no matter how effectively fire is used (Grelen 1976). Therefore, development of a herbaceous plant community may have to be judged by plant diversity rather than by herbaceous productivity On forest sites. To this end, indicator plants can be used as barometers of the health of herbaceous plant communities.

If overstory competition and understory brush are controlled, these upland longleaf pine sites can support rich and productive herbaceous plant communities dominated by pinehill bluestem. Also, these results suggest that pinehill bluestem could be used as an indicator of management success in establishing and maintaining herbaceous plant communities on upland longleaf pine sites in the West Gulf Coastal Plain. Examples of other species that could be used as indicators on similar sites are swamp sunflower and grassleaf goldaster.

[2] Pest, R.K.; Wentworth, T.R.; White, P.S. 1990. A flexible, multipurpose method for measuring vegetation. 35 p. Draft document on file with: University of North Carolina, Department of Biology, Chapel Hill, NC.

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LONG-TERM CHANGES IN FLOWERING AND CONE PRODUCTION BY LONGLEAF PINE

William D. Boyer'

Abstract-Cone production by longleaf pine has been followed for up to 30 years in regeneration areas at five to nine coastal plain sites from North Carolina to Louisiana. A rapid increase in the size and frequency of cone crops has occurred since 1988 following 20 years of relative stability. Cone production for the last 10 years averaged 38 cones per tree versus 14 cones per tree for the preceding 20 years. This change was evident at most sites, including the Escambia Experimental Forest where longleaf pollen shed has been recorded since 1957 and counts of female flowers in regeneration areas since 1970. Although pollen production was cyclic, no long-term change was evident. The recent increase in cone production seems due to both an increase in flower production and an increase in the fraction of flowers surviving to become mature cones.

INTRODUCTION

Longleaf pine *(Pinus palustris* Mill.) is a poor seed producer compared to other southern pines, and seed crops large enough for adequate natural regeneration are relatively rare. Most information on the size of longleaf pine seed crops in the past is anecdotal. Wahlenberg (1946) noted that good seed crops may occur every 5 to 7 years. Heavy seed crops may occur over much of the longleaf range once in 8 to 10 years (Maki 1952). Longleaf seed years have been characterized by relative terms such as failure, light, medium, heavy, or bumper, but these terms have not been tied to actual numbers such as cones per tree or seeds per acre.

In order to achieve satisfactory natural regeneration, the available seed supply must feed all the many predators with enough left over to establish a satisfactory seedling stand. An average of 360 cones per acre is needed to provide for the first seedling. A minimum of 750 and preferably 1,000 or more cones per acre is usually needed for successful regeneration (Boyer and Peterson 1983). The size of longleaf pine cone crops varies greatly from year to year, and also from place to place (Boyer 1987). This irregularity in seed production by longleaf pine is a major problem for the natural regeneration of this species (Croker and Boyer 1975).

Long-term records of longleaf pine cone production were obtained from natural regeneration trials initiated between 1966 and 1969. The tests included nine coastal plain sites from North Carolina to Louisiana, plus two in the montane longleaf forests of central Alabama. Cone production records from these tests, covering the 20-year period from 1966 through 1985, were reported earlier (Boyer 1987). Cone production records for the following 10 years, through 1995, are included in this report.

METHODS

Cooperative operational tests of longleaf pine natural regeneration were established at 11 sites within the southeastern longleaf pine belt. One test site is the Escambia Experimental Forest, Escambia County, AL. Four sites are on national forests in Louisiana, Mississippi, Alabama, and Florida. Three sites are on State forests in Florida, South Carolina, and North Carolina. Two sites are on private lands in Alabama and Georgia, and one is on a military reservation in Florida.

At each of 10 sites, two tests were established within stands ranging in size from 16 to 128 acres and averaging 64 acres. One was a test of the two-cut and the other the three-cut shelterwood method of natural regeneration (Croker and Boyer 1975). Several tests of the two-cut method only were established on the Escambia Experimental Forest. All tests were located in maturing stands of longleaf pine nearing a saw log rotation.

Twenty-five sample points were established within each test area. Two seed trees nearest each sample point were marked for annual springtime binocular counts of female flowers and conelets (first- and second-year pistillate strobili) using the method described by Croker (1971). Cones produced by each sample tree the preceding fall were also counted. This count included all the cones on the ground under each sample tree plus a binocular count of the cones remaining in each tree. Sample trees were not replaced when removed by cutting or natural mortality, so their number has declined over the years.

Counts ended in 1974 at three sites, two in the montane longleaf type and one on the coastal plain in Mississippi, when the parent overstory was removed following successful regeneration of both tests at each site. Cone count data from the two montane longleaf sites have been omitted due to exceptionally high cone production there as compared to monitored coastal plain sites. For the 8-year period from 1967 through 1974, the montane sites averaged 6.3 times as many cones per tree as five coastal plain sites with records covering the same period of time.

Counts ended at three additional coastal plain sites following 1978, 1979, and 1987 cone crops. Counts were resumed at these three sites, in new shelterwood stands, beginning in 1991, 1992, and 1994. Five coastal plain sites (one each in South Carolina, Georgia, Florida, Alabama, and Louisiana) have nearly complete cone count records,

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with 142 of 144 year-site cells filled. Eight cells at three sites were filled by estimates derived from springtime counts of enlarging conelets. Years of record at each coastal plain site, for both cone and flower counts, are given in table 1. The years listed for flower counts include only those with follow-up cone counts from the same sample trees.

Annual pollen shed by longleaf pine has been monitored on the Escambia Experimental Forest since 1957, using the method described by Grano (1958).

Annual cone counts on regeneration test sites were made to determine the size of cone crops normally needed for satisfactory natural regeneration, and also the frequency of their occurrence at different locations. Binocular counts of flowers and conelets were made to determine their potential value as predictors of cone crop size and so provide some lead time to prepare for an approaching good cone crop.

RESULTS

Long-Term Cone Production

Records of cone production by longleaf pine on coastal plain sites now cover the 30 years from 1966 through 1995. Average annual cone production for all years of record at each location ranged from 7.3 to 37.8 and averaged 21.2 cones per tree (table 2). These results suggest that longleaf pine cone production may increase with increasing distance from the coast.

Table I-Coastal plain sites and years of record for flower and cone counts

State and county	Flower counts: Started (flower yr)	Flower counts: Years counted	Cone counts: Started (cone yr)	Cone counts: Years counted
NC				
Bladen	1969	7	1968	15
SC				
Chesterfield	1'970	23	1969	27
GA				
Decatur	1968	23	1967	29
FL				
Santa Rosa	1968	24	1967	29
Okaloosa	1969	12	1968	22
Leon	1967	7	1966	16
AL				
Escambia	1970	25	1966	30
MS				
Perry	1967	6	1966	9
LA				
Grant	1968	18	1967	27

Table 2-Average annual cone production on coastal plain sites

State	County	Cones/tree (average)
North Carolina	Bladen	18.2
South Carolina	Chesterfield	37.8
Georgia	Decatur	10.9
Florida	Santa Rosa	14.3
	Okaloosa	7.3
	Leon	19.6
Alabama	Escambia	22.4
Mississippi	Perry	14.2
Louisiana	Grant	36.2
Average		21.2

'fear-to-year variation in cone production for all sites combined was very high, ranging from a low of less than one cone per tree in 1966 to a high of 65 cones per tree in 1987 (fig. 1). A minimum of 750 cones per acre is usually needed for adequate regeneration. This means cone production must average 30 or more cones per tree given 25 residual seed trees per acre in a shelterwood stand.

Both the size and frequency of monitored longleaf pine cone crops have increased substantially during the last 10 years. Cone production for all sites from 1986 through 1995 averaged 35.6 cones per tree. The average for the preceding 20 years was 14.0 cones per tree. For all sites combined, the frequency of cone crops adequate for regeneration (30 or more cones per tree) has changed from an average of once per 6.7 years before 1986 to once per 1.7 years since. A 5-year moving average for cone production at all sites illustrates the change (fig. 2). An apparent region-wide heavy longleaf cone crop in 1996 could push the 5-year average above 50 cones per tree.

Longleaf Flowering and Cone Production

A good longleaf pine cone crop depends on initiation of a large number of female flowers. Although a good female flower crop always precedes a good cone crop, a good cone crop does not always follow a good female flower crop. Pollen supply is another critical factor and, based on 9 years of observation, cone crop size was also closely related to pollen density in the flower year (Boyer 1974). However, large crops of both female and male (staminate strobili) flowers do not necessarily coincide. Weather conditions that promote production of female flowers in southern pines may not be the most favorable for production of male flowers (Boyer 1981).

Escambia Experimental Forest

The Escambia Experimental Forest is the only site where longleaf pine pollen supply has been monitored over a long period of time. This, along with counts of female flowers, permits some exploration of the role of both in year-to-year variations in cone production.

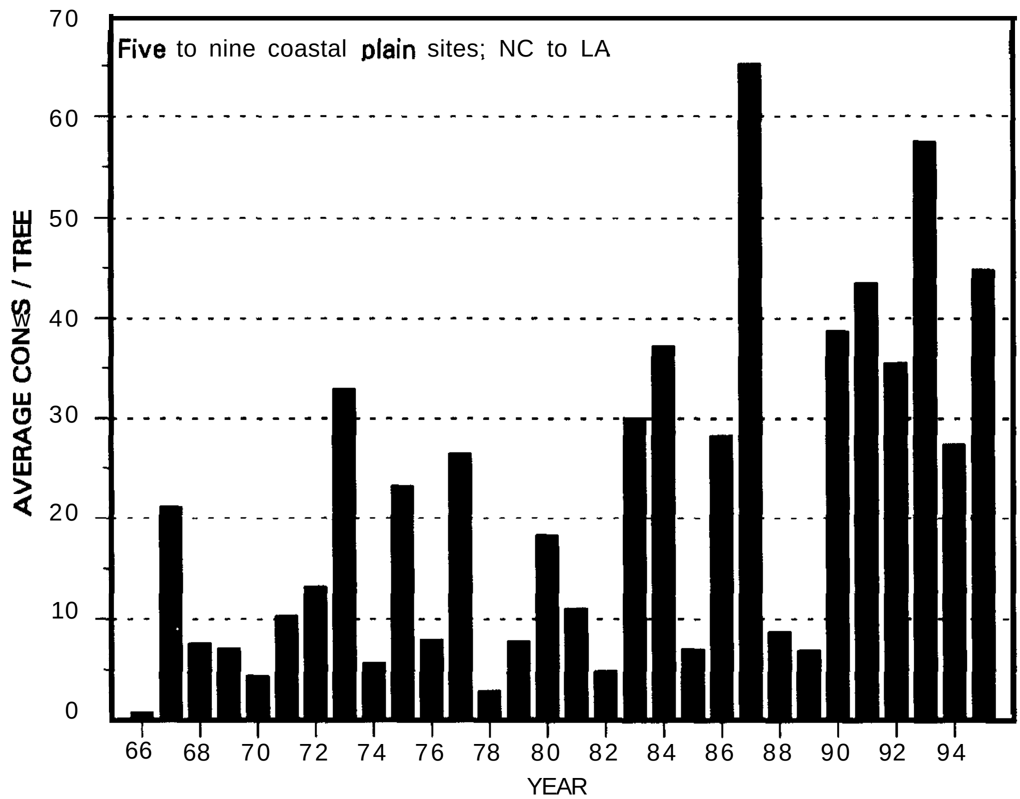

Figure I-Average annual cone production per tree for all coastal plain sites.

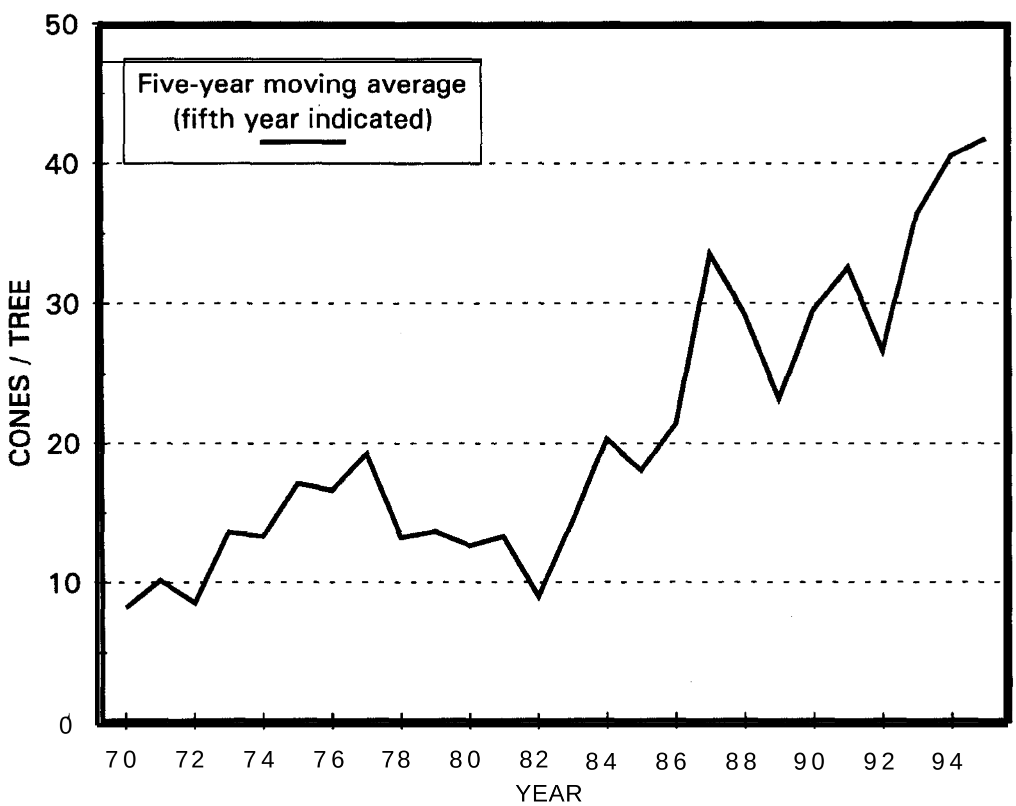

Figure Z-The 5-year moving average of cones per tree for all coastal plain sites.

Cone production by longleaf pine on Escambia Experimental Forest over a 38-year period (1958-95) ranged from a low of 0.2 cones per tree in 1989 to 128.1 cones per tree in 1993, with an overall average of 21 .O cones per tree (fig. 3). The average cone production for the 28 years before 1986 was 16.6 cones per tree. For the 10 years from 1986 through 1995, the average was 33.1 cones per tree, an increase of nearly 100 percent. The increase can be entirely attributed to the heavy cone crops in 1987 and 1993. Omit these 2 years and the average for the remaining 8 becomes 12.4 cones per tree.

Annual pollen supply over 40 years of record (1957-96) has ranged from 0.6 to 24.5 and averaged 7.4 thousand grains per square centimeter (cm^2). While cyclic, there is no indication of any long-term increase in pollen supply (fig. 4). Pollen supply averaged 8.4 thousand grains per cm^2 over the first 20 years, and 6.3 during the last 20 years. In 1957 and 1966, the pollen supply exceeded 20 thousand grains per cm^2 leading to a higher average for the first 20 years.

Flower counts on sample trees over the 27 years from 1970 through 1996 ranged from 0.2 to 80, and averaged 30.6 per tree (fig. 5). Flower production, both male and female, was less variable from year to year than cone production. Considering only the 25 years with matched flower and cone counts from the same sample trees, the coefficient of variation for annual flower counts was 67.9, and for cone counts 138.0 percent. The coefficient of variation for pollen supply over the same 25-year period was 58.2 percent.

Pollen supply for the 38 years from 1957 through 1994 was related to subsequent cone production (1958-95), although it was not a strong relationship, with a coefficient of determination (r^2) of 0.43. An adequate pollen supply, however, seemed necessary for a good cone crop. Cone production for the 16 years with pollen supply less than 5 thousand grains per cm^2 averaged 7.0 cones per tree. For the 12 years with pollen supply in excess of 10 thousand grains per cm^2, cone production averaged 45.1 cones per tree.

Flower counts were more closely related to subsequent cone production, with an r^2 of 0.66. Adding pollen supply increased the r^2 value only to 0.68. There was also a relatively weak relationship between flower counts and pollen supply over 27 years of record, with an r^2 of 0.46.

The large year-to-year variability in pollen supply, flower counts, and cone production on the Escambia Experimental Forest was reduced by 5-year moving averages for all three variables (fig. 6). All values are tied to the year of cone maturity, so that pollen supply and flower counts for the spring of one year are shown under the following year, when these flowers matured into cones. Both the high and especially the low points in the cycles for all three variables generally coincided. After 1986, however, the gap between flower counts and subsequent cone production closed, indicating a rather sharp reduction in the number of flowers per mature cone. Before 1986, there was an average count of 2.1 flowers per cone which declined to 1 .0 for the years 1986 through 1995. Flower

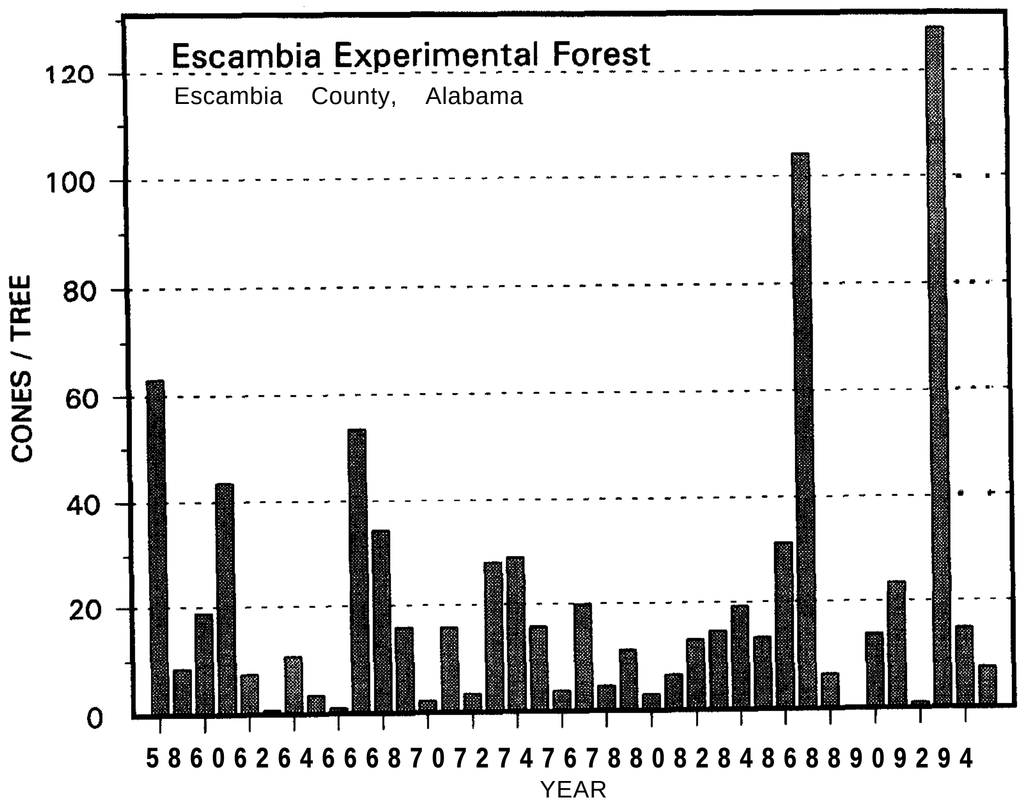

Figure 3-Average annual cone production per tree on the Escambia Experimental Forest.

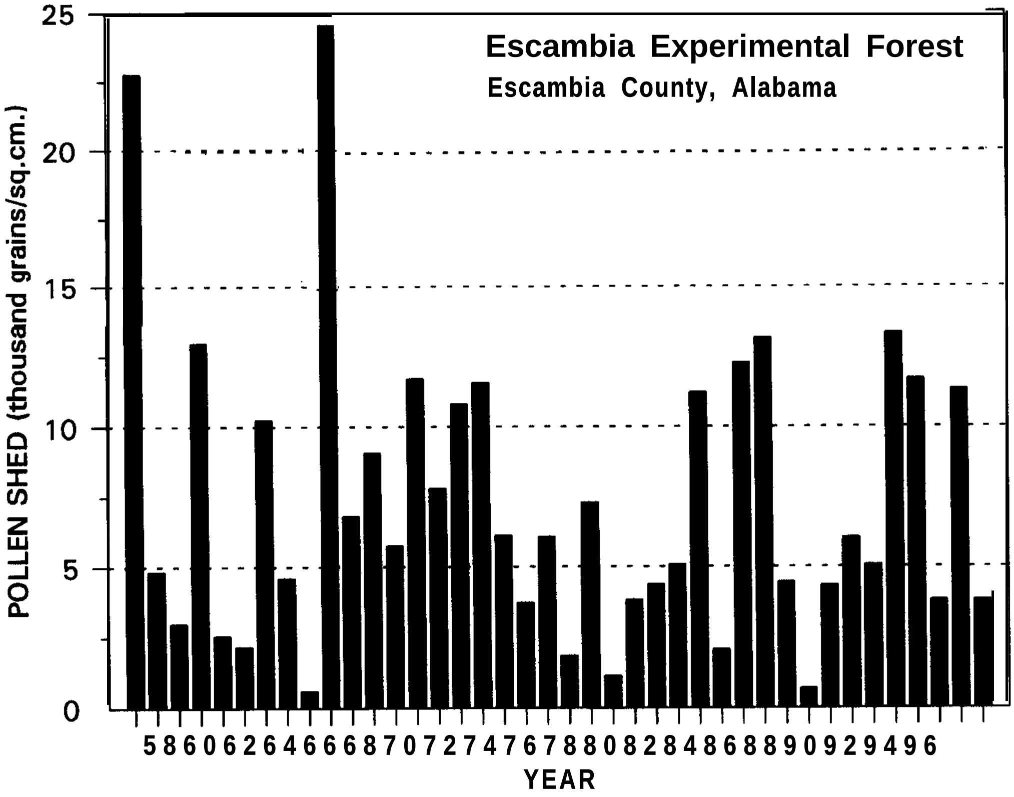

Figure 4-Annual pollen shed by longleaf pine on the Escambia Experimental Forest.

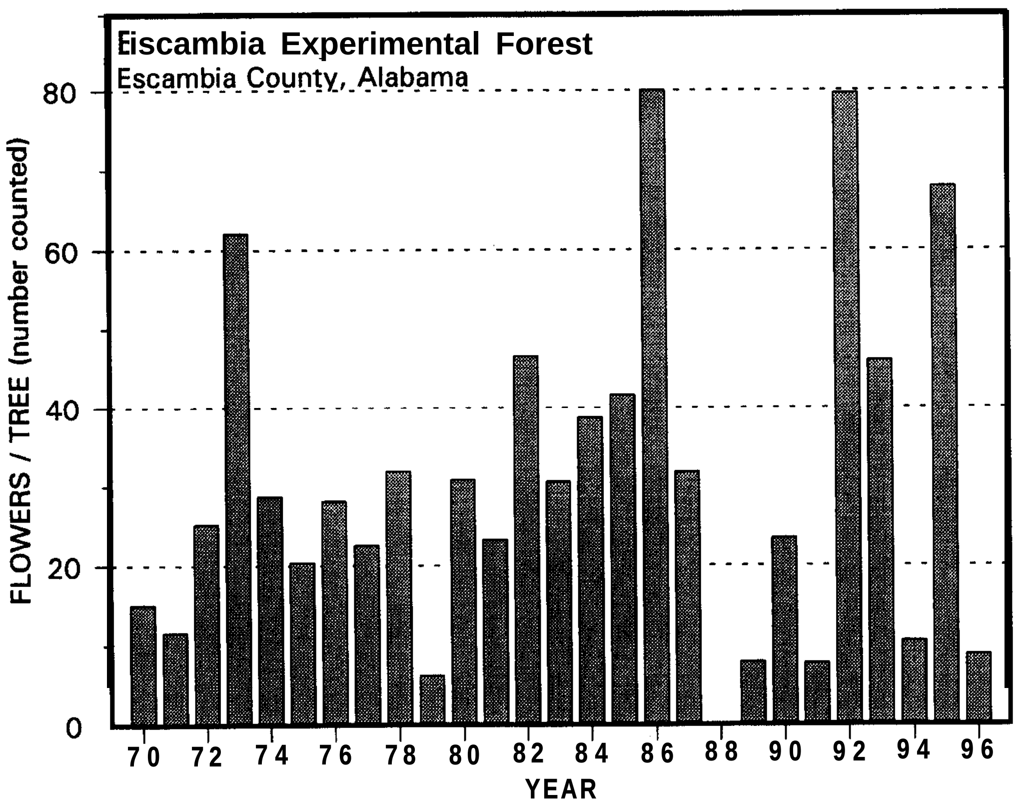

Figure 5-Average annual flower counts per tree on the Escambia Experimental Forest.

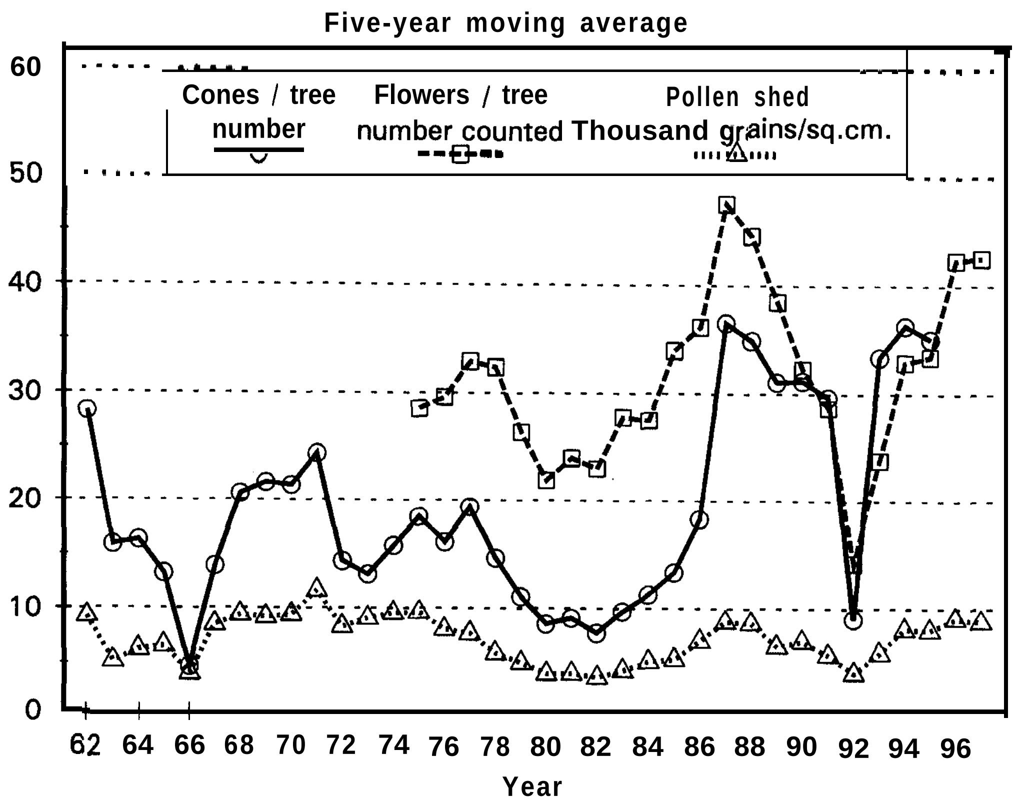

Figure 6-The 5-year moving averages for cone production, flower counts, and pollen supply on the Escambia Experimental Forest.

counts averaged 28.1 per tree before 1986 and 32.9 per tree after, an increase of only 17.1 percent. Cone production for the same trees over the same 25-year period averaged 13.4 per tree before 1986 and 33.1 per tree after, an increase of 147 percent! On the Escambia Experimental Forest, at least, it seems that the large increase in cone production observed after 1985 was due in small part to an increase in production of female flowers, but in larger part to an increase in the number of flowers that survived to become mature cones.

Five Coastal Plain Sites

All five coastal plain sites, including the Escambia Experimental Forest, that were monitored over a relatively long period of time showed increases in flower counts and cone production after 1985 compared to the average for all earlier years. Based on average flower and cone counts per tree for all five sites combined, flower counts increased by 59 percent and cone production by 110 percent (table 3).

The 17.1 percent increase in flower production for the Escambia Experimental Forest was the smallest. Increases in flower counts on the remaining four sites ranged from 40 to 211 percent. Cone production for these same sites increased from 30 to 1,175 percent. At four of the five locations, increases in cone production exceeded the increases in flower counts, suggesting that a larger fraction of flowers survived to become mature cones. The exception was Grant Parish, LA, where an increase of 40 percent in flower counts was greater than the 30 percent increase in cone production.

The average percent increase in flower counts since 1984, for all five coastal plain sites, was 75.1, while the increase in cone production was 337.6. The average for percent change greatly exceeded the increase based on average flower and cone counts for crops in 1986 and later versus the earlier years, since the greatest percentage increases were at locations with the lowest average cone production before 1986. The log of percent increase in cone production at the five sites was strongly related to average size of cone crops before 1986, with an r^2 of 0.88.

Average flower counts and, to a greater extent, cone counts were much less variable among the five coastal plain sites for cone crop years after 1985 than for the earlier years. The coefficient of variation for flower counts declined from 33 to 22 percent, and for cone production from 75 to 25 percent.

DISCUSSION AND CONCLUSIONS

The average size of longleaf pine cone crops on monitored coastal plain sites over the 10 years from 1986 through 1995 was more than double the average size for the preceding 20 years. This change appears due to both an increase in the number of female flowers per sample tree and to an increase in the number of flowers that survived to become mature cones. The relative contribution of these two factors varied among locations.

Table 3-Changes in flower 'counts and cone production on five coastal plain sites for cone crop years of 1985 and earlier versus 1986 and later

		Flower counts per tree			Cone counts per tree		
State	County	Earlier years	Later years	Change	Earlier years	Later years	Change
		---- Average ----		Percent	---- Average ----		Percent
SC	Chesterfield	34.0	48.5	42.6	33.4	54.2	62.3
GA	Decatur	16.1	50.0	210.6	2.8	35.7	1,175.0
FL	Santa Rosa	21.5	35.6	65.6	7.6	28.4	273.7
AL	Escambia	28.1	32.9	17.1	13.4	33.1	147.0
LA	Grant	43.3	60.5	39.7	39.4	51.2	29.9
All sites		28.6	45.5	59.1	19.3	40.5	109.8

Longleaf pollen shed, recorded at only one location, was cyclic over a 40-year period with no evident long-term change. An adequate pollen supply along with a good female flower crop appeared necessary requirements for a good cone crop.

Among the five locations with relatively continuous records, the increase in cone production was greatest at the three central Gulf Coast sites, less at the Atlantic Coast and West Gulf sites. Cone production at the Gulf Coast sites was much lower than the other two sites over the first 20 years. The percent increase in cone production was closely related to the average size of pre-1986 cone crops. The site with the largest gain (Decatur, GA) was that with the smallest average pre-1986 cone crop size, and the site with the smallest gain (Grant, LA) was that with the largest average pre-1986 cone crop size. The order is the same for the remaining three sites. Cone production since 1985 at the three Gulf Coast sites is still lower than at the other two sites, but the differences are much smaller.

The sudden and dramatic increase over the last 10 years in the size and frequency of good longleaf pine cone crops certainly suggests some favorable changes in environmental conditions associated with the cone production process. What these changes may be is open to speculation. In view of the regional scale of its occurrence, the most likely cause is some change in climatic conditions. Whether this is a permanent change, or only part of some long-term cycle, remains to be seen, provided flower and cone production records can be continued into the future.

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THE EFFECTS OF PLANTING TOOL ON PLANTING PRODUCTIVITY AND SURVIVAL OF LONGLEAF PINE BARE-ROOT SEEDLINGS

Rhett Johnson, Dale Pancake, Mark Hainds, and Dean Gjerstad'

Abstract-An evaluation was made of the effects of hand planting tool (shovel or dibble) on planting productivity and survival of longleaf pine *(Pinus palustris)* seedlings on two adjacent sites in the upper Coastal Plain of Alabama. In addition, the effects of storage time between lifting and outplanting on survival were measured. Seedlings were planted with both shovels and dibbles on each of two sites harvested in 1995. Site A was clearcut, broadcast-burned in December of 1995, and the site prepared with a Savannah 3-in-1 plow. Site B was clearcut and aerially sprayed with a tank mix of 18 ounces of Arsenal (imazapyr) and 25 ounces of Garlon (triclopyr) per acre in October of 1995. A broadcast burn was performed in December 1995 and the site bedded with the Savannah 3-in-1 plow later that month. Planting began in January of 1996. On each day, shovels and dibbles were used to plant simultaneously on the site. Seedlings were stored at 55 °F between lifting and planting. Storage time ranged from 0 days (planted on the day of lifting) to 13 days. Planting productivity differences were statistically insignificant, averaging 146.8 seedlings per man per hour with shovels and 141.8 seedlings per man per hour with dibbles. Survival at the end of one year also did not differ between implements on individual sites or overall on both sites. Survival on site A was 85 percent with shovels and 86.25 percent with dibbles. On site B, mean survival was 71.88 percent with shovels and 71.46 percent with dibbles. Overall survival was 78.44 percent with shovels and 78.95 percent with dibbles. Due to study design, statistically linking survival to storage time was impossible, but survival of seedlings planted with shovels 0, 1, 3, 6, 7, 9, 10, and 13 days after lifting averaged 87.5 percent, 82.5 percent, 76.25 percent, 81.25 percent, 62.5 percent, 73.75 percent, 72.5 percent and 65 percent, respectively. Survival of seedlings planted with dibbles on the same dates was 87.5 percent, 85 percent, 66.25 percent, 75 percent, 70 percent, 60 percent, 77.5 percent and 80 percent. One year after planting, 22 percent of shovel-planted seedlings had initiated height growth, as had 23 percent of seedlings planted with dibbles. The incidence of height growth initiation declined as storage time increased up to 7 days of storage.

INTRODUCTION

Although there is little documentation, many foresters believe that longleaf pine bare-root seedlings are best planted by planting machine. Machine planting, however, requires a level of site preparation not necessary for hand planting. Less intensive site preparation can lessen adverse effects on the site and often lowers costs. Hand planting is commonly accomplished in the Southeast with dibbles or planting bars. Other tools occasionally used by planters include hoedads and planting shovels. In this study, planting productivity and seedling survival were compared for dibbles and planting shovels.

STUDY AREA

The Solon Dixon Forestry Education Center is located in the upper Coastal Plain of south-central Alabama approximately 60 miles north of the Gulf Coast. The 5,350-acre teaching and research forest ranges from xeric ridges to forested wetlands, and from bottomland hardwood stands to upland longleaf pine stands. The two sites chosen for this study are adjacent and were occupied by similar, mature, mixed pine/hardwood stands prior to clearcutting in 1995. The soils are loamy sands and moderately well drained. There is a slight slope on each site and both have northeastern aspects. Each was site prepared in 1995 using broadcast fire and a Savannah 3-in-1 plow pulled behind a crawler tractor equipped with a V-blade. Both operations took place in December of that year. In addition, one site (site B) was aerially sprayed with a tank mixture of 18 ounces of Arsenal (imazapyr) and 25 ounces of Garlon (triclopyr) per acre prior to the fire. The plow incorporated soil, organic matter, and some coarse woody debris into beds spaced approximately 10 to 12 feet apart and standing 1 to 1.5 feet high.

METHODS

Planting

The beds were planted in 6-foot intervals with bare-root longleaf pine seedlings obtained from the E.A. Hauss nursery, operated by the Alabama Forestry Commission and located approximately 70 miles from the Dixon Center. All seedlings used in the study were lifted on January 21, 1996 and stored at 55 °F in a refrigerated cooler until outplanting. Planting began on site A on January 21 with freshly lifted seedlings. Planting was done by staff of the Dixon Center, all experienced hand planters. On each day, half of the crew planted with shovels and half with dibbles. On the next planting day, the implements were exchanged to eliminate differences in planting speed or ability. The shovels were used very much like dibbles, i.e., a planting slit was created rather than a dug hole (Blake and South 1991). At the end of each day, the number of seedlings planted with each implement was recorded, seedlings per man-hour calculated, and the block marked with pin flags to assist in subsequent tracking. The planting continued across the two sites until both were planted. Planting took place on the day the seedlings were lifted and 1, 3, 6, 7, 9, 10, and 13 days after lifting. In each case, daily productivity

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was calculated and the blocks identified by day of planting and implement used.

Subsequent Measurements

One year after planting, the sites were sampled to determine survival by day of planting and implement. In addition, data were collected on the incidence of height growth initiation in each block. Evaluation of differences in height growth incidence and survival between sites and among storage time blocks was complicated because of confounding effects, and no conclusions could be reliably drawn.

RESULTS

Planting Productivity

Productivity (trees per man per hour) varied on a day-to-day basis both by implement and by day (table 1). Mean planting productivity with shovels and dibbles was 146.8 and 141.8 trees per man per hour, respectively. Daily rates ranged from highs of 174 trees per man per hour with the shovel and 175 trees per man per hour with the dibble to lows of 121 trees per man per hour with the shovel and 123 with the dibble. Figure 1 depicts this data graphically.

Seedling Survival

Overall survival with each implement across both sites was remarkably similar. On site A, mean survival after 1 year of seedlings planted with shovels was 85 percent. On the same site, mean 1 -year survival of dibble-planted seedlings was 86.25 percent. Survival on site B averaged 71.88 percent for seedlings planted with shovels and

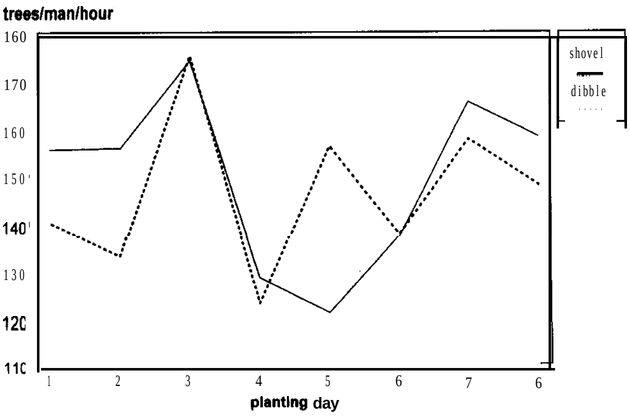

Figure I-Planting productivity for shovels and dibbles by day.

71.46 percent for seedlings planted with dibbles. Overall survival after 1 year across sites was 78.44 percent for shovel-planted trees and 78.95 for dibble-planted seedlings.

Survival by implement by days of storage is indicated in table 2 and graphically depicted in figure 2. Because the sites were not planted simultaneously and site preparation treatment varied between sites, comparisons cannot safely be made between sites. However, survival on site A was 88.1 percent for seedlings planted on the day of lifting, and 84.4 percent for seedlings planted 1 day later. Seedlings planted on those days with shovels survived at the rates of 88.75 percent and 85 percent, respectively. Those planted on the same days and same site with dibbles survived at

Table I-Planting productivity

Day	Site	Implement	Trees/man/hour
1	A	Shovel	155.3
	A	Dibble	140.0
2	A	Shovel	155.6
	A	Dibble	133.0
3	B	Shovel	174.0
	B	Dibble	175.0
4	B	Shovel	128.5
	B	Dibble	123.2
5	B	Shovel	121 .0
	B	Dibble	156.0
6	B	Shovel	137.2
	B	Dibble	137.7
7	B	Shovel	165.3
	B	Dibble	157.5
8	B	Shovel	158.0
	B	Dibble	148.0
Mean productivity:		Shovel	146.8
		Dibble	141.8

Table 2-Year seedling survival by implement and storage time

Site	Days of storage	Implement	Survival rate
			Percent
A	0	Shovel	87.50
	0	Dibble	87.50
A	1	Shovel	82.50
	1	Dibble	85.00
B	3	Shovel	76.25
	3	Dibble	66.25
B	6	Shovel	81.25
	6	Dibble	75.00
B	7	Shovel	62.50
	7	Dibble	70.00
B	9	Shovel	73.75
	9	Dibble	60.00
B	10	Shovel	72.50
	10	Dibble	77.50
B	13	Shovel	65.00
	13	Dibble	80.00

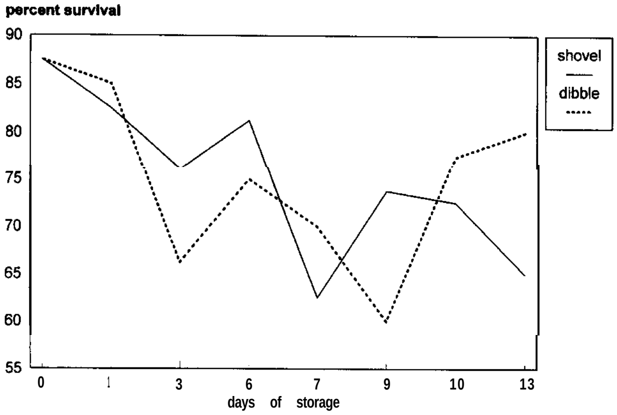

Figure 2—Seedling survival after 1 year by planting implement and storage time.

87.5 percent and 83.75 percent. On site B, seedlings were planted after 3, 6, 7, 9, IO, and 13 days of storage. Overall survival rates for those days was 71.25 percent, 78.1 percent, 66.25 percent, 66.88 percent, 75 percent, and 72.5 percent, respectively. Seedlings planted on site B with shovels had the following survival rates: 3 days storage: 76.25 percent; 6 days: 81.25 percent; 7 days: 62.5 percent; 9 days: 73.75 percent; 10 days: 72.5 percent; and 13 days: 65 percent. For seedlings planted on the same site on the same days with dibbles, survival rates were 66.25 percent, 75 percent, 70 percent, 60 percent, 77.5 percent, and 80 percent.

Height Growth Initiation

Height growth initiation was recorded 1 year after outplanting. Height growth was exhibited by 23 percent of seedlings planted with shovels and 22.4 percent of seedlings planted with dibbles after one growing season. Height growth initiation by implement by day is detailed in table 3 and depicted graphically in figure 3.

DISCUSSION

General Conditions

This study was begun just prior to a major catastrophic event, Hurricane Opal, which caused the compression of the site preparation treatments and subsequent outplanting into a much shorter time frame than desired. Planting only 1 month after the bedding operation allowed very little settling of the beds and was a cause of concern. In addition, the burn was conducted only 2 months after the herbicide treatment, likely compromising the effectiveness of the chemicals. Good rains accompanied and followed the planting operation, with 1 inch falling on the day before planting began and nearly 2 more inches falling during the 2-week planting period. Nearly a month passed before the next rainfall on March 7.

Planting Productivity

Planting productivity varied widely from day to day but mean planting productivity did not differ significantly between implements. Variations might best be explained by within- and between-site variations (amount of coarse woody debris, etc.), weather conditions, individual planter capability, and varying enthusiasm for the project. Suggestions that the less-productive crew always seemed to include the principal investigator I choose to discount as scurrilous rumor.

Table 3-One-year height growth initiation by implement and by storage time

Implement	Storage time	Height growth
		Percent
Shovel	0	51.4
Dibble	0	34.3
Mean	0	42.9
Shovel	1	36.4
Dibble	1	39.7
Mean	1	38.1
Shovel	3	10.5
Dibble	3	28.3
Mean	3	19.4
Shovel	6	12.0
Dibble	6	31.7
Mean	6	21.9
Shovel	7	7.9
Dibble	7	12.5
Mean	7	10.2
Shovel	9	7.6
Dibble	9	8.3
Mean	9	8.0
Shovel	10	10.0
Dibble	10	11.3
Mean	10	10.7
Shovel	13	11.1
Dibble	13	7.8
Mean	13	9.5
Mean (shovel)		23.0
Mean (dibble)		22.4

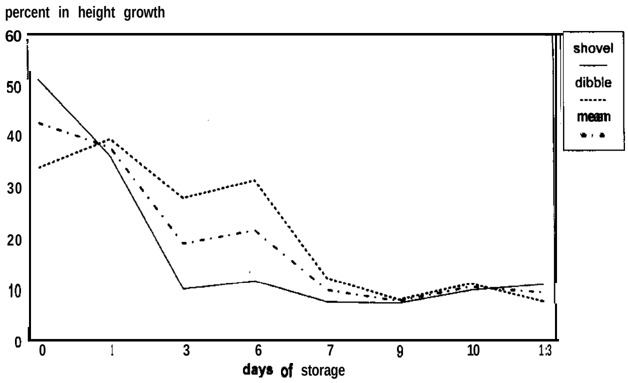

Figure 3-Height growth initiation by planting implement and storage time after one growing season.

Survival

Survival was at acceptable levels for operational purposes throughout the study. Survival at 1 year did not differ for implements across both sites and no significant trend could be detected for storage time. Survival did drop after 1 day of storage, but trees stored longer were planted on a different site. Survival of trees with longer storage times varied so much that no statistically significant trend could be identified.

Height Growth Initiation

Early height growth is generally deemed desirable for longleaf seedlings. Decreased exposure to brown spot needle blight *(Scirrhia acicala)* is one result, and early height growth is often thought to be an indicator of continued vigor through the life of the tree (Boyer 1988). Although the confounding effects of site and site preparation differences make statistical analysis risky, there is a relatively strong indication of an inverse relationship between storage time and early height growth initiation. There was no difference in rate of height growth initiation between seedlings planted with shovels and those planted with dibbles.

CONCLUSIONS

Machine planting of these sites was impossible because of the amount of coarse woody debris incorporated into the beds by the Savannah 3-in-1 plow. Hand planting was accomplished successfully with both shovels and dibbles and no differences were detected between implements in planter productivity, seedling survival, or height growth initiation. Survival was best when seedlings were outplanted quickly after lifting, although no compelling trend was noted. Height growth initiation seemed to be linked fairly strongly to storage time, with early outplanting leading to increased incidence of first-year height growth. The combination of the Savannah 3-in-1 plow treatment, high-quality seedlings, good seedling care and proper planting techniques, and good soil moisture conditions can yield success in establishment of longleaf stands using bare-root seedlings and hand planters.

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DISEASES OF FOREST TREES: CONSEQUENCES OF EXOTIC ECOSYSTEMS?

William J. Otrosina'

Abstract-Much attention is now given to risks and impacts of exotic pest introductions in forest ecosystems. This concern is for good reason because, once introduced, an exotic pathogen or insect encounters little resistance in the native plant population and can produce catastrophic losses in relatively shot-l periods of time. Most native fungal pathogens of forest trees have co-evolved for eons with their hosts and have reached a sort of balance between them and populations of susceptible tree species. Recent studies on various forest types have indicated a higher incidence of certain fungal pathogens than were previously thought to occur. These pathogens are either the type not normally thought of as highly virulent or are those that have not been previously reported as a serious problem on a particular host. For example, pathogenic fungi belonging to both the *Leptographium* complex and *Heterobasidion annosum,* are associated with mortality after prescribed burning in certain longleaf pine stands. Yet, this tree species has traditionally been ranked as highly tolerant to these fungi. Could these observations reflect some manifestation of "exotic ecosystems," whereby the conditions under which particular tree species evolved are no longer present or are altered in some way that increases their susceptibility to these fungi? With the current emphasis on ecosystem restoration and alternative skicultural regimes, it is critical to address such questions in order to avert losses in forest productivity.

INTRODUCTION

Forest tree species and all other living organisms have evolved under various environmental conditions through eons of time. Nearly all species that have ever lived are now extinct (Raup 1986). Adaptations to climatic factors, soils, pests, diseases, and a host of disturbance events, operating at a variety of scales, have forged the characteristics of each tree species we now observe, including their functions in forest ecosystems.

From the perspective of forest pathological processes, individual tree species and ecosystems are in some form of quasi-equilibrium with various pathogens. This is in contrast to situations involving introduced pests or exotic organisms, which generally cause rapid and catastrophic mortality on native tree species. On the other hand, many root disease pathogens that have co-evolved with their hosts often cause excessive mortality and disruption of long-term stand management goals. Why then, in a theoretically stable system from the host-pathogen perspective, are there significant problems with various diseases in coniferous forest stands over a wide range of forest types and ecological conditions? Have presettlement forest conditions changed, through past land uses, to the extent that unstable or "exotic ecosystems" are created by various management activities which have led to undesirable losses due to various forest tree diseases?

For many decades, forest pathologists have studied the effects of various management regimes and their relationships to forest tree disease. As a result, an empirical understanding of relationships between site factors, disturbance, past and present management practices, and silvicultural procedures relative to many forest diseases has been attained. In the light of these discerned relationships, the purpose of this paper is to introduce the concept of exotic ecosystems, defined as unstable ecosystems arising from rapid edaphic and environmental changes brought about by past land use or current management practices. These will be presented in the context of how various silvicultural regimes, disturbances, and past land use practices have interacted to create disease problems.

ROOTDISEASE

Annosus Root Disease

Caused by the fungus *Heterobasidion annosum* Fr.(Bref.), this disease is often devastating on temperate zone conifers worldwide. Two biological species of this fungus occur in western North America. One, called "S," attacks primarily true firs and Sequoia while the other, called "P," attacks mainly pines and juniper. In the Eastern United States, only the P group has been found to date.

The fungus attacks pines (P group) by spores landing on freshly cut stump surfaces. The spores germinate and rapidly colonize portions of stumps, with mycelia growing downward and further colonizing stump roots. Healthy trees whose root systems contact infected stump roots become infected, thus creating ever-widening gaps or disease centers in affected stands (Otrosina and Cobb 1989). Based upon isozyme and DNA studies (Otrosina and others 1992, 1993; Garbelotto and others 1996), the P group in the Western United States was probably rare until presettlement times. It may have occupied niches created by natural wounding events such as blowdowns or possibly fire scars and was a part of Western United States pine ecosystems, creating occasional openings in stands.

By the late 19th century, timber harvesting was conducted on a large scale. Another boom in timber harvesting occurred during the 1950's as a result of post-World War II housing demand (MacCleery 1992). As a result, freshly cut stump surfaces were created in large amounts over 40 to 50 years in old-growth east-side Sierra Nevada pine stands. Many of these stands were subjected to selective harvesting with repeated entries. These partial cutting

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techniques often resulted in stem-damaged residual trees, soil compaction, and root damage. Because fresh stump surfaces are an ideal niche for *H. annosum* colonization, populations of the P group increased dramatically, increasing the likelihood of disease transmission to residuals by root contacts with infected stump roots. The fungus, once in a stand, is intractable and can survive for over 60 years (Otrosina and Cobb 1989). Thus, stand development is affected far into the rotation with the disease perpetuating itself by continued spread in ever-widening mortality centers.

Fire exclusion also has affected annosum root disease incidence in many stands. For example, a general shift in species composition has taken place in the Sierra east-side forest type as a result of fire exclusion. Once park-like stands of predominantly ponderosa pine are now dominated by shade-tolerant, true fir species (Petersen 1989). The S biological species of *H. annosum* is widespread on true firs (Otrosina and Cobb 1989, Otrosina and others 1992) and apparently infects firs more frequently as a result of direct infection through natural wounds or means other than freshly cut stumps (Garbelotto and others 1996). This is in contrast to the P group of *H. annosum* in pine species, which had a more restricted range on pines prior to management activities. The characteristically overstocked stands of firs resulting from fire exclusion have a high incidence of root disease that renders them susceptible to catastrophic insect outbreaks (Hertert and others 1975) and wildfires (Otrosina and Ferrell 1995). Thus, fire exclusion can be thought of as a disturbance resulting in an exotic ecosystem in which current tree species assemblages exist in a pathologically, entomologically, and silviculturally unstable system driven by widespread root disease.

Another example of exotic ecosystems arising from fire exclusion and the presence of root disease is the present decline in health of *Sequoiadendron giganteum* (Lindl.) Buckholz stands in the Sequoia-Kings Canyon National Park. Decades of aggressive fire exclusion have encouraged the ingrowth of shade-tolerant true firs under old growth *S. giganfeum.* Because true firs can be infected with the *H. annosum* S group in the absence of harvesting or thinning activities, the resultant presence of firs in sequoia stands may be responsible for transmitting the fungus to the sequoia via root contacts (Piirto and others 1992). Normally, periodic fires would minimize the true fir component in these stands, thereby reducing the risk of transmission of *H. annosum.*

LONGLEAF PINE, FIRE, AND ROOT DISEASE

Leptographium spp. and *Heterobasidion annosum*

Longleaf pine (*Pinus palustris* Mill.) once occupied over 30 million hectares throughout the Southern United States. At present, only about 5 percent of the original longleaf pine sites are occupied by this species. Changes in land use such as agriculture, commercial development, and conversion to other forest species such as loblolly pine (*P. taeda* L.) and slash pine (*P. elliottii* Engelm.) have contributed to the dramatic decrease in the range of longleaf pine.

Fire is an essential component of longleaf pine ecosystems, being necessary for the establishment of reproduction and for maintaining stand health. This tree species co-evolved with fire as an essential component of its life cycle. Over the past several years, increased mortality has been reported to occur in certain stands, and this mortality appears to be associated with prescribed burning (Otrosina and others 1995). A preliminary research study conducted on a 40-year-old longleaf pine stand at the Savannah River Site in New Ellenton, SC, revealed that burned plots had three times greater mortality 1 year post-burning than unburned check plots. Histological observations on fine roots (<2 mm in diameter) of longleaf pine obtained from the upper few centimeters of soil in the relatively cool burns have shown internal tissue damage when compared to roots from unburned check plots (Otrosina and others 1995). Also, twofold to threefold differences in isolation frequency of the root pathogens *H. annosum* and *Leptographium* species were associated with roots of mortality trees (Otrosina and Ferrell 1995). A recent follow-up study on these plots 3 years post-burn revealed a still higher isolation frequency of *Leptographium* species as compared to check plots (fig. *1). H. annosum* also was isolated in higher frequency in burn plots 3 years post-treatment, although at a lower frequency than 1 year after burning (fig. 1).

The association of *Leptographium* species with fire and mortality is significant because this fungal genus contains many forest tree root pathogenic species which have varying degrees of pathogenicity toward pine species (Harrington and Cobb 1988, Nevill and others 1995). Many

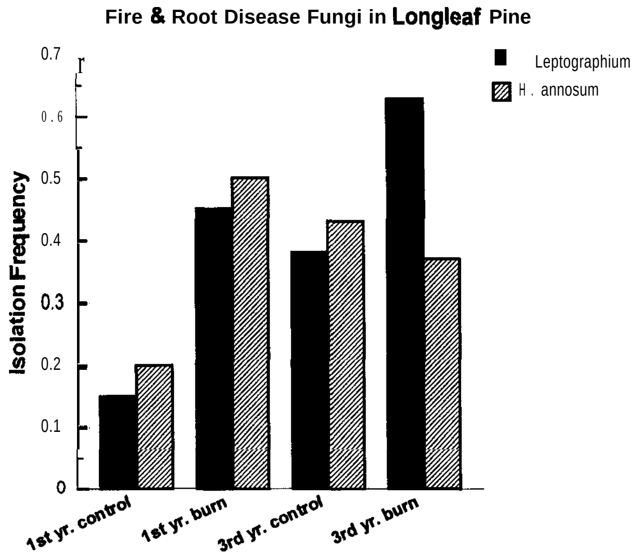

Figure l-Isolation frequency of *Heterobasidion annosum* and *Lepfographium* species in 40-year-old longleaf pine. Data were taken 1 and 3 years after burning in prescribed burned and unburned research plots at the Savannah River Site, New Ellenton, SC.

Leptographium species are also associated with various species of root-feeding bark beetles which can serve as vectors or as wounding agents that allow introduction of root pathogenic fungi (Harrington and Cobb 1988). Observations of insects in larger woody roots of post-fire longleaf pine have been documented (Otrosina and others 1995) but their roles with respect to these fungi and longleaf pine mortality have not been established.

Regarding these associations with fire, fungi, and insects in longleaf pine, obvious questions arise. Why, in a tree species that is adapted to and has evolved with fire, are we observing root pathogens and associated mortality in such high frequency? What are the roles of these various fungal species and insects in relation to the observed longleaf pine mortality? Longleaf pine has been regarded as either tolerant or resistant to root disease (Hodges 1969) and prescribed fire has been reported to decrease incidence of annosum root disease in southern pines (Froelich and others 1978).

Observations based upon windthrown trees suggest that on some sites, severe erosion of up to 2 feet of top soil may have severely restricted longleaf pine root systems to the upper 60 to 70 cm of soil profile (Otrosina unpublished data). Longleaf pine has evolved in deep sands and develops an extensive tap root system in these soils. Thus, although regenerated within physiographically correct sites, longleaf pine on eroded soils are forced into a new ecosystem structure, an exotic ecosystem, with respect to current soil conditions. These conditions, in turn, may produce unstable and unpredictable outcomes when standard management practices are employed. Precisely what relationships exist between fire, mortality, root disease fungi, and soil conditions form the basis for now ongoing research.

IMPLICATIONS

There are many more examples in forest pathology and entomology where man has unknowingly created certain conditions whereby native organisms, both fungal pathogens and insects, have become serious problems threatening forest sustainability (Goheen and Otrosina 1997, Otrosina and Ferrell 1995). The activities of man have rapidly and dramatically changed landscapes and ecosystems over a short period of time. The adaptations developed over eons of evolutionary time in forest tree species may no longer serve these species when forced into sometimes radically "new" ecosystem structures. These new structures are characterized by interactions not experienced by the tree species in an evolutionary sense, resulting in an unpredictable and unstable or chaotic system (Moir and Mowrer 1995) susceptible to various and unexpected disease problems. The exotic ecosystem concept put forth here is a new viewpoint on subjects contemplated by forest pathologists, entomologists, and silvicutturists, encompassing well-known abstractions such as predisposing factors, stress, disturbance regimes, and sustainability.

Some viewpoints regarding endemic forest tree root diseases embrace the idea that because these disease causing fungi are endemic to forest ecosystems, they perform beneficial functions among which are creating gaps in forest canopies, decomposing woody debris, or producing cavities for wildlife. These views assert, depending upon management objectives, that root diseases may or may not be detrimental. Such a notion presumes their function and regulatory dynamics are the same at present as they were prior to various management activities. Nevertheless, attention must be granted to the issue that some ecosystems may now be comprised of tree species that are maladapted to current conditions, resulting in varying degrees of instability.

For example, after years of successful wildfire suppression and politically motivated resistance to use of prescribed burning as a silvicultural tool, many forest stands whose natural history involved periodic burning now have large accumulations of litter and fuel. The recent focus on forest health issues acknowledges the importance of fire in many forest ecosystems and are recommending reintroduction of fire to these stands. Forest stands in these situations should be regarded as exotic ecosystems with the appropriate caution exercised. The new set of initial conditions may bring about unexpected forest health problems when fire is reintroduced in many stands. On the other hand, many forest ecosystems are quite resilient and stable under various management regimes; however, it is imperative that we strive to understand disease processes resulting from these new sets of conditions in order to identify the ecosystems and related conditions under which instability and unpredictability develop.

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FIRST STEPS IN DEVELOPING JABBERWOCKY: A THREE-DIMENSIONAL, BIOLOGICALLY BASED INDIVIDUAL TREE MODEL FOR LONGLEAF PINE

Rick Smith and Greg L. Somers'

Abstract-A three-dimensional, biologically based model for longleaf pine is being developed for natural resource managers at Eglin Air Force Base. The model has two purposes. It will provide "traditional" growth and yield functionality for defining management of existing longleaf stands. What is more important is it will serve as a simulator to aid managers at Eglin in defining preferable ecosystem management strategies and developing a sustainable ecosystem.

We present the general structure by the model to provide an understanding of how the biological basis and spatial detail of the model will provide the functionality required by a forest ecosystem simulator. The primaty components of the system are tree, climate, solar radiation, and soil. We will spatially model all components of the tree, that is, crown, roots, bole. Three integrated geometric models are being used to facilitate the calculation of resource availability and growth.

We describe the data and the measurement methods being used to collect the wide range of variables necessary for the spatial detail required by this model.

INTRODUCTION

Ecosystem management has restructured public land managers' thinking on forest land management. The shift in emphasis from single-rotation monoculture management to ecosystem management has found both forest land managers and researchers lacking in knowledge, tools, and training. As we move to ecosystem management the modeling of a wide range of spatial and temporal scales is necessary. The processes that compose an ecosystem range from physiological processes operating in milliseconds to forest succession covering hundreds of years. The spatial and temporal resolution of existing models is limiting. Most existing models use multiyear measurements until harvest for development. The unit in these models is the stand. Size-class distributions represent the trees in the stand. A tree's size-class predicts its other characteristics. Existing longleaf pine models do not provide the juxtaposition of individuals in the stand or other detailed spatial information. Ecosystem management requires predictions of processes other than just tree growth. These "other" processes demand more spatial detail than is possible in a stand model. Similarly, the single-rotation multiyear temporal scale of existing models will not allow the modeling of physiological or successional processes due to the differing scales of time.

The demands of ecosystem management of longleaf pine stands require a model to provide management guidelines and integrate a wide range of research. It is imperative that the resulting model be able to integrate a large body of present and future independent research for the evaluation of management practices and how they alter the ecosystem.

Unquestionably, a system as complex as an ecosystem will never allow the development of a model that can incorporate all agents and processes. This is impossible because future research and changing environmental conditions will constantly change our understanding of the processes and agents that compose an ecosystem. In response to this problem, model development methods are being used that will allow the model to evolve. Appropriate model development methods will allow the model to grow with ecosystem management research. It is with these considerations, problems, and goals in mind that the Jabberwocky model is being developed.

BACKGROUND

A great deal of thought and energy has gone into the design of Jabberwocky. To understand the reasoning leading to the form of the model we must understand the problems being addressed. We divide these problems into biological, data, and design considerations.

Biological Considerations

One goal of this research is to develop a model that is applicable to any stand structure, for example, even-aged, uneven-aged, shelterwood, thinned, etc. This goal is the primary reason for taking an individual tree approach. The basis of the model is the individual tree because a tree is an autonomous biological unit with clearly defined components. A stand is the result of the interactions of the individuals. If we can accurately model the interactions of one tree on another then it is possible to develop a model that is applicable to any stand structure. This is the biggest challenge being addressed in the development of this model. The accurate modeling of competition requires a great deal of spatial information. Thus, Jabberwocky must be a three-dimensional, individual-tree model.

The long-term goal of Jabberwocky evolving to an ecosystem model requires the model to be compatible with data sources covering a wide range of spatial and temporal scales. The spatial models being developed will provide the ability to model a wide range of processes without redeveloping the model, but rather by adding functionality.

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Another goal of this project is to develop a model that is usable throughout the natural range of longleaf pine. If there is to be any hope of achieving this goal, Jabberwocky must incorporate the environmental factors of growth and the biological bases of stand dynamics. The existing models of longleaf pine stands are predominantly empirical in their form. They are very precise predictors. However, they tend to be poor performers in regions where the model is uncalibrated. We believe we can make reliable extrapolations by using biological drivers.

Data Considerations

The model is being developed in the next 5 years for the managers at Eglin Air Force Base. This eliminates the use of fixed-area plots. The slow growth rates in the sandhills require a minimum 5-year remeasurement period. Stem analysis is being used to rapidly collect bole and branch growth data for the last 5 years for trees scattered throughout the base. The need for detailed crown architecture data also requires that destructive methods be used to map the crown in detail. While using destructive measurements for model development, we require fixed-area plot data for validation and evaluation of the model. As mentioned, one goal is to develop a model for use throughout the natural range of longleaf pine. The destructive measurement of individual trees is an efficient method for collecting data across the range of conditions on Eglin. These methods also provide an efficient approach for collecting data across the natural range of longleaf pine.

Design Considerations

The limited capabilities of humans to understand complex systems also limit ecosystem models. The complexity of an ecosystem is one, if not several, orders of magnitude greater than anything expressed in existing longleaf pine models. We must understand complexity and use its attributes to our advantage to be successful in modeling an ecosystem. Software engineers have devoted much time and energy to developing an understanding of complex system methods that improve the development process of large software systems. The result is a list of attributes that all complex systems share (Booch 1994). These attributes are:

(1) A complex system is hierarchical in form-"Frequently, complexity takes the form of a hierarchy, whereby a complex system is composed of interrelated subsystems that have in turn their own subsystems, and so on, until some lowest level of elementary components is reached" (Courtois 1985).

We can decompose a complex system into a hierarchy that will allow us to define the basic components of a system and more easily examine the system and its structure.

(2) A system's primitive components are arbitrary and up to the observer-"The choice of what components in a system are primitive is relatively arbitrary and is largely up to the discretion of the observer of the system. What is primitive to one observer may be at a much higher level of abstraction for another" (Booch 1994).

The decomposition of a system strictly depends on the needs and interests of the person analyzing the system. There are no absolutes defining the components a model should contain.

(3) Intracomponent linkages are stronger than intercomponent-"Intracomponent linkages are generally stronger than intercomponent linkages. This fact has the effect of separating the high frequency dynamics of the components-involving the internal structure of the components-from the low-frequency dynamics-involving interaction among components" (Simon 1982).

The difficulty with analyzing complex systems is the difficulty people have with simultaneously considering a large number of processes. If we can isolate a subsystem and analyze it without having to consider the influence of other subsystems on it, we can focus more clearly on the subsystem being studied.

(4) Hierarchic systems contain a few different kinds of subsystems-"In other words, complex systems have common patterns. These patterns may involve the reuse of small components, such as cells found in both plants and animals, or of larger structures, such as vascular systems, also found both in plants and animals" (Booch 1994).

These common patterns allow us to reuse portions of a model to expand. We do not have to "recreate the wheel." It is only necessary for the person analyzing the system to realize the commonality of the patterns in the system.

(5) Stable complex systems evolve from simple systems—"A complex system that works is invariably found to have evolved from a simple system that worked. A complex system designed from scratch never works and cannot be patched up to make it work. You have to start over, beginning with a working simple system" (Gall 1986).

It is important that the ecosystem model be developed in increments. It must start as a simple model and slowly, through incremental development, gain the complexity required to model an ecosystem.

An object-oriented modeling approach makes the attributes of a complex system an advantage instead of a difficulty. The Jabberwocky model is being developed through object-oriented analysis, design, and programming.

A biologically based ecosystem model establishes exacting spatial and temporal requirements. The processes that take place within an ecosystem operate at very different time scales from milliseconds to millennia. Using longleaf pine trees as the focus, we can represent most processes on an annual basis without loss of information. However, the development of a complete longleaf ecosystem model is contingent on the ability of the model to be able to run at both small and large time increments. The model must be flexible enough to incorporate predictors of instantaneous processes (photosynthesis, light availability); daily or within-day processes (water transport, diurnal cycles of gas exchange); yearly, growing season and within-growing-Season processes (understory growth, carbon allocation, seed production). Operating a model annually for the period required provides multiyear projections. The model must have a minimum temporal resolution of yearly increments, but it must also have a spatial structure that Will allow the modeling of within-year processes. The ability of the model to run on annual increments does not require high spatial resolution. However, within-season processes can require high spatial resolution. The spatial resolution of a model must be proportional to the temporal resolution. No one spatial model can accommodate all these processes. We are developing Jabberwocky using several integrated geometric models to provide the spatial and temporal flexibility necessary.

Existing Models

The Tree and Stand Simulator (TASS) family of models (Mitchell 1975, Goudie 1980) is the basis of Jabberwocky. The three-dimensional crown dynamics, bole growth, and biological representations in TASS provide a solid basis for model development. TASS has many deficiencies for ecosystem modeling. We will adapt and extend the approaches used in TASS. First, the incorporation of light-transmittance and light-extinction models is necessary for modeling shading and its influence on growth for all plants. Second, the TASS model uses site index as a basis for site productivity. The use of site index severely limits the geographical range and the types of stands that the model covers. Jabberwocky is being developed using soil and weather variables to alter the growth trajectories instead of site index, due to this limitation. TASS models stands for a single rotation and does not include a regeneration component. Jabberwocky will contain a regeneration component to allow it to represent naturally regenerated stands.

We will avoid the extensive modeling of root systems. This is due to the lack of available information and the high cost associated with this area of research. Basic models of root structure are being developed from very simple measures of lateral and tap roots. The purpose of this area of research will be to define the edaphic resources available rather than the modeling of structural root dynamics.

The initial model will contain only longleaf pine. We will add other ecosystem components, such as other tree species and understory species, through cooperative modeling efforts with ongoing and planned longleaf research by other investigators at Eglin Air Force Base.

GENERAL DESCRIPTION OF RESEARCH

Crown Architecture, Dynamics, and Modeling

Three spatial models will facilitate modeling of stand, tree, and within-crown processes. A voxel (three-dimensional matrix) model will represent the canopy. Its primary purpose will be to facilitate light environment calculations at the canopy level. A crown model will represent the exterior shape of the crown adjusted for competition and crown contact. This model will model the variables of greatest interest to most foresters such as height growth and diameter growth throughout the bole. Finally, an "explicit" Spatial model will pseudo-realistically model all the features of the tree including bole, branches, foliage, and roots. It Will facilitate the modeling of within-crown processes that require a high spatial resolution. The explicit model and the crown model will be compatible. This means the branch tips of the explicit model will be on the hull of the crown model. All the geometric models will share information.

Foliar Dynamics and Distribution

An objective of this research is to develop a three-dimensional leaf area distribution for longleaf pine trees. Many authors have used foliar distributions based on either leaf area or mass for a variety of species (Kinerson and others 1974, Waring and others 1981, Hagihara and Hozumi 1986, Remphrey and Powell 1988). The canopy foliar distribution developed by Kinerson and others (1974) for loblolly pine was based on a vertical negative exponential function. Hagihara and Hozumi (1986) used a vertical Weibull distribution to model the foliar distribution of *Chamaecyparis obtusa* (Sieb. and Zucc) Endi. These continuous distributions provide a means to model foliar distribution at the stand or canopy level but have little utility for individual trees. Models of a tree's foliar distribution are usually geometric distributions. Mitchell (1975) modeled the distribution of foliage by age by dividing the crown into concentric shells. Goudie (1980) also used this technique. Grace and others (1987) used concentric shells to model foliar distribution as well, but the shells related to photosynthetic capacity. Research will focus on merging these approaches to develop a foliar distribution that will allow a parsimonious, but sufficient, representation of foliage within the crown of a tree.

To understand the relationship between foliage and growth throughout a tree we must understand more than the simple physical properties of foliage. We must know the photosynthetic capacity of the foliage. The measurements of foliage include its spatial distribution and maximum photosynthetic capacity (P_{max}). Authors have found a high correlation of specific leaf nitrogen with photosynthetic capacity in a variety of crops, shrubs, and trees (Field and Mooney 1983, Charles-Edwards and others 1987, Hinckley and others 1992). Research is being conducted on the relationship between foliar nitrogen and its location in the crown. We will develop a refined foliar distribution that will represent not only the leaf area of the tree but also the contribution of foliage at a given location to growth.

Wood Growth, Sapwood, and Distribution

The proportion of respiration to photosynthate production defines the carbon budget and the resulting growth, and possibly death, of a tree. The major consideration of living tissue in a tree is in the foliage and surface of the bole and branches. McMurtrie and Wolf (1983) and West (1987) developed catabolic-anabolic relationships for modeling stand and individual tree biomass dynamics. Whitaker and Woodwell (1967) established the ratio of leaf area to bark surface area as a growth limiting factor. Westman (1987) used procedures modified from Whitaker and Woodwell to compare the net productivity of red fir (*Abies magnifica* A. Murr.) and white fir [*A. concolor* (Gord. and Glend.) Lindl.]. Keane and Weetman (1987) also concluded the ratio of leaf surface area to wood surface area played an important role in the net productivity for different stocking levels of lodgepole pine (*Pinus contorta* Dougl. ex. Loud). Woody surface area distributions and growth relationships in combination with foliage are critical components for developing a spatially explicit, biologically based, individual-tree model. Similarly, we will model growth on the bole using the branch and leaf area distributions.

There are two reasons to model the relationship of sapwood basal area to leaf area throughout the bole. The first reason is to provide a means to predict the leaf area and increase the sample size for bole growth measurements at minimal effort. Second, it will allow us to incorporate the pipe model as a mechanism to influence and control growth. Shinozaki and others (1964a, 1964b) published the original version of the Pipe Model. Simply stated, there is a proportional amount of unit thickness pipes to each unit of leaves. This theory provides an easy method for estimating leaf surface area (Waring and others 1981, Blanche and others 1985). Image analysis is being used to measure sapwood basal area on the sample discs. An evaluation is underway to define which methods are the most reliable and consistent for sapwood area measurement. Leaf area is being measured by systematically sampling age cohorts of foliage throughout the crown. Measures of conductance along the bole will be taken in the future to calibrate the pipe model component of the model.

Destructive Sampling Methods

The destructive sampling methodology used by Mitchell (1969, 1975) and Goudie (1980) is the basis for collecting the data for the longleaf model. Their field methods provide a launching point for this study. We collect diameter growth data along the bole by stem analysis. To obtain detailed crown architecture information, we remove branches from the crown while the tree is standing. We tag the branches before removal to allow repositioning on the bole for mapping. We next cut and lower the branches to the ground. Branch removal continues to a bole diameter of approximately 4 inches. We next top the tree and lower the top to the ground. Finally, we fell the tree and cut it into sections. To measure the architecture, we place the sections in their original orientation on the ground. Then we clamp the branches back on the bole. We reconstruct the growth history of each branch by three-dimensional mapping. The methods of Maguire and Hann (1987) and Kershaw and others (1990) are being used to determine branch mortality. This is required to provide the data necessary to model the change in the base of the live crown due to competition (crown rise), and to estimate the leaf area of the crown in the past, which is used for developing growth equations. We weigh all the tree components. We remove discs at 1 -meter intervals along the bole and on a subsample of branches. We measure the discs of ring area, sapwood basal area, and conductance. We measure annual rings and sapwood by image analysis.

Light Environment

We will incorporate light measurements in later stages of the study. We will collect light measurements by a combination of hemispherical photographs and photoelectric diodes. A double sampling and subsampling with these tools will provide light environment measurements within and below tree crowns. A hemispherical photograph analysis system and methods developed by Smith and Somers (1993) provide a method to take and interpret the hemispherical photographs. We will use light data in combination with the foliar and wood distribution to define how the foliage and branches influence the light environment and vice versa.

Weather and Soils

National Oceanic and Atmospheric Administration data and any local weather data will drive the model. We measure the soils at all study locations. The soil is analyzed for both physical and nutrient properties. The relationship of the physical properties of the soil to growth is of great importance because of the greater ease of measurement. This will help ensure the model's utility over a wide range of sites. We will not include soil dynamics over time in the model initially, due to its complexity.

Model Analysis and Specification

We must consider the long-term expansion of the model to an ecosystem in its development. We are using a formal method to provide a specification of the system. This is the first step in a formal process to guarantee the development and continued utility of the model as it evolves to an ecosystem model.

Software engineering is the development of a software system by teams using sound engineering principles and techniques to produce a correct, reliable, and maintainable product by a proven method (Somerville 1992). Problems in the development of a large software system parallel the problems encountered in the development of an ecosystem model. The development of an ecosystem model will require a team effort by researchers using scientific principles and techniques to produce a correct and reliable understanding of ecosystem processes. However, there is nothing inherent in the scientific method that guarantees the maintainability of the resulting model. There is not a proven method to use for such a comprehensive task. Software engineering provides a process that can help guide the development process and aid in all stages of model development. This development process is the software lifecycle or waterfall model. This process is being adapted to the needs of ecosystem model development (fig. 1).

The phases of the waterfall model are analysis, design, implementation, maintenance, and testing. The waterfall model does not allow for incremental development. The development process is over once the software system is implemented and the system is being maintained. Thus, the original waterfall model includes only those paths along the waterfall (fig. 1). We add a path from maintenance to analysis to allow incremental development and a simulation phase. The simulation phase is necessary to help in

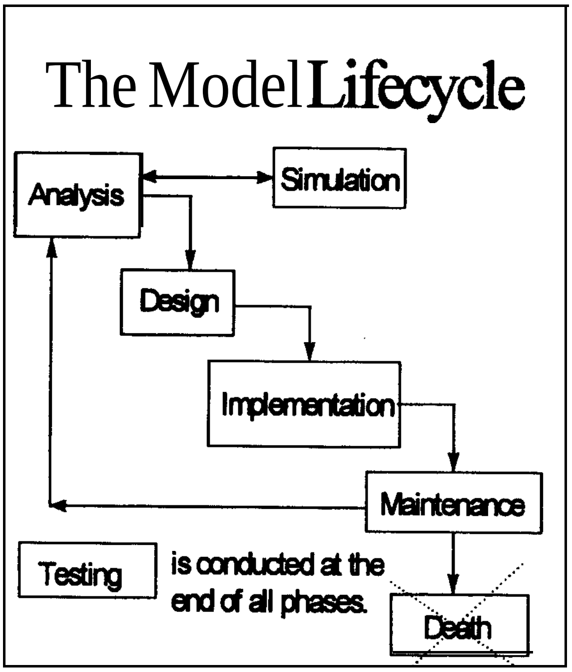

Figure I-The incremental model.

defining the requirements and to provide guidance for future research. The purpose of the analysis phase is to define the requirements of a system in detail through text and diagrams. The diagrams represent the processes in the model, the objects in the model, and the flow of information between them. Decomposing an ecosystem by focusing on the objects that form it is object-oriented analysis. Object-oriented modeling is being used to develop the model because it takes advantage of the attributes of complexity described earlier. It lends itself more naturally to a hierarchical decomposition that will allow us to isolate and focus on ecosystem components independent of the influence of other components. The incremental development process works by modifying and reusing objects for model expansion.

The Fusion method (Coleman and others 1994) is being used for object-oriented model development. We selected Fusion from many possible object-oriented methods due to its complete approach, from analysis to maintenance and redevelopment, and its clear demarcation of phases of development. The first phase of the Fusion method is the development of the object model, lifecycle model, and operational model to represent the object-oriented decomposition of the system.

DISCUSSION AND CONCLUSIONS

The research to collect the data necessary for the development of Jabberwocky is off to a healthy and fruitful start. The data collection phase will continue for the next 3 years to obtain a minimum of 120 trees. Future areas of data collection are light, roots, and sapwood conductance. While the general form of the model and the functionality it must provide are clear, there is a great deal of work to be done on its design and implementation.

The current focus of this research is on developing a model for Eglin Air Force Base. The long-term goal is the development of a system for the natural range of longleaf pine to model not only the stand, but the entire ecosystem.

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THIRTY YEARS OLD-THE REGIONAL LONGLEAF PINE GROWTH STUDY

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Abstract-From 1964 to 1967, the USDA Forest Service established the Regional Longleaf Pine Growth Study in the Gulf States. The original objective was to obtain a database for the development of growth and yield predictions for naturally regenerated, even-aged longleaf pine (*Pinus palustris* Mill.) stands. Initially, 185 plots were installed to cover a range of ages, densities, and site qualities. Plots are remeasured on roughly a 5-year cycle. A total of 305 plots are now in the study They are located in central and southern Alabama, southern Mississippi, southwest Georgia, northern Florida, and the sandhills of North Carolina. Within this distribution are four time replications of the youngest age class that have been installed to detect growth changes over time. All four time replications are located on the Escambia Experimental Forest in Brewton, AL. The original study has been expanded to include the development of taper equations, site index curves, pole prediction models, and pine straw production models. As part of the Southern Global Change Project, the Regional Longleaf Pine Growth Study plots and database were used to examine the impacts of climate (precipitation and atmospheric temperature) on longleaf pine productivity in relation to stand age, site quality, and stand density. As a part of this project, studies related to longleaf pine needle fall, specific leaf area, and projected leaf area were conducted. Studies were also conducted to determine the stability of parameters in growth models over time and the inclusion of weather variables in growth models. The Regional Longleaf Pine Growth Study project represents a stable long-term data base and an active "field laboratory" for natural, even-aged, longleaf pine stands. The value of this project increases as more and more ownerships in the South consider longleaf pine management alternatives. Public and private land managers are seeking a range of ecological and economic outcomes related to the restoration, rehabilitation, and regeneration of longleaf pine.

INTRODUCTION

In 1964, the USDA Forest Service established the Regional Longleaf Pine Growth Study (RLGS) in the Gulf States. The original objective of the study was to obtain a database for the development of growth and yield predictions for naturally regenerated, even-aged longleaf pine (*Pinus palustris* Mill.) stands. Plots were installed to cover a range of ages, densities, and site qualities. The study accounts for possible growth change over time by adding a new set of plots in the youngest age class every 10 years. The project is in its sixth measurement period (30-year measurement). Research utilizing this existing longleaf pine database has been expanded to include utility pole and pine litter production.

METHODS

The study consists of 305 permanent l/l 0- and 1/5-acre measurement plots located in central and southern Alabama, southern Mississippi, southwest Georgia, northern Florida, and the sandhills of North Carolina. Plot selection was based upon a rectangular distribution of cells formed by four stand-age classes ranging from 20 to 80 years, five site-index classes ranging from 50 to 90 feet at 50 years, and five density classes ranging from 30 to 150 square feet per acre. The oldest plots will be in the 120-year age class with the completion of the current 30-year remeasurement.

Within this distribution are four time replications of the youngest age class. All four replications are located on the Escambia Experimental Forest in Brewton, AL. As a part of the RLGS, plots in the youngest age class were first established in 1964 and new sets of plots have been added in this age class every 10 years. Plots are located to achieve similar initial site qualities and ages, and are thinned to their target basal areas.

At the time of establishment, plots are assigned a target basal area class of 30, 60, 90, 120, or 150 square feet per acre. They are left unthinned to grow into that class if they are initially below the target basal area. In subsequent remeasurements, the plot is thinned back to the previously assigned target if the plot basal area has grown 7.5 square feet per acre or more beyond the target basal area. The thinnings are generally of low intensity and are done from below.

Net (measurement) plots are circular and IA-acre (14 net plots are l/l O-acre) in size surrounded by a similar and like-treated half-chain wide isolation strip, with both surrounded by a half-chain wide protective buffer strip that receives extensive management. Plots are inventoried, and treated as needed, every 5 years. The measurements are made during the dormant season (October through March) and it takes 3 years to complete a full remeasurement of all plots. Cooperators are asked to use cool, winter burns on a 3-year cycle to control hardwood competition.

Each tree on the net plot with a d.b.h. >0.5 inches is numbered by progressive azimuth from magnetic north and has its azimuth and distance from plot center recorded. At every remeasurement, each tree has its d.b.h. recorded to the nearest 0.1 inch, and its crown class and utility pole class and length determined. A systematic subsample of trees from each l-inch d.b.h. class has been permanently selected and measured for height to the live-crown base, total height, and, if the tree is dominant or co-dominant, for age from seed.

Associated Studies

The RLGS represents a stable, long-term database and an active "field laboratory" for natural, even-aged, longleaf pine

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stands. The value of this project increases as more and more ownerships in the South consider longleaf pine management alternatives. Public and private land managers are seeking a range of ecological and economic outcomes related to the restoration, rehabilitation, and regeneration of longleaf pine. The plots are also available for cooperative studies that would not harm the plots or interfere with future activities. An example is our USDA Forest Service Southern Global Change Program (SGCP)/RLGS project (which is nearing completion). This study was undertaken to examine the productivity of natural stands of longleaf pine in relation to competition and climatic factors.

Using the existing RLGS plots and database, the project is investigating the relationship between productivity (biomass) of natural stands of longleaf pine in relation to stand age, site quality, stand density (competition), and the climatic factors of precipitation and atmospheric temperature. A major component of the SGCP project was to examine longleaf pine litter (pine straw) production. Needle fall has been monitored monthly since August 1992 via litter traps on a representative subsample of plots across the range of site, age, and density combinations. Efforts are underway to model annual litter production (tons per acre, dry weight) as a function of stand variables. The results from the various components of the project will be published as individual manuscripts.

Other studies directly associated with the RLGS sites include: (1) soil samples have been taken on the RLGS plots to provide baseline data and to improve estimates of site productivity; (2) utility pole information is being used to develop relationships between stand characteristics, thinning activities, and pole production; (3) efforts are being completed to improve estimates of longleaf pine taper equations by including crown ratio as an independent variable; (4) data are being examined in an effort to improve the estimates of site index for naturally regenerated longleaf pine stands; (5) basal area and mortality models are being developed to improve the predictions of stand dynamics; (6) prescribed burning history has been added to the database; (7) old-growth stands are being identified and measured to improve estimates of growth and mortality for longer rotations and to assess the stability of old-growth stands; and (8) economic projections are being developed.

RESULTS

The 30-year remeasurement is nearing completion. Efforts continue to examine longleaf pine litter (pine straw) production, which was a major component of the SGCP; and utility pole production, which was an addition to the 25-year measurement cycle.

Over the course of the RLGS, several stand and individual tree-level models have been developed to provide data to evaluate management alternatives. Individuals interested in predicting stand growth and mortality are directed to the works of Farrar (1979, 1985), Somers and Farrar (1991), Farrar and Matney (1994), and Quicke and others (1994 and in press). Work will continue to incorporate new data and refine growth relationships as new models are developed.

Through the 25-year remeasurement, there are 28 publications and numerous presentations that are a direct result of the RLGS. Another 14 related publications use information from the RLGS. (The Appendix provides a listing of these.)

CONCLUSION

The RLGS has adapted to changes in the resource base and shifting public concerns over the last 30 years. The initial installation in the mid-60's resulted in 185 sample plots. This number increased to 267 in 1986 and is now at 305. As the number of plots have grown and in response to changing questions, the objectives of the RLGS have expanded. It is no longer meaningful to have growth projection models estimate only to stand-level merchantable basal area and total volumes in pulp and saw timber. Users are demanding more information on multiple products, and want trees per acre and merchantable volume by d.b.h. classes, to answer their current questions. The RLGS is keeping pace with ever-changing demands and is proving once again that well designed, long-term studies are wise research investments.

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HARVESTING LONGLEAF PINE STRAW ON THE KISATCHIE NATIONAL FOREST, LOUISIANA

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Poster Summary

INTRODUCTION

Pine needles (straw) have long been gathered for mulch in the Southern United States. Harvesting of pine straw can substantially increase profits from management of small forest holdings. However, repeated removal of pine straw from the forest floor may reduce timber yields. Since timber prices are high and expected to remain so for several years, management should ensure good timber growth. The objective of this study was to determine how pine straw harvesting practices influence longleaf pine (*Pinus palustris* Mill.) productivity, nutrition, and needle cast.

PROCEDURES

The 40-ha study site is on gently rolling ground in Rapides Parish, LA. Soils are Ruston and Smithdale (Typic Paleudults) sandy loams. The longleaf pine stands on the site originated from direct seeding in 1956. From the time of seeding, the site was prescribed burned triennially as part of a range management program. Burning retarded development of woody vegetation in the understory.

We installed a randomized, complete block, split-plot design with four blocks as replicates in the spring and early summer of 1990 (Haywood and others 1995). The two main-plot treatments within each block were: (1) no fertilizer applied and (2) 50 kilograms per hectare (kg per ha) nitrogen (N) and 56 kg per ha phosphorus (P) broadcast evenly over the entire main plot on April 23, 1991, as 280 kg per ha diammonium phosphate fertilizer (DAP). Management of the subplots for pine straw includes: (1) check-no treatment after 1990; (2) burned only-the subplots were burned with strip headfires in March 1991 and February 1994; (3) burned and two straw harvests-in addition to receiving treatment 2, the subplots were rotary mowed and the straw was harvested in early 1992 and 1993; and (4) burned and four straw harvests-the subplots were thinned and mowed in 1990, burned in August 1991, and rotary mowed and harvested annually in early 1992 through early 1995. When straw was to be harvested it was first collected in windrows with a tractor-mounted straight-bar rake and then baled mechanically. The bales were weighed and samples were taken so that moisture content and dry matter production could be determined (Haywood and others 1995).

In January 1991 and 1996, d.b.h. and tree height of longleaf pines over 10 centimeters (cm) in d.b.h. were measured, and the inside-bark volume per ha (i.b. per ha) was calculated (Haywood and others 1995). Litter traps were used for the monthly collection of needle-fall samples. Nutrient analyses were done on randomly collected samples of soil to a depth of 15 cm and living on needles from the upper crowns of dominant longleaf pine trees. Bulk density samples of the mineral soil were randomly taken to a depth of 10 cm. A rainfall simulator was used to determine infiltration and runoff water quality for a 0.4 meter-square (m^2) subplot. Treatment-to-treatment differences in longleaf pine or soil properties were subjected to appropriate statistical analysis.

NEEDLE FALL AND STRAW HARVEST

From 1991 through 1995, 18 percent of the longleaf pine straw consistently fell from January through July (720 kg per ha), and total annual needle fall averaged 4,040 kg per ha. There were no statistically significant treatment-to-treatment differences in average total yearly needle fall. Actual yields of harvested pine straw did not decline with management.

SOIL PROPERTIES

In July 1994, bulk density was significantly greater for the burned-and-two-straw-harvests [1.39 grams per cubic centimeter [g per cm^3)] than for the check (1.33 g per cm^3) or burned-only treatment (1.34 g per cm^3). Bulk density after three harvests (1.44 g per cm^3) was significantly greater than bulk density after two harvests. Water infiltration was reduced by harvesting. It averaged 10.3 centimeters per hour (cm per h) on the no-harvest treatments, 6.4 cm per h after two harvests, and 5.5 cm per h after four harvests. Sediment loss, as an index of erosion, and sediment concentration were increased by harvesting. Sediment loss averaged 35 kg per ha and sediment concentration averaged 0.08 grams per liter (g per l) for the no-harvest treatments. After two harvests, sediment loss averaged 125 kg per ha and sediment concentration averaged 0.15 g per l. After four harvests,

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sediment loss averaged 360 kg per ha and sediment concentration averaged 0.39 g per l.

NUTRITION

The application of N and P increased available soil P concentration to 8.63 milligrams per kilogram (mg per kg), compared to a concentration of 2.56 mg per kg on the unfertilized plots. As a result, fertilization also significantly increased the concentration of P in the living needles. The concentration of P in the living needles was 700 mg per kg on the unfertilized plots and 890 mg per kg on the fertilized plots. Harvesting pine straw did not influence soil or foliar P concentrations. Foliar nitrogen concentrations were unaffected by fertilization.

LONGLEAF PINE YIELDS

On the unfertilized plots, 5-year pine growth with four straw harvests was almost 8 m^3 i.b. per ha less than 5-year pine growth with no harvesting of straw. However, 5-year pine growth with broadcast fertilization and four straw harvests was almost 2 m^3 i.b. per ha greater than 5-year pine growth for the fertilized-no-harvest treatments. The 39-year-old longleaf pines averaged 215 m^3 i.b. per ha of wood volume across all treatments. We believe that the continual harvesting of straw provided weed control, and the combination of fertilizer and weed control is known to increase pine productivity.

BEST MANAGEMENT PRACTICES

Recommended best management practices for lands where pine straw is harvested are to periodically fertilize with 150 to 200 kg per ha N and 56 kg per ha P, avoid soils with more than 10 percent slopes and streamside areas, and carefully mow and rake to expose less mineral soil. Our findings partly confirm these recommendations, and we support the use of these management practices. Pine straw harvesting lessens fire hazard, provides annual revenue, and if done properly can increase total farm income. Part of this extra income should be used to correct any site damage.

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RESTORATION OF NATIVE PLANT COMMUNITIES IN LONGLEAF PINE LANDSCAPES ON THE KISATCHIE NATIONAL FOREST, LOUISIANA

James D. Haywood, Alton Martin, Jr., Finis L. Harris, and Michael L. Elliott-Smith[1]

Poster Summary

INTRODUCTION

In January 1993, the Kisatchie National Forest and Southern Research Station began monitoring the effects of various management practices on overstory and midstory trees, shrubs, and understory woody and herbaceous vegetation in several longleaf pine (*Pinus palustris* Mill.) stands. The monitoring of these stands is part of several Ecosystem Management Projects. These projects address the effects of different seasons of burning, group selection cutting, removal of off-site pine species, and shelterwood management on forest vegetation. One of our goals is to identify common plants that are usually present in longleaf pine forests once the silviculturist's objectives are met.

SEASON-OF-BURNINGPROJECT

We are monitoring characteristics of vegetation in stands burned periodically in winter, spring, or summer to determine whether management activities are restoring old-growth attributes. On the Catahoula Ranger District (RD), the forests are on gently rolling uplands of Ruston and Smithdale (Typic Paleudults) sandy loams. On the Vernon RD, the forests are on gently rolling uplands of Malbis (Plinthic Paleudult) fine sandy loam. Hardwoods are more numerous on the Catahoula RD than on the Vernon RD. However, the overstories and midstories of the stands are dominated by longleaf pine with scattered loblolly pine (*P. taeda* L.), southern red oak (*Quercus falcata* Michx.), and sweetgum (*Liquidambar styraciflua* L.). Other species that may be present include flowering dogwood (*Cornus florida* L.), blackgum (*Nyssa sylvatica* Marsh.), blackjack oak (Q. *marilandica* Muenchh.), post oak (Q. *stellata* Wangenh.), black oak (Q. *velutina* Lam.), mockernut hickory [*Carya tomentosa* (Poir) Nutt.], sassafras [Sassafras *albidum* (Nutt.) Nees], and tree sparkleberry (*Vaccinium arboreum* Marsh.).

In the understory, woody plants and blackberry are kept in check by burning. Species present in significant numbers include southern red oak, flowering dogwood, blackberry (*Rubus* spp.), waxmyrtle (*Myrica cerifera* L.), blueberry (*Vaccinium* spp.), poison oak [*Toxicodendrom toxicarium* (Salisb.) Gillis], and grape (*Vitis* spp.). Pine seedlings cannot grow well in these stands because the overstory basal areas range from 98 to 124 square feet per acre (ft^2 per acre).

The herbaceous species present in greatest numbers are pinehill bluestem [*Schizachyrium scoparium* var. *divergens* (Hack.) Gould], low panicums (*Dichanthelium* spp.), grassleaf goldaster [*Heterotheca graminifolia* (Michx.) Shinners], swamp sunflower (*Helianthus angustifolius* L.), goldenrods (*Solidago* spp.), and bracken fern [*Pteridium aquilinum* var. *pseudocaudatum* (Clute) Heller].

GROUP SELECTION AND REMOVAL OF OFF-SITE PINE PROJECT

On five ranger districts, we are demonstrating that group selection and off-site pine removal can restore an uneven-aged structure to longleaf pine forests while sustaining habitat for threatened and endangered species and maintaining a diverse understory of herbaceous and woody plants. Conditions in these longleaf pine stands include a stand with a preexisting uneven-aged structure on the Evangeline RD, even-aged forest adjacent to savanna on the Kisatchie RD, and even-aged forest with a brushy understory on the Winn RD. An analogue of the uneven-aged longleaf pine forest type is the uneven-aged ponderosa pine (*P.* ponderosa Dougl. ex Laws.) forest type of the Western United States. In these forests, there are groups or clusters of trees of similar ages adjacent to other groups of another age class.

SHELTERWOODPROJECT

On the Catahoula RD, we are monitoring seed crops and understory vegetation in a longleaf pine shelterwood with reserves. This shelterwood is on a Ruston and Smithdale rolling upland and has 35 ft^2 of basal area per acre. It was retained for red-cockaded woodpecker (*Picoides borealis*) habitat. The most numerous species in the diverse understory are pinehill bluestem, fringe nutrush (*Scleria ciliata* Michx.), grassleaf goldaster, pencilflower [*Stylosanthes biflora* (L.) BSP.], Texas dutchmanspipe (*Aristolochia reticulate* Nutt.), and bracken fern.

INDICATORPLANTS

These monitoring efforts have led to interesting findings about herbaceous plant productivity and community health. Statistics from several sites that have been prescribed burned several times, but not within the last two growing seasons, are given in table 1. These results support several conclusions about herbaceous plant productivity: (1) herbage productivity in the pasture of native herbaceous vegetation is probably near the maximum for upland soils in central Louisiana without fertilization; (2) herbage yields decrease with increasing overstory basal

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Table I-Selected stand information relating overstory and understory woody plant density to herbaceous plant productivity

Stand description	Overstory basal area	Understory (pine seedlings not counted)	Current-year herbage production
	Ft²/acre	Stems/acre	Lbs/acre
Native pasture	none	6,900 (2.3 ft tall)	2,900
Shelterwood with reserves	35	9,900 (2.0 ft tall)	1,700
Longleaf forest	98	12,500 (0.5 ft tall)	1,500
Longleaf forest	106	65,200 (1.7 ft tall)	670

[a] Average height of understory stems, excluding pines.

area; and (3) once a pine overstory has reached full stocking, efforts to increase understory herbage production by rotary mowing or burning will have marginal success. If hardwood brush or a midstory is present, herbaceous productivity will decline even further.

Since herbaceous plant productivity does not necessarily respond to management treatment, how we determine whether a treatment affects the health of a herbaceous plant community should not be based solely on its productivity. Rather, the focus should be on species richness and species distribution. To this end, indicator plants can be used as barometers of herbaceous community health. Based on our work, indicators of a healthy understory in upland longleaf pine landscapes might include pinehill bluestem, swamp sunflower, and grassleaf goldaster. Indicator plants would help forest managers quickly recognize sites needing treatment and or those sites where no treatment is required so that managers could best allocate their resources. With limited training, forest personnel can recognize many plants year-round in the field. The use of pictures and computer images could help with identification.

Nutrient Dynamics

Moderator:

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FOLIAR NITROGEN AND PHOSPHOROUS DYNAMICS OF BLACK CHERRY AND RED MAPLE TREES GROWING IN GREAT SMOKY MOUNTAINS NATIONAL PARK

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Abstract—The overall goal of this investigation was to determine foliar nutrient dynamics (N and P) of black cherry and red maple trees growing at two locations differing in elevation, ozone, exposure, and other microsite and edaphic attributes within Great Smoky Mountains National Park. At the low elevation site, the two species both exhibited smaller amounts and proportions of leaf P remaining in abscised foliage (i.e., lower magnitude and efficiency) compared with the higher elevation site. Red maple was more efficient than black cherry regarding phosphorous (i.e., maple retains less P in abscised foliage) retranslocation. There are strong indications that translocation of mobile nutrients from senescing foliage is of greater magnitude and efficiency at the higher compared to the lower elevation site. These indications are strongest during the first year of sampling (1994) and are primarily associated with P, although some differences do occur for N as well. The tendency for greater differentiation to occur in terms of P translocation (both magnitude and efficiency) suggests that soil P availability is the primary nutritional distinction between the two elevations. It is likely that this cycling differential exists because the higher elevation soils have lower P availability compared to the lower elevation soils.

INTRODUCTION

Switzer and Nelson (1972) found that approximately 40 Percent and 60 percent of the annual requirements of N and P in loblolly pine (*Pinus taeda* L.) could be accounted for by internal nutrient cycling. Similar results have been reported for other plant species (Chapin and Kedrowski 1983, Killinbeck 1996). However, our understanding of this phenomenon and its subsequent effect on plant growth, nutrient cycling, and adaptation to environmental stresses remains very limited (Killinbeck 1996).

Nutrient resorption is dependent on many factors including site fertility, water, and light (Chapin and Moilanen 1991, Hocking 1982, Killinbeck 1996, Small 1972). In addition, internal nutrient cycling has been shown to be altered by environmental factors such as acid rain (Oren and Schulze 1989) and ozone (Wright and others 1991).

The overall goal of this investigation was to determine foliar nutrient dynamics (N and P) over a 2-year period (1994 through 1995), for black cherry (*Prunus serotina* Ehrh.) and red maple (*Acer rubrum* L.) growing at two locations differing in elevation, ozone exposure, and other microsite and edaphic attributes within Great Smoky Mountains National Park (GRSM).

Specific objectives include an estimation of N and P internal translocation associated with foliage of red maple and black cherry, and a comparison of the magnitude and efficiency of this translocation for both species between two sites that differ in elevation as well as other attributes (soil characteristics, aspect, slope, site history, etc.). The terms “magnitude or quantity” refer to the amount of an element (N or P) undergoing translocation on an individual leaf basis (NT or PT), while “efficiency” is defined relative to the proportion of summer foliar content of N or P that is removed prior to foliage senescence (NTC or PTC).

Findings from this study will provide supplemental data to the Tennessee Valley Authority for parameterization of a physiologically based process model (TREGRO) (Weinstein and Yanai 1994). Results will also give a linkage information gathered on the physiological responses of these selected trees from the two locations in GRSM (Samuelson and Kelly 1997).

METHODOLOGY

Location

The study was located at two sites differing in elevation within GRSM. Twin Creeks, a low elevation site [600 meters (m)] is located 2 kilometers (km) from Gatlinburg, TN. Cove Mountain is a high elevation site (1200 m) located approximately 15 km from Gatlinburg. Scaffolding (two towers per site) was constructed at each site to access the upper canopies of mature, dominant black cherry and red maple. Soils were a loamy-skeletal, siliceous, mesic Typic Hapludult at Twin Creeks and a loamy-skeletal, siliceous, mesic Typic Haplumbrept at Cove Mountain (Samuelson and Kelly 1997). For more detailed site descriptions, refer to Samuelson and Kelly (1997).

Data Collection

Leaves were collected within the crowns of trees in July (live) and November (senesced), 1994 and 1995. Leaves were collected in groups of five (one sample). Sample numbers varied by year, site, and species, depending on tree size and availability of leaf material (table 1). Black cherry samples were collected from two trees at Cove Mountain and three trees at Twin Creeks. Regarding red maple, samples were collected from one and two trees for 1994 and 1995, respectively, at Cove Mountain. At Twin Creeks, samples were collected from two and three trees in 1994 and 1995, respectively.

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Table l-The amount of P and N (mg per leaf) remaining in abscised foliage by species and location for 1994 and 1 995[a]

Year and species	Location[b]	N[c]	PT	N	NT
1994					
Red maple	TC	7	0.149 a	7	3.702 a
	CM	8	0.462 a	8	2.600 a
Black cherry	TC	12	0.055 a	14	1.866 a
	CM	9	0.310 b	11	2.388 a
Both species	TC	19	0.090 a	21	2.477 a
	CM	17	0.382 b	19	2.478 a
1995					
Red maple	TC	18	0.393 a	18	3.192 a[d]
	CM	11	0.649 b	11	4.221 b
Black cherry	TC	17	0.002 a	17	1.149 a
	CM	2	0.064 a	2	1.066 a
Both species	TC	35	0.203 a	35	2.200 a
	CM	13	0.559 b	13	3.736 b

[a] PT=mg per leaf of phosphorus, NT=mg per leaf of nitrogen; means in rows followed by the same letter are not significantly different ($p < 0.05$) according to t-tests.
[b] TC=Twin Creeks, CM=Cove Mountain.
[c] N=number of samples (5 lvs per sample).
[d] Significant at $p < 0.10$.

Laboratory Analysis

Before determination of N and P, leaves were dried to a constant weight (70 °C), ground to pass a 20-mesh sieve, then analyzed for total N and P. Reference samples were analyzed in duplicate (at least every 20 samples, ≥ 5 percent) to determine accuracy and precision.

Total N was determined by thermal conductivity (Sweeney and Rexrod 1987) using a Leco N Determinator (Model FP 228, Leco Corp., St. Joseph, MI) for 1994 samples. A Perkin-Elmer 2400 Series 2 C, H & N analyzer (Perkin-Elmer Corp., Norwalk, CT) was used for 1995 samples. Phosphorus was determined colorimetrically (Milton Roy Co., Rochester, NY, Spectronic 501) on samples dry-ashed at 500 °C for 8 hours and taken up in dilute HCL (Jackson 1958).

The potential for foliage from the two sites to differ in terms of N and P leachability was assessed by placing randomly selected leaves in zippered plastic bags containing 50 ml distilled, deionized H_2O. Samples were agitated for 1 hour and then the solution was chemically analyzed (ICAP).

Data Analysis

Statistical analysis bonsisted of t-tests for comparison of response variables between species and the two sites. Differences with probability levels less than or equal to 5 percent are discussed.

RESULTSANDDISCUSSION

Phosphorus

In 1994 at the low elevation site (Twin Creeks), the two species both exhibited smaller amounts and proportions of leaf P being retained in abscised foliage (i.e., lower magnitude and efficiency) compared with the higher elevations (tables 1 and 2). This was also true in 1995 for red maple analyzed individually and when both species were included simultaneously in the statistical analysis. No differences between locations were evident in 1995 for black cherry (tables 1 and 2).

Since red maple is more active in internal translocation of P than black cherry (table 3), it is possible that the 1995 P results for both species combined may be driven by differences in species composition of samples between the two sites. Red maple is indicated in table 3 to be more efficient than black cherry (i.e., maple retains less P in abscised foliage) and composed the majority of the 1995 samples (n) at the high elevation site (Cove Mountain). In 1994, red maple and black cherry sample numbers (n) were very similar at both sites. Consequently, skewed results due to over-representation of red maple are unlikely in that year.

Some caution should be exercised concerning P translocation data for red maple. There were indications that greater tendencies existed for P to leach from the foliage of that species at the high elevation site (data not shown). Consequently, some differences between summer

Table 2-The proportion of P and N (percent) July foliar content remaining in abscised foliage by species and location for 1994 and 1995[a]

Year and species	Location[b]	N[c]	PTC	NTC
1994				
Red maple	TC	7	10.1a	71.2 a
	CM	8	53.6b	57.3 b
Black cherry	TC	12	6.9 a	61 .0 a
	CM	9	42.1a	57.4 a
Both species	TC	19	8.1 a	64.4 a
	CM	17	47.5b	57.4 a
1995				
Red maple	TC	18	51.1a	72.9 a
	CM	11	70.6b	72.6 a
Black cherry	TC	17	11.9a	59.2 a
	CM	2	13.7a	56.9 a
Both species	TC	35	32.1a	66.2 a
	CM	13	61.8b	70.2 a

[a] PTC=percent phosphorus remaining, NTC=percent nitrogen remaining; means in rows followed by the same letter are not significantly different ($p < 0.05$) according to t- tests.
[b] TC=Twin Creeks, CM=Cove Mountain.
[c] N=number of samples (5 lvs per sample).

Table 3-Species comparisons within each location[a]

Location[b]	Year	Species	PT	NT	PTC	NTC
TC	1994	Red maple	0.149 a	3.702 a	10.1 a	71.2a
		Black cherry	0.055 a	1.866 b	6.9 a	61 .Ob
	1995	Red maple	0.393 a	3.192 a	51.1 a	72.9a
		Black cherry	0.002 b	1.149 b	11.9 b	59.2b
CM	1994	Red maple	0.462 a	2.600 a	53.7 a	57.3a
		Black cherry	0.310 a	2.388 a	42.1 a	57.4a
	1995	Red maple	0.649 a	4.221 a	70.6 a	72.6a
		Black cherry	0.064 b	1.066 b	13.7 a	56.9a

[a] PT=mg per leaf of phosphorus, NT=mg per leaf of nitrogen, PTC=percent phosphorus remaining, NTC=percent nitrogen remaining; means in rows followed by the same letter are not significantly different ($p < 0.05$) according to t-tests.
[b] TC=Twin Creeks, CM=Cove Mountain.

verses autumn foliage contents may not be due to internal translocation alone.

Greater efficiency of internal translocation for P at the high elevation site may be reasonable given that extractable soil P is lower there (Samuelson and Kelly 1997). Levels of extractable soil P at the high elevation probably reflect P deficiency for many deciduous tree species while those at the low elevation are marginal to nondeficient. Some contend that efficiency is inversely related to nutrient availability (Killinbeck 1996).

Nitrogen

There are fewer indications of meaningful differences between sites for N translocation than was the case for P (table 1). The magnitude of N translocation was quite similar for all species when compared between sites in 1994. However, there was an indication that N translocation was more efficient at the low elevation site for red maple in 1994 (table 2). In 1995, greater quantities of N were translocated in red maple and both species combined at the higher elevation, but no differences occurred in efficiency (tables 1 and 2).

Again, comparisons of N translocation between the two species within locations indicated that red maple was more active in translocation than black cherry. This was particularly true at the lower elevation site where both N magnitude and efficiency were highest for maple (table 3).

The 1995 results could be caused by (1) a heavier weighting toward red maple sampling at high elevation (i.e., since red maple at both sites was more efficient than black cherry) or (2) lower soil N availability at the upper elevation. The latter possibility is conjecture since total soil N and ammonium levels were higher at the upper elevation. However, mineralization rates there may be less rapid than at the lower site due to greater extremes in temperature and, if so, greater efficiency in N translocation could be a credible adaptation.

CONCLUSIONS

There are strong indications that translocation of mobile nutrients from senescing foliage is of greater magnitude and more efficient at the higher elevation site (Cove Mountain) compared with the lower (Twin Creeks). In comparisons of the two species evaluated, red maple also appears to transfer greater quantities of N and P and to be more efficient in this process. These indications are strongest during the first year of sampling (1994) and are primarily associated with P, although some differences do occur for N as well (tables l-3). The tendency for greater differentiation to occur in terms of P translocation (both magnitude and efficiency) suggests that P availability is the primary nutritional distinction between the two elevations. While both sites are likely deficient in soil N (although this study was not designed to ascertain the degree to which deficiencies exist), the differential between the two is greatest for P. It is likely that this cycling differential exists because the high elevation is P deficient while the lower is not.

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FOLIAR AND BELOWGROUND NUTRIENT DYNAMICS IN MIXED HARDWOOD FOREST ECOSYSTEMS

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Abstract-Many hardwood forest stands are composed of mixtures of species. The contribution of each species to ecosystem processes, including nutrient cycling, is poorly understood. This research was designed to quantify aboveground and belowground nutrient cycling processes in mixed hardwood forests. Nitrogen and phosphorus retranslocation rates were determined for a variety of species found in these forests. There were significant differences in nutrient retranslocation rates between the species sampled. Leaf litter decomposition followed a linear decay pattern, while decomposition of fine root tissue followed an exponential decay pattern. Patterns of nutrient immobilization and mineralization in fine root tissue differed markedly from those of decaying leaf tissue. These results indicate that the decay patterns of both above- and belowground components should be measured to fully elucidate nutrient cycling processes in forest systems.

INTRODUCTION

In natural ecosystems, nutrients are often limiting to plant growth with nitrogen (N) and phosphorus (P) commonly the most limiting nutrients. Many studies have examined the patterns of carbon (C), N, and P storage and cycling in forest ecosystems. In second-growth aggrading forest stands, large quantities of nutrients are stored in the woody biomass, but mortality of this component can be low and trees that die exhibit slow decomposition rates of the large woody components. These components can immobilize nutrients for prolonged periods during the decay process and subsequent nutrient mineralization can take many decades (Alban and Pastor 1993). A large proportion of the nutrient transfer processes occur through the production, senescence, death, and subsequent decomposition of annual aboveground litterfall and belowground fine root biomass (Binkley 1986).

Nutrient retranslocation can be an effective mechanism by which both individual members of the forest community and the forest ecosystem as a whole conserve nutrients (Chapin and Kedrowski 1983, Ostman and Weaver 1982). At the individual plant level, plants capable of efficient retranslocation have a significant ecological advantage over individuals that are inefficient at nutrient retranslocation. May and Killingbeck (1992) demonstrated that preventing normal nutrient retranslocation in *Quercus ilicifolia* reduced plant growth by approximately 50 percent and seed production by 90 percent. Differing rates of nutrient retranslocation can also have a direct impact on the chemical characteristics of the leaf-fall that is produced in a forest stand. These differences in foliar chemistry may directly affect nutrient cycling processes in forest stands (Blair 1988, McClaugherty and others 1985). In this way, either positive or negative feedback mechanisms influencing nutrient cycling processes can be established.

The specific objectives of this study were:

(1) To quantify the patterns of foliar nutrient retranslocation in various species during autumnal leaf senescence.

(2) To determine the patterns of leaf decomposition of individual species and a cohort of leaf tissue consisting of a mixture of leaf types in proportion to the annual leaf-fall in the stand.

(3) To determine decomposition dynamics of the indigenous mix of fine root tissues from a mesic forest stand.

METHODS

Study Site Description

The site selected for this study is located in Putnam County in west-central Indiana. The soil at this site is a Russell silt-loam (fine-silty, mixed, mesic Typic Hapludalf) which developed from moderately thick loess deposits [70 to 100 centimeters (cm)] overlying glacial till. The vegetation, in decreasing order of total basal area, is dominated by white oak, *Q. alba* (56.7 percent); sugar maple, *Acer saccharum* (12.7 percent); mixed hickories, including *Carya ovalis*, *C. ovata*, and *C. cordiformis* (11.9 percent); northern red oak, *Q. rubra*, (9.6 percent), and black walnut, *Juglans nigra* (3.7 percent) with these species composing 95 percent of the basal area. The site index for oak is approximately 90 feet at a base age of 50 years and approaches the highest productivity levels for upland oak-hickory stands in the Midwest. The soil is characterized by high N availability and moderate to moderately high soil P availability based on comparisons to other oak-hickory dominated forests (Kaczmarek 1995).

Foliar Nutrient Retranslocation

Nutrient retranslocation rates were determined for eight different species. The species selected-white oak, northern red oak, sugar maple, yellow poplar (*Liriodendron*

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tulipifera), shagbark hickory, beech (*Fagus grandifolia),* black walnut, and flowering dogwood (*Cornus florida)* are common associates in many mixed hardwood forests, and the presence of all these species on this single site allows nutrient retranslocation rates to be determined under uniform environmental and edaphic conditions. Six individuals of each species were selected. All trees sampled occupied dominant or codominant canopy positions in the overstory with the exception of sugar maple, beech, and flowering dogwood, which occurred as sapling size individuals in the understory. Leaves from the midcrown position were shot from the overstory trees. Leaves from the understor-y sugar maple, beech, and dogwood were collected with pruning poles. At the conclusion of the growing season, senescent leaves were collected from the identical trees that were sampled during the summer season. The autumnal sampling consisted entirely of senescent foliage collected as it fell from the tree. Both N and P retranslocation rates were calculated as fall nutrient concentrations divided by midsummer nutrient concentrations.

Analysis of variance was used to determine whether statistically significant differences existed between summer and fall N and P concentrations and nutrient retranslocation efficiencies (percentages). All comparisons were made with the General Linear Model (GLM). If this model revealed significant differences among species, then mean separation tests were performed using Duncan's Multiple Range Test (SAS Institute 1985).

Leaf Litter and Fine Root Decomposition Dynamics

Litter decomposition dynamics were determined for two types of litter. The first litter type was white oak litter, which represented approximately 55 percent of the total leaf-fall mass. The second type of litter consisted of mixed litter of white oak, sugar maple, and hickory leaf litter in the relative proportion of 55 percent, 30 percent, and 15 percent, respectively. This is the same proportion as that of the total leaf-fall accounted for by these species. Litter bags were constructed from 1.5 millimeter (mm) nylon mesh, measured 20 cm by 20 cm, and contained 4 grams (g) of leaf tissue. Litter decomposition bags were placed in the field in December and natural movement of the litter layer due to wind and snowfall events incorporated these bags into the forest floor by the following spring.

Decomposition rates were determined over a period of 780 days. At sampling intervals of 0, 143, 233, 353, 503, and 780 following placement in the field, four litter bags of white oak litter and mixed species litter were retrieved and oven-dried at a temperature of 65 °C. Total N and P concentrations were determined for samples on each collection date. Initial mass and N and P concentrations were used with the mass remaining and N and P concentrations at each subsequent sampling period to determine patterns of net immobilization and mineralization. Initial N and P contents and the total N and P contents at each of the five sampling times were calculated. Increases in total nutrient content from the initial time were considered as net immobilization of the **nutrient,** while decreases in total nutrient content were considered to be net mineralization of the nutrient.

The indigenous fine roots (2 mm or less in diameter) were collected. No effort was made to sort the fine root tissue into various species. Decayed fine roots were discarded. Fine roots were washed under distilled water to remove the adhering silt and clay particles. Root decomposition bags were formed by placing 500 milligrams (mg) of fine root tissue in 0.5 mm nylon mesh bags measuring 8 cm by 8 cm.

The decomposition study was initiated in August 1993 and spanned the period lasting through March 1995. At the beginning of the study, 72 total fine root decomposition bags were placed in the mineral soil at a depth of 10 cm. At each of the sampling times, nine fine root decomposition bags were retrieved. Following installation of the decomposition bags in August 1993, sampling occurred at 30, 90, 210, 270, 330, 390,450, and 570 days. After the decomposition bags were retrieved from the field, they were rinsed under distilled water on a 0.106 mm sieve to remove any silt and clay particles adhering to the tissue. The root tissue was dried at a temperature of 65 °C for a period of 48 hours. Mass loss was determined as the difference between initial weight and the weight remaining at each given sampling period. Nitrogen and P concentrations were measured and total nutrient contents calculated as described for leaf litter.

RESULTSANDDISCUSSION

Summer and Fall Foliar N and P Concentrations

Summer foliar N and P concentrations exhibited wide species differences. Summer foliar N concentrations ranged from 1.83 percent in flowering dogwood to 2.69 percent in black walnut (table 1). The dominant overstory species in this stand-white oak, hickory, sugar maple, and northern red oak-had summer foliage N concentrations that fell within a relatively narrow range (2.0 to 2.2 percent). Nitrogen concentrations of black walnut and yellow-poplar foliage were higher than these of most other species present in the stand. Summer foliar P concentrations did differ significantly by species, but these differences were generally of a smaller magnitude than differences in foliar N concentrations (table 2). Black walnut had the highest foliar P concentrations at 0.21 percent, while flowering dogwood and beech had the lowest summer P concentrations of 0.15 percent. The remaining species had midsummer foliar P concentrations ranging from 0.18 to 0.19 percent.

Nitrogen concentrations in senescent foliage ranged from 0.7 percent in yellow-poplar foliage to 1.2 percent in black walnut foliage (table 1). Nitrogen concentrations in beech and black walnut foliage were significantly higher than N concentrations in most other species. For these two species, high summer foliar N concentrations were also reflected in high N concentrations in the senescent foliage.

Table 1—Mean[a] summer and fall nitrogen concentrations (Percentage of dry mass) and nitrogen retranslocation efficiencies of white oak, northern red oak, sugar maple, Yellow-poplar, shagbark hickory, beech, black walnut, and flowering dogwood

Species	Summer foliage (N)	Fall foliage (N)	Nitrogen retranslocation
	------------ Percent ------------		
White oak	2.19 cd	0.84 cd	61.7 b
Red oak	2.05 de	0.89 bc	56.4 bc
Sugar maple	1.97 de	0.77 cd	60.7 bc
Poplar	2.48 ab	0.68 d	72.5 a
Hickory	2.09 cd	0.78 cd	62.8 b
Beech	2.31 bc	1.05 ab	54.2 bc
Walnut	2.69 a	1.20 a	55.1 bc
Dogwood	1.83 e	0.87 c	51.6 c

[a] Means in the same column followed by the same letter do not differ significantly from one another at the 5 percent level using Duncan's Multiple Range Test.

Table 2—Mean[a] summer and fall phosphorus concentrations (percentage of dry mass) and phosphorus retranslocation efficiencies of white oak, northern red oak, sugar maple, yellow-poplar, shagbark hickory, beech, black walnut, and flowering dogwood

Species	Summer foliage (N)	Fall foliage (N)	Phosphorus retranslocation
	------------ Percent ------------		
White oak	0.188 ab	0.071 ab	62.0 ab
Red oak	0.180 b	0.089 a	51.2 bc
Sugar maple	0.178 b	0.062 ab	64.1 ab
Poplar	0.180 b	0.047 b	73.9 a
Hickory	0.175 b	0.071 ab	55.7 abc
Beech	0.150 c	0.076 ab	49.3 bc
Walnut	0.208 a	0.089 a	55.9 abc
Dogwood	0.148 c	0.081 a	43.1 c

[a] Means in the same column followed by the same letter do not differ significantly from one another at the 5 percent level using Duncan's Multiple Range Test.

In contrast, yellow-poplar midsummer foliage was characterized by high N concentrations, but by low N concentrations in the senescent foliage. The remaining species had similar N concentrations in senescent foliage with concentrations ranging from 0.77 to 0.89 percent. Phosphorus concentrations in senescent foliage showed an approximate twofold range of values (table 2). Yellow-poplar had the lowest P concentrations of approximately 0.05 percent, while P concentrations in black walnut and northern red oak were almost twice that level (0.09 percent). Species can be grouped into several categories based on nutrient characteristics in the senescent foliage. Black walnut had high N and P concentrations, white oak and sugar maple had medium N and P concentrations, while yellow-poplar had low N and P concentrations.

Nitrogen and Phosphorus Retranslocation Efficiencies

Nitrogen retransiocation rates, expressed as the difference in midsummer and fall foliar nutrient concentrations, ranged from 52 percent in flowering dogwood to 73 percent in yellow-poplar (table 1). Yellow-poplar, on the basis of high summer nutrient status and low N concentrations in the fall foliage, had higher N retranslocation rates than any other species sampled. The range of N retranslocation values obtained in this study (52 to 73 percent) are within the range of N retranslocation values commonly reported for deciduous hardwood species. Ostman and Weaver (1982) found that N retranslocation of chestnut oak foliage in southern Illinois ranged from 76 to 80 percent. Boerner (1984), working in mixed oak forests in Ohio, found that N retranslocation was 50 and 48 percent for chestnut oak, and 46 and 31 percent for white oak growing on xeric and mesic sites, respectively. Pregitzer and others (1992) investigated foliar N retranslocation in sugar maple stands throughout Michigan and Minnesota and found that N retranslocation efficiency ranged from 47 to 63 percent.

Chapin and Kedrowski (1983) reported P retranslocation efficiencies that ranged from 11 to 89 percent in various temperate deciduous tree species. Phosphorus retranslocation efficiencies were 51 to 59 percent for chestnut oak stands in southern Illinois (Ostman and Weaver 1982). Boerner (1984) found that P retranslocation efficiencies were 44 and 45 percent for chestnut oak, and 66 and 52 percent for white oak growing on xeric and mesic sites, respectively. Phosphorus retranslocation in sugar maple has been found to exhibit wide variability (38 to 65 percent) across the species range (Pregitzer and others 1993).

The results of the current study support the findings of previous studies which have shown that N and P retranslocation is a significant nutrient conservation mechanism. The current study is unique in that nutrient retranslocation efficiencies were determined for a large number of species within a single uniform environment. Significant differences in nutrient retranslocation between species suggest that these species could respond differently to gradients in soil N and P availability. Once nutrient demands are initially satisfied by the soil supply, efficient nutrient retranslocation may tend to conserve internal nutrient supplies and reduce the quantities of nutrients that must be obtained from the soil to support each new foliage cohort. In this sense, efficient nutrient retranslocation can serve to decouple seasonal fluctuations in plant nutrient demand from seasonal changes in soil nutrient supply. Differences in nutrient retranslocation rates can also influence characteristics of the leaf-fall at individual sites, thereby affecting nutrient cycling processes.

Leaf Litter Decomposition Dynamics

Initial leaf litter N concentrations ranged from 0.79 percent for white oak to 1.05 percent for hickory leaf litter (table 3). The initial nutrient concentration of the mixed bag litter was calculated as the weighted mean of white oak, sugar maple, and hickory litter. Mean P concentrations in the individual species leaf litter ranged from 0.057 percent for sugar maple leaves to 0.080 percent for hickory leaves with a weighted mean P concentration of 0.065 percent for the mixed species litter (table 3).

Leaf litter decomposition for both the white oak and mixed species litter followed a linear decay pattern (fig. 1). Mass loss progressed at a relatively constant rate throughout the 780-day period. The similar pattern for white oak and mixed species litter is probably due to the inclusion of a large percentage of white oak litter in the mixed species bags. Previous studies have demonstrated that *Quercus* species often exhibit slow decomposition rates due to their chemical characteristics. The current study indicates that the inclusion of sugar maple and hickory leaves with white oak leaves does not increase decomposition rates. Any "priming effect" of hickory and sugar maple on white oak decomposition rates is negligible for litter on this site and litter composition. The time required for 50 percent of the leaf litter to decompose is 1.8 years for white oak litter and 1.6 years for mixed litter. The time for 80 percent of the litter to decompose increases to 3 years for white oak and 2.7 years for mixed litter. The rates of litter decomposition measured in this study compare relatively closely to the rates measured in other studies in similar climates with similar litter composition. McClaugherty and others (1985) reported similar rates of mass loss for white oak and sugar maple foliage in southern Wisconsin. Kelly and Beauchamp (1987) observed similar rates of mass loss for mixed oak foliage in Tennessee. Decomposition rates of chestnut oak foliage in North Carolina (Blair 1988) were also comparable. The similar rates of decomposition of oak-dominated foliage across various sites may be related to the similar chemical composition of many types of oak foliage. This suggests that litter chemical characteristics, rather than site environmental conditions, may be the primary control over decomposition. Site characteristics exert an indirect effect on decomposition by determining species composition of the stand and the chemical characteristics of the litter produced on the site (Prescott 1995), but may have a relatively minor direct influence on decomposition rates.

Table 3—Initial nitrogen and phosphorus concentrations of white oak, sugar maple, hickory, mixed foliage, and fine roots

Tissue type	Nitrogen Concentration	Phosphorus Concentration
	---------- Percent ----------	
White oak leaves	0.79	0.065
Sugar maple leaves	0.90	0.057
Hickory leaves	1.05	0.080
Weighted mean for mixed foliage	0.86	0.065
Fine roots	1.71	0.133

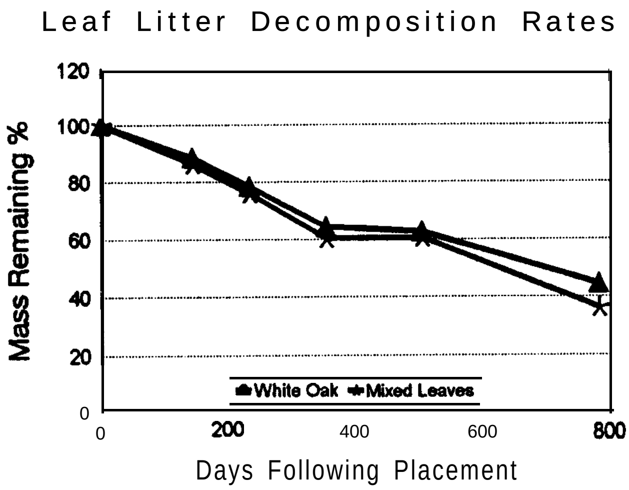


Figure I-Rates of mass loss for white oak and mixed litter.

Changes in N and P concentrations show similar trends for both litter types during the decay process (figs. 2 and 3). Nitrogen concentrations show gradual increases from initial levels of approximately 0.8 percent to 1.5 to 2.0 percent after 780 days in the field. Phosphorus concentrations in both litter types also demonstrated increases over the 780-day period from 0.065 percent to approximately 0.15 percent for white oak litter, and 0.19 percent for mixed litter. When changes in litter mass are combined with changes in nutrient concentrations over time, patterns of nutrient immobilization and mineralization become clear. For N, nutrient dynamics may be best described as a three-phase model. Both litter types exhibit net N mineralization over the initial 143-day period (fig. 2). Following this initial net release of N, N is immobilized in both leaf litter types. Sampling at 503 days demonstrated that significant quantities of N were released from the previous sampling interval. While N was released from the peak period of immobilization, both litter types still retained approximately 85 percent of their initial N contents. At this time, both litter types converged to the same point. At the final sampling interval (780 days), both litter types retained 80 percent of their initial N content. This suggests that relatively little N is released for over 2 years following leaf-fall and that freshly fallen leaf tissue serves as a minor source of nutrients. Using an annual leaf production rate of approximately 4,900 kilograms (kg) per hectare (ha) per year (Kaczmarek and others 1995), less than 10 kg per ha of N would be released from a single cohort of leaf litter after

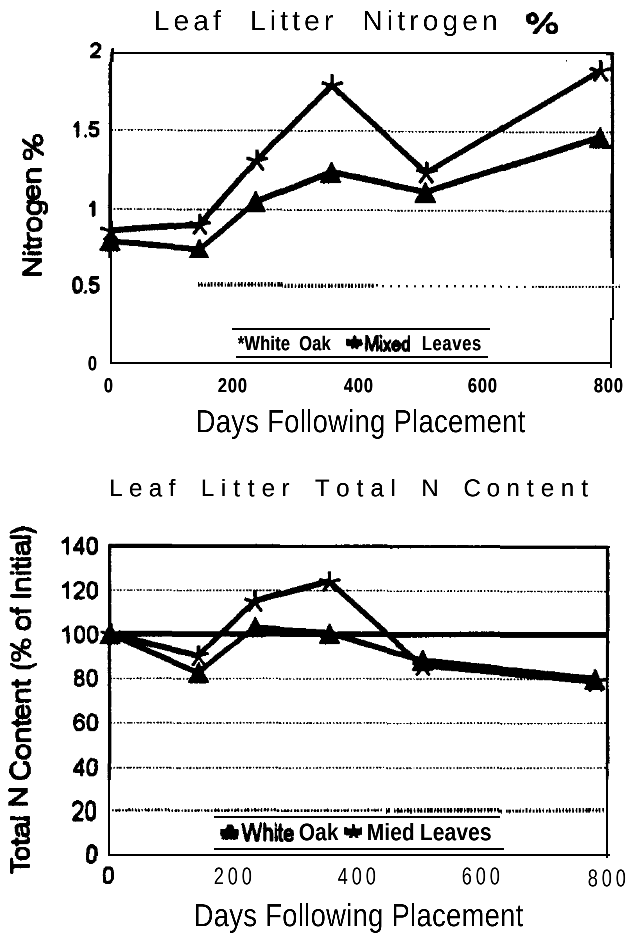


Figure Z-Nitrogen concentrations (top graph) and changes in total N content (bottom graph) for white oak and mixed litter. Points above the loo-percent line indicate net N immobilization while points below the loo-percent line represent net N mineralization.

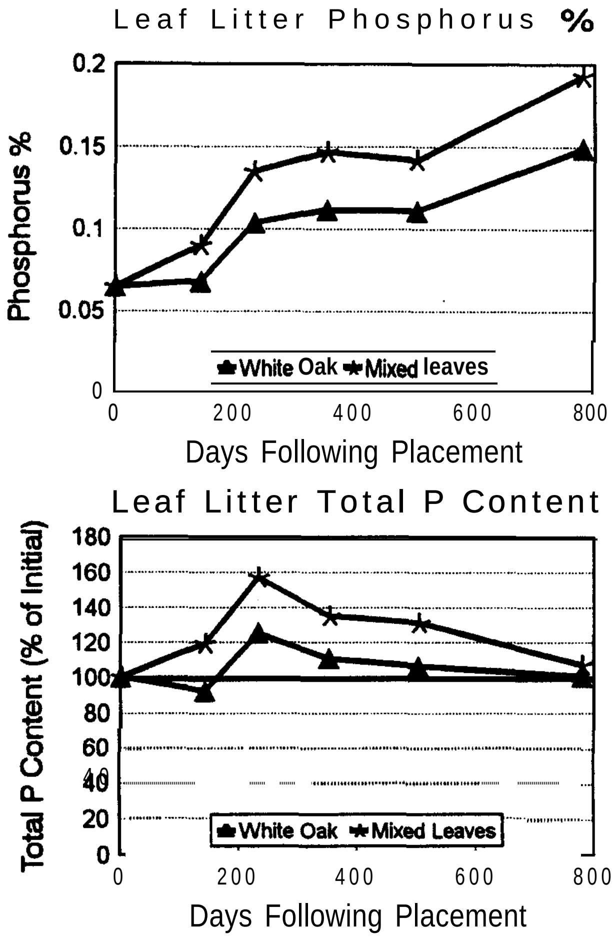


Figure 3-Phosphorus concentrations (top graph) and changes in total P content (bottom graph) for white oak and mixed litter. Points above the loo-percent line indicate net P immobilization while points below the loo-percent line represent net P mineralization.

approximately 2 years. Longer time periods are clearly necessary for a cohort of leaf tissue to become a large net source of N in this stand.

Patterns of P immobilization and mineralization (fig. 3) for white oak litter show similar trends in the pattern of N mineralization. White oak litter exhibited a three-phase decomposition model with an initial period of P mineralization followed by periods of immobilization and, finally, mineralization. Mixed litter did not show an initial P release phase, but rather exhibited P immobilization followed by mineralization. At the end of the 780-day period, both litter types had released significant quantities of P, which were immobilized during earlier phases of decomposition, but total P contents were approximately equal to total P contents at time 0. By the end of this period, both litter types had converged to similar points which, as for N, demonstrates that initial differences in litter characteristics are most pronounced early in the decomposition process. As decomposition proceeds, initially different litter types appear to be converted into more similar chemical components, and further decomposition dynamics appear to follow convergent paths.

Similar patterns of N and P immobilization and mineralization have been found in many but not all studies. Blair (1988) and Bockheim and others (1991) observed the general pattern of small initial net mineralization of N followed by varying degrees of N immobilization. The degree of N mineralization appears to be time-dependent. The decay sequence should be carried out for a sufficient time period to observe all phases of the decomposition process. Melillo and others (1989) proposed that a three-phase model incorporating initial periods of net N mineralization followed by immobilization, and finally substantial N mineralization, was a general step in the process of the conversion of organic debris to stable soil organic matter. Patterns of P retention and release have been found to be more variable. Blair (1988) found wide species differences in patterns of P retention and release. Bockheim and others (1991) likewise observed large differences in P dynamics during the decomposition process. Rustad and Cronan (1988), working with species characterized by high initial P concentrations, found immediate net P mineralization without any P immobilization throughout the decomposition process. Polglase and others (1992) found that high soil P availability led to the production of leaf litter with high inorganic P concentrations. This inorganic P was labile and subject to rapid leaching losses during the early phases of decomposition.

Fine Root Decomposition Dynamics

Fine roots collected from this stand were characterized by high N concentrations and moderate to moderately high P concentrations based on comparisons of fine root tissue collected from other oak-hickory dominated stands (Kaczmarek 1995). Decomposition rates during the early phase of decomposition of this tissue, based on comparisons to leaf litter discussed previously, were rapid. In contrast to leaf litter decomposition, which followed linear decay dynamics, the native fine root mix followed an exponential decay pattern (fig. 4). Mass loss was rapld and approached 50 percent within 1 year in the field. Based on exponential decay functions, approximately 1.2 years would be required for 50 percent mass loss to take place and 80 percent of the mass would be lost within 2.8 years. The time required to reach 80 percent mass loss for root tissue (2.8 years) compares closely to the time required for the mixed litter to lose 80 percent of its mass (2.7 years). The difference in linear and exponential decay models reveals that there are clear differences in the early stages of decomposition, but also suggest that these different tissues reach convergent points during the latter stages of decomposition.

Changes in N concentrations (fig. 5) in the decaying fine root tissue showed a similar pattern to decaying leaf litter. Following an initial decrease in N concentrations after 30 days in the field, N concentrations rose steadily, reaching 2.2 percent by the end of the study. Phosphorus concentrations were more variable throughout the sampling period; following a sharp decrease after 30 days, they generally followed an increasing trend for the remainder of the study. The patterns of N and P immobilization and mineralization of fine root tissue was distinctly different

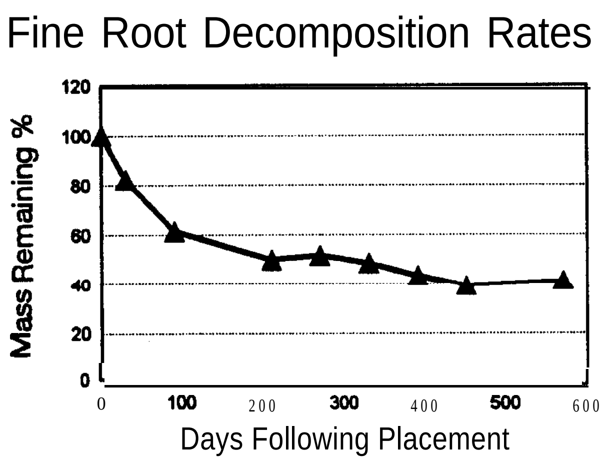
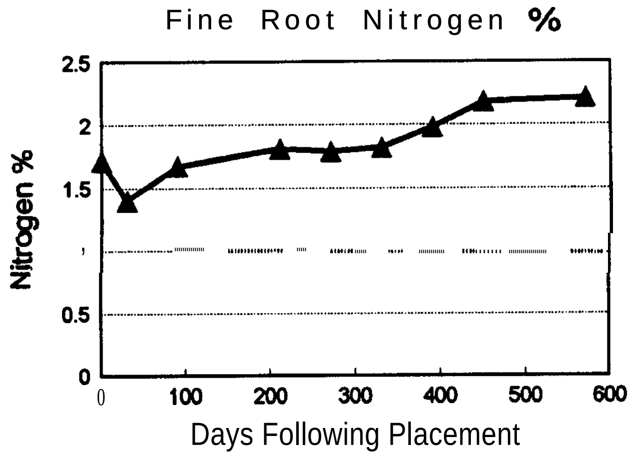


Figure 4—Rates of mass loss for fine root tissue.



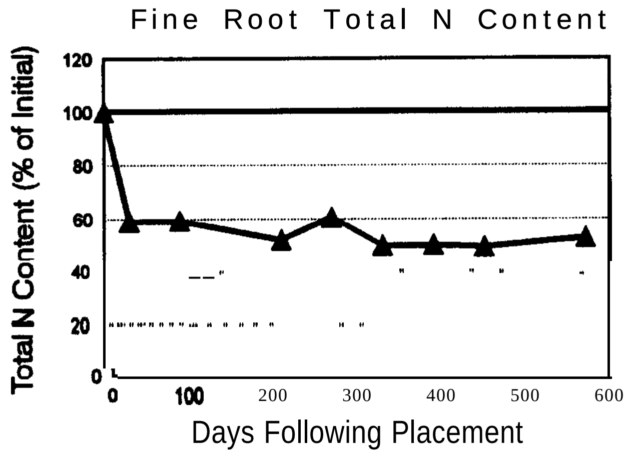
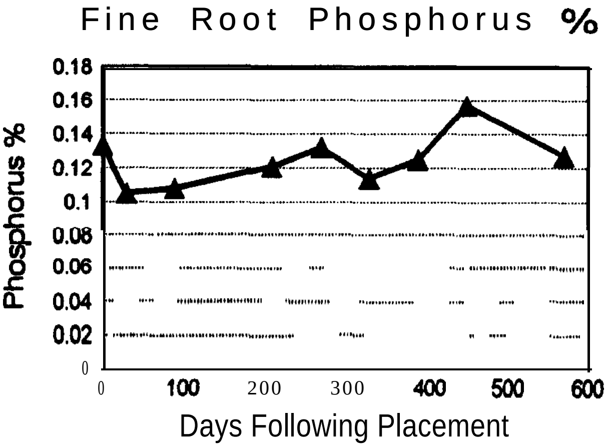


Figure 5—Nitrogen concentrations (top graph) and changes in total N content (bottom graph) for fine root tissue. Points above the loo-percent line indicate net N immobilization while points below the loo-percent line represent net N mineralization.

from the patterns observed for leaf litter. Within 30 days of placement in the field, more than 60 percent of the total N contained in the fine root tissue was released. After this point, little additional N was released. Changes in total P content (fig. 6) exhibited a similar trend with approximately 45 percent of the total P content being released within 30 days in the field. Further releases of P were slow and steady with more than 60 percent of the total P content being released by the end of the study. Combined, these data indicate that belowground nutrient dynamics follow a distinctly different pattern from the patterns observed in decaying leaf tissue. The possible reasons for these differences between nutrient release patterns for fine roots and leaf litter may relate to wide differences in initial N and P concentrations. Both N and P concentrations in fine root tissues were approximately double the concentrations of the leaf litter utilized in the study. High P concentrations in the fine root tissue may have made this nutrient subject to rapid leaching during the early phases of decomposition. The high N concentrations of the fine root tissue may have made C, rather than N, the primary factor controlling decomposition rates.



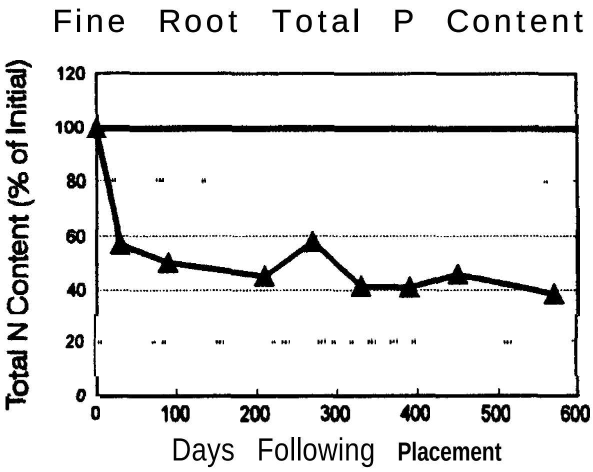


Figure 6-Phosphorus concentrations (top graph) and changes in total P content (bottom graph) for fine root tissue. Points above the loo-percent line indicate net P immobilization while points below the loo-percent line represent net P mineralization.

CONCLUSIONS

There were significant differences in nutrient retranslocation rates between the species sampled. These differences may, in themselves, have important ecological consequences under nutrient-limited conditions. Differing nutrient retranslocation rates may also influence chemical characteristics of the leaf litter produced on a given site. These differences may then be reflected in differences in decomposition dynamics. This study also clearly indicates that belowground organic matter components must be considered to fully understand nutrient cycling processes. Belowground decomposition dynamics clearly differed from the aboveground measurements in this study. In particular, patterns of nutrient immobilization and mineralization differed significantly between aboveground and belowground tissues.

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THE ROLE OF FINE ROOT DYNAMICS IN THE N AND P CYCLES OF REGENERATING UPLAND OAK-HICKORY FORESTS

Travis W. Idol, Phillip E. Pope, Jennifer Tucker, and Felix Ponder, Jr.'

Abstract-h naturally regenerating hardwood forest stands, inputs of organic matter and nutrients from fine root turnover and decomposition are significant but not well-quantified. Four forest stands in southern Indiana-aged 6, 12, 31, and approximately 100 years since clearcutting at the time of the study-were chosen to represent the different developmental stages of upland temperate hardwood forest stands. Changes in live and dead fine root biomass and fine root growth were monitored to calculate total fine root decomposition. Autumnal aboveground litter-fall was collected to compare above- and belowground litter nutrient inputs. Results indicate that, on an annual basis, N and P inputs to the soil from fine root decomposition are greater than or equal to, the total amount of N and P held in the aboveground litterfall for all but the youngest stand. The ratio of aboveground fine root N and P inputs decreases with stand age beginning about 10 years after harvest. This indicates that fine root turnover and decomposition in these upland oak-hickory forests is the major pathway for biological cycling of nutrients from stand ages 10 to 80 years.

INTRODUCTION

Management of many forests in the central hardwood forest region consists of infrequent clearcuts or selective harvests done on the scale of only a few hectares. This is especially true in Indiana since much of the landscape is dissected into private and public lands. Natural regeneration is usually relied upon to reforest harvested sites; often, site preparation and postharvest monitoring of stand regeneration is neglected.

Past research on temperate deciduous stands has revealed that the direction and magnitude of stand development are strongly influenced by the nature of the regenerating vegetation and the nutrient dynamics of the site (Hughes and Fahey 1994, Mattson and Swank 1989, Mroz and others 1985, Palik and Pregitzer 1991, Polglase and Attiwill 1992, Weigel 1996). A few studies have focused on fine root dynamics of regenerating or disturbed stands in tropical ecosystems (Berish and Ewel 1987, Raich 1980, Silver and Vogt 1993), and only one investigated these dynamics in temperate hardwood forests of the United States (Yin and others 1989).

Fine roots, like leaves, tend to be relatively short-lived, both physically (Hendrick and Pregitzer 1993, Joslin and Henderson 1987) and functionally (Kuhns and others 1985), ranging from a few weeks to 1 or 2 years. Therefore, the rapid turnover and eventual decomposition of fine roots and leaves are important carbon and nutrient inputs to the soil (Joslin and Henderson 1987, McClaugherty and others 1982, Ruess and others 1996). Changes in species composition and growth rates in developing forest stands alter the nutrient demands over time. Since leaf area and fine root biomass also change with the age of the stand (Yin and others 1989), the relative importance of the turnover and decomposition of these tissues in supplying N and P to the soil will vary. Quantifying these changes is important in understanding the nutrient cycles of upland temperate hardwood forests.

This study was developed with these factors in mind. Specifically, we wanted to investigate the influence of stand development on the rates of fine root decomposition, the amount of autumnal aboveground litterfall, the N and P contributions of fine root decomposition to the soil, and the total N and P held in the autumnal litterfall.

SITE DESCRIPTIONS

Our study is being implemented at the Southern Indiana Purdue Agricultural Center, located in Dubois County, IN. The area is in the Crawford Upland Section of the Shawnee Hills Natural Region (Homoya and others 1985). The ecological landtype phase most common in these stands is classified as *Quercus alba-Acer saccharum/Parthenocissus* dry-mesic ridges (USDA 1995). The soils are of different series within the family of fine-silty, mixed, mesic Ultic Hapludalfs (USDA 1996). The area is characterized by rolling hills, and all plots in this study are located on 10 to 30 percent slopes with southern and western aspects. All four stands have historically been dominated by oak *(Quercus)* and hickory (*Carya*) species at maturity. Site index for white oak is approximately 20 to 21 meters at 50 years (Kaczmarek 1995). The three regenerating stands were clearcut in 1991, 1985, and 1969, respectively (Sites 1, 2, and 3). The fourth is a mature oak-hickory stand, 80 to 100 years old (Site 4).

Species Composition

The vegetation of the 6-year-old stand (Site 1) is composed of many small tulip poplar (*Liriodendron tulipifera* L.) [28,500 stems per hectare (ha)], white oak (Q. *alba* L.) (19,000 stems per ha), and sugar maple (*Acer saccharum* Marshall) (11,400 stems per ha), saplings with greenbriar (*Smilax* spp.) (11,000 stems per ha), blackberry (*Rubus* spp.) (10,200 stems per ha), and Virginia creeper [*Parthenocissus quinquefolia* (L) Planchon] (10,200 stems per ha) in the understory. In the 12-year-old stand (Site 2), the overstory vegetation is a mixture of black cherry (*Prunus serotina* Ehrhart) (210 stems per ha), red oak (Q.

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rubra L.) (200 stems per ha), eastern redbud (*Cercis canadensis* L.) (170 stems per ha), dwarf sumac (*Rhus copallina* L.) (160 stems per ha), and sugar maple (160 stems per ha). The basal area of the 31 -year-old stand (Site 3) in 1990 was 14 m^2 per ha. The overstory in this stand is a mixture of sugar maple (700 stems per ha), black cherry (410 stems per ha), and sassafras (200 stems per ha) (Yu, in press). The basal area of the mature stand (Site 4) in 1987 was 16 m^2 per ha. The overstory basal area is dominated by white oak (12 m^2 per ha), with sugar maple (2 m^2 per ha), and hickory [C. *ovata* (Miller) K. Koch and C. *glabra* (Miller) Sweet] (2 m^2 per ha) present in smaller amounts (Kaczmarek 1995). The sapling layer is dominated by sugar maple (740 out of a total of 770 stems per ha) with several American beech (*Fagus grandifolia* Ehrhart) and white ash scattered throughout (Yu, in press).

METHODS

Fine root biomass was sampled over a 30 centimeter (cm) depth, according to the coring method of Joslin and Henderson (1987). Fine root growth was estimated with the ingrowth technique, using soil collected from the site in which the ingrowth cores were placed (Conlin and Lieffers 1993, Joslin and Henderson 1987). Ten to 15 core samples per site were collected approximately every 60 days from July 1995 until December 1995, and then again in 1996 from April to June. Fine roots were separated from the soil in a hydro-pneumatic elutriation machine (Smucker and others 1982). Fine roots were separated into live and dead categories according to tissue integrity, color, and sheath covering (Clemsson-Lindell 1994). All samples were dried in an oven at 65 °C to a constant weight for at least 48 hours before being weighed.

If changes in live and dead fine root biomass and the fine root growth rate over a specific time period are known, then the total fine root decomposition during that time period can be calculated. Because the change in live fine root biomass during any time period is a function of fine root growth (an addition of live fine root mass) and fine root death, or mortality (a subtraction from the live fine root mass), fine root mortality can be calculated by subtracting the change in live fine root mass from the fine root growth rate.

Symbolically, where GROWTH = fine root growth, LFR_1 = live fine root mass at time 1, LFR_2 = live fine root mass at time 2, and MORT = fine root mortality: $LFR_2 - LFR_1 = GROWTH - MORT$. By rearranging the terms of the expression: $MORT = GROWTH - (LFR_2 - LFR_1)$.

Similarly, the change in dead fine root mass during any time period is a function of additions to the dead fine root pool due to fine root mortality and subtractions from the dead fine root pool due to fine root decomposition. By knowing the fine root mortality rate, the fine root growth rate, and the change in dead fine root mass during a specific time period, fine root decomposition can be calculated.

Symbolically, where DECOMP = fine root decomposition, DFR_1 = dead fine root mass at time 1, and DFR_2 = dead fine root mass at time 2: $DFR_2 - DFR_1 = MORT - DECOMP$. By rearrangement of the terms of the expression: $DECOMP = MORT - (DFR_2 - DFR_1)$ or $DECOMP = GROW - (LFR_2 - LFR_1) - (DFR_2 - DFR_1)$.

Ten to 15 littertraps, 0.71 by 0.71 meters on a side or approximately 0.5 m^2 in area and 10 cm deep, were placed within each site. Autumnal litterfall was collected weekly from October 8 to December 18, 1995. Samples were separated according to species and air dried in a greenhouse before being weighed.

Nutrient analyses were performed on representative subsamples of live fine roots and aboveground litter-fall. Total N was determined according to the micro-Kjeldahl method (Keeney and Nelson 1982). Total P was determined by digesting approximately 0.1 gram of the ground plant tissue in a mixture of perchloric acid and peroxide at a temperature of approximately 220 C. After the digestion was complete, the samples were diluted with double- distilled water, and the P content of the resulting solution was determined according to the phosphomolybdate blue colorimetric procedure (Olsen and Sommers 1982). The average N and P concentrations from all fine root or litterfall samples within a site were used to calculate N and P inputs or contents of the litter sources.

RESULTS AND DISCUSSION

Patterns of Fine Root Decomposition

Figure 1 illustrates the seasonal patterns of fine root decomposition from July 1995 to July 1996 for all four sites. The peak time for fine root decomposition occurred during the fall and winter of the year, from October 1995 to March 1996. For the four stands in this study, annual rates of fine root decomposition peaked at 10 years of age, and decreased thereafter (table 1).

Patterns of fine root decomposition across stands of varying age are not well understood. The pattern of increasing then decreasing fine root decomposition with stand age (table 1) suggests that the biomass and longevity of fine roots in younger stands are lower than in older stands. As the stand

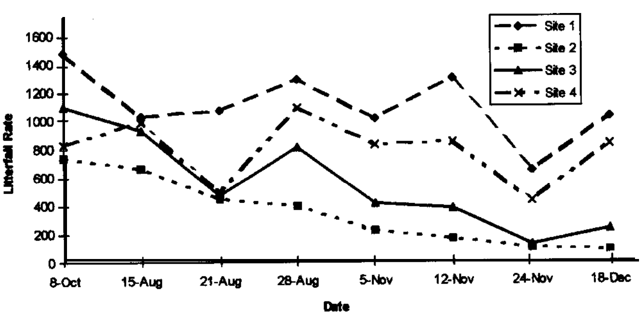

Figure l-Effect of season upon fine root decomposition (g per m^2- day) across a 100-year chronosequence of upland hardwood forest stands.

Table I-Annual rates of fine root decomposition, aboveground litterfall, and the N and P contents of litter sources across a 100-year chronosequence of upland hardwood forest stands

Stand age (1995)	Site	Fine root decomp.	Aboveground litter-fall	Fine root N return	Fine root P return	Litter-fall N content	Litterfall P content
- Years -	No.	*- - - Kilograms per hectare per year - - -*					
4	1	7,150	8,970	57.8	6.51	82.3	7.98
10	2	10,110	2,820	70.5	7.28	27.3	2.71
29	3	7,720	4,480	64.9	4.94	36.7	2.96
80–100	4	6,460	6,360	50.5	3.94	52.2	4.13

ages, there is more fine root mass which can potentially turn over, but less of a percentage of this standing biomass actually turns over during any given time interval. Consequently, total fine root decomposition in younger stands increases over time as long as increases in total fine root biomass are greater than increases in fine root longevity. This presumably is the case in Sites 1 and 2, the 6- and 12-year-old stands. As the dominant canopy trees establish themselves and canopy tree dieback decreases, fine root biomass will reach a maximum level, but fine root longevity will continue to increase. This would mean that total fine root decomposition would decrease over time. This presumably is the case for Sites 3 and 4, the 31- and 80- to 1 OO-year-old stands.

Fine Root Biomass

Table 2 lists the seasonal and annual levels of fine root biomass in the chronosequence of stands investigated. The assumption of increasing fine root biomass with stand age is justified in this case. Total fine root biomass increases from the 6- to the 12-year-old stand, decreases from the 12- to the 31 -year-old stand, but then increases again from the 31- to the 80 to 100-year-old stand. The levels of fine root biomass in the 12- and 80 to 100-year-old stands are similar, suggesting that reestablishment of belowground fine root biomass occurs within 10 years after a harvest in these upland hardwood forests.

The decrease in fine root biomass in the 31-year-old stand is perhaps due to a change in canopy species composition. The canopy of this stand is dominated by pioneering species like sassafras and black cherry, whereas the canopy of the 80 to 100-year-old stand is dominated by white oak. Reduced vigor and tree damage or death due to windstorms has been observed in this stand. It is possible that these pioneering species will lose their canopy dominance over the next few decades, being replaced by oak, hickory, and maple species.

Litterfall

Figure 2 illustrates the rates of aboveground litterfall during the autumn of 1995. For the 12- and 31 -year-old stands (Sites 2 and 3), litterfall rates generally decreased during the collection period. However, for the 6- and 80 to 100-year old stands (Sites 1 and 4), litterfall rates remained high though the last collection date. Overall, litterfall was highest in the youngest stand, lowest in the 1 e-year-old stand, and then increased with stand age thereafter (table 1).

The high rate of litter-fall in the youngest stand (Site 1) is contrary to what was expected (table 1). With a much lower leaf area than stands with closed canopies, litter-fall in very young stands is expected to be low (Gholz and others

Table 2—Seasonal patterns of total fine root biomass (kg per hectare on a dry weight basis) across a 100-year chronosequence of upland hardwood forest stands

Collection date	Total fine root biomass collected: Site 1 6 yrs old	Site 2 12 yrs old	Site 3 31 yrs old	Site 4 80-l 00 yrs old
	- - - Kilograms per hectare - - -			
6/29/95	178	320	265	301
8/27/95	194	275	208	277
10/21/95	388	392	224	290
12/18/95	176	322	200	277
4/13/96	196	190	174	213
6/15/96	203	311	233	270
Average	222	302	217	271

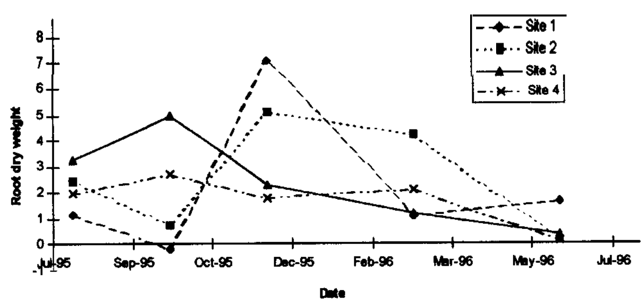

Figure 2-Changes in weekly aboveground autumnal litterfall rates (kg per ha-week) across a 100-year chronosequence of upland hardwood forest stands.

1985, Hughes and Fahey 1994, Polglase and Attiwill 1992). There are two possible explanations for why this is not the case in this study. First, much of the vegetation in Site 1 is herbaceous annuals and short-lived perennial vines and shrubs. Turnover of this material could be high enough to lead to the higher-than-expected values. Adding to this high indigenous litter-fall rate is the influx of litter material from surrounding mature stands. From personal observations, it seems that a significant component of the litterfall in Site 1 came from mature trees in stands surrounding the plots in the harvested stand. Together, this seems to yield the higher-than-expected litter-fall rates in Site 1. Because the total leaf area of oak and hickory stems within Site 1 is not known, this off-site litter could not be separated from the total litterfall collections.

N and P Inputs

Potential N and P inputs from fine roots in the 12- and 31-year-old stands (Sites 2 and 3) exceeded the total nutrient content present in the litterfall. Since fine root biomass reached preharvest levels more quickly than leaf area, contributions of N and P from fine root decomposition may exceed inputs from aboveground litterfall until maximum leaf area is reached in the stand. If forest floor decomposition is assumed to be approximately equal litterfall in the 80 to 100-year-old stand, then N and P contributions from fine roots are approximately equal to contributions from aboveground litter-fall in this stand. In the 6-year-old stand (Site 1), the combination of less fine root biomass, rapid turnover of aboveground biomass, and the influx of litter from outside the stand means that fine root contributions to N and P inputs are less important than inputs from aboveground litterfall. In the 12- and 31-year-old stands (Sites 2 and 3), high fine root biomass and decomposition yield N and P inputs in excess of the amounts of N and P held in annual litter-fall.

CONCLUSIONS

Polglase and Attiwill (1992) express the commonly held opinion that nutrient returns to the soil from plant litter are derived mainly from leaf fall and stem death from stand self-thinning. They surmise from their measurements of aboveground productivity and litterfall return that in young mountain ash (Eucalyptus *regnans*) stands, soil nutrient reserves supply the majority of N taken up by the vegetation. Joslin and Henderson (1987) recognized the importance of fine root turnover to the inputs of organic matter and nutrients in mature hardwood forests. Our study suggests that, for upland oak-hickory forests, fine root decomposition is the major pathway for N and P return to the soil from about age 10 years until maturity, at age 80 to 100 years. Mineralization of these organic forms of N probably accounts for the majority of the N taken up by the regenerating vegetation in these stands.

Soil nutrient availability is an important part of understanding soil quality and forest productivity. To adequately quantify the biological sources of plant-available soil N and P, measuring aboveground litter-fall returns is not sufficient. Inputs of N and P from fine root decomposition can exceed litter-fall inputs from 10 years until 70 or 80 years of age. Fine roots also supply organic N and P compounds to the soil throughout the year, not just during the fall and winter. Because of the high activity of rhizosphere microorganisms, mineralization of the N and P in decomposing fine roots may be more rapid than from forest floor litter. Thus, a complete understanding of nutrient cycling, nutrient availability, and soil quality in upland hardwood forest stands must consider the belowground turnover of plant tissues as well as the aboveground turnover of leaves, branches, and stems.

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Silvicultural Systems

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TWO-AGED SILVICULTURAL SYSTEMS: DIAMETER DISTRIBUTION AND PREDICTIVE MODELS FOR DETERMINING MINIMUM RESERVE TREE DIAMETERS

Jeffrey W. Stringer'

Abstract-Two-aged silvicultural systems are currently being studied for implementation in Eastern hardwood forests. However, implementation of these systems can be constrained by the reduction in harvesting receipts due to the value left standing in reserve trees. This study developed best-fit equations for predicting the minimum diameter at breast height for reserve trees occupying approximately 20 $feet^2$ of basal area per acre. The mean stumpage value averaged $312.12 per acre for reserve trees selected using standard silvicultural criteria of codominant trees of average diameter and $229.48 per acre for reserve trees selected from the trees having the smallest diameters of those meeting minimum reserve requirements. These values represented 24.8 and 17.1 percent of the total timber receipts. Prediction equations developed in this study can be used as marking guidelines, providing the forest owner with the maximum timber harvesting receipts possible while maintaining a reasonable timber production potential in the reserve trees.

INTRODUCTION

The two-aged system is currently being evaluated for use in Eastern hardwood forests (Beck 1986, Miller and others 1995, Sims 1992). Types of the two-aged system, including deferment cutting and irregular shelterwoods, when initiated in sawtimber-sized stands, involves the retention of 15 to 40 feet $(ft)^2$ of basal area per acre of overstory trees, termed reserves or standards (Nyland 1996). This provides, at least initially, for the rapid growth of the understory and the development of two age classes (Miller and Schuller 1995). These two-aged types have the ability to deliver several important biologic and managerial advantages compared to other regeneration cuts commonly employed in the region, such as clearcutting (Smith and others 1989). Specifically they can provide stands capable of simultaneously providing roundwood and highly valued sawtimber or veneer, maintenance of visual or esthetic standards, and an uninterrupted production of propagules for the development of advanced regeneration throughout a rotation. The latter may be critical in maintaining our ability to regenerate stands, particularly those composed of intermediate and shade intolerant species.

Selection of reserve trees and use of the two-age system should reflect the following concerns:

(1) Availability of appropriate reserve species. Species must be commercially valuable and posses the necessary lifespan to sustain themselves for a second rotation length. In many instances stands will not contain overstory species meeting this criteria; therefore, cuts to develop two-age stands would not be appropriate.
(2) Individual trees must maintain their vigor and bole quality after the initial cut (Brinkman 1955, Miller 1996, Smith 1965). This requires that individual tree selection criteria be developed and adhered to during marking.
(3) Individual trees must be able to survive harvest and postharvest environments. This requires that topographic position, soil characteristics, and the relative size of reserve versus cut trees be taken into account when selecting reserve trees.
(4) Timber harvesting operators must be able to successfully implement harvests.
(5) Impacts of leaving a limited number of mating individuals on the mating systems and potential loss of heterozygosity in progeny, may be of concern in developing two-age stands with extremely low densities. Investigation of this potential problem is currently underway.
(6) The ability to generate reasonable monetary return in the initial cut.

The latter is an important concern if the two-aged system is to be used on private lands. Forest owners, particularity nonindustrial private forest owners, are sensitive to reductions in timber harvesting receipts. Maintaining large stumpage values in reserve trees may limit the use of this system on nonindustrial private forest lands. Therefore, if the two-aged system is to be widely deployed, reserve trees must be selected based on their ability to meet silvicultural objectives as well as to minimally impact harvesting receipts. In the majority of cases, this means selecting reserve trees of the smallest diameter possible that will still meet two-aged timber production objectives. The need for selecting relatively small reserve trees is exacerbated when low stocking levels are encountered. This often precludes the selection of the best trees as reserves. Thus, it is critical to develop individual tree marking guides which will provide for silvicultural objectives in the reserves and allow for implementation of commercial harvests if the two-aged system is to be established as viable options in silvicultural operations on nonindustrial private forest lands.

This study was designed to provide the following:

(1) the diameter at breast height (d.b.h.) distribution of potential reserve trees in sawtimber stands in eastern Kentucky;
(2) useful models for predicting the minimum d.b.h. requirements for reserve tree candidates in stands maintaining <20 ft^2 per acre in reserve basal area; and

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(3) the stumpage value of reserve trees and the percentage of total harvesting receipts contained in the reserves.

The predictive equations can be used to determine minimum d.b.h. requirements for reserve trees, as well as to determine the volume contained in reserve trees. This information can be used by forest managers to determine volume and value reductions in harvest receipts, and by silviculturists and marking crews for determining target diameters for reserve trees.

METHODS

Six .1 O-acre circular plots were randomly established in each of seven timber sale tracts on the Daniel Boone National Forest in eastern Kentucky. These tracts were part of standard sales packages and each tract contained a number of different stands (represented by the plots) growing over a wide range of site indexes (black oak site index 62 to 95, base age = 50). Each of the 42 plots was assumed to represent the stand in which it was contained. Individual measures for trees $\geq$ 5 inches d.b.h. in each plot included species, d.b.h., crown class, live crown ratio, and USFS tree grade (Stringer and others 1989) or potential tree grade (Yaussy 1991). Two sets of potential reserve trees were selected in each plot. Each reserve tree selected was a relatively long-lived species, having a live crown ratio of >40 percent, and a USFS tree grade or potential tree grade of $\leq$2. Set I trees were selected from codominant trees of average d.b.h. Set II trees were selected from trees having the smallest d.b.h. that met the criteria mentioned above. The average d.b.h. of both Set I and Set II trees was determined for each plot. Both linear and curvilinear equations were used to generate best-fit models for Set II means (i.e., the dependent variable was the minimum d.b.h. of the reserve tree candidates) for the primary species groups. Independent variables tested included those that could easily be generated from common timber harvesting or silvicultural data sets, including: total stand basal area per acre, average stand d.b.h., average d.b.h. of the codominant trees, and total stand volume per acre. Graphs were generated for each species or species group. Each graph included the plotting of each mean plot d.b.h. for Set II trees and the best-fit equation.

The International 1/4-inch volume was determined for each tree (Hahn and Hansen 1991). Stumpage value was also determined for each tree using average regional values for the appropriate species groups. Total volume and value per acre were determined for each tract as well as for each set of potential reserve trees. The percentage of the total timber volume and value that was contained in reserve trees of both Set I and Set II was determined.

RESULTS AND DISCUSSION

Descriptive tract data are presented in table 1. All tracts contained sawtimber volumes that were readily merchandisable and were representative of timber harvests in the region. The tract sizes were also common to eastern Kentucky and reflected the dissected nature of the topography. Both reserve tree sets were relatively close to meeting their target basal area objective of 20 ft^2 per acre.

Best-Fit Equations

Best-fit equations for predicting the minimum d.b.h. of reserve trees was obtained using the mean d.b.h. of the codominant trees in the stand as the independent variable. The three most numerous species or species groups contained in both Set I and Set II included: *Quercus alba*, *Q. prinus*, *Acer* spp. (*A. saccharum* and *A. rubrum*). Best- fit equations were for all species and species groups combined as well as for individual groups. A best-fit equation was also developed for the minor species group, which included *Liriodendron tulipifera*, *Carya* spp., *Q. rubra, and Fraxinus americana.* Significant differences were found among species or

Table l-Descriptive statistics and potential reserve basal area by tract

Tract	Area	Diameter at breast height	Board feet	Total BA	Reserve BA Set I[a]	Set II[b]
	Acres	*Inches*	*Int. 1/4"*	*Ft^2/acre*		*Ft^2a^{-1}*
1	23	14.3	16,270	124	21.9	19.6
2	33	14.9	14,880	112	22.4	17.8
3	9	14.3	15,930	116	20.0	21.1
4	15	13.5	16,380	118	20.5	19.7
5	19	10.8	15,390	114	19.2	18.1
6	13	13.5	16,910	124	20.7	20.9
7	15	14.6	15,600	116	21.3	16.5
Mean	18	13.7	15,908	118	20.7	19.1

[a] Set I is composed of codominant trees of average d.b.h. that met the following reserve tree criteria: relatively long-lived species, live crown ratio of >40 percent, USFS tree grade or potential tree grade of $\leq$2.

[b] Set II is composed of trees having the minimum d.b.h. that still meet the minimum criteria for reserve trees as listed above.

species groups. Figure 1 shows the minimum diameter of Set II reserve trees for each plot, and the best-fit equation,

$$y = 2.035041 + .669431 * d.b.h. \ (r^2 = 0.30). \quad (1)$$

While this equation can be useful in determining overall predictions for entire forests, the high degree of variability precludes its use as a tool for developing criteria for individual stands or tracts. Variation is decreased when plotting individual species and species groups and the coefficient of variation increases substantially at this level of analysis (fig. 2). Figure 2(a) shows the plot for Q. *alba* with the best-fit equation,

$$y = sqrt(-2.119e{+}02 + 2.779e{+}01 * x) \ (r^2 = 0.44). \quad (2)$$

This indicates that the minimum diameter of reserve trees for this species was only 1 to 2 inches below the average diameter of the codominants in the stand. In contrast, the minimum diameters for *Q. prinus* reserve trees produced a best-fit equation,

$$lny = .755 + .112 * x \ (r^2 = 0.43) \quad (3)$$

which indicates that reserve trees can be selected from individuals having a d.b.h. of 2 to 4 inches less than the average codominates in the stand [fig. 2(b)]. Figure 2(c) shows the plot for *Acer* spp. with the best-fit equation,

$$y\text{^}2 = 51.621 + 4960.533/x\text{^}2 \ (r^2 = 0.13). \quad (4)$$

The results of this study indicate that reserve tree selection for *A. rubrum* and *A. saccharum* would be independent of codominant d.b.h., with the average minimum d.b.h. of acceptable reserve trees approximately 8 inches. However, the large differential in size between the potential reserve trees and the codominants might increase harvest damage to an unacceptable level (Hesterberg 1957). Selection of reserve trees in this species group would be driven primarily by their position relative to cut trees, rather than by concern over their meeting minimum diameter requirements. The remaining species, primarily *Liriodendron tulipifera, Carya* spp., Q. *rubra, and F. americana,* were not present in great enough numbers to warrant individual analysis and were grouped together for analysis [fig. 2(d)] with a best-fit equation,

$$y\text{^}2 = -209.529 + 24.085 * x, \ (r^2 = 0.64)) \quad (5)$$

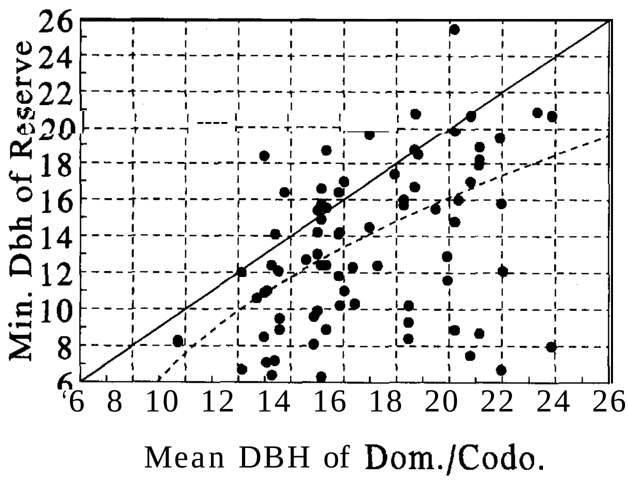

Figure l-Mean minimum d.b.h. requirements of two-age reserve trees. Points represent the average minimum d.b.h. of 20 ft^2 per acre of reserve trees relative to the average d.b.h. of codominant stems in each stand. Dotted line represents the plot of the best-fit equation for these points ($y = 2.035041 + .669431 * d.b.h.$ ($r^2 = 0.30$)).

Effect of Reserve Tree Selection Criteria on Stumpage Values

The stumpage values of Set I reserve trees averaged $312.12 per acre and Set II reserve trees averaged $229.48 per acre (table 2). These values represented 24.8 and 17.1 percent of the timber receipts of the tracts. The difference of approximately $82 per acre would pay for the site preparation costs normally associated with natural regeneration of the commercial species found in the study. The stumpage value determined for the reserve trees is highly conservative and was obtained using the regional average price for stumpage of average grade. As the grade of the codominant trees increases so will the discrepancy in stumpage value between Set I and Set II trees. Regardless, selecting reserve trees with diameters greater than that necessary may decrease the ability of foresters to implement this practice in nonindustrial private forests and will decrease the revenues for site preparation activities.

Table 2-Value per acre of reserve trees left as 20 ft^2 basal area per acre

Tract	Set I Average d.b.h.		Set II Minimum d.b.h.	
	$/acre	*Percent*	*$/acre*	*Percent*
1	301.50	23.0	238.59	18.4
2	334.09	32.1	186.85	16.9
3	289.03	22.6	245.00	20.2
4	322.82	22.5	223.97	22.5
5	328.41	17.9	273.72	14.6
6	281.36	23.3	248.41	20.7
7	327.63	32.5	189.79	13.9
Mean	312.12	24.8	229.48	17.1

Two sets of criteria were used to select reserve trees. Set I: reserves selected from trees of average d.b.h. of the codominates, and Set II: reserves selected from trees having the smallest d.b.h. of trees meeting minimum reserve requirements (USFS tree grade or potential tree grade ≤ 2, live crown ratio >40 percent, long-lived, commercial species).

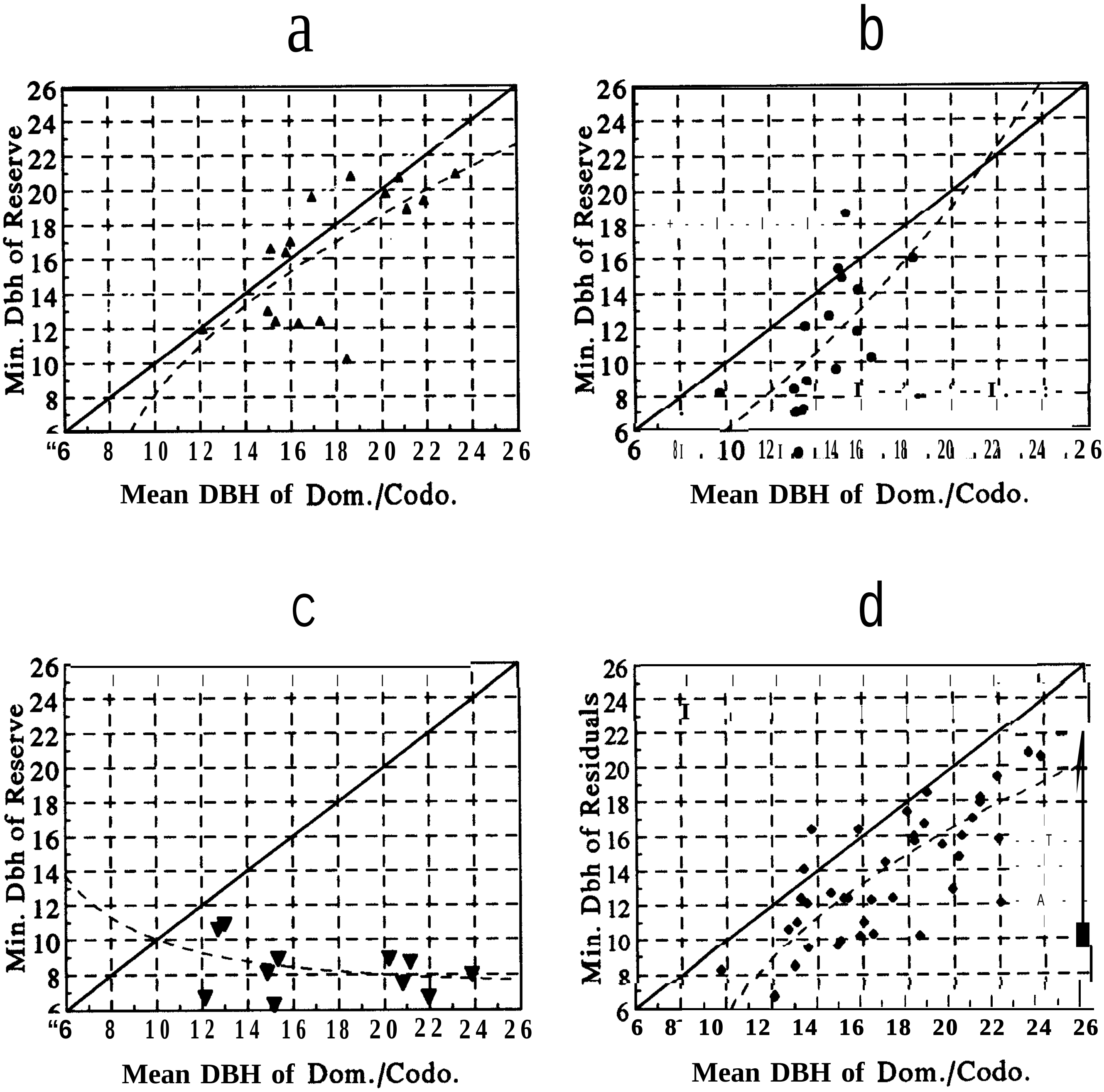

Figure 2—Mean minimum d.b.h. requirements of two-age reserve trees by species and/or species groups. Points represent the average minimum d.b.h. of 20 ff per acre of reserve trees relative to the average d.b.h. of codominant stems in each stand. Dotted line represents the plot of the best-fit equation for these points. (a) *Q. alba*, y = sqrt (-2.119e +02 + 2.779e +01*x) (r^2 = 0.44); (b) *Q. prinus*, lny = .755 + .112*x (r^2 = 0.43); (c) Acerspp., y^2= 51.621 + 4960.533/x^2 (r^2 = 0.13); (d) other species including *Liriodendron tulipifera, Carya* spp., *Q. rubra, and Fraxinus americana* y^2 = *-209.529 + 24.085*x*, (r^2 *= 0.64).*

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GROWTH AND EPICORMIC BRANCHING OF RESIDUAL TREES FOLLOWING DEFERMENT CUTTING IN RED OAK-SWEETGUM STANDS

James S. Meadows[1]

Abstract-Growth and epicormic branching of residual trees were evaluated following deferment cutting in three red oak-sweetgum (*Quercus* spp.-*Liquidambar styraciflua* L.) stands on minor streambottom sites in west-central Georgia. Deferment cutting consisted of complete removal of all stems except previously selected residual trees, to a target basal area of 10 to 15 square feet per acre. Diameter growth of residual trees during the 3-year period following deferment cutting averaged 0.63 inches across all species on all three sites. However, 3-year diameter growth response of oaks was much higher, and averaged 2.10, 1.25, and 1.36 inches for willow oak (Q. *phellos* L.), water oak (Q. *nigra* L.), and overcup oak (Q. *lyrata* Walt.), respectively. In contrast, 3-year diameter growth of green ash (*Fraxinus pennsylvanica* Marsh.) and sweetgum averaged only 0.68 and 0.64 inches, respectively. Production of new epicormic branches on the butt logs of residual trees averaged 7.9 sprouts over the 3-year period, but varied considerably by species. In general, oaks (especially water oak) produced many new epicormic branches, whereas green ash and water tupelo (*Nyssa aquatica* L.) produced very few. However, much variation was found within a species; production of new epicormic branches was highly dependent upon initial vigor of individual trees.

INTRODUCTION

Deferment cutting, also known as the irregular shelterwood method (Smith 1986), is a possible regeneration alternative to clearcutting. In this technique, a stand near rotation age is cut heavily and an underwood of either natural or artificial regeneration is allowed to develop. The two stories, the older residual trees from the previous stand and the younger regeneration from the new stand, are then allowed to develop together as a two-aged stand (Beck 1987). This technique is designed to create a new even-aged stand while leaving 10 to 25 square feet of basal area per acre from the previous stand, primarily for aesthetics.

This alternative regeneration method may be attractive to landowners because it maintains at least some high forest cover continuously on the site, while allowing the development of even-aged stands. Most commercially important hardwood species are best suited to even-aged management (Clatterbuck and Meadows 1993). Continuous maintenance of some forest cover not only improves the aesthetic appearance of the new stand, but also maintains continuous mast production for wildlife. Deferment cutting to produce a two-aged stand provides the benefits of clearcutting (nearly full sunlight to the forest floor to encourage the even-aged development of shade-intolerant species), but reduces the negative attributes associated with clearcutting (unsightly appearance and the loss of mast production from the site for 20 to 30 years).

Beck (1987) observed the development of a two-aged stand 20 years after a deferment cutting in a northern red oak (*Q. rubra* L.) stand in the Southern Appalachian Mountains. The residual overstory responded well, in terms of both diameter and volume growth, to the nearly unlimited growing space provided by the deferment cutting, with little or no loss in bole quality due to excessive epicormic branching. Regeneration in the new stand was similar in both species composition and size to that in an adjacent clearcut of the same age. Consequently, deferment cutting appears to be a viable regeneration alternative to clearcutting, at least in Appalachian hardwood stands, but the technique has not been tested in southern bottom-land hardwood forests.

To address the feasibility of deferment cutting in southern bottom-land hardwood forests, this study evaluated the growth and bole quality development of residual trees following deferment cutting in three red oak-sweetgum stands on minor streambottom sites in west-central Georgia. Specific objectives addressed in the study were (1) to determine the effects of deferment cutting on diameter growth and epicormic branching of residual trees, and (2) to assess the extent of logging damage to residual trees and its effects on tree vigor, epicormic branching, and bole quality.

METHODS

Study Area

The study area consists of three sites within the floodplain of the Flint River in west-central Georgia, on land owned by the Georgia-Pacific Corporation. Two of the three sites are high flats that support small sawtimber stands composed primarily of red oak and sweetgum. The third site is a low flat that supports a small sawtimber stand composed predominantly of water tupelo, green ash, and overcup oak, but with some red oaks and sweetgum on the higher areas. All three stands were about 55 to 70 years old.

Treatments

Two treatments were applied in this study: (1) deferment cutting, and (2) control. Deferment cutting consisted of complete removal of all stems except previously selected residual trees. Target basal area was 10 to 15 square feet per acre. Increment cores from residual trees served as the control treatment, and were used to compare pre- and posttreatment diameter growth.

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Sims (1992) emphasized the importance of selecting vigorous trees of desirable species to be left as residuals following deferment cutting. In general, residual trees should be capable of growing in both volume and value for an extended period of time under very open stand conditions without excessive loss through windthrow, other mortality, or degrade.

Consequently, trees selected as residual trees in this study were classified as preferred growing stock trees, as described by Putnam and others (1960). They were generally the most vigorous and most desirable trees in the stand, and were selected on the basis of the following desirable characteristics: (1) must be in good condition and show no evidence of disease or previous damage; (2) must be of a desirable species for the site and for management objectives; (3) must be in the dominant or codominant crown class; (4) must be capable of being left indefinitely; and (5) must currently meet, or be capable of eventually meeting, the requirements for at least a 16-foot Grade 1 saw log, as defined by Rast and others (1973).

Residual trees were spaced at least 2 chains (132 feet) apart, so that they experienced essentially open-grown conditions after treatment. If possible, residual trees will be left for the duration of the next rotation, or at least until the time of the first thinning in the new stand.

The deferment cutting operation was performed by contract logging crews in September 1993. All trees were directionally felled with a mechanized feller. Rubber-tired skidders were used to remove the merchantable products, in the form of longwood, from the woods.

Plot Design

One square, 20-acre treatment plot was established at each of the three sites. Deferment cutting to a target basal area of 10 to 15 square feet per acre was applied across the entire 20-acre plot.

One square, 4.9-acre measurement plot was established in the center of each 20-acre treatment plot at each site. Each measurement plot is 7 by 7 chains (462 by 462 feet). Corners were permanently marked with PVC pipe driven into the ground. All residual trees within the measurement plots were permanently identified with a numbered aluminum tag.

Measurements and Statistical Analysis

Variables measured on all residual trees included species, diameter at breast height (d.b.h.), merchantable height, height to the base of the live crown, total height, crown class, tree class, length and grade of all saw logs, as defined by Rast and others (1973), and the number of epicormic branches on each 16-foot log section. At the end of each growing season after treatment, d.b.h. and the number of epicormic branches on each 16-foot log section were remeasured.

As described by Meadows (1993), 'logging damage to individual residual trees, in the form of root, bole, or crown injuries, was assessed on the basis of three factors: (1) type of damage, (2) severity of damage, and (3) location of damage.

Data were subjected to analysis of variance for a randomized complete block design with three replications (sites) of two treatments, for a total of six experimental units. All effects were considered fixed. *Alpha* was set at 0.05. Plot- level variables represented the mean for all residual trees on each measurement plot. Means were separated through the use of Duncan's New Multiple Range Test.

RESULTS AND DISCUSSION

Stand Conditions

Based on a pre-harvest inventory conducted during August 1993,[2] stand density across the three sites ranged from 94 to 104 square feet of basal area per acre. Average d.b.h. of upper-canopy trees ranged from about 14 to 18 inches on the two high flat sites, and from 14 to 15 inches on the low flat site. Most of the larger trees in all three stands were oaks (average d.b.h. of oaks was 18.2 inches). Red oaks (primarily willow and water oaks) and sweetgum accounted for 60 to 70 percent of the basal area on the two high flat sites. Other species scattered throughout these two stands included elm (*Ulmus* spp.), sugarberry (*Celtis laevigata* Willd.), overcup oak, maple (*Acer* spp.), green ash, and water tupelo. On the low flat site, water tupelo accounted for 76 percent of the basal area. Other species found in the stand included green ash, overcup oak, sweetgum, red oaks, elm, and maple.

Deferment cutting removed approximately 87 percent of the basal area at each of the three sites, creating essentially open-grown conditions for the residual trees scattered across the areas. Residual stand density ranged from 7.5 to 10.4 trees and 11.5 to 14.9 square feet of basal area per acre. Average d.b.h. of residual trees ranged from 15 to 16 inches across the three sites. Oaks were the largest residual trees, with an average d.b.h. of 18.0 inches. Residual trees on the two high flat sites were primarily sweetgum, red oak (principally water and willow oaks), elm, green ash, and overcup oak, with lesser amounts of water hickory [*Carya aquatica* (Michx. f.) Nutt.], water tupelo, common persimmon (*Diospyros virginiana* L.), and swamp chestnut oak (*Q. michauxii* Nut-t.). Residual trees on the low flat site were predominantly water tupelo and green ash, with lesser amounts of sweetgum, overcup oak, red oak, and sugarberry.

Diameter Growth

Average cumulative diameter growth of residual trees over the 3-year period following deferment cutting is compared to average cumulative diameter growth of residual trees over the 3-year period prior to treatment in table 1. There were no significant differences between posttreatment

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[2] Personal communication. 1993. Robin G. Clawson, School of Forestry, Auburn University, 108 M.W. Smith Hall, Auburn, AL 36849.

Table l-Average cumulative diameter growth of residual trees for the 3-year period before and the 3-year period after deferment cutting

Treatment	Cumulative diameter growth		
	Year 1	Year 2	Year 3
	-----------	Inches	--------
Pre-treatment	0.25[a]	0.53	0.83
Posttreatment	0.22	0.49	0.83

[a] Differences between treatment means within each year are not statistically significant.

diameter growth and pre-treatment diameter growth during any of the 3 years of the study period. In fact, residual trees across all three sites grew an average of 0.83 inches in diameter in 3 years, exactly the same rate of growth observed prior to treatment. Consequently, deferment cutting had no effect on diameter growth of residual trees after 3 years, a result both unexpected and unexplained.

Individual species groups varied in their diameter growth response to deferment cutting (fig. 1). As a group, red oaks responded well to release and grew an average of 1.5 inches in d.b.h. during the 3 years following deferment cutting, as compared to an average growth rate of 1 .1 inches during the 3 years prior to treatment. In contrast, essentially no diameter growth response was observed in green ash, sweetgum, or the white oak group (primarily overcup oak with a few swamp chestnut oaks).

Diameter growth response of individual oak species is presented in fig. 2. Willow oak responded very well to

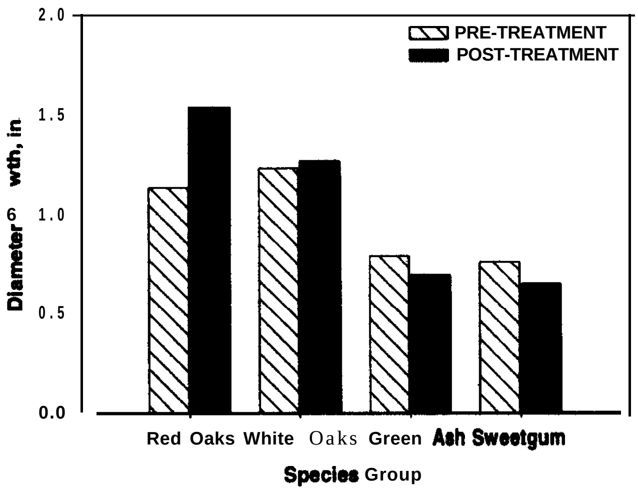

Figure l-Cumulative diameter growth of residual trees, by species group, during the 3-year period following deferment cutting.

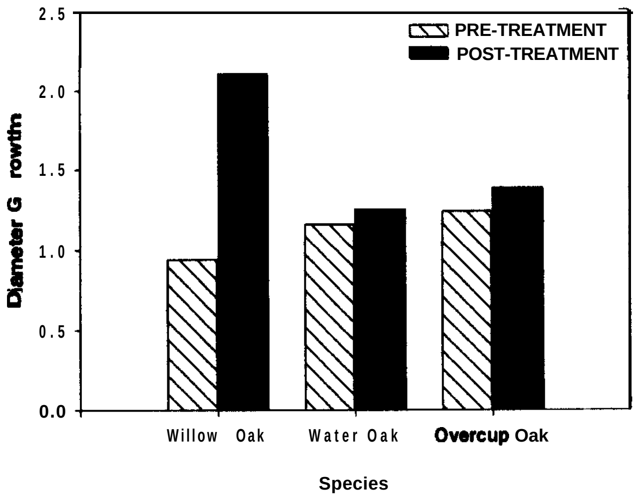

Figure 2—Cumulative diameter growth of residual trees of three oak species during the 3-year period following deferment cutting.

deferment cutting and grew an average of 2.1 inches in d.b.h. over the 3-year period, more than double its average pre-treatment growth rate of 0.9 inches. Both water and overcup oaks produced only small increases in diameter growth 3 years after deferment cutting.

Although deferment cutting had no statistically significant effect on diameter growth of residual trees, when averaged across all species, it does appear that diameter growth of willow oak, and, to a lesser extent, water and overcup oaks, will be increased by deferment cutting. These increases will likely become more pronounced as the study progresses.

Epicormic Branching

The cumulative production of new epicormic branches on both butt logs and upper logs of residual trees during the 3-year period following deferment cutting is summarized in table 2. Across all species and across all three sites, deferment cutting resulted in the production of 7.9 new epicormic branches on the butt logs and 10.6 new epicormic branches on the upper logs of residual trees. In

Table 2-Number of new epicormic branches produced on both butt logs and upper logs of residual trees during the 3-year period following deferment cutting

Log position	Cumulative total of new epicormic branches		
	Year 1	Year 2	Year 3
Butt log	3.7	6.6	7.9
Upper logs	3.2	7.8	10.6
Total	6.9	14.4	18.5

general, as few as five epicormic branches are enough to cause a reduction in grade of butt logs of hardwood trees (Meadows and Burkhardt, in press). In this study, nearly eight new epicormic branches were produced on the butt logs of residual trees. Although log grade has not been reevaluated since the deferment cutting was conducted, it is likely that many of the butt logs of residual trees have experienced a one-grade reduction in log grade as a result of new epicormic branches produced in response to deferment cutting. This probable reduction in log grade may also result in a significant loss of value of the standing timber.

Differences in epicormic branching among species— Species varied greatly in the number of new epicormic branches produced in response to deferment cutting (fig. 3). These observations support the contention that hardwood species vary considerably in their propensity to produce epicormic branches following some type of disturbance (Meadows 1995). For example, red oaks, classified by Meadows (1995) as highly susceptible to epicormic branching, averaged 20.6 new epicormic branches on the butt log 3 years after deferment cutting, whereas green ash, classified as a much more resistant species by Meadows (1995), averaged only 2.5 new epicormic branches on the butt log. White oaks and sweetgum, both classified as highly susceptible by Meadows (1995), actually ranked intermediate between the red oaks and green ash in the production of new epicormic branches in this study.

On average, the three primary species of oaks found in this study produced numerous epicormic branches in the 3-year period following deferment cutting (fig. 4). Generally, more new epicormic branches were produced on upper logs than on butt logs. All three oak species produced at least 14 new epicormic branches on the butt log; water oak, with an average of 23.5 new epicormic branches, was the most prolific sprouter. Meadows (1995) classified all three of these

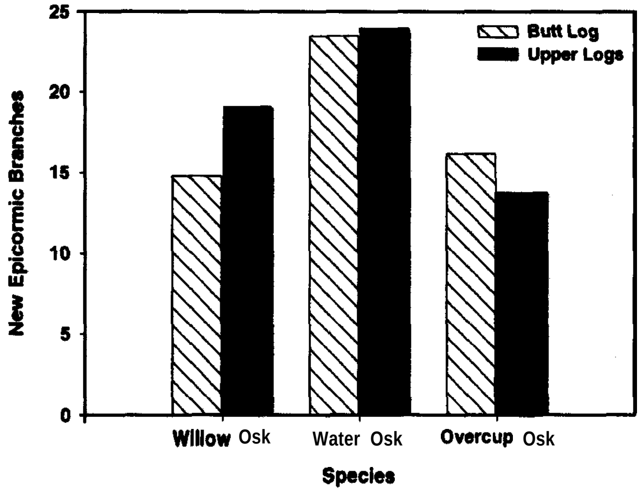

Figure 4-Number of new epicormic branches produced on both butt logs and upper logs of residual trees of three oak species during the 3-year period following deferment cutting.

oak species as highly susceptible to epicormic branching, an assessment certainly supported by these data.

Differences in epicormic branching among crown classes-Production of new epicormic branches also varied greatly among crown classes (fig. 5). The data form an orderly progression of increasing production of new epicormic branches from the dominant crown class through the codominant class to the intermediate class. Meadows (1995) proposed that tree vigor greatly affects the propensity of an individual hardwood tree to produce epicormic branches following some type of disturbance. Under this hypothesis, high-vigor trees are much less likely to produce epicormic branches than are low-vigor trees. Given that crown class is a reasonably adequate indicator

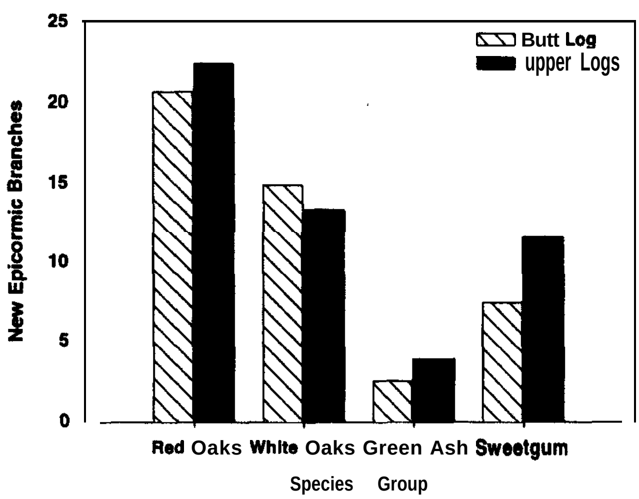

Figure 3-Number of new epicormic branches produced on both butt logs and upper logs of residual trees, by species group, during the 3-year period following deferment cutting.

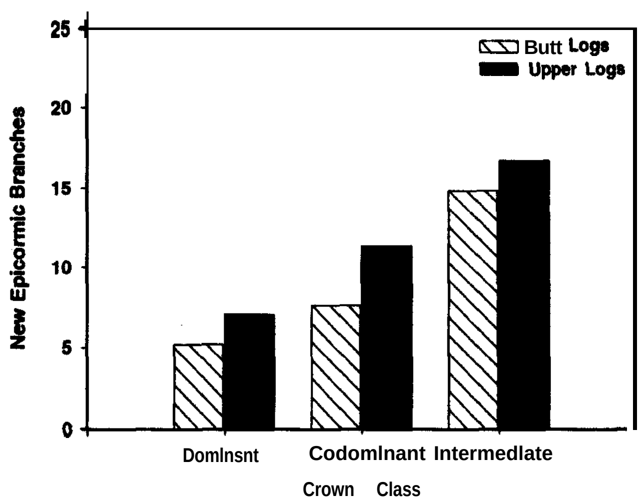

Figure 5—Number of new epicormic branches produced on both butt logs and upper logs of residual trees, by crown class, during the 3-year period following deferment cutting.

of tree vigor, the results obtained in this study tend to support the hypothesis that the production of new epicormic branches increases as initial tree vigor declines.

The apparent relationship between tree vigor and production of new epicormic branches was also observed across red oak crown classes (fig. 6). Dominant and codominant red oaks averaged 12.8 and 16.2 new epicormic branches on the butt log, respectively, whereas less-vigorous, intermediate red oaks averaged 52.3 new epicormic branches 3 years following deferment cutting. Even though red oaks are classified as highly susceptible to epicormic branching (Meadows 1995), the data from this study indicate that this inherent propensity to produce epicormic branches is diminished in high-vigor trees, even of highly susceptible species. However, intermediate red oaks, which represent a combination of highly susceptible species and low-vigor trees, were very prolific sprouters because they were unable to suppress their inherent propensity to produce epicormic branches.

Epicormic branching varied greatly not only among species but also among crown classes, especially within the red oak group. These observations support the hypothesis proposed by Meadows (1995) that the propensity of an individual hardwood tree to produce epicormic branches following some type of disturbance is inherently controlled at the species level, but is greatly modified by tree vigor, such that high-vigor trees, even of a highly susceptible species, are much less likely to produce epicormic branches than are low-vigor trees of the same species.

Logging Damage

A survey of logging damage across all three sites revealed that an average of 47 percent of the residual trees were damaged at least to some extent. This proportion of damaged trees is unacceptably high, particularly for stands in which residual trees are so widely scattered that skidder operators have ample space to maneuver. However, most of the logging damage found in this study was minor and probably will not result in a permanent loss of tree vigor.

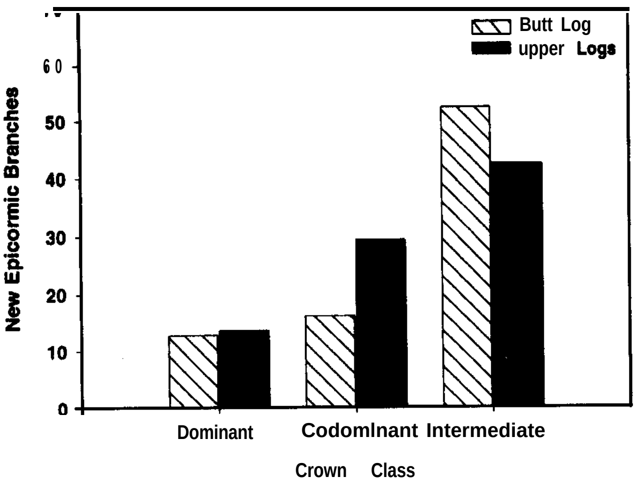

Figure 6-Number of new epicormic branches produced on both butt logs and upper logs of residual trees, by red oak crown class, during the 3-year period following deferment cutting.

The extent of the logging damage varied widely among the three sites, and ranged from 24 percent on one of the high flats to 65 percent on the other high flat. Logging damage on the more difficult terrain encountered on the low flat was 45 percent. Because different logging crews were contracted to cut each of the three sites, it is apparent that much of the differences in logging damage observed among the sites was due to differences among the logging crews in proper harvest planning and skidder operation.

Most of the damage occurred as logs pulled by the skidder scraped the lower boles and/or exposed lateral roots of residual trees. Although some degree of logging damage must be expected during any partial cutting operation, the extent of damage can be minimized through better planning of the logging operation and through more careful skidder operation.

CONCLUSIONS

Surprisingly, deferment cutting had no significant effect on average diameter growth of residual trees, except in willow oak, where diameter growth more than doubled during the 3-year period following treatment.

Deferment cutting also resulted in the production of numerous new epicormic branches along the boles of residual trees. However, the extent of epicormic branching varied widely among species and among crown classes. High-vigor, upper-crown-class trees produced considerably fewer new epicormic branches than did low-vigor, lower-crown-class trees, especially among red oaks.

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LEAVE-TREE MARKING VERSUS MARKING TO CUT— A COMPARISON OF SILVICULTURAL TACTICS

James M. Guldin, Fernando Carrillo, Miguel Acosta, and Raymond P. Guries'

Abstract-Leave-tree marking, or marking trees for retention, is commonly used in uneven-aged silviculture in western States but not in southern pines. We compared marking accuracy in one study (six It-hectare stands) in which leave trees were marked, with that from a second study (sixteen 40-acre stands) in which trees were marked for cutting. Each study included similar shelterwood and single-tree selection treatments. Acceptable marking accuracy was defined as marking a stand to within ± 10 percent of the residual basal area target. Accuracy of leave-tree marking was acceptable in most tests, as was accuracy of cut-tree marking. With leave-tree marking, the tendency to undermark a stand leads to more, not less, overstory removal; this is important in uneven-aged silviculture, in which regeneration can be suppressed if too many leave trees are retained. Leave-tree marking might also be helpful in stands for which pre-harvest inventory information is limited, because it permits a direct tally of residual trees and basal area.

INTRODUCTION

Reproduction cutting methods in which a residual stand is retained after cutting, such as the even-aged shelterwood and uneven-aged single-tree selection methods, challenge the technical ability of both the silviculturist and the marking crew. If too few trees are retained, seed production and shelter may be foregone; if too many trees are retained, regeneration may become suppressed. The best silvicultural prescription is of little value if the marking crew is unable to mark the stand to achieve the prescribed stocking and stand structure.

When marking a reproduction cutting in a stand, a marking crew must distinguish between trees that are to be cut and those to be retained. This is usually done by marking and tallying the trees that are to be cut. This method has the advantage of generating a precise tally of volume being harvested. But if done carelessly, cut-tree marking can make crew members more concerned about the timber volume being harvested rather than about the desirable attributes of the trees being retained.

The main criterion for successful reproduction cutting is whether the stand successfully regenerates, not how much volume is removed. A properly marked stand is one that retains the best phenotypes at prescribed levels of stocking. But as the target stand structure becomes more complicated, so does accurate marking. For example, uneven-aged reproduction cutting requires leaving both the target residual basal area (RBA) and the proper distribution of trees across diameter classes. This is difficult for marking crews that lack experience with the method.

In Western States, silviculturists in uneven-aged stands have often used leave-tree marking, or marking trees for retention, instead of cut-tree marking (Becker 1995). Leave-tree marking provides a direct tally of the residual stand rather than of the trees being cut; crews that use cut-tree marking typically do not tally the residual stand. In addition, leave-tree marking allows experienced markers to compensate for diameter classes that have a deficit of trees by marking a comparable basal area in classes that have surplus trees. These advantages are especially useful when uneven-aged stands with complicated residual stand structures are being marked.

But leave-tree marking for reproduction cutting is uncommon in southern silviculture. Foresters sometimes mark leave trees in dense plantations or natural stands at the time of the first thinning, but use of a "logger-select" method, or no marking at all, is more common. Leave-tree marking has been used increasingly to mark residual trees in shelterwood and seed-tree stands on national forest land, but cut-tree marking is almost always used concurrently to meet other administrative requirements.

The objectives of this study were to compare the accuracy of leave-tree marking with that of cut-tree marking, and to briefly examine the advantages and disadvantages of leave-tree marking applied to southern pine stands.

METHODS

Comparisons were based on data from two separate studies in which the method of marking was carefully monitored, but in which the marking was otherwise done much as it is in operational practice. In one study, trees were marked for retention; in the other, trees were marked for cutting.

First Study-Leave-Tree Marking

Study area-Leave-tree marking data were obtained from a study of Montezuma pine (*Pinus montezumae* Lamb.) in Mexico. Montezuma pine, Mexico's most important commercial conifer, is a yellow pine that attains a diameter of 1 meter (m) and a height of 35 m (Perry 1991). The study was located approximately 100 kilometers east of Mexico City at Campo Experimental San Juan Tetla (CE

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SJT), which is administered by Region Centro of the Instituto Nacional de Investigaciones Forestales y Agropecuarias (INIFAP), the national forestry research organization of Mexico. The stand lies at an elevation of 3300 m and has a southeasterly aspect. Topography is gentle to moderately steep (10 to 30 percent). Soils are deep, fertile, and of volcanic origin; the litter layer is over 0.5 m deep at some locations within the stand.

The 40-hectare (ha) stand used in this study was dominated by Montezuma pine, with minor proportions of three other conifers-a white pine (*P. ayacahuite* var. *veitchii* Shaw), a yellow pine (*P. teocote* Schl. & Cham.), and a fir (*Abies religiosa* Mart.). Hardwoods in the stand included an alder (*Alnus firmifolia* Fernald), willows (*Salix oxylepis* C.K. Schneid. and other *Salix* spp.), and an oak (*Quercus laurina* H.& B.). The understory is dominated by small *Alnus* spp., *Quercus* spp., *Salix* spp., and *Senecio* spp. The understory is dense (-20,000 stems per ha); walking through the stand is difficult.

Before treatment, stand basal area was 37.6 m^2 per ha, of which 32.8 m^2 per ha was Montezuma pine. Montezuma pine composed 70 percent of the stems and 87 percent of the basal area per ha. The quadratic mean diameter of Montezuma pine was 61.3 centimeters (cm), and 3.5 percent of the Montezuma pine trees in the study had diameters greater than 90 cm. Dominant Montezuma pines were approximately 35 m tall and 90 years old. Mature white pines were of similar size, and the largest tree measured was a fir with a diameter exceeding 1.4 m.

Installation of study plots-Eight square 4-ha treatment plots were located in January 1995. Each of these contained one square, concentrically located, 1 -ha measurement plot. In January 1996, two replications of four treatments were installed, with one replication x treatment combination per 4-ha plot. The four treatments included two different shelterwood prescriptions, a single-tree selection prescription, and an uncut control (table 1). A 25 percent cruise of each 4-ha plot was used to develop a plot-specific marking tally for the reproduction cutting treatment in each plot. Marking tallies listed the number of trees to be retained by species and 5-cm diameter classes.

The shelterwood treatments were developed using spreadsheet software. For each treatment, the target number of trees within each diameter class was identified, and adjustments were made as marking proceeded to ensure that the tally matched the target RBA.

For the single-tree selection treatments, desired stand structure was obtained by applying the "BDq" approach (Leak 1964, Marquis 1978) using spreadsheet software. Several diameter classes had deficits of trees when compared to the target q. Since meeting the RBA target was thought to be more important than meeting the target q, the basal area deficit was distributed among the diameter classes that had surplus trees. This was done by developing a second q curve just for the surplus classes, such that the cumulative difference in basal area between the first and second q curves was equal to the deficit. Thus, six separate marking tallies-four shelter-wood and

Table l-Target stand structure for the Montezuma pine study and the shortleaf pine study

Treatment	Target RBA[a]	Dmax[b]	Dmin[c]	Keep[d]	q[e]
Montezuma pine study					
	d/ha	*cm*	*cm*	*Pct*	
Shelterwood, heavy	20	87.5	52.5	80	n/a
Shelterwood, moderate	15	87.5	62.5	75	n/a
Single-tree selection	21	87.5	n/a	n/a	1.21
Shortleaf pine study					
	ft²/ac	*In*	*In*	*Pct*	
Shelterwood					
a. Pine	40	n/a	14-18	80	n/a
b. Pine-hardwood	30	n/a	14-18	80	n/a
Single-tree selection					
a. Pine	60	20	n/a	n/a	1.44
b. Pine-hardwood	50	20	n/a	n/a	1.44

[a] RBA is the residual basal area (m^2/ha) in the pine component.
[b] Dmax is the maximum diameter class retained.
[c] Dmin is the minimum diameter class retained.
[d] Keep is the percentage of trees retained in diameter classes between Dmax and Dmin to improve residual tree quality.
[e] q is the ratio between the number of stems in adjacent diameter classes.

two single-tree selection tallies-were prepared for the six 4-ha plots being marked.

Marking trees for retention-Three two-person marking crews did the marking, and a seventh person supervised the marking tally. One 4-ha treatment typically required three passes by the marking crews, and took 3 to 4 hours to mark. When a candidate residual tree was found, its diameter at breast height (d.b.h.) was measured and called out to the tally person. If the tally person indicated that the tree was acceptable for retention, the south face of the tree's bole was marked by blazing a smooth area on the bark surface (not to the cambium) with a machete (traditional Mexican technique), and spraying it with paint.

The tally person kept a cumulative tally of marked trees in all diameter classes, and compared this with the target residual stand based on the pre-hat-vest inventory. The marking tally typically deviated from the target, because of sampling error and silvicultural considerations such as size and spacing of residual trees. The challenge for the tally person was to balance the deviations in the tally by basal area. This was done by calculating the unmarked target basal area in the diameter classes where the target was not obtained, and by marking an equivalent basal area of trees in the diameter classes where the target was exceeded. With experience, this balance was obtained in the woods as the markers worked their way through the stand. All trees in the stand that were not marked with paint were subject to be cut.

Second Study-Marking Trees to Cut

Study area-Data on marking trees to cut were obtained from a replicated operational research study in 52 mature shortleaf pine (*P. echinata* Mill.) and pine-hardwood stands on south- and southwest-facing slopes in the Ouachita and Ozark National Forests (Baker 1994, Guldin and others 1994). Methods for stand selection and random assignment of treatments have been described elsewhere (Baker 1994, Guldin and others 1994).

Four treatments (16 stands) from the larger study were used in this comparison (table 1). In two of the treatments, pine shelterwood and pine single-tree selection, retention of hardwoods in the residual overstory was minimized; RBA targets were almost entirely pine. In the remaining two treatments, pine-hardwood shelter-wood and pine-hardwood single-tree selection, retention of 10 feet $(ft)^2$ per acre of hardwoods was required. In the present study, however, only the accuracy of marking in the pine component of the stands is considered.

Installation of study plots-In 1991, a pre-harvest inventory (10 percent, using 0.2-acre fixed-radius plots) was conducted in each stand by national forest personnel. A reproduction cutting treatment was randomly assigned to each stand. Research team silviculturists then used the pre-harvest inventory data to develop marking guidelines unique to each stand based on each stand's randomly assigned prescription.

Twelve research plots were installed within the harvested area of each 40-acre stand (Baker 1994, Guldin and others 1994). Each plot consisted of a variable-radius (basal area factor 5.0) overstory plot, a fixed-radius (O.l-acre) midstory plot, and nested shrub and herbaceous plots. In this comparison, residual stand conditions are based on only the merchantable-sized trees (trees 3.6 inches in d.b.h. and larger) on overstory and midstory subplots. Marking accuracy for each treatment was based on the observed after-cut condition of each plot, relative to the target RBA, across 48 plots.

Marking trees for cutting-Trees to be cut were identified directly. For even-aged treatments, instructions were to leave the target pine RBA (30 or 40 ft^2 per acre, depending on the treatment) primarily from the upper crown classes by marking primarily from below. For uneven-aged treatments, the pre-harvest stand structure was compared with a BDq target structure with a specified RBA (50 or 60 ft^2 per acre, depending on the treatment). A marking tally was generated from the difference between the pre-harvest inventory and the BDq target, after adjusting for deficit diameter classes by adding equivalent basal area in surplus classes according to the q (Leak 1964, Marquis 1978), as described previously.

Marking was done by national forest marking crews in summer and fall of 1992, in conformity with standard practice in the USDA Forest Service, Southern Region. Trees were marked for cutting based on the marking tally provided by the research team. Marking guidelines included a tally of the number of trees per acre and per stand to cut by 2-inch diameter classes.

Calculation of Marking Accuracy

For each study, marking accuracy was calculated as the deviation in residual basal area (dRBA):

dRBA = (observed RBA after cut) - (target stand RBA).

Because the Montezuma pine study is in metric units and the shortleaf pine study is in English units, dRBA was standardized as a percentage deviation (percent dRBA) from the target RBA as follows:

percent dRBA = dRBA/(target stand RBA).

This allows direct study-to-study comparisons of marking accuracy. Positive values for dRBA and percent dRBA indicate that the observed RBA is greater than the target RBA, or that too many trees were retained. Negative values of dRBA and percent dRBA indicate that too few trees were retained.

RESULTS

Leave-Tree Marking

Marking accuracy was acceptable in two of the three reproduction cutting methods with Montezuma pine at CE SJT (table 2). In both the moderate shelterwood and the single-tree selection treatments, marked RBA was within 1

Table 2—Mean marking accuracy data for the treatments in the study

Treatment	Target RBA	Marked RBA	dRBA	Percent dRBA
Montezuma pine study				
	---	-------m²/ha-	....	
Heavy shelterwood	20.03	16.02	-4.01	-20.0
Moderate shelterwood	15.02	15.26	0.24	1.6
Both shelterwoods	17.52	15.64	-1.88	-9.2
Single-tree selection	20.98	20.12	-0.86	-4.1
All treatments	18.67	17.13	-1.54	-7.5
Shortleaf pine study				
	--------	ft²/ac	....	
SW, pine[a]	40.0	39.04	-0.96	-2.4
SW, pine-hardwood	30.0	32.26	2.26	7.5
Both shelterwoods	35.0	35.65	0.65	2.6
STS, pine[b]	60.0	64.92	4.92	8.2
STS, pine-hardwood	50.0	55.35	5.35	10.7
Both STS treatments	55.0	60.14	5.14	9.5
All treatments	45.0	47.89	2.89	6.0

[a] SW: shelterwood.
[b] STS: single-tree selection.

m² per ha (5 percent) of the target. However, the heavy shelterwood method was marked too heavily, with RBA 4 m² per ha (20 percent) under target. When marking, crews found it difficult to justify retaining trees of poor form in the smaller diameter classes simply to meet the target RBA.

When both shelterwood treatments were combined, the overall marking accuracy was acceptable (table 2), within 2 m² per ha (9.2 percent) under the target. Again, this RBA was slightly lower than intended.

Marking accuracy for all three treatments combined was also within acceptable limits. The marked RBA was 1.54 m² per ha (7.5 percent) under the target. Therefore, we judged marking trees for retention to be an acceptably accurate method of marking; deviations were in the direction of retaining slightly less RBA than the prescribed target.

Cut-Tree Marking

Marking accuracy was acceptable in both the pine and pine-hardwood shelterwood treatments in the Ouachita shortleaf pine study (table 2). The pine shelterwood treatment was overmarked slightly, with RBA averaging -1 ft' per acre (2.4 percent) below the target. In the pine-hardwood shelterwood, the pine component was undermarked slightly; RBA was a little more than 2 ft² per acre (7.5 percent) greater than the target. For the shelterwood treatments combined, marking accuracy was within 1 ft² per acre (2.6 percent) of the target.

In the single-tree selection stands, cut-tree marking was slightly less accurate but still acceptable (table 2). The pine component was slightly undermarked in the pine single-tree selection stands; RBA was about 5 ft² per acre (8.2 percent) greater than the target. The pine-hardwood treatments were of marginally unacceptable accuracy—mean RBA was just over 5 ft² per acre (10.7 percent) greater than the target RBA. For the two single-tree selection treatments combined, actual RBA exceeded target RBA by 5.1 ft² per acre (9.5 percent)-just within the 10 percent margin of acceptable accuracy.

Marking accuracy was also well within the pre-established standard for all cut-tree marking treatments combined. The marked RBA was just less than 3 ft² per acre (6 percent) higher than target RBA. All of these data indicate that cut-tree marking was acceptably accurate, though marginally so in some treatments.

Comparison of Methods

Percent dRBA figures for both studies show that marking accuracy was generally acceptable-within 10 percent (table 3). Overall, cut-tree marking was the more accurate method in the pine shelterwood treatments. However, leave-tree marking was slightly more accurate than cut-tree marking in the single-tree selection stands. Marking accuracy was unacceptable (percent dRBA greater than 10 percent) in only one of the six treatment and marking combinations.

In both treatments with leave-tree marking, after-cut stands had negative deviations from the target, indicating the

Table 3-Marking accuracy (percent dRBA), leave-tree marking versus cut-tree marking in shelterwood and single-tree selection treatments

Treatment	Percent dRBA leave-tree marking	Percent dRBA cut-tree marking pine	Percent dRBA cut-tree marking pine-hardwood
Shelterwood	-9.2	-2.4	7.5
Single-tree selection	-4.1	8.2	10.7
All treatments	-7.5	2.9	9.1

stands were overcut slightly (table 3). Conversely, three of the four cut-tree marking treatments had after-cut stands with positive deviations from the target (table 3), indicating a slightly undercut stand (more overstory residual basal area than the target). Undercutting was more likely in the single-tree selection than in the shelterwood treatments, and more likely in the pine-hardwood treatments than in the pine treatments.

DISCUSSION

These data suggest that leave-tree marking can be a feasible alternative to cut-tree marking; both were generally similar in marking accuracy. Overall, leave-tree marking generally resulted in accuracy within 10 percent of the RBA target. Leave-tree marking was slightly less accurate than cut-tree marking where the shelterwood method was employed, but slightly more accurate than cut-tree marking when the single-tree selection method was used. Generally, as the residual stand structure was increasingly complicated (higher RBA or an increasing hardwood component), cut-tree marking became less accurate.

This comparison is not extremely robust statistically. The two studies were established in different forest types in different countries, by different marking crews. Edaphic, climatic, and physiographic conditions differed between studies, and different experimental designs and units of measurement were used. But key elements of the comparison are robust-all marking plans in both studies were developed in very much the same way by the same investigator. Comparable silvicultural systems were analyzed, and the percent dRBA marking accuracy statistic was designed to equalize data based on different measurement units.

Leave-tree marking has several attributes that justify its consideration as an alternative to cut-tree marking. First, the method allows timber markers to concentrate directly, rather than indirectly, on the trees to leave. If too much attention is paid to marking the trees to cut, the residual stand becomes a byproduct of the harvest-especially in the valuable larger size classes. Leave-tree marking results in a marking job more in line with the silvicultural rationale by which the decision to retain a residual stand was initially made.

Second, the tendency of markers to undermark-to put paint on fewer trees than is specified on the marking tally—leads to different results under the two methods. When marking trees to cut, undermarking results in RBAs that exceed target levels. For example, pines in the single-tree selection stands in the Ouachita study were undermarked by 5 ft^2 per acre, and pines in the pine-hardwood treatment were undermarked by over 10 ft^2 per acre. These RBAs may be sufficiently high to preclude adequate development of regeneration through the cutting cycle. Conversely, when marking trees to leave, undermarking results in RBA that is lower than the target level, as in the heavy shelter-wood treatment in the Mexico study. This results in a less dense residual overstory than intended-and such an overstory is more favorable for establishment and development of regeneration than one that is too dense.

Leave-tree marking has another advantage when applied to the single-tree selection method. Existing practice in uneven-aged silviculture requires a pre-harvest stand inventory to prepare the marking tally. This inventory has a sampling error associated with it. Under cut-tree marking, all trees marked to cut are tallied-essentially a 100 percent tally of trees being cut. Thus, that original pre-harvest sampling error will be carried into the residual stand, since the 100 percent marking tally has, by definition, no error. The result is that the target RBA may be missed by a factor directly related to the sampling error in the pre-harvest inventory.

On the other hand, if leave-tree marking is used, all trees marked to leave are tallied. This gives a direct calculation of the target RBA. The pre-harvest sampling error is placed "on the logging deck" in the trees being cut. This is a more desirable silvicultural situation especially if accurate retention of the residual stand is critical, as it can be for uneven-aged reproduction cutting.

From this, it follows that leave-tree marking may provide a way to mark uneven-aged stands accurately without a pre-harvest inventory. If a reasonable target residual BDq structure for average stand conditions can be developed for typical stands in a given ecological land type, then one could mark directly to that target. The requirement of a pre-harvest inventory has hindered the use of uneven-aged silviculture in certain situations, such as national forest land in which district technical support is becoming increasingly limited. However, this would work only if the stand was fairly typical. Otherwise, extreme care would be needed to avoid potentially serious deviations from the target.

Certainly, leave-tree marking has disadvantages. Foremost among them is the considerable effort and time that goes into determining the volume to be harvested. For example, Region 8 of the USDA Forest Service has developed detailed procedures for estimating the volume of timber being harvested based on a subsample of trees marked for cutting. Such procedures would require extensive modification to enable them to generate accurate volumes under leave-tree marking. On the other hand, Region 8 has occasionally conducted area-estimation sales for even-aged stands, and this could be done for uneven-aged stands as well.

Second, new procedures for monitoring harvests will be needed when leave trees are marked because the trees being cut are unmarked. It would be important to clearly identify stand boundaries to prevent cutting of unmarked trees in stream protection zones or beyond project boundaries. Procedures for preventing cutting of unmarked trees (tracer paint, for example) would have to be replaced by procedures for preventing cutting of marked trees (stump inspections for marks that have been removed or obscured).

Third, leave-tree marking can be more labor-intensive than cut-tree marking. In a shelterwood where RBA is being reduced from 90 to 30 ft^2 per acre, there are relatively few leave trees to be marked. However, in a well-balanced uneven-aged stand where RBA is being reduced from 75 to 60 ff per acre, leave-tree marking will be much more labor-intensive than cut-tree marking because the bulk of the basal area must be marked. Thus, if leave-tree marking has a role in southern silviculture, it may well be as a method applied in converting even-aged stands to uneven-aged structure, where stand basal area is taken from 100 to 120 ft^2 per acre to 50 to 60 ft^2 per acre, and where the quality of residual trees must be considered.

Finally, paint on residual trees after the cut may be visually unattractive. One modification might be to mark trees inconspicuously, such as with a vertical stripe from groundline to 3 feet on the side that faces away from roads. Another might be to use colors that blend into the forest. A third might be to change colors from one harvest to the next, especially where short cutting cycles (3 to 5 years) are employed.

In summary, leave-tree marking may be a useful alternative to cut-tree marking in certain silvicultural applications. Our data suggest that crews can mark with similar accuracy by both methods. A broader operational test would be needed to identify the practical modifications required for administration of timber sales. Given its practical advantages, especially relative to uneven-aged reproduction cutting, leave-tree marking might have a place in the repertoire of the silviculturist.

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Intermediate Management

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TEN-YEAR GROWTH RESPONSE OF RED AND WHITE OAK CROP TREES TO INTENSITY OF CROWN RELEASE

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Abstract-A thinning study of 60-year-old northern red oak (*Quercus rubra* L.), black oak (Q. *velutina* Lam.), and white oak (Q. *alba* L.) was superimposed on an existing crown-release study in the Boston Mountains of Arkansas during the summer of 1965. In the new study, individual crop trees were released to achieve relative stocking densities of 40 percent, 60 percent, or 80 percent, and control. The rule thinning method, which defines a thinning radius based on d.b.h., was employed. Ten-year diameter-growth response was influenced by the previous crown release treatment, species, and relative stocking density. Rule thinning can be used to effectively release potential red and white oak crop trees in intermediate-aged mixed oak stands. However, some competing trees-such as leaning trees, and large-diameter trees up-slope from the crop tree-may reduce growth benefits. These situations have to be considered for successful application of rule thinning.

INTRODUCTION

Several hundred thousand acres of forest land in northern Arkansas support overstocked, even-aged stands of pole- to small sawtimber-size oaks. Although many stands are on medium to good sites (site index of 60 to 70 feet at 50 years), diameter growth averages only about 1 inch in 10 years. Growth in these stands can be increased by areawide thinning to target stocking densities (Dale and Hilt 1986, Graney and Murphy 1994), which reallocates site resources to fewer trees, shortens time required to grow products to a given size, and allows utilization of low-vigor and poor-quality stems that would ordinarily die. However, this type of thinning does not guarantee effective release of all high-quality, potentially high-value stems (Lamson and others 1990, Smith and others 1994). Although there are markets for small hardwood roundwood in northern Arkansas, the value of the product is often too low to make these thinnings profitable.

Crop-tree release could provide an alternative means of increasing or maintaining growth of high-quality stems. The crown-touching method of crop-tree release (Smith and Lamson 1986, Lamson and others 1990) is a simple, straightforward, and effective method of releasing selected crop trees by removing the competing trees whose crowns touch the crown of the selected crop tree. Rogers and Johnson (1985) have suggested a crop-tree release technique they call rule thinning. In this method, diameter at breast height (d.b.h.) and a specified relative stocking are used to determine the thinning radius around the crop tree.

This paper summarizes lo-year diameter-growth response of red oaks [northern red (Quercus *rubra* L.) and black (Q. *velutina* Lam.)] and white oak (*Q. alba* L.) to crown release achieved by rule thinning. It describes the effects of first and second crown-release treatments on diameter growth of red and white oak crop trees and describes the effect of relative stocking density on crop-tree growth.

METHODS

Study Region

The Boston Mountains are the highest and most southern member of the Ozark Plateau's physiographic province. They form a band 30 to 40 miles wide and 200 miles long from north-central Arkansas westward into eastern Oklahoma. Elevations range from about 900 feet in the valley bottoms to 2,500 feet at the highest point. The plateau is sharply dissected, and most ridges are flat to gently rolling and are generally less than 0.5 mile wide. Mountainsides consist of alternating steep simple slopes and gently sloping benches.

Annual precipitation averages 46 to 48 inches, and March, April, and May are the wettest months. Extended summer dry periods are common, and autumn is usually dry. The frost-free period is normally 180 to 200 days long.

Study Description

Original study treatments-This study utilized 272 individual red and white oak crop trees that had been part of the crown-release and fertilization study established on Ozark National Forest land in 1974 (Graney 1987). The study was installed in three overstocked 50-year-old mixed oak poletimber stands on south- or west-facing mountain benches. In each stand, 40 to 48 red oak and 40 to 48 white oak crop trees were selected for the crown-release and fertilization treatments. All study trees were tightly grown, small-crowned codominants that required release. For each species group, one-half of the trees were randomly assigned crown release or no release, and each tree was randomly assigned one of three N-P fertilizer treatments. Crowns were released by removing two major competitors and only remaining smaller trees until the basal area based on a lo-factor prism count around each crop tree was reduced to about 70 ft^2 to approximate B-level stocking. Before treatment, mean d.b.h. for red oak sample trees was 8.33 inches, mean d.b.h. for white oak sample trees was 8.08 inches, and stand basal area averaged 122 ft^2 per acre. Sample-tree d.b.h. was

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measured to the nearest 0.01 inch annually from 1974 through 1985. The diameter measurement point for each tree was identified by a painted band.

Present study treatments and analysis-For each species, there were two sequences of thinning (one-release and two-release) and four relative stocking densities (40 percent, 60 percent, 80 percent, and no control of density), for a total of eight treatments (table 1).

Sample trees were released using the rule thinning method (Rogers and Johnson 1985). It is a two-step procedure:

1. Find the thinning radius in feet for a given stocking target and crop-tree d.b.h. Remove all trees within the boundary defined by the thinning radius.
2. Survey the area outside the thinning radius of the crop tree to determine if a tree larger than the crop tree is nearby. If such a tree is present, determine its d.b.h. and thinning radius. If the crop tree falls within the thinning radius of the larger tree, then the larger tree is removed.

Thinning-radius values for a range of tree diameters are presented in Rogers and Johnson (1985) (table 2). Thinning-radius values representative of those employed in the present study are:

Crop-tree d.b.h.	Relative stocking (%) 40	60	80
Inches	*- - - Thinning radius (ft) - - -*		
8	11.8	8.1	5.3
10	14.2	9.7	6.4
12	16.6	11.4	7.5
14	18.9	13.0	8.5

Crop trees receiving the 40 percent treatment were released from crown-touching competition on at least three sides but usually on four sides, while the 60 percent treatment resulted in release on three sides but

Table 1 -Mean stand and tree characteristics after treatment and 10 years of growth by species (n=17 for each species x treatment combination)

Treatments: Release	Stocking	After treatment: D.b.h. Mean (range)	Basal area Mean (range)	10-year change: D.b.h. Mean (range)	Basal area Mean (range)
	Percent	*----Inches----*	*----Ft²/acre----*	*----Inches----*	*----Ft²/acre----*
Red oaks (age = 61; site index = 62)					
First	40	10.3 (8.4-13.2)	40 (30-50)	12.3 (9.7-16.0)	47 (40-60)
	60	10.5 (9.9-14.7)	57 (50-70)	12.4 (10.6-16.7)	66 (50-80)
	80	10.3 (8.2-14.6)	80 (70-90)	11.7 (9.2-16.3)	89 (70-100)
	Control[a]	10.4 (8.0-15.1)	126 (100-150)	11.4 (8.9-16.3)	121 (110-140)
Second	40	10.9 (8.1-13.3)	42 (30-50)	13.1 (9.5-15.5)	55 (30-70)
	60	10.9 (8.2-13.3)	56 (50-70)	12.9 (10.3-15.5)	66 (50-80)
	80	10.8 (8.0-14.0)	75 (60-90)	12.4 (9.4-15.4)	84 (70-100)
	Control[b]	10.5 (7.9-14.6)	92 (80-110)	11.9 (8.5-16.7)	97 (70-120)
White oak (age = 63; site index = 59)					
First	40	9.5 (8.0-14.5)	43 (30-50)	11.4 (9.5-16.0)	52 (40-70)
	60	9.3 (7.6-11.6)	56 (40-70)	11.1 (9.6-14.4)	61 (50-70)
	80	9.4 (7.4-12.1)	84 (80-100)	10.6 (7.9-13.8)	95 (80-110)
	Control[a]	9.3 (7.2-11.0)	131 (80-170)	10.4 (8.3-12.3)	128 (100-150)
Second	40	10.8 (8.2-13.4)	43 (40-50)	13.2 (9.8-15.4)	54 (40-70)
	60	10.9 (7.4-13.4)	56 (50-60)	12.9 (8.9-15.8)	66 (50-90)
	80	10.9 (7.9-13.1)	75 (70-80)	12.5 (9.2-14.6)	84 (70-100)
	Control[b]	10.7 (8.0-12.2)	90 (80-110)	12.1 (9.3-13.6)	99 (90-120)

[a] Control trees not released in 1974 or 1985.
[b] Control trees partially released in 1974 but not released in 1985.

Table 2-Analysis of variance probabilities of greater F-value and Error II Mean Squares for red and white oak periodic annual diameter growth for 1986-1990, 1991-1995, and 1986-1995

		Red oaks			White oak		
		Periodic annual growth			Periodic annual growth		
Source of variation	DF	1986-90	1991-95	1986-95	1986-90	1991-95	1986-95
		Pr > F					
Rep	16	0.8502	0.2019	0.5257	0.4668	0.2044	0.3010
Release	1	0.0001	0.1071	0.0002	0.0001	0.0143	0.0001
Release x rep [Error I]	16	0.3612	0.2917	0.3933	0.7521	0.6786	0.6630
Stocking	3	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
Release x stocking	3	0.3273	0.4318	0.5968	0.1380	0.5733	0.3396
		Mean square x 100 (*inches*^{2})					
Error II	96	0.1434	0.1915	0.1633	0.1087	0.1561	0.1216
Total	135						

occasionally in release on two sides. The 80 percent treatment released trees on one side at best and often effected no release from crown-touching competition. Control trees that were not released either in 1974 or in 1985 had crown-touching competitors on four sides, while controls released only in 1974 were often still free of crown competition on one side.

Crown-release and stocking-density treatments were applied in June and July 1985. Sample-tree d.b.h. was measured in the fall of 1985 following treatment and annually thereafter through 1995. Average tree and stand characteristics following treatment in 1985 and lo-year change in d.b.h. and basal area values are shown in table 1.

The study had a completely randomized split-plot design with one-release or two-release representing the whole plot, and relative stocking densities (40 percent, 60 percent, 80 percent, and no control of density) representing the subplots. Data were analyzed by analysis of variance with treatment effects tested at the 0.01 level of significance. Differences among treatment means were tested using the LSMEANS option of the General Linear Model procedure in SAS (SAS Institute 1989).

RESULTS

Over the lo-year measurement period, red and white oak crop trees receiving two release treatments produced significantly greater diameter growth than trees receiving the single crown release. However, this response was pronounced for only the first 5 years following treatment. While response to a second release was slightly greater over the second 5-year period, the difference in diameter growth was not significant at the 0.01 level (table 2).

Response to intensity of crown release (stocking level) was highly significant for each 5-year period. There was no Significant interaction between number of release and stocking level for either species group (table 2).

Response to a First or Second Crown Release

When red and white oak crop trees received a second crown release, the second release treatment usually enabled the trees to maintain their previous rate of diameter growth. However, trees that had received no previous crown release responded to the release with increased diameter growth, and by the sixth through tenth years after release these trees were growing at about the same rate as the previously released trees (fig. 1).

Diameter growth of red and white oak trees that received only a single crown release generally declined throughout the lo-year measurement period but was still greater than diameter growth of the controls that received no release (0.15 in. vs. 0.10 for red oaks and 0.14 in. vs. 0.11 for white oak). Thus, some response to a single crown release can be expected to persist for about 20 years following release. This finding is consistent with the 20-year response reported for white oak poles in southern Illinois (Schlesinger 1978), but overall response in the present study is less than reported by Schlesinger (1978). To maintain growth rates observed for red and white oak crop trees at the end of the previous study, another effective crown release would be required within 10 years after the first release (fig. 1).

Response to Stocking Density

Response of red and white oak crop trees to stocking density varied somewhat by species and the previous

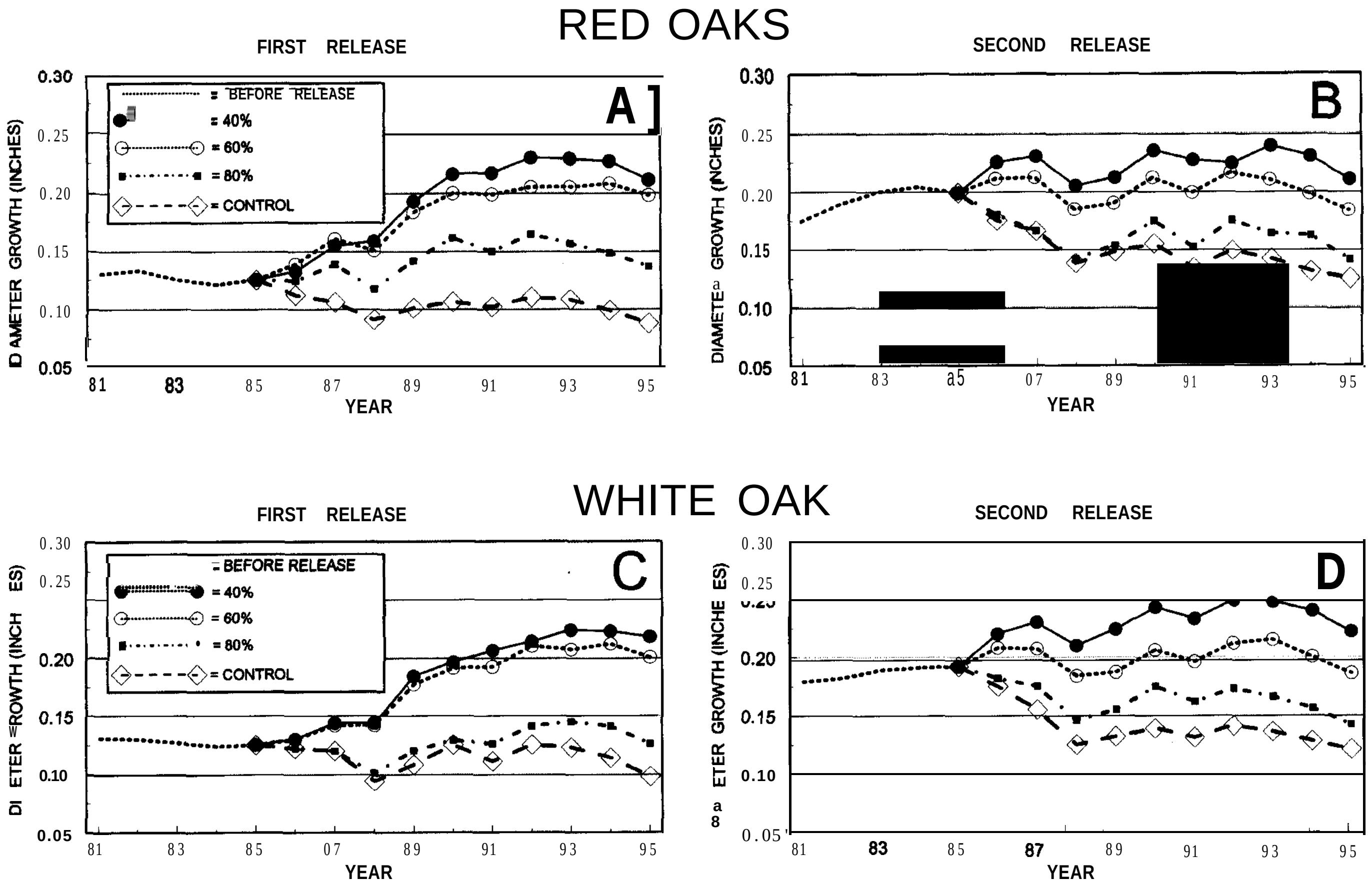

Figure I-Mean annual growth of red and white oaks following first or second crown release treatments and at four relative stocking densities.

release treatment. However, the 60 percent and 40 percent relative stocking treatments produced the greatest responses in both red oaks and white oak.

Red oaks receiving the first crown release in 1985 did not have a significant growth response the first year after treatment, although growth of the released trees was greater than that of the nonreleased controls. After the first year, all red oaks that received only one release grew significantly better than the controls. Diameter growth of the once-released red oaks that were released to 40 percent and 60 percent increased rapidly by the fourth year and reached a maximum at 7 to 9 years after treatment. Once-released red oaks released to 40 percent stocking exhibited the greatest overall growth, the difference was not significantly greater than red oaks released to 60 percent stocking. Trees released to 80 percent stocking grew better than controls but significantly less than trees that received the 40 or 60 percent stocking treatments (table 3).

Red oaks that had received a previous crown release exhibited an immediate and significant diameter-growth response to a second crown release to 40 percent or 60 percent relative stocking density. Diameter growth of trees released to 80 percent stocking density was about the same as that of the control trees over the 1 O-year period. Although annual diameter growth of red oaks released to 40 percent stocking was consistently greater than that of those related to 60 percent stocking over the IO-year measurement period, differences between growth for the 40 percent treatment and growth for the 60 percent treatment were not significant. Diameter growth of red oaks receiving the control and 80 percent treatments generally declined over the lo-year period, but growth of the trees released to 80 percent stocking declined at a slower rate (table 3).

Diameter growth of white oak sample trees that received only one crown release did not respond to that release immediately. In white oaks, significant response to crown release began the third year after treatment. Response was significant only for the 40 percent and 60 percent stocking treatments. Unlike once-released red oaks that were released to an 80 percent stocking density, once-released white oaks receiving the 80 percent stocking treatment did not grow significantly more than controls. Once-released white oaks, like once-released red oaks, responded similarly to the 40 percent and 60 percent density treatments, and maximum diameter growth occurred about 7 to 9 years after release (table 3).

Table 3-Least square means comparisons for mean annual diameter growth response of red and white oaks to a first or second crown release and four relative stocking densities

	First release				Second release			
	Relative stocking (percent)				Relative stocking (percent)			
Species/year	Control[a]	80	60	40	Control[b]	80	60	40
Red oak								
1986	.112a	.124a	.138a	.132a[c]	.175a	.180a	.211b	.225b[c]
1987	.106a	.138b	.160b	.154b	.166a	.166a	.212b	.230b
1988	.091a	.117b	.150b	.158b	.128a	.142a	.185b	.205b
1989	.101a	.141b	.183c	.192c	.138a	.154a	.190b	.212b
1990	.106a	.161b	.199bc	.215bc	.155a	.175a	.212b	.235b
1991	.102a	.149b	.198c	.216c	.134a	.152a	.199b	.227b
1992	.110a	.164b	.204c	.229c	.149a	.175a	.216b	.244b
1993	.108a	.156b	.204c	.228c	.142a	.164a	.210b	.239b
1994	.099a	.148b	.207c	.226c	.131a	.162a	.198b	.230b
1995	.088a	.136b	.197c	.210c	.125a	.141a	.184b	.210b
Mean	.102a	.143b	.184c	.196c	.144a	.161a	.202b	.226b
White oak								
1986	.122a	.122a	.130a	.130a[c]	.175a	.182a	.208b	.220b[c]
1987	.120a	.120a	.142a	.144a	.155a	.175a	.207b	.230b
1988	.094a	.101a	.142b	.144b	.125a	.146a	.184b	.210b
1989	.108a	.120a	.177b	.184b	.132a	.155a	.187b	.224c
1990	.125a	.129a	.191b	.196b	.139a	.175b	.206c	.243d
1991	.111a	.126a	.192b	.206c	.131a	.162a	.196c	.233d
1992	.125a	.141a	.210b	.214b	.141a	.173a	.212b	.249c
1993	.123a	.145a	.207b	.224b	.136a	.166a	.215b	.248c
1994	.114a	.141a	.212b	.223b	.128a	.156a	.200b	.240c
1995	.098a	.126b	.200c	.218c	.121a	.142a	.186b	.222c
Mean	.114a	.127a	.180b	.188b	.138a	.163a	.200b	.232c

[a] Control trees not released in 1974 or 1985.
[b] Control trees partially released in 1974 but not released in 1985.
[c] Values in rows followed by the same letter are not significantly different at the 0.01 level.

White oak crop trees also responded immediately and significantly to a second crown release, but only for the more intensive release treatments. Diameter-growth responses to the 40 percent and 60 percent treatments were about the same for the first 3 years after release, but diameter growth of trees released to 40 percent stocking was significantly greater than that of trees released to 60 percent stocking for the remainder of the study. White oaks released to 80 percent stocking generally grew better than controls, but differences were not significant over the 10- year period. Diameter growth for both control and 80 percent stocking treatments generally declined over the 10- year period (table 3).

DISCUSSION

If applied as recommended, rule thinning gives a selected crop tree the growing space at a prescribed target stocking density. However, the method does require measurement of crop-tree diameter and corresponding thinning radius to identify competing trees to be removed. The method also requires consideration of noncrop trees larger than the crop tree that are outside of the crop tree's thinning radius but large enough to compete with the crop tree. This requirement could confuse marking crews initially. Strict application of the rule thinning method does not provide for removal of competing trees that are not within the crop tree's thinning radius or the larger noncrop trees' thinning radius but lean toward the crop tree and touch or even overtop the crop tree's crown. This situation occurred in each stand and usually involved large-diameter residual stems located on steep interbench slopes above the crop trees. Although our Boston Mountain oak stands are essentially even-aged, they usually include five or more trees per acre that were not removed in the previous harvest because of their quality, species, or size. These stems are usually cull or very low quality with large crowns and often have significant lean. When located on steep interbench slopes, these large-crowned, leaning stems often influence a much larger area than their diameter would suggest. Such trees must be considered when the rule thinning method is applied. In the present study, leaning trees that were in competition with the crop tree but that were not designated for removal by application of the method were removed in most instances.

Response to partial crown release may persist for as long as 20 years, but to produce acceptable rates of diameter growth and to maintain these growth rates, release treatments will have to be more intensive than the partial release applied in the previous study and may have to be repeated on a 10- or 15-year cycle.

The rule thinning crown release to 40 percent residual stocking density would be roughly equivalent to the crown-touching release procedure recommended for stands of pole- and small sawtimber-sized mixed hardwoods in the Appalachians (Lamson and others 1990, Smith and others 1994).

CONCLUSIONS

Crown release can be an effective method for increasing growth of red and white oaks in heavily stocked stands of intermediate-aged, pole- and small sawtimber-size mixed oaks in the Boston Mountains. Annual diameter growth of tightly grown codominant red and white oak crop trees can be increased from current levels of about 0.1 inch to 0.2 to 0.25 inch with effective crown release. However, to maintain the higher rates of diameter growth, additional crown release would be required after a 10- to 15-year interval.

The rule thinning method has important advantages. It is based on established and accepted oak stocking guides which define growing space requirements, and it was developed for upland mixed oak stands in the Missouri Ozarks. The method is straightforward and provides a system for providing consistent release of oak crop trees to a prescribed stocking. However, the method does require measurement of crop-tree diameter and thinning radius, and the evaluation of competing trees that are not within the defined thinning radius of the designated crop tree. The method also does not make provision for leaning trees that compete with the sample tree's crown but are not within thinning radii.

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CAMBIAL INCREMENT OF 43-YEAR-OLD WHITE OAK (QUERCUS ALBA L.) CROP TREE RESPONSES TO FERTILIZER AND CROWN RELEASE ON A TENNESSEE UPLAND SITE

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Abstract-Cambial responses to fertilization, crown release, and fertilization x release treatments with untreated controls, and treatment-by-year interactions were studied in pole-sized (approximately 43 years old) white oak (*Quercus alba* L.) crop trees. In the main study, fertilizer was applied by broadcast to plots at a rate of 150 Ibs. N and 35 Ibs. P_2O_5 per acre, and crown release removed competing trees around crop trees (dominate or codominate trees selected for favorable timber characteristics) in randomly selected plots during spring 1993. Another fertilizer application was applied during spring 1995 at the same rate and method as the first application. Bole diameter, measured at 4.5 ft aboveground line (d.b.h.); scaling diameter inside-bark (d.i.b.) and radial increment, both variables measured at 17.3 ft aboveground; form class; and stem taper were examined. D.b.h., d.i.b., increment, and form class were measured for 4 years beginning with 1992 pretreatment data; stem taper was measured for 1995 only. Stem taper and form class did not differ significantly among treatments. Although annual d.b.h. and d.i.b. differences among treatments were not significant, pooled mean annual d.b.h. and d.i.b. increased significantly each year at compound annual rates of 2.9 percent (9.44 in. in 1992 to 10.29 in. in 1995) and 3.1 percent (7.28 in. in 1992 to 7.97 in. in 1995), respectively. Radial increments for release (0.12 in.) and fertilization x release (0.12 in.) treatments were significantly greater than the control (0.09 in.) in 1993. The fertilization x release treatment continued to significantly increase increment (0.14 in.) more than fertilization and control treatments (0.11 in both treatments) in 1994. By 1995, increment for fertilization x release (0.18 in.) was significantly greater than release, fertilization, and control (0.12, 0.11, and 0.10 in., respectively). Fertilization x release treatment provided greater cambial increment for the first 3 years on mid-rotation white oak crop trees. Should trends continue, the fertilization x release treatment will improve volume in the first log and may improve log form more than release, fertilization, and the control treatments.

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EARLY THINNINGS IN A YOUNG, SPROUT-ORIGIN, BOTTOM-LAND HARDWOOD STAND IN SOUTH CAROLINA

Mark B. Tinsley and Lawrence E. Nix'

Abstract-A 23-year-old, sprout-origin, bottom-land hardwood stand along the Congaree River in South Carolina was commercially thinned using three different methods: "corridor, " "leave-tree," and "trainer-tree." The stand consisted of 260 to 320 trees per acre of typical, mixed bottom-land species, with 26 to 31 cords per acre, including about 40 percent commercial oaks, and 100 to 140 crop trees per acre. Thinnings were marked to produce a 10 to 12 cords-per-acre harvest and to leave at least 90 crop trees per acre. After one growing season, impact of thinning methods on quality of residual stand, especially the crop trees, was determined by measuring logging damage to lower boles, epicormic sprouting along first 16-foot log, and grape vine severance. All thinning methods produced a commercial level of product and left 80+ crop trees per acre, which were 30 to 40 percent commercial oaks. The crop trees in the 'trainer-tree" method averaged 1 .1 epicormic sprouts on first 16-foot log, while those in the "corridor" and "leave-tree" methods averaged 3.4 sprouts. Vine severance, which was considered a stand quality enhancement, was greatest in the "trainer-tree" method.

INTRODUCTION

Early thinnings in bottom-land hardwood stands provide much needed income for forest landowners. Many hardwood silviculturists such as Gingrich (1971), Carvell (1971), and Kennedy and Johnson (1984) were recommending early thinning in hardwood stands 20 or 30 years ago. The main objective of thinning is the improvement of the residual stand by favoring or concentrating growth on vigorous, high-quality crop trees (Carvell 1971). Simultaneously generating an intermediate income which might otherwise be lost to imminent natural mortality is highly desirable (Gingrich 1971). Kellison and others (1988) present the benefits of early thinning in terms of cumulative board foot gains. They give examples of the greater cumulative yields that result from beginning a planned thinning schedule at early stand ages. Gingrich (1971) states that yield data clearly indicates the potential for reducing the rotation length in hardwood stands by early thinning. Gingrich (1971) and Catvell (1971) report increases from 30 to 40 percent in individual tree diameter growth on thinned hardwood sites.

Many silviculturists feel that the first thinning should take place as soon as a practical commercial thinning can be made (Carvell 1971, Gingrich 1971, Kennedy and Johnson 1984). Kellison and others (1988) indicate that early manipulation of stocking levels at age 20 to 25 years can increase the productivity and value of bottom-land hardwoods significantly. In fact, they suggest that the thinning of pole-sized trees at about 25 years offers considerably more promise in improving stand development than cleaning or thinning at younger ages.

The beneficial results from hardwood thinning also depend on species composition, tree vigor, and potential stem quality (Clatterbuck and Hodges 1988, Kennedy and Johnson 1984). Ideally, the forester would like to keep the better-quality stems growing steadily by removing the less desirable trees before their competition retards the growth of the more desirable trees.

When thinning in bottom lands, the more valuable, high-quality species are favored, such as cherrybark (*Quercus pagoda*) and shumard oaks (*Q. Shumardii*) (Kennedy and Johnson 1984). Also favored in bottom lands are good sweetgum (*Liquidambar styraciflua*), sycamore (*Platanus occidentalis*), and green ash (*Fraxinus pennsylvanica*). However, it is more important to favor a high-quality stem of a species of lower value, than it is to favor a poorly formed, low-quality stem of a highly valued species (Kennedy and Johnson 1984). Therefore, the selection of crop trees should take into account each individual tree in relation to the quality and growth potential of others nearby in the stand (Clatterbuck and others 1987). The wide range in quality among and within the different bottom-land species presents some real silvicultural challenges. Multiple stump sprouts and other defective stems should be harvested to allow better-quality single stems to use the growing space. Yet all poor-quality trees cannot be removed in a single thinning without leaving the stand understocked (Gingrich 1971).

Historically, the first commercial thinning in bottom-land hardwoods begins when trees reach small sawtimber size (Kennedy and Johnson 1984). However, increasing markets for hardwood pulpwood make it possible to commercially thin young (20 to 25 year old), sprout-origin, pole-size stands on productive sites in the first bottoms of major rivers in the Southern United States (Kellison and others 1988). The primary objective of the present study is to demonstrate that this early thinning can be accomplished without reducing future stand quality in such valuable stands.

METHODS

The study area is a first bottom, 23-year-old, sprout-origin, bottom-land hardwood stand along the Congaree River near Columbia, SC. After several decades of being selectively cut over, the stand was KG blade sheared in 1971 and now consists of 260 to 325 trees per acre of typical, mixed bottom-land species with 28 to 31 cords per

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acre. From 30 to 40 percent of the basal area per acre is in commercial oaks with about 90 to 140 potential crop trees per acre of different species, e.g., miscellaneous oaks, sycamore, sweetgum, elm (*Ulmus* spp.), green ash, and maple (*Acer* spp.). Two parts of the stand used in the study are reasonably good oak sites with a site index (base age 50) of 85 to 95 for cherrybark oak and are moderately to well-drained silty clay loams. Thinning treatments were applied in a randomized complete block design with 4-acre plots, l-chain buffer areas, four blocks or replications of a control, and three thinning methods, on about 75 acres. Twenty-foot-wide skidding corridors delimit all plots and blocks for treatment monumentation and future tree measurements.

In order to be practical all treatments were to be commercial, removing at least 10 cords per acre of trees 6 inches in diameter at 4.5 feet height (d.b.h.). Based on the average d.b.h. of the stand (9.2 inches), this corresponded to removing about 100 trees per acre. The "trainer tree" treatment was to leave a few trainer stems as residuals around each of the crop trees. Only enough volume to be commercial was to be removed, so only 100 trees per acre were marked. Since there were at most about 320 trees per acre, if the 100 crop trees per acre with two trainers for each were needed, then not enough could be cut. So it was determined to harvest merchantable trees on about a 20 by 20-foot spacing (100 per acre). But trees had to be marked so that the logger's production was maintained and the harvesting scheme was readily apparent. This meant marking trees of marginal diameter that would aid in finding the merchantable trees to be cut.

The second treatment was the "leave tree," where theoretically all lower-crown-class trees are harvested and only crop trees remain. To accomplish this goal, the marking was reversed to leave 100 trees per acre, so the minimum number of crop trees per acre was determined by the 20 by 20-foot spacing. Sometimes, crop trees were closer than 20 feet apart; in those cases, they were left. The 20 by 20-foot spacing was a maximum distance as long as 10 cords per acre were harvested.

The third treatment was to be an "efficient" corridor method. Again, at least 100 trees per acre were to be removed, or about one-third of the volume. So one-third of the area of each acre was harvested by cutting 20-foot corridors, leaving 40-foot strips uncut. Since the corridor method is indiscriminant as to which tree it harvests, as many good trees as poor trees were cut. The corridors were marked in a herringbone pattern at no more than 60" angles to the main skid trails, in order to minimize turning damage caused by the full-length trees.

Vines

As in most bottom-land stands, vines (*Vitus* spp.) in this area were very prevalent. On the very fertile, bottom-land sites, lush vine growth is common and can be a major problem in management of high quality hardwoods; in some areas it may completely eliminate high-quality crop trees. During harvesting the thinning treatments cut or pulled vines out of the residual crowns; therefore, vine presence and condition were monitored before and after thinning. For each residual crop tree vines were classified as follows: (1) cut-if the vine was completely severed, (2) live-if the vine was unharmed by harvesting and growing in the canopy of the crop tree, (3) both-if a crop tree had at least one vine live and one cut, (4) no vines-trees that had vines pulled completely out of their canopy or never had vines, (5) present—meaning vines simply grew on the bole of the crop tree, and (6) overtop-meaning vines had overtopped the crop tree, with the potential for causing increased epicormic sprouting.

Logging Damage

The success of the thinning operation depended upon the proper execution of the harvesting operation. Thus, it was important to design a harvesting scheme that maximized efficient tree removal and minimized residual damage from machinery movement, felling, and skidding. Because loggers usually have no immediate economic interest in the residual stand, incentives were offered to curtail the residual damage caused by reckless or careless harvesting. The thinning objective of each treatment was explained, and the forest manager adjusted the stumpage for the loggers proportionally to production. However, some damage was inevitable as in any logging operation. The damage to residual crop trees was classed as "back," "fell," "skid," and "turn," which are self explanatory. Only damage to crop trees was reported.

Epicormic Sprouts

The grade of hardwood logs largely determines their value. Log grade reflects the size and number of clear lumber cuttings which can be made from a specific log; thus, any silvicultural practice which causes reductions in grade, subsequently decreases the financial returns from timber management. For this reason, along with harvesting damage, the response of crop trees in epicormic sprouting was monitored. Epicormic sprouts in the first and second log of all crop trees were counted.

In view of the predisposition of some stems to have epicormic sprouts (Smith 1966), this characteristic Was included in the criteria for choosing crop trees. Designated "crop trees" were based on the following criteria: (1) dominant or codominant, (2) good form and vigor, (3) no vines or damage, (4) no signs of being prone to epicormic branching, and (5) at least one clear 16-foot log.

Experimental Design

Analysis of variance with a randomized complete block design was used to determine whether treatments differed in their effects on residual stand quality. Response variables were number of crop trees per acre, epicormic sprouting, logging damage, and vine severance, which was considered a positive response for future quality Of crop trees.

RESULTS

Number of Crop Trees

There was no difference in the number of crop trees per acre in the corridor, leave, and trainer thinning treatments after thinning (fig. 1). The control plots consistently had more crop trees, however (140 versus 90 per acre). The trainer tree thinning had a significantly higher percentage of oak crop trees than did any other treatment (fig. 2), perhaps because, often, potential crop trees were left as "trainers." No significant differences were found among other thinning treatments.

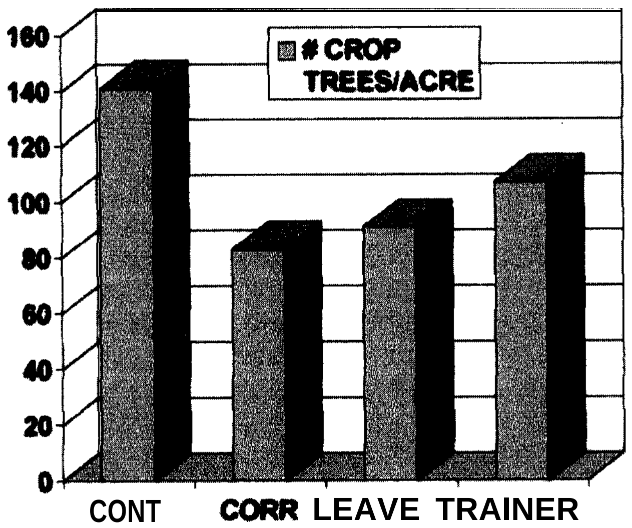

Figure I-The number of crop trees per acre before and after thinning by three methods in a young, sprout-origin, red river bottom land in South Carolina.

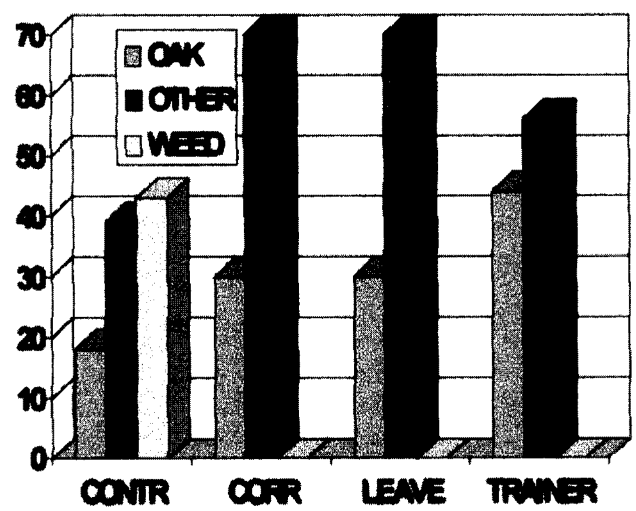

Figure 2—The proportion in percentage of oak and other crop trees after thinning by three methods in a young, sprout-origin, red river bottom land in South Carolina.

Effects on Vine Condition

How thinning methods affected vine composition in the residual stand is shown in figure 3. There were significant differences between the control and the other treatments, i.e., any thinning reduced vines; and this was a positive effect on future stand quality. In the corridor thin, machinery did not get among residuals; thus, there was little difference in vines between the control and the corridor thin. However, there was a significant difference between the corridor and the trainer and leave thins (fig. 3), probably because more bigger trees were cut in these thinnings than in the others. The cut vine difference between the corridor and trainer thins resulted because there were more codominant trees cut in the trainer thin and vines were mainly in codominants. Wide differences occurred in the study area because of present vine position in the canopies, i.e., they started with the sprouts and often suppressed dominant stems causing them to become subordinate. With vines present, there was no difference between corridor and leave thins, but there was a difference between corridor and trainer thins, probably because of vine positioning, i.e., an adjacent tree had to be harvested to remove a vine and there were more adjacent removals in the trainer than in the corridor thin (fig. 3). No difference occurred between the leave and trainer thins for this variable. The overtop vine condition occurred mainly in dominants and codominants and thus was not thinned out. This condition was hard to see in the summer prior to thinning and arises when a vine has no place else to grow. However, this condition can be in any crown class, especially in a sprout origin stand, and may cause a tree to regress to a lower crown class and to epicormically sprout, reducing grade.

Logging Damage

Logging damage was reduced by the following factors: (1) good harvest design, (2) excellent communication with the loggers, and (3) cash incentives for loggers. Although overall damage was slight, the trainer and leave treatments

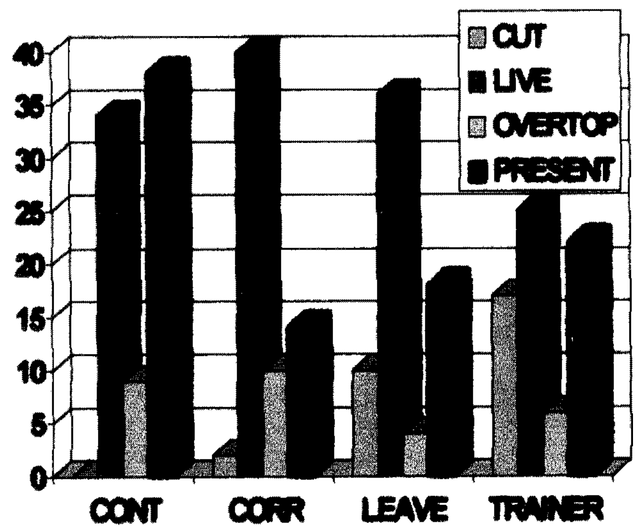

Figure 3-The distribution in percentage of vine types on crop trees after thinning by three methods in a young, sprout-origin, red river bottom-land in South Carolina.

were significantly greater than the corridor, with 5 to 6 percent incidence, while the corridor treatment had only 2 percent incidence (fig. 4). However, damage in excess of 2 to 3 percent could be considered critical when crop trees are in short supply as they were in this stand.

The use of a small feller/buncher helped in maneuvering through the residuals, but occasionally there was trunk wounding or "back damage," especially in the trainer thin, where the feller or skidder often backed into a residual crop tree. When the small feller was not productive enough to suit the loggers, they used a large, full-production feller/buncher, especially in the corridor thin. Some residual trees were used by loggers as pivot points in turning whole-length trees, but frequently trees used as turn trees were later harvested. In the corridor thin, trees were felled in a herringbone pattern in relation to main skid trails and to the road, and were pulled out with a minimum amount of turning. Also the existence of trainer stems appeared to be vital for protecting residual crop trees. Stems left to protect or buffer crop trees from mechanical or skidding damage are very beneficial, but there were many more crop tree residuals in the trainer tree thin plots. Thus, more damage occurred to potential crop trees in this treatment.

The distribution of logging damage among types reported can be summarized as follows (fig. 5): (1) "Back" damage—although least damaged overall, the corridor thin crop trees incurred this type of damage more than any other, where there was less room to maneuver. Actual backing damage occurred most in the leave-tree thin because more trees were cut, leaving fewer residuals to protect crop trees. Damage in the corridor thin occurred only when the feller turned perpendicular to corridor. (2) "Fell" and "turn" damage-this was negligible in all thinning treatments (<1 percent). No fell damage occurred to crop trees in the corridor thin. (3) 'Skid" damage-it was difficult to distinguish this damage from the turn type, but all thinnings had the same distribution with least actual damage in the corridor thin simply because overall damage was least there (fig. 4). Overall, damage was low because trees were felled, held upright, then the feller backed up and set trees down on the just-cut stump to bunch them, i.e., the operator cleared bunching area as he moved forward.

Epicormic Sprouting

The epicormic sprouting was monitored prior to thinning treatments; and although it was prevalent (25 percent of crop trees), no difference was found among crop trees in any of the treatment areas. However, a significant difference in epicormic sprouts was found between the trainer-tree thin and the other treatment areas a year after thinning (fig. 6). The trainer thin had fewest sprouts in either log or total, whereas there was no difference in the

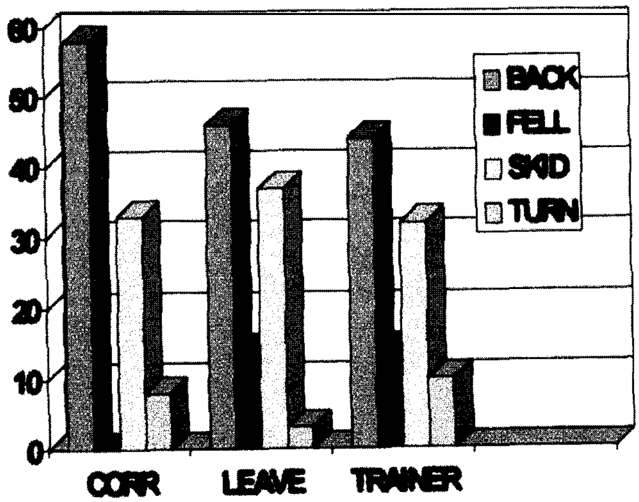

Figure 5—The distribution in percentage of types of logging damage to crop trees after thinning by three methods in a young, sprout-origin red river bottom land in South Carolina.

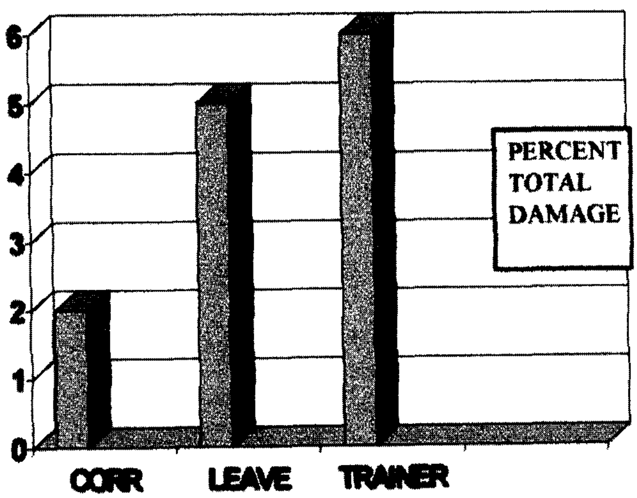

Figure 4-Total logging damage in percentage to crop trees after thinning by three methods in a young, sprout-Origin red river bottom land in South Carolina.

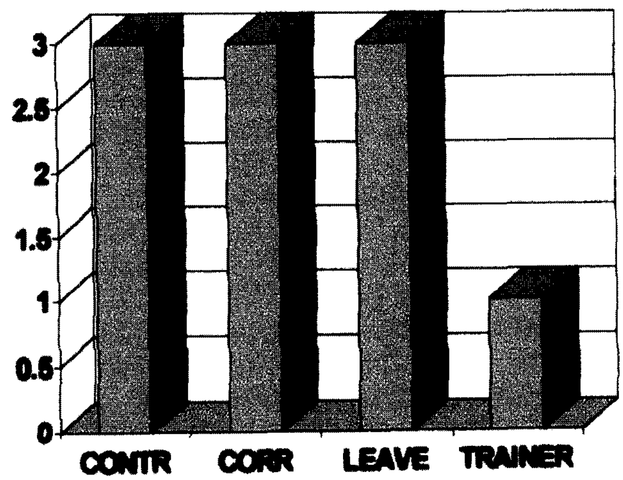

Figure 6-The number of epicormic sprouts in the first log of crop trees after thinning by three methods in a young, sprout-origin, red river bottom land in South Carolina.

others. Although unexpected, the sprouting in the corridor thin may be because many crop trees were deliberately left along the 20-foot-wide corridors in full sunlight and subsequently developed epicormic branches on one side. In the leave tree treatment, number of stems per acre was drastically reduced (from 300+ to 90+) and the increase in epicormic sprouts was expected. The relatively high number of sprouts in the control, which remained undisturbed, is an enigma. Perhaps it is due to the continued vine infestation in otherwise desirable crop trees. Initially, there was 25 percent vine infestation in crop trees and at least 25 percent of all potential crop trees had epicormic sprouts.

In the early fall when the last measurements were made, vines in the overtopping position were difficult to see among the crop tree crowns, especially in the denser control plots. Perhaps with the low incidence of logging damage, the greatest benefit of these early thinnings might have been the vine removal from residual crop trees, both through actual cutting of vine stems during logging and from tearing vines from the crowns of crop trees during removal of subordinate trees acting as "vine ladders."

CONCLUSIONS

All thinning objectives in this study were met by the three methods tried. Any of the three methods may prove useful in accomplishing various early thinning objectives in similar young bottom-land stands. With proper planning and cooperation, thinning can be done on a commercial basis with a minimal amount of damage to potential crop trees. Although the corridor thin seemed more efficient, the loggers preferred and produced more wood per acre in the leave tree thinning, where nearly 14 cords per acre were cut. In the trainer thin, more potential crop trees were left with fewer epicormic sprouts and vines and a higher percentage of oaks than in the other methods. However, this thinning was the most difficult to mark and the least productive for the loggers to implement. The effects of these logging methods on future stand quality will be monitored closely in the next several years and over the next decade.

ACKNOWLEDGMENT

The authors would like to express their greatest appreciation to Frank McCleod, Consulting Forester of Shaw, McLeod, Belser, and Hurlbutt of Sumter, SC, for his invaluable technical assistance and encouragement during the course of the study. Appreciation is also extended to the owners of the study tract, Robert Boardman, and the Boardman Carton Trusts, for their willingness to provide a substantial area of valuable young bottom-land hardwoods for the wide range of thinning treatments employed in the study.

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IMPACT OF INTERMEDIATE HARVEST TREATMENTS ON THE DISTRIBUTION AND THE DEVELOPMENT OF BOTTOM LAND OAK REGENERATION

Lawrence E. Nix, Damien Bonal, and Jon E. Barry[1]

Abstract-Establishing desirable oak seedlings with properly timed intermediate harvest of midstory and defective overstory trees was examined after fail harvest treatments were applied to a nearly mature bottom-land hardwood stand. Three harvest treatments were assigned to twenty-five 2-acre plots by random drawing. The treatments were: no harvest, low basal area removal (20 square feet per acre), and high basal area removal (40 square feet per acre). Two years after the harvests, the number of established oak seedlings was significantly higher (1,300 per acre) in the harvested areas than in the control (150 per acre) with no difference between the two harvests. Survival of seedlings was much greater in the high removal plots than in the low removal plots. More new red oak seedlings grew in the high removals in 1993 than died during the winter. Distribution of seedlings was positively correlated with the absence of herbaceous or midstory competition, the presence of skidder activity, and a mature oak seed-tree nearby. This last factor seemed to strongly affect the distribution of the seedlings. Since many seedlings were broken by the logging equipment, the height of the seedlings was greater in the control plots than in the treatment plots. Seedlings were also taller in the high removals than in the low removals. Presence of skidder activity improved growth of new seedlings, perhaps due to the impact of the equipment on the understory, and the midstoty competition.

INTRODUCTION

Natural regeneration of hardwood stands is most often accomplished by commercial clearcutting and felling of the residual stems (Hannah 1987, Kellison and others 1981). Reproduction of hardwood species comes from either stump sprouts, seedling sprouts, or true seedlings. Successful oak (*Quercus* spp.) regeneration usually results from hardy sprouts of stumps less than 30 centimeters (cm) (12 inches) d.b.h. (diameter at 4.5 feet) or advanced oak reproduction, i.e., seedlings greater than 5 feet tall (Sander 1971).

In bottom-land hardwood forests, site conditions differ significantly from those of upland stands, and silvicultural treatments have been adapted to obtain regeneration (Aust and others 1985, Tolliver and Jackson 1988). In order to reproduce, bottom-land oak seedlings frequently must survive early seasonal soil saturation or flooding (Pezeshki and Chambers 1985), acorn consumption (Goodrum and others 1971), browsing by wildlife during the growing season (Hill 1986), and competition with more shade-tolerant species for light, moisture, and available nutrients (Carvell and Tryon 1961, Chambers and Henkel 1988, Sander 1971).

An experiment was designed in 1991 in a Congaree River bottom in South Carolina (Barry and Nix 1993) to test whether a properly timed intermediate harvest (an improvement cut) of midstoty and defective overstory trees could be used to increase the establishment of oak seedlings after a good acorn crop.

The objective of the current study was to determine whether the stand disturbance in 1991 had improved the establishment, distribution, and continued development Of the oak seedlings 2 years after cuttings were applied. Site conditions in the disturbed stands were characterized as to hog rooting activity, presence of thick grass, skidder activity, canopy cover, debris, presence of nearby oak seed-trees, and diameter and species of these seed-trees. It was hypothesized that these factors could have a significant influence on oak regeneration survival and development.

The importance of logging activity in the distribution and development of oak reproduction had been previously observed. Nix and Lafaye (1993) found that the red oak seedling distribution in a nearby clearcut red river bottom-land hardwood stand was concentrated along skid trails and turnaround areas. Relatively wet conditions during logging operations resulted in appreciable scarification of the soil. The heavy traffic of the logging machines dispersed the acorns and buried them in the ground where they were in contact with the mineral soil, hidden from animals, and less likely to be displaced by floodings. These types of activities in 1991 resulted in initial oak seedling establishment from 1 to 2,000 seedlings per acre (Barry and Nix 1993).

MATERIALS AND METHODS

The study area is located near Columbia, SC, in two 20-hectare (50 acres) Red River bottom-land hardwood stands in a first bottom of the Congaree River. The study plots are about 1,800 meters (1,900 yards) from the river and on a moderately well-drained, low site. Flooding occurs more than once in most years but not in some, from December to May (Patterson and others 1985). The soil is deep and moderately well-drained with brown to dark brown Congaree loam, Chewacla loam, Chastain silty clay loam, and Tawcaw silty clay loam subsoils (Lawrence 1978).

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Barry and Nix (1993) reported that elm (*Ulmus spp.*), hackberry (*Celtis spp.*), red maple (*Acer rubrum*), and sweetgum (*Liquidambar styraciflua*) accounted for more than 56 percent of the basal area removed during the improvement cut operation. The remaining overstory included a large number of cherrybark (*Q. pagoda*), water (*Q. nigra*), laurel (*Q. laurifolia*), willow (*Q. phellos*), overcup (*Q. lyrata*), and swamp chestnut (Q. *michauxii*) oaks. Pawpaw (*Asimina triloba*) and switch cane (*Arundinaria gigantea*) were abundant in the understory as well as many herbs and sedges (*Cyperaceae*) and vines (*Vitus spp.*). The stands are in excess of 80 years old. The site has been commercially managed for timber for 25 to 30 years and at least parts of the study sites have been selectively harvested in the past. Ditches, canals, and dikes related to agriculture are present, but were built well before the establishment of the stands.

As detailed by Barry and Nix (1 993), the two stands were divided into twenty-five 0.65-hectare (1.6 acres) plots. Ten plots were located in one stand called the "Red Oak Stand" (based on the species composition) and 15 plots in another stand called the "Mixed Oak Stand." Three levels of cuttings (0, 20, and 40 square feet basal area per acre removed) were assigned to the plots by random drawing. Cutting was done in December 1991, by a commercial logging crew. Equipment drivers were to enter plots only from skid trails. Trees were directionally felled with a small feller machine, limbed in place with chain saws, and skidded along predesignated trails to the logging deck. Initial results of these cuttings were reported by Barry and Nix (1993). Acorns were abundant: 150 to 200 thousand per acre.

After the flooding subsided in the spring of 1993, all oak seedlings that could be found on the 25 plots were flagged. Brightly colored flagging attached to seedlings made the relocation of the seedlings possible for later data recording and allowed some seedlings to be followed during the growing season and for the next several years.

A total of 21 temporary systematic samples were placed per plot at 0.5 chain spacing. For each sample, measurements were recorded on 10.1 square meter (1/400 acre) circular subplots, which are commonly used for this type of research (Hook and Stubbs 1965). The measurements were taken from early May to early June. For each subplot, the number of oak seedlings was counted and marked as red or white oak, and whether there were thick grass, skidder activity, or debris, an oak seed-tree in the overstory canopy, or evidence of hog rooting. The overstory basal area per acre was measured for each subplot using a BAF10 prism. Canopy closure was measured at each point using a spherical crown densiometer. The canopy vegetation was also divided into three categories: overstory only, midstory only, or both. The number of seedlings per acre for each stand, each thinning intensity, and for the entire forest was also recorded.

Development of Seedlings

In order to follow the development of the seedlings, the sampling done in June 1992, under the seed-trees by Barry and Nix (1993) was repeated in 1993. Three dominant or codominant oaks were selected from each plot. Under the crown of each seed-tree, four 10.1 square meter (1/400 acre) circular subplots were taken. In each sample the number of oak seedlings was counted. The "age" of each seedling, i.e., whether it was a new seedling (1 or 2 growing seasons) or a residual seedling (3 or more growing seasons), and whether it was a red or a white oak seedling were recorded. Height of each seedling was also measured ±1.25 centimeters (0.5 inch). At each subplot, hog rooting, skidder activity, thick grass, debris, and canopy closure were recorded. The overstot-y basal area around each seed-tree and the diameter of the seed-tree were also recorded.

The number of seedlings per acre for each stand, each thinning intensity, and for the entire forest was also recorded. Since these numbers were based on the data recorded under the oak seed-trees, they were reduced by a factor of 66 percent, which corresponds to the approximate non-oak component as a percentage of total stand basal area for trees greater than 10 centimeters (4 inches) in d.b.h. (Barry and Nix 1993).

In order to be sure that the field-estimated "age" of the seedlings was correct, vascular rings were counted under magnification for 31 oak seedlings selected at random on different plots. A paired t-test was conducted for the variable age and no significant difference at the 5 percent level appeared between the means of the two estimations. Thus, the estimates of the age of the seedlings in the field seemed to be accurate enough.

Statistical Analysis

The height, stocking, and number of seedlings were compared using a General Linear Models Procedure with analysis of variance with a 5 percent probability to determine if there were significant differences among the treatments (SAS 1985). In order to compare the results in 1992 and 1993, a paired t-test was conducted on the number of seedlings in 1992 and 1993. In order to determine which factors influenced the number and the height of the seedlings, an analysis of variance was conducted using these two variables as dependent variables and the factors studied as independent variables.

RESULTSANDDISCUSSION

Two years after the improvement cutting of midstory and defective overstory trees, the vegetative factors measured were greatly different in cut and uncut plots of two bottom-land stands (table 1). However, the intensity of hog rooting, herbaceous vegetation, skidder activity, and the number of mature oak seed-trees did not vary statistically between the light and heavy cuttings (table 1). There was an increase of 746 well-distributed seedlings per acre in the cut plots as compared to the uncut, with no difference between the two cuttings (table 2). Barry and Nix (1 993) found similar relationships in the stands in 1992.

Table l-Occurrence of seed-trees, hog rooting activity, skidder activity, thick grass, and tree canopy in improvement cut bottom-land stands of South Carolina

Factors	Thinning intensity		
	None	Light	Heavy
	- Percentage of plots sampled -		
Seed-tree	53a	65a	57a
Hog rooting	19	10a	5a
Skidder	—	69a	79a
Grass	3	33a	45a
Overstory	9	54a	63a
Midstory	19a	15a	14a
Mid + Overstory	72	31a	23a

Means followed by the same letter in a row are not significantly different (LSD, =0.05).

Table 2-Bottom-land red and white oak seedlings in relation to intensity of cutting in bottom lands of South Carolina

Thinning intensity	Total seedlings	Red oak seedlings	White oak seedlings
	Per acre		
None	466	335a	131
Light	1212a	378a	834a
Heavy	1418a	785	633a

Means followed by the same letter in a column are not significantly different (LSD, =0.05).

The number of seedlings in the uncut and the lightly cut plots significantly decreased from 1992 to 1993 (fig. l). Survival of seedlings was best in the heavy cutting, and even more new red oak seedlings grew in 1993 than died during the late summer and winter in these areas. The conditions in the heavy cuttings might be more favorable for oak seedlings to survive and for new seedlings to develop. The number of seedlings appeared to be positively related to the absence of herbaceous or midstory competition, presence of a mature oak seed-tree above the seedlings, and skidder activity or debris (table 3). No clear relationship was found between the number of seedlings and the activity of hogs or the amount of canopy overhead.

The number of seedlings of red oak or white oak species depended mostly on the species of the seed-tree in the overstory (fig. 2). Thus, success of these cuttings seemed

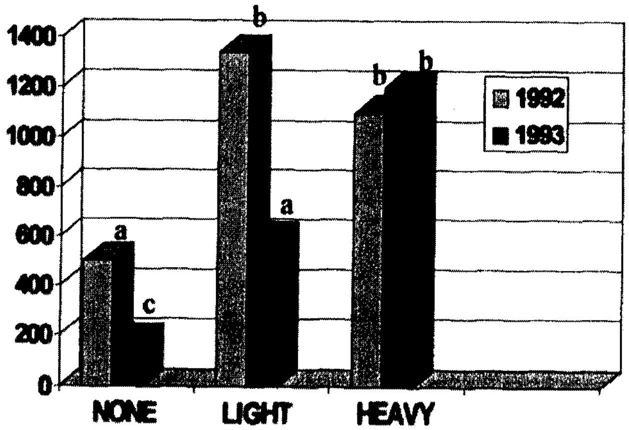

Figure l-Bottom-land oak seedlings per acre under seed-trees in 1992 and 1993 in relation to intensity of cutting (bars with the same letter are not significantly different, LSD, =0.05).

Table 3-Number of bottom-land oak seedlings as related to thick grass, hog rooting, seed-tree, skidder activity, debris, and three types of canopies

Factor	Presence	Absence	Debris
	Per acre		
Grass	580a	1,208a	—
Rooting	788a	1,068a	—
Seed-tree	1,600b	248	—
Skidder	1,408b	572	1,048a
Canopy type	Midstoty	Both	Overstory
	Per acre		
	572a	932a	1312a

Means followed by the same letter in a column are not significantly different (LSD, =0.05).

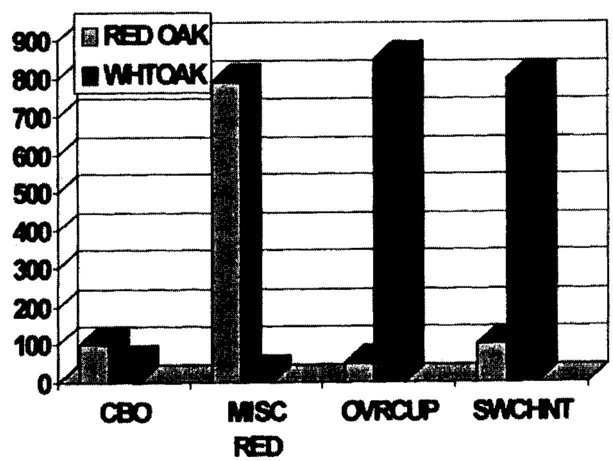

Figure 2-Total red and white oak seedlings per acre under cherrybark, miscellaneous red, overcup, and swamp chestnut oak seed-trees in improvement cut stands.

to be correlated with the number and the distribution of the mature oak trees after the treatments. The number of cherrybark oak seedlings was much less than that of the other oak species. These treatments may not be useful for this species or it might be possible that the acorn crop in 1991 for the cherrybark oak trees was lower than for the other oak trees.

Since many residual seedlings were broken in the cut plots, the mean height of the seedlings was greatest in the uncut plots, by 12.9 centimeters (5.08 inches) (table 4). Seedlings were also taller in the heavy cutting than in the light cutting. The latter difference was due to the effect of residual seedlings. The height of the new oak seedlings did not vary among the treatments. The number of new seedlings in the uncut areas may be too few to make accurate statistical comparisons.

Height growth of seedlings was positively correlated with the presence of thick, coarse grass or hog activity (table 5). However, the sample may have been too small to provide reliable results. Height growth of seedlings was greatest when no midstory vegetation occurred under the seed-trees. This suggests that control of midstory vegetation either mechanically or with herbicides as suggested by Hannah (1987) and Hodges and Janzen (1987) might favor the success of oak regeneration.

Table 4-Height of bottom-land oak seedlings under seed-trees according to intensity of thinning

Thinning intensity	Overall	Red oak	White oak	Residual	New
	---------- Centimeters	-------------			
None	34.5	38.5	33.1	38.7	13.4a
Light	21.6a	20.9a	21.9a	24.2a	18.4a
Heavy	24.2a	26.4a	21.7a	28.5a	19.1a

Means followed by the same letter in a column are not significantly different (LSD, =0.05).

Table 5—Height of bottom-land oak seedlings in relation to thick grass and hog rooting activity in thinned stands

Factor	Total seedlings	Residual seedlings	New seedlings
	---------- Centimeters	----------	
Grass	27.2a	28.7a	25.4
No grass	22.4b	27.7a	18.4a
Rooting	29.3a	34.2	20.0a
No rooting	23.3b	27.0a	18.6a

Means followed by the same letter in a column are not significantly different (LSD, =0.05).

Since many residual seedling stems were broken by the logging activities, the mean height of the total seedlings was greatest when there was no skidder activity. However, new oak seedlings were at least 3.3 centimeters (1.3 inches) taller with presence of skidder activity or logging and flooding debris than without (table 6). The reason for such responses might be the impact of the equipment on the understory and midstory vegetation. The further survival and development of these oak seedlings will be monitored closely over the next decade.

ACKNOWLEDGMENT

The authors would like to express their greatest appreciation for the technical assistance and encouragement provided by Angus B. Lafaye, Chief Forester of Milliken Forestry in Columbia, SC. Appreciation is also extended to Francis Bieldler III, owner of the study tract, and to Marion Burnsides, President of the Millaree Hunt Club, for the warm hospitality generously provided during the course of the study.

Table 6-Height of bottom-land oak seedlings in relation to skidder activity and debris in thinned stands

Factor	Total seedlings	Residual seedlings	New seedlings
	--------	Centimeters	--------
No skidder activity	29.9	35.3	15.6
Skidder activity	23.0a	26.3a	18.9a
Debris	24.4a	30.0a	19.8a

Means followed by the same letter in a column are not significantly different (LSD, =0.05).

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IMPACTS OF THREE TIMBER STAND IMPROVEMENT THINNING OPTIONS ON LOW-QUALITY SOUTHERN MIXED-HARDWOOD STANDS

Brian P. Oswald and Thomas H. Green'

Abstract-The impact of three thinning options (strip, single-tree selection, and strip with selection between strips) on low-quality southern mixed-hardwood stands was evaluated in northern Alabama. Although stand level comparisons showed no significant differences between options, individual dominant trees benefitted from the thinning treatments, exhibiting increased basal area growth during the period of the study. Intermediate treatments such as these thinning options may provide landowners with sufficient growth of selected high-quality trees to warrant the more intensive management activities on similar sites as utilized in this study.

INTRODUCTION

In general, hardwood stands in the Eastern United States have developed with little or no silvicultural or management activities. Since European settlement, these stands have been subjected to repeated cuttings (often diameter-limit cuts), insects, disease, and fire. Many of these stands are composed of mixed stands of residual individuals from past activities and a variety of shade-tolerant species (McGee 1980).

There are about 90 million acres of pure hardwood forestland in the Eastern United States. The bottom-land hardwood resource has been severely reduced in area over the last 60 years, much of it the result of conversion to agricultural uses. Although the rate of area decrease has slowed in the last 15 years (McWilliams and Faulkner 1991), the 40 million acres of bottom-land hardwoods found in 1952 has been reduced to about 29.8 million acres. Most of these forests are in private holdings (90 percent in 1988), with private nonindustrial landowners owning about 66 percent of the land (Saucier and Cost 1988).

The current hardwood stand condition in the South ranges from high-quality stands of pure or mixed even-aged timber to low-quality stands that are understocked and composed of often less than desirable species (McGee 1982). Many of these stands are continuing to deteriorate in quality as diameter-limit and individual-tree selection cuttings remove the few remaining high-quality (based on genetic quality or market factors) trees and leaving a residual stand of less-desirable species of low growth potential or low market quality.

The demand for hardwood products is increasing (McWilliams 1988, Hair 1980). it is projected that by the year 2030, the demand for hardwoods will triple, rising from the present 3.0 billion cubic feet to 9.6 billion cubic feet. Hardwood management has not kept pace with the intensive research and management strategies utilized in southern pine forests. The best management practices for these forests have not been determined. Thinning of low-quality stands is usually not practiced since the basal area of marketable trees and acceptable growing stock is low and control costs of non-desirable species high (McGee 1982). Increasing demands for fuelwood and other hardwood products have made more intensive management of these low-quality stands possible and profitable (Koch 1980, McGee 1982, Reynolds and Gatchell 1979, Reynolds and Schroeder 1978). Intermediate thinnings may reverse the decrease in quality of these stands by removing undesirable species and trees of poor quality. The objective of this study was to quantify the silvicultural impacts of three timber stand improvement thinnings on low-quality southern mixed-hardwood bottom-land stands.

METHODS

Four square, 1 -acre study plots were established on each of two research sites: the Wheeler Wildlife Refuge (WWR) southeast of Decatur, AL; and the U.S. Army Redstone Arsenal (RSA) in Huntsville, AL. Both locations represented moderately productive bottom-land mixed-hardwood stands with white oak (*Quercus alba L.),*water oak (*Q. nigra* L.), southern red oak (*Q. falcata* Michx.), black oak (*Q. velutina* Lam.) and willow oak (Q. *phellos* L.) as well as sweetgum (*Liquidambar styraciflua* L.), hickories (*Carya Nutt.* spp.), red maple (*Acer rubrum* L.) and elms (*Ulmus* L. spp.) in addition to other minor species in the overstory and understory. Soils on both sites were Melvin silty clay loams.

All trees greater than 2 inches in diameter at breast height (d.b.h.) within each plot were measured and mapped in the summer of 1986. Measurements made included species, location in plot, height, and d.b.h. The location of each tree was determined through the placement of a 16-square grid superimposed on each 1 -acre plot, with the distances from each tree to two designated grid corners recorded.

Treatments utilized at each site were: control (no tree removal); selection cut (removal of all trees except identified crop trees to 75 square feet BA); strip cut (removal of all trees within six 12-foot-wide strips spaced 36 feet apart, leaving approximately 75 square feet BA); and strip-selection cut (removal of all trees within four 12-foot wide strips and any except desired crop trees between

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strips to leave approximately 75 square feet BA). All removals were performed with chainsaws in 1987. The sites were revisited at the end of the 1993 growing season and the heights and d.b.h. of all residual trees recorded.

The basal area per plot was determined for both measurement periods (BA1 and BA2), as was per-plot basal area growth (BAG) and diameter growth (Growth). Statistical analysis (ANOVA and Tukey's range test) on this RCB experimental design was performed using a SAS (SAS Institute, 1991) statistical package on the mainframe computer at Alabama A&M University.

RESULTS AND DISCUSSION

The mean basal areas (square feet per acre) by plot for each of the four thinning treatments on the two sites are shown in table 1. There was no significant difference between sites for any of the treatments. Basal area for the control plots was significantly ($p>0.05$) greater than for any of the treatments. This was expected, since each of the thinning treatments reduced basal area to approximately 75 square feet, while the control plots were left at their original density.

Table I-Mean basal area (square feet per acre) for two sites and four thinning treatments

Site	Plot	BA1	BA2	BAG	Growth
Redstone	Control	101.8[a]	115.4[a]	13.6	119.9
	Selection	75.1	90.1	15.0	140.8
	Strip	70.0	84.7	14.8	159.2
	St/Sel	53.5	72.7	19.2	142.7
Wheeler	Control	108.3"	131 .0[a]	24.3	209.4
	Selection	74.0	69.2	4.9	42.4
	Strip	61.4	80.1	18.7	183.7
	St/Sel	64.2	73.7	9.5	148.1

BA1 = BA/plot 1987; BA2 = BA/plot 1993; BAG = (BA2-BA1)
[a] = Significantly different within same column.

No significant differences were found between treatments for basal area growth (BAG) when both sites were combined and only treatment effects analyzed. The negative BAG of the selection thinning treatment on the Wheeler site was the result of mortality of large trees that died between the two measurement dates. We believe the lack of significant differences in response to the thinning treatments may be accounted for by not having removed enough BA initially. If the residual basal area had been reduced to between 30 and 50 square feet, we believe we would have observed greater BAG, but residual basal areas of this level are associated with a shelterwood system, not an intermediate thinning treatment.

There were significant differences between mean tree basal area (table 2) and specific species' response to thinning treatment (table 3). After treatments were applied, trees within the strip/selection plots had consistently greater BA2, BAG, and Growth than trees within other treatments, and significantly greater BAG and Growth on those plots than trees that had been selection thinned. There were insignificant differences in BAG and Growth between the control and the strip and selection treatments (table 2).

Red Oak, willow oak, black oak, water oak, and white oak (Q. *alba*) had the greatest BA in both 1987 and 1993, with red oak significantly greater in basal area (BA) than all species except the other oaks (table 3). The hickories (*Carya* spp.), green ash (*Fraxinus pennsylvanica*), sweetgum, and red maple were grouped together in BA both years, with the remaining species a third group. These

Table 2-Mean per-tree basal area for each thinning treatment

Treatment plot	Strip No.	Strip Mean	Strip selection No.	Strip selection Mean	Selection No.	Selection Mean	Control No.	Control Mean
		- - - - - - - - - - - -	- - - Square feet - - -					
BA1	360	0.36 BC	230	0.51 AB	259	0.57 A	686	0.31 c
BA2	343	0.48 BC	172	0.84 A	250	0.64 B	632	0.39 C
BAG	343	0.11 AB	172	0.21 A	250	0.06 B	632	0.07 AB
Gr	343	0.10 B	172	1.69 A	250	0.39 B	632	0.65 AB

No. = Number of trees within treatment plots; BA1 = BA/plot in 1987; BA2 = BA/plot in 1993; BAG = (BA2-BA1); Gr = Diameter Growth.
Within-row means not followed by same letter are significantly different ($p<0.05$).

Table 3-Mean basal area and diameter growth for each species (+2 occurrence) found within four treatment plots[a]

Species	BA1	BA2	BAG	Growth
	-Square feet-			Inches
Quercus falcata	0.73 A	0.98 A	0.22 AB	1.56 B
Q. phellos	0.64 AB	0.78 AB	0.13 ABC	0.91 BC
Q. velutina	0.59 AB	0.78 AB	0.16 ABC	1.14 BC
Q. nigra	0.51 AB	0.64 ABC	0.10 ABC	0.88 BC
Q. alba	0.40 BC	0.49 BCD	0.08 BC	0.73 BC
Carya spp.	0.22 CD	0.27 DE	0.04 C	0.44 BC
Fraxinus pennsylvanica	0.19 CD	0.29 DE	0.06 C	0.70 BC
Liquidambar styraciflua	0.15 CD	0.20 DE	0.04 C	0.58 BC
Acer rubrum	0.12 D	0.20 DE	0.06 BC	0.93 BC
Ulmus americana/rubra	0.06 D	0.09 E	0.03 C	0.56 BC
Nyssa sylvatica	0.05 D	0.08 E	0.03 C	0.61 BC
Cercis canadensis	0.03 D	0.30 CDE	0.27 A	3.06 A
Carpinus caroliniana	0.03 D	0.04 E	0.01 C	0.35 C

BA1 = Basal area/plot in 1987; BA2 = Basal area/plot in 1993; BAG = Basal area growth (BA2- BA1); Growth = Diameter growth.
Within-column means not followed by same letter are significantly different ($p<0.05$).

groups match the results of a study performed on upland hardwood sites throughout northern Alabama (Zhang and others 1994).

The greatest BAG was by redbud (Cercis *canadensis)* (0.268 square feet), but not significantly more than the oaks. The other species had no significant differences in BAG between species. Significantly greater growth was also produced by redbud than any of the other species, where little significant variation was observed. Individual redbud appeared to have taken advantage of the increase in available resources that resulted in these thinning operations, but their low numbers (6) and small basal area (table 3) made little impact at the stand level, and would have little impact on the market value of these stands.

CONCLUSIONS

Even though growth of individual trees was stimulated by thinning, this increase was not sufficient to offset the reduction in growing stock with thinning. Therefore, stand level growth was not increased by thinning. Depending on the management objective, thinning may be a suitable intermediate treatment for hardwoods, concentrating growth of overstory trees in the stand on a few large individuals. Any of these regimes should provide additional growth response in the higher quality species if the residual BA is decreased, and undesired species removed in the thinning activity. Strip thinning appears to accomplish this objective as well as single-tree selection. As management and silvicultural options are considered for low-quality, mixed-hardwood forests of the Southern United States, intermediate operations may play a large role in the successful management of individual trees within these forests but will not affect stand level productivity. Care must be taken that whatever option is chosen, the newly available resources do not go to the undesirable understory species such as redbud, rather than to the more valuable overstory oak species.

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PRECOMMERCIAL THINNING OF WATER TUPELO STANDS ON THE MOBILE-TENSAW RIVER DELTA: STAND COMPOSITION 3 YEARS AFTER TREATMENT

J.C.G. Goelz, J.S. Meadows, T.C. Fristoe, and D.A. White'

Abstract-We thinned water tupelo (*Nyssa aquatica* L.) and cleaned (severed all stems) the less desirable Carolina ash (*Fraxinus caroliniana* Mill.) and black willow (*Salix nigra* Marsh.) in three 4-year-old stands that arose following clearcutting of mature water tupelo- dominated stands. In this paper we investigated trends only in trees per acre. Although thinning and cleaning immediately reduced the numbers of the corresponding targeted species, the stumps sprouted and differences among treatments were not evident 3 years after treatment. However, future stand dynamics may reveal differences that are not apparent in trees per acre at 3 years after treatment. The results for water tupelo suggest that these differences will be evident soon. The results for ash and willow suggest that cleaning will have a modest long-term effect on these stands.

INTRODUCTION

Mature water tupelo stands typically are more dense than other hardwood stands (Putnam and others 1960, Goelz 1995). Young stands arising after clearcutting are also dense, particularly due to prolific sprouting from the stumps and roots of severed stems of water tupelo and Carolina ash. Black willow of seed origin often becomes well-established. Most of the stems in these stands will die during natural thinning and thus their growth will be lost to mortality rather than harvested. Furthermore, the Carolina ash and black willow are not merchantable species on these sites. As ground conditions often preclude using rubber-tired or tracked equipment for thinning, we became interested in pre-commercial thinning to achieve a merchantable size (currently, 3-inch top diameter) at an earlier age, reducing rotation length as well as reducing unsalvageable losses of growth to mortality.

Kennedy (1983) and McGarity (1979) indicate that thinning is not particularly beneficial for mature water tupelo stands. DeBell (1971) and Kennedy (1982) reported poor survival of stumps in young coppice-origin water tupelo stands. Although initial sprouting was abundant, as few as 9 percent of the stumps had living sprouts by age 6 (Kennedy 1982).

The general purpose of this paper is to describe changes in species composition after pre-commercial thinning and cleaning treatments. We were particularly interested to determine whether cleaning would effectively control less desirable species and if thinning would maintain vigor of residual sprouts and thus maintain water tupelo as the dominant species on the site. In this paper, our only variables of interest are stems per acre of the four dominant species: water tupelo, Carolina ash, black willow, and baldcypress [*Taxodium distichum* (L.) Rich.].

Initial results from this study (Goelz and others 1993) indicate that thinning increases annual diameter growth of water tupelo by 27 to 37 percent over unthinned plots, although cleaning does not improve growth. The treatments had negligible influence on the number of water tupelo seedlings, although flooding that extended into June during the first growing season following treatment probably caused a 30 percent reduction in seedling numbers. Dissimilar to the results of DeBell (1971) and Kennedy (1982), mortality of tupelo stump sprouts was negligible.

METHODS

We chose three locations, or stands, on Kimberly-Clark Corporation land on the delta of the Mobile and Tensaw Rivers in southern Alabama. At the time of treatment in autumn of 1990, each location had a 4-year-old stand arising after the native water tupelo stands were clearcut. All stems over 2 inches in diameter at breast height (d.b.h.) were felled when the stands were clearcut. The locations are good for water tupelo and are densely stocked with water tupelo, Carolina ash, baldcypress, and black willow, with other species present.

We used a 2 by 2 factorial design. The first factor consists of two treatments: thinning or not thinning water tupelo. Thinning comprises two components: (1) All water tupelo stumps were thinned to one or two best sprouts where "best" was defined as the largest well-formed sprout that originated low on the stump. When two well-spaced sprouts of good form and low origin were present, both were left. If only one good sprout was present, that one sprout was left. (2) Water tupelo seedlings were thinned with a machete wherever they occurred in a dense patch (more than 20 per 100 square feet, in patches of 100 square feet or larger). The tallest water tupelo seedlings were left at a density of approximately 1 per 36 square feet (or a nominal 6 by 6 foot spacing).

The second factor consists of two treatments: cleaning or not cleaning the Carolina ash and black willow. All ash and willow were cut as close to the ground as possible with a chainsaw. These factors provide four treatment combinations: (1) no thinning, no cleaning (control); (2) no thinning, cleaning; (3) thinning, no cleaning; (4) thinning and cleaning.

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We placed eight 0.786-acre square treatment plots in each location. As the soils near the riverbank are much different from the rest of the stand, all treatment plots were at least 1 2 chains (792 feet) from the river. The square measurement plot (0.304 acre) was in the center of each treatment plot. All stems greater than or equal to 3 feet in height were counted. Stems were tallied by species, origin (sprout or seedling), and size class (class one represents stems less than 2.5 inches d.b.h. and class two represents larger stems).

Analyses were by analysis of variance (ANOVA). We used an alpha of 0.05. The design is a 2 by 2 factorial with two levels for thinning, two levels for cleaning, and three locations (equivalent to blocks) with two replications per location. Effect of location was considered fixed. We tested interactions of location with the treatment factors. We also included time, or year, in the design as a factor. As time did not represent evenly spaced units (before treatment, immediately after treatment, 1 year posttreatment, 3 years posttreatment) we could not treat year as a continuous covariate. We also included all interactions of time with treatments and location. We conducted ANOVA's for each species at each measurement time-pretreatment, immediate posttreatment, 1 year after treatment, and 3 years after treatment.

We estimated linear regression equations to predict number of stems at 3 years after treatment using the following as potential predictor variables: the number of stems immediately after treatment in each size class, number of stems removed by the treatments, and dummy variables for treatments, but not locations. Final models were selected by backward elimination/forward addition. All analyses were conducted on transformed data (square root of stems per plot).

RESULTSANDDISCUSSION

Trends in Trees per Acre

Water tupelo-Trees per acre of water tupelo were averaged across locations in figure 1. Significant factors were the main effects location and year, and the interaction terms locationclean, location.thin, clean.thin, and thin.year. The main effect for thinning was not significant. Rather, the effect of thinning was dependent on location and year. Trees per acre on thinned plots were significantly less than unthinned plots at age 0, and were significantly greater than unthinned plots at 1 year after treatment. By 3 Years after treatment, thinned and unthinned plots did not differ in numbers of water tupelo stems. The thinned stumps produced multiple re-sprouts; however, they had naturally thinned themselves by 3 years after treatment. The slopes for the plots that were thinned or thinned and cleaned are negative from 1 to 3 years after treatment, while the slopes for plots that were not thinned were positive. The slopes for the unthinned plots reflect a recovery from mortality following a long, late flood prior to the growing season following treatment. Although stumps on the thinned Plots produced many resprouts, the negative slope suggests that number per acre will be less than for the unthinned plots in the near future.

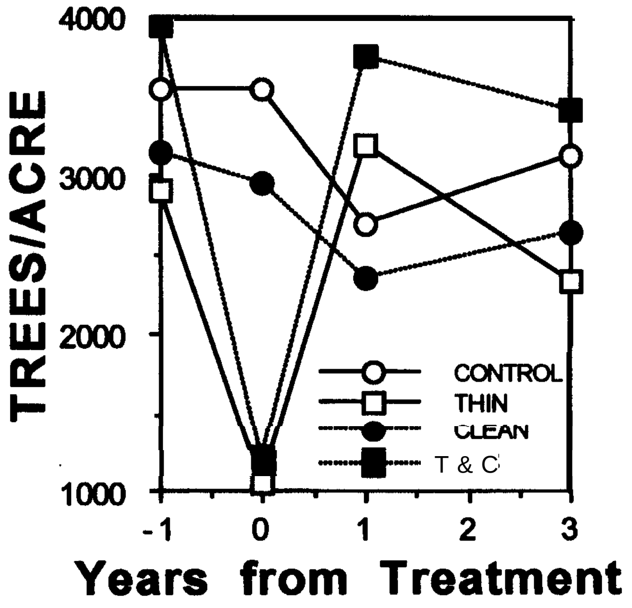

Figure l-Trees per acre of water tupelo. Year "-1" represents pre-treatment conditions rather than 1 year prior to treatment. Year "0" represents measurements taken shortly after treatment.

Carolina ash-Trees per acre of Carolina ash were averaged across locations in figure 2. Significant factors were the main effects clean and year, and the interaction terms location.clean, and clean.year. Thus, the effect of cleaning is dependent on location and year. Although the

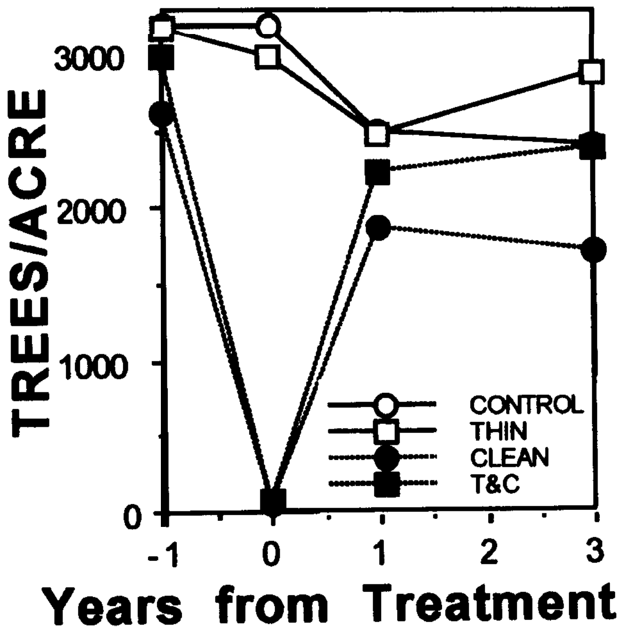

Figure 2—Trees per acre of Carolina ash. Year "-1" represents pre-treatment conditions rather than 1 year prior to treatment. Year "0" represents measurements taken shortly after treatment.

effect ot cleaning was significant immediately after treatment, 1 year later there were no significant differences among treatments in trees per acre of Carolina ash.

Black willow-Trees per acre of black willow were averaged across locations in figure 3. Significant factors were the main effects location, clean, thin, and year, and the interaction terms location.clean, location.thin, location.year, clean.year, thin.year, and location.clean.year. Immediately after treatment, cleaning had a significant effect on numbers of willow stems, although this effect varied with location-one location had much more willow than the other two locations. However, by 1 and 3 years after treatment, the thinning treatment had a significant effect while cleaning had no significant effect on number of willow stems. Although thinning of the water tupelo may indeed benefit the willow, we consider it to be as likely that the thinned plots had greater recruitment of willow by random chance-the distribution of willow appeared patchy.

Baldcypress-Trees per acre of baldcypress were averaged across locations in figure 4. Significant factors were the main effects location, clean, and thin, and the interaction term clean.thin. By 3 years after treatment, baldcypress differed only among locations. Baldcypress was not directly affected by thinning or cleaning, and severing the other species provided no significant benefit to the baldcypress.

Prediction Equations

Water tupelo stems ≥2.5 inches d.b.h.-The final equation was:

SQRT (Trees/Acre) = 25.204 + 0.342 (Trees/Acre ≥ 2.5" at time 0) .

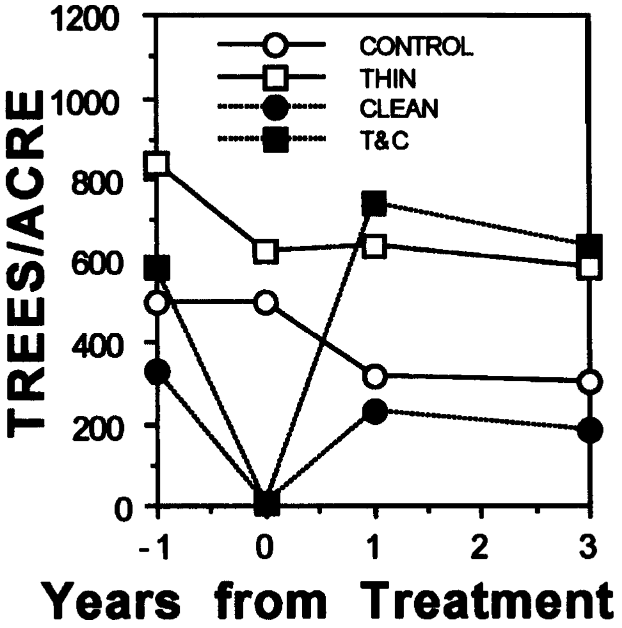

Figure 3-Trees per acre of black willow. Year "-1" represents pre-treatment conditions rather than 1 year prior to treatment. Year "0" represents measurements taken shortly after treatment.

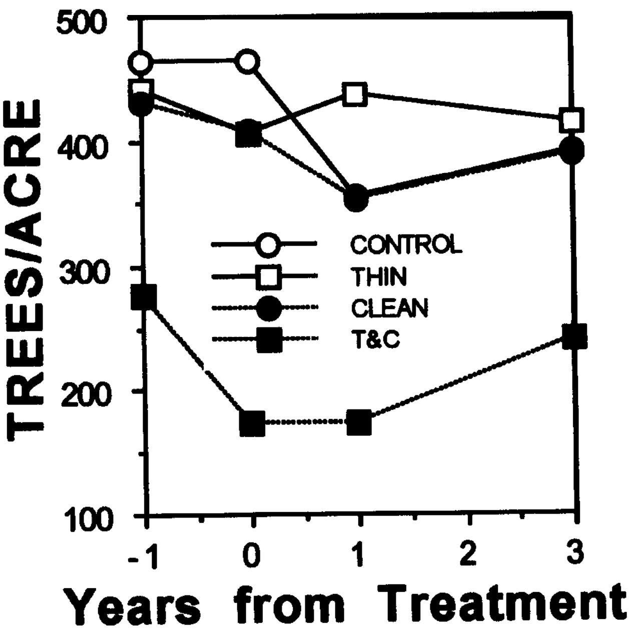

Figure 4-Trees per acre of baldcypress. Year "-1" represents pre-treatment conditions rather than 1 year prior to treatment. Year "0" represents measurements taken shortly after treatment.

The adjusted r^2 was 0.878 and the standard error was 3.6. None of the dummy variables for treatments nor the number of stems removed by the treatment entered the equation. This suggests that it matters little how a stand arrives at a given number of stems per acre at age 4—whether the number reflects intrinsic attributes of the stand or that the stand had been thinned-thus, pre-commercial thinning can be effective in controlling stems per acre. Based upon stocking guides (Goelz 1995), about 300 trees per acre would be a good target at age 7 (which is 3 years after treatment). Using the equation above, this would imply a target of about 60 trees per acre ≥2.5 inches d.b.h. at age 4.

Carolina ash stems-The final equation was:

SQRT (Trees/Acre) = 22.934 + 0.0671 (Trees/Acre at time 0) + 0.0668 (Trees/Acre removed at time 0) .

The adjusted r^2 was 0.814 and the standard error was 10.2. The coefficients for trees remaining and for trees removed are practically identical. This suggests cleaning does not effectively reduce the number of Carolina ash stems. Rather, you will have the same number of Carolina ash stems at age 7 whether you clean or not at age 4.

Black willow stems-The final equation was:

SQRT (Trees/Acre) = 10.322 + 0.089 (Trees/Acre at time 0) + 0.126 (Trees/Acre removed at time 0) .

The adjusted r^2 was 0.776 and the standard error was 1 l .7. The coefficient for trees removed is approximately 1.4 times the coefficient for the number of trees remaining at time 0. This suggests if you sever a willow tree at age 4, by aye 7 **you will have 1.4 willow stems for every stem you** severed.

Black willow stems ≥2.5 inches d.b.h.-The final equation is:

$$SQRT (Trees/Acre) = 4.223 - 3.780 (CLEAN) + 0.045 (Trees/Acre of both size classes at time 0).$$

The adjusted r^2 is 0.856 and the standard error is 3.5. The magnitude of the coefficient for the intercept (1.284) is not significantly different from the coefficient for the dummy variable for the cleaning treatment **(-1.149).** This suggests that cleaning basically eliminates the presence of larger willow stems 3 years hence. If the water tupelo can approach crown closure in this time period, the very shade-intolerant willow will not survive. We observed this on one of our locations.

CONCLUSIONS

Thinning water tupelo initially caused drastic reduction in the number of water tupelo stems. The stumps sprouted again, and, by 1 year after treatment, there were more stems of water tupelo in the thinned plots. However, by 3 years after treatment, thinned plots did not have numbers of water tupelo stems that were significantly different from unthinned plots. The trend suggests that thinned plots will have fewer stems than unthinned plots in the near future. Although cleaning initially eliminated stems of Carolina ash and willow, by 3 years after treatment the number of ash and willow stems was as high as in the plots that were not cleaned. Thus, the effects of thinning on stems per acre of water tupelo will likely become greater as stand dynamics proceed, while the effects of cleaning appear to be modest. A more complete picture of the efficacy of the treatments will be obtained with a description of basal area growth and individual tree diameter growth.

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FIRST-YEAR GROWTH AND BOLE QUALITY RESPONSES TO THINNING IN A RED OAK-SWEETGUM STAND ON A MINOR STREAMBOTTOM SITE

James S. Meadows and J.C.G. Goelz[1]

Abstract-Four thinning treatments were applied to a red oak-sweetgum (Quercus spp.-*Liquidambar styraciflua* L.) stand on a minor streambottom site in west-central Alabama in September 1994: (1) unthinned control; (2) light thinning to 70 to 75 percent residual stocking; (3) heavy thinning to 50 to 55 percent residual stocking; and (4) B-line thinning to desirable residual stocking for bottomland hardwoods. The thinning operation consisted of a combination of low thinning and improvement cutting, in which the objective was to remove most of the pulpwood-sized trees as well as sawtimber-sized trees that were damaged, diseased, of poor bole quality, or of an undesirable species. Prior to treatment, the stand contained 196 trees per acre with a basal area of 121 square feet per acre. Average diameter of trees larger than 3.5 inches in diameter at breast height (d.b.h.) was 10.7 inches. Stocking averaged 107 percent across the 24-acre study area. Light thinning reduced stand density to 83 trees and 82 square feet of basal area per acre, increased average d.b.h. to 13.5 inches, and reduced stocking to 69 percent. Heavy thinning reduced density to 49 trees and 64 square feet of basal area per acre, increased average d.b.h. to 15.5 inches, and reduced stocking to 52 percent. B-line thinning reduced stand density to 65 trees and 86 square feet of basal area per acre, increased average d.b.h. to 15.6 inches, and reduced stocking to 70 percent. Approximately 24 percent of the residual trees across the thinned areas experienced at least some degree of logging damage from the harvesting operation. None of the thinning treatments had a significant effect on diameter growth of individual trees, across all species, during the first year after thinning. Though not statistically significant, diameter growth of red oaks was greater across the thinned areas than in the unthinned areas. Thinning also had no significant effect on the production of new epicormic branches on the butt log of residual trees. However, epicormic branching varied widely across both species and crown class.

INTRODUCTION

Profitable management of hardwood stands for sawtimber production depends not only on maintenance of satisfactory rates of growth, but also on successful development and maintenance of high-quality logs. In general, partial cuttings, usually in the form of some combination of thinning and improvement cutting, can be used in most mixed-species bottomland hardwood forests to: (1) enhance growth of individual trees, (2) improve species composition of the stand, and (3) improve bole quality of residual trees (Meadows 1996).

Thinning has been shown to dramatically increase diameter growth of residual trees within several different hardwood types, such as central upland oaks (Hilt 1979, Sonderman 1984b), Allegheny cherry-maple (*Prunus* spp.- *Acer* spp.) (Lamson 1985, Lamson and Smith 1988), and mixed Appalachian hardwoods (Lamson and others 1990). In general, the heavier the thinning, the greater the diameter growth response. For example, Hilt (1979) reported a 100 percent increase in periodic diameter growth of the 40 largest trees per acre in an upland oak stand in Missouri following the heaviest thinning treatment.

However, as thinning intensity increases, residual stand density decreases to a point where site occupancy is less than optimum. Although very heavy thinning greatly increases the diameter growth of individual residual trees, stand density becomes so low that stand-level basal area growth and volume growth are much reduced. In short, the stand does not fully realize the potential productivity of the site. Minimum residual stocking levels necessary to maintain adequate stand-level growth and to ensure full occupancy of the site have been recommended to be 46 to 65 percent in central upland oaks (Hilt 1979) and 45 to 60 percent in cherry-maple stands (Lamson and Smith 1988). A very heavy thinning in a young water oak (Quercus *nigra* L.) plantation (equivalent to a residual stocking of 33 percent) reduced density such that stand volume growth will be suboptimal for a long period of time (Meadows and Goelz, in press).

Increased thinning intensity is also associated with increased degrade in bole quality (Sonderman 1984a, 1984b; Sonderman and Rast 1988). Specifically, the number and size of live and dead limbs increase significantly as residual stocking decreases, particularly on upland oak species. On the other hand, Sonderman and Rast (1988) reported that the production of epicormic branches on residual oak stems decreased with increasing thinning intensity. As the intensity of thinning increases, the proportion of dominant and codominant trees in the residual stand also increases. These vigorous, upper-crown-class trees are less likely to produce epicormic branches than are less vigorous, lower-crown-class trees (Meadows 1995). Although these conclusions seem to be conflicting, there does appear to be a trade-off between improved diameter growth and the potential for adverse effects on bole quality, as thinning intensity increases and residual density decreases.

Thinning is also used to improve species composition (Meadows 1996). In general, the goal is to decrease the proportion of low-value species and thus increase the

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proportion of high-value species. This objective is usually most important at the first thinning, but should be a major consideration whenever a partial cutting is conducted in a mixed-species stand.

These four components of thinning, increased diameter and volume growth of individual trees, increased stand-level basal area and volume growth, maintenance or enhancement of bole quality, and improved species composition, are critically important for the profitable management of hardwood stands for high-quality sawtimber production. Ideally, a thinning regime should be designed to optimize value growth of the stand, as determined by these four components. Because maximization of all four components is not biologically possible, some compromises or trade-offs in expected benefits must be accepted.

Thinning in southern bottomland hardwood stands has received little attention from researchers over the years. Existing guidelines, such as those recommended by McKnight (1958), Johnson (1981), and Meadows (1996), are general in nature, and are based more on experience and observation rather than on specific research results. To effectively manage southern bottomland hardwood stands for high-quality sawtimber production, we need quantitative thinning guidelines for each of the various forest types found in southern bottomlands. These guidelines should include recommendations on: (1) timing of thinning, (2) intensity of thinning, and (3) marking rules designed to optimize value growth of the stand.

This study marks the establishment of a series of thinning studies in red oak-sweetgum stands on minor streambottom sites across the South. The series will consist of at least 12 studies installed over the next 10 to 15 years, using similar study designs, treatments, and methods.

This initial study addressed, as will each of the individual studies in the series, two specific objectives: (1) to determine the growth and bole quality responses Of individual trees to several levels of thinning; and (2) to determine the effects of several levels of thinning on stand growth, development, and yield. Additionally, the results from the entire series of studies will be combined to address the following long-term objectives: (1) to develop practical guidelines for the intermediate management Of southern bottomland hardwood stands; (2) to test the applicability of various levels of recommended residual stocking across a wide variety of site and stand conditions; and (3) to develop a growth and yield model for managed stands of southern bottomland hardwoods.

METHODS

Study Area

The study is located within the floodplain of the Tombigbee River in southwestern Pickens County, near Aliceville, in west-central Alabama, on land owned by Gulf States Paper Corporation. The study area is located within a 74-acre stand composed primarily of red oak, sweetgum, and hickory (*Carya* spp.). Stand age at the time of study installation was approximately 60 years. A timber inventory conducted by Company personnel in April 1993 indicated an average sawtimber volume of 6,520 board feet per acre (Doyle scale), with approximately 81 percent of the volume in red oak, and an estimated pulpwood volume of 12.5 cords per acre.*

Based on preliminary observations and measurements, we classified the stand as a small sawtimber stand on a high-quality site, with high initial stocking. There was no evidence of previous harvesting activity in the stand.

Plot Design

Plot design followed the recommendations for standard plots for silvicultural research, set forth by the USDA Forest Service's Northeastern Forest Experiment Station (Marquis and others 1990).

Individual treatments were applied to a 2.0-acre, rectangular treatment plot, measuring 4 by 5 chains (264 by 330 feet). Treatments were applied uniformly across each treatment plot. One measurement plot was located on the interior O.&acre rectangle of each treatment plot. Each measurement plot was 2 by 3 chains (132 by 198 feet), providing a 1 -chain (66 feet) buffer around each.

The four treatments were replicated three times and were assigned randomly to treatment plots within each replication. The 12 treatment plots covered an area of 24 acres.

Treatments

Thinning intensity was defined by four levels of residual stocking, based on the stocking guide for southern bottomland hardwoods developed by Goelz (1995). Specifically, the study consisted of four treatments: (1) an unthinned control; (2) light thinning to 70 to 75 percent residual stocking; (3) heavy thinning to 50 to 55 percent residual stocking; and (4) B-line thinning to desirable residual stocking following partial cutting in well-managed, even-aged southern bottomland hardwoods, as recommended by Putnam and others (1960).

The thinning operation consisted of a combination Of low thinning and improvement cutting, in which the objective was to remove most of the pulpwood-sized trees as well as sawtimber-sized trees that were damaged, diseased, Of poor bole quality, or of an undesirable species. Modified hardwood tree classes, as originally defined by Putnam and others (1960), formed the cutting priority for each treatment. Trees were removed from the cutting stock and cull stock classes first, and then from the reserve growing stock class, if necessary, until the target residual stocking was met.

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[2] Personal communication. 1993. Sam G. Hopkins, Research Manager, Gulf States Paper Corporation, P.O. Box 48999, Tuscaloosa, AL 35404.

The thinning operation was performed by a contract logging crew in September 1994. All trees were directionally felled with a mechanized feller. Rubber-tired skidders were used to remove the merchantable products, in the form of longwood, from the woods. Most of the material cut was marketed as pulpwood.

Measurements and Statistical Analysis

A preharvest survey was conducted to determine species composition and initial stand density on each 0.6-acre measurement plot. Variables measured on all trees included species, diameter at breast height (d.b.h.), crown class, and tree class. After the stand was marked for thinning, but prior to harvest, the length and grade of all saw logs, as defined by Rast and others (1973), and the number of epicormic branches on each 16-foot log section were recorded on those trees designated as "leave" trees. Merchantable height, height to the base of the live crown, and total height were also recorded on a subsample of leave trees. At the end of the first year after thinning, d.b.h. and the number of epicormic branches on each 16-foot log section were remeasured.

As described by Meadows (1993), logging damage to individual residual trees, in the form of root, bole, or crown injuries, was assessed on the basis of three factors: (1) type of damage, (2) severity of damage, and (3) location of damage.

Data were subjected to analysis of variance for a randomized complete block design with three replications of four treatments, for a total of 12 experimental units. All effects were considered fixed. *Alpha* was set at 0.05. Plot-level variables represented the mean for all residual trees on each measurement plot. Means were separated through the use of Duncan's New Multiple Range Test.

RESULTSANDDISCUSSION

Stand Conditions Prior to Thinning

Prior to thinning, the stand contained 196 trees per acre with a basal area of 121 square feet per acre. Quadratic mean diameter of trees larger than 3.5 inches d.b.h. was 10.7 inches. Stocking averaged 107 percent across the 24-acre study area. No significant differences in any of these pretreatment parameters were found among the four levels of thinning.

Prior to treatment, the stand was a typical, even-aged, mixed-species stand of bottomland hardwoods. Measures of stand density and other observations indicated that the stand could benefit from thinning. For example, average stocking across the entire study area was 107 percent. Goelz (1995) recommended thinning bottomland hardwood stands with stocking greater than 100 percent.

Species composition across the study area prior to thinning was predominantly red oak, hickory, and sweetgum. Various species of red oaks, principally water, cherrybark (*Quercus falcata* var. *pagodifolia* Ell.), and willow (Q. *phellos* L.) oaks with lesser amounts of southern red (Q. *falcata* Michx.) and Shumard (*Q. shumardii* Buckl.) oaks, accounted for approximately 45 percent of the basal area and were found primarily in the upper canopy. Quadratic mean diameter of red oaks was 16.1 inches. Shagbark hickory [*Carya ovata* (Mill.) K. Koch] and mockernut hickory [C. *tomentosa* (Poir.) Nutt.] together accounted for about 25 percent of the basal area. Hickories were found primarily in the mid-canopy, but scattered individuals occurred as upper-crown-class trees. Sweetgum comprised approximately 12 percent of the basal area and occurred primarily as lower-crown-class trees. Other species scattered throughout the stand included white oak (Q. *alba* L.), overcup oak (*Q. lyrata* Walt.), swamp chestnut oak (Q. *michauxii* Nutt.), green ash (*Fraxinus pennsylvanica* Marsh.), and various elms (*Ulmus* spp.).

Stand-Level Responses to Thinning

Light thinning reduced stand density to 83 trees and 82 square feet of basal area per acre, increased quadratic mean diameter to 13.5 inches, and reduced stocking to 69 percent. It removed 62 percent of the trees and 31 percent of the basal area. Heavy thinning reduced density to 49 trees and 64 square feet of basal area per acre, increased quadratic mean diameter to 15.5 inches, and reduced stocking to 52 percent. It removed 73 percent of the trees and 43 percent of the basal area. B-line thinning reduced stand density to 65 trees and 86 square feet of basal area per acre, increased quadratic mean diameter to 15.6 inches, and reduced stocking to 70 percent. It removed 68 percent of the trees and 37 percent of the basal area. All thinning treatments produced stand characteristics significantly different from the unthinned control. Average d.b.h. of trees removed during the logging operation ranged from 7.1 inches in the light thinning treatment to 8.3 inches in the B-line thinning treatment. Overall average d.b.h. of trees removed was 8.0 inches.

Thinning also improved the species composition of the residual stand. All thinning treatments increased the proportion of red oak and decreased the proportions of both sweetgum and hickory within the residual stand. Most of the sweetgum and hickory removed from the stand were lower-crown-class trees.

Stand conditions 1 year after thinning are summarized in table 1. A small amount of mortality occurred in both the unthinned control and the B-line thinning treatments, at the rate of 2 trees per acre during the first year after thinning. No mortality was observed in either the light or heavy thinning treatments.

Slight increases in basal area and stocking were observed for all treatments during the first year after thinning, with the largest increases found in the light thinning treatment. Increases in quadratic mean diameter were also found among all treatments, with the largest increase observed in the heavy thinning treatment. Because light thinning left more trees per acre, we expected it to produce the highest stand-level growth rates (in basal area and stocking), excluding the unthinned control. By the same token, because heavy thinning left fewer trees, we expected it to

Table I-Stand conditions 1 year after application of four thinning treatments

Treatment	Trees/acre	Basal area	D.b.h.	Stocking
		Sq ft/ac	Inches	Percent
Control	182 a[a]	118 a	10.9 b	103a
Light	83 b	85 b	13.9 ab	71 b
Heavy	49 c	66 c	16.0 a	54 c
B-Line	63 bc	87 b	15.9 a	71 b

[a] Treatment means within columns not followed by the same letter are significantly different at the 0.05 level of probability, as determined by Duncan's New Multiple Range Test.

produce the highest individual-tree growth rates, leading to the greatest increase in quadratic mean diameter. However, none of these first-year increases in basal area, stocking, or quadratic mean diameter were statistically significant.

Individual-Tree Diameter Growth

We found no significant differences among treatments in first-year diameter growth of individual trees. Across all species within treatments, trees in the unthinned control plots grew an average of 0.09 inches in diameter. In contrast, residual trees in the thinned plots exhibited a slightly higher diameter growth response, and averaged 0.15, 0.18, and 0.16 inches during the first year after light thinning, heavy thinning, and B-line thinning, respectively.

Even though thinning had no significant effect on first-year diameter growth, individual species groups varied in their growth response to the four levels of thinning (fig. 1). Diameter growth of residual red oaks (primarily cherrybark, water, and willow oaks) and sweetgum appeared to respond well to all thinning treatments. For example, both light and heavy thinning resulted in about twice as much diameter growth as was observed in the unthinned control plots, for both species groups. Diameter growth response of both groups to B-line thinning was somewhat less than that observed for both light and heavy thinning. In contrast, first-year diameter growth of hickory was uniformly low and was unaffected by thinning treatment. However, none of these first-year differences within species groups were statistically significant.

Although these results are preliminary and are not statistically significant, it does appear that diameter growth of residual trees will be increased by all thinning treatments, especially among the red oaks. We anticipate that treatment effects will increase as the study progresses.

Epicormic Branching

Production of new epicormic branches on the butt logs of residual trees was low during the first year after treatment and did not differ significantly among the four levels of thinning. In fact, trees in all treatments averaged fewer than one new epicormic branch on the butt log.

However, species varied greatly in the number of new epicormic branches produced in response to the four levels of thinning (fig. 2). In red oaks and, to a lesser extent, in sweetgum, the number of new epicormic branches generally increased with increasing thinning intensity. Epicormic branching response among hickory species was highly variable and yielded no obvious trends. However, it is important to note that even though there appeared to be treatment effects, at least within sweetgum and the red oak group, both species groups produced an average of fewer than 1.5 new epicormic branches on the

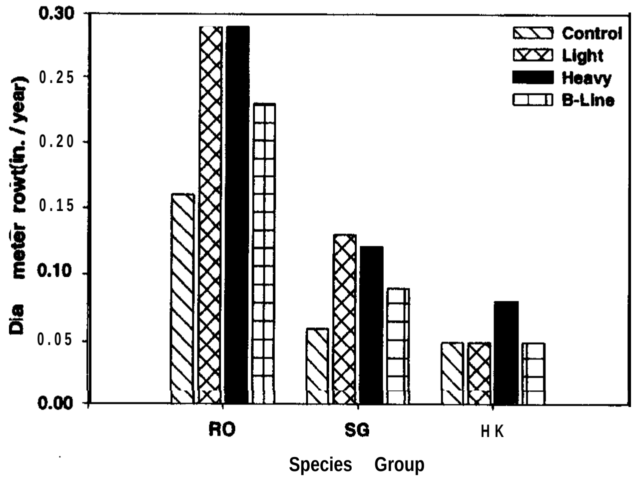

Figure I-Diameter growth of residual trees, by species group, during the first year after application of four thinning treatments (RO=red oak, SG=sweetgum, HK=hickory).

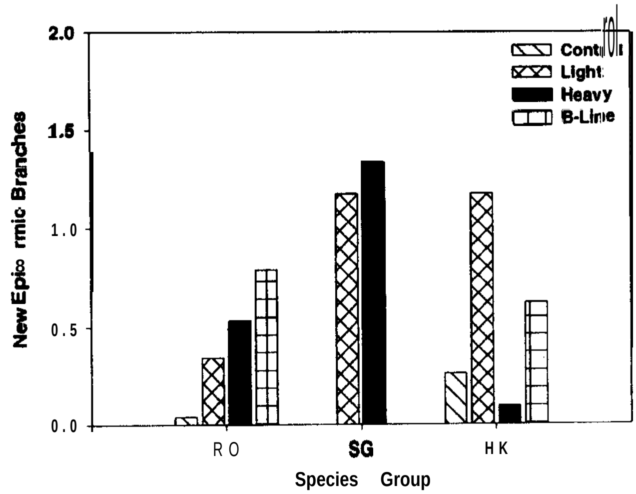

Figure 2—Number of new epicormic branches produced on the butt logs of residual trees, by species group, during the first year after application of four thinning treatments (RO=red oak, SG=sweetgum, HK=hickory).

butt log. Consequently, thinning had little effect on production of new epicormic branches during the first year after treatment.

Production of new epicormic branches also varied among crown classes (fig. 3). Lower-crown-class trees, as a group, produced more epicormic branches than did upper-crown-class trees, as a group, in response to thinning. Given that crown class is a reasonably adequate indicator of tree vigor, our data indicate that the production of new epicormic branches increases as initial tree vigor declines. In other words, residual trees of low vigor are more susceptible to the production of new epicormic branches than are residual trees of high vigor, when subjected to thinning.

These results tend to support the hypothesis advanced by Meadows (1995) that the propensity of an individual hardwood tree to produce epicormic branches in response to some disturbance, such as thinning, is largely controlled by the species and initial vigor of the particular tree. Meadows (1995) noted that hardwood species vary greatly in their likelihood to produce epicormic branches, and categorized most bottomland red oaks and sweetgum as highly susceptible to epicormic branching. Meadows (1995) also speculated that tree vigor is the mechanism that controls the production of epicormic branches when a tree is subjected to some type of disturbance, such that healthy, vigorous trees, even of susceptible species, are much less likely to produce epicormic branches than are trees in poor health. Our observations in this study that epicormic branching varied not only by species but also among crown classes lend credence to these hypotheses.

Logging Damage

We surveyed the extent of logging damage across the study area following the thinning operation and found that

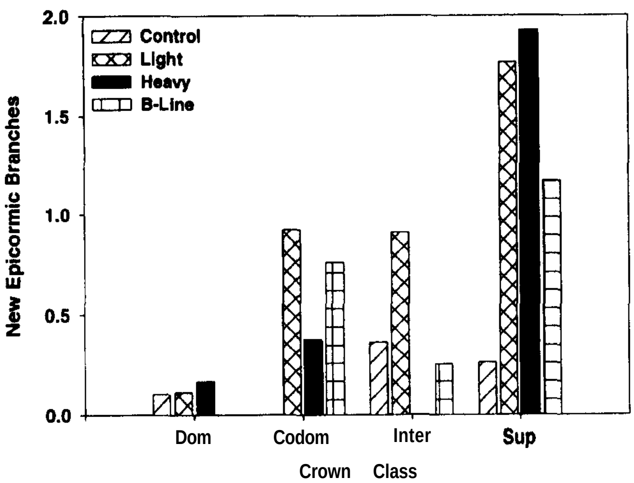

Figure 3-Number of new epicormic branches produced on the butt logs of residual trees, by crown class, during the first year after application of four thinning treatments (DOM=dominant, CODOM=codominant, INTER=intermediate, SUP=suppressed).

24 percent of the residual trees experienced some type of damage. The extent of damage varied somewhat across treatments, but these differences were not statistically significant. The proportion of residual trees damaged ranged from 20 percent in the heavily thinned plots to 32 percent in the plots subjected to B-line thinning. Most of the logging damage observed in this study was minor, and does not indicate a permanent loss of tree vigor.

The overall average of 24 percent in this study was considerably lower than that reported by Meadows (1993) following partial cutting in a riverfront hardwood stand in the Mississippi Delta. In that study, Meadows (1993) found that 62 percent of the residual trees had been damaged at least to some extent.

Most of the damage observed in this study and in the one reported by Meadows (1993) occurred as logs pulled by the skidder scraped the lower boles of residual trees. Although some degree of logging damage must be expected during any partial cutting operation, the extent of damage can be minimized through better planning of the logging operation and through more careful skidder operation.

CONCLUSIONS

Thinning had no significant effect on average diameter growth across all species during the first year after treatment, but red oaks seemed to increase in growth more than did other species groups.

Thinning also had no significant effect on the production of new epicormic branches along the butt logs of residual trees during the first year after treatment. However, epicormic branching varied widely among species and among crown classes.

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SEASONAL LATERAL ROOT GROWTH OF JUVENILE LOBLOLLY PINE AFTER THINNING AND FERTILIZATION ON A GULF COASTAL PLAIN SITE

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Abstract-In 1989, two levels each of stand density and fertilization were factorially established in an 8-year-old loblolly pine plantation on a P-deficient site. Levels of stand density were nonthinned at 2,732 trees per hectare and thinned at 721 trees per hectare. Fertilizer levels were none or application of 150 kilograms P plus 135 kilograms N per hectare. In 1994, stand basal areas of the nonthinned and thinned plots were 42 and 25 square meters per hectare, respectively, and a second thinning on the previously thinned plots left 15.6 square meters per hectare. The previously fertilized plots were refertilized with 200 kilograms N, 50 kilograms P, and 50 kilograms K per hectare. In 1994 and 1995, tree growth was quantified at the end of the growing season, and lateral root initiation and elongation, soil temperature, and soil water content were measured throughout the growing season. The maximum rate of loblolly pine root growth occurred in May through July with more root growth in the 0- to 5-cm depth than in the 5- to 30-cm depth. A positive relationship between soil water content and root growth was observed. Thinning stimulated root growth 5 years after initial thinning and immediately after rethinning. Fertilization did not affect root growth 5 years after application and refertilization had a limited positive effect on root growth. Although tree growth was not immediately affected by treatment reapplication, a positive relationship was found between current annual tree volume increment and root elongation during peak root growth. We conclude that root system growth is sensitive to environmental variables that affect root metabolism in May through July, and that on the Gulf Coastal Plain, loblolly pine volume gains after silvicultural treatment result, in part, from an increase in soil resource uptake.

INTRODUCTION

The availability of water and mineral nutrients often limits the productivity of southern pine forests on Gulf Coastal Plain sites (Allen 1987, Allen and others 1990, Bassett 1964, Cregg and others 1988, Dougherty 1996, Moehring and Ralston 1967). Low transpiration rates and a high water table during winter result in adequate water availability in the early growing season, but with increased evapotranspiration and reduced precipitation as the growing season progresses, water deficits arise (Knight and others 1994, Moehring and Ralston 1967). In addition, phosphorus (P) and nitrogen (N) deficiencies are common throughout the South (Allen and others 1990, Dougherty 1996), and can produce significant gains in loblolly pine volume (Allen 1987, Fisher and Garbett 1980).

With adequate resource availability, photosynthate is preferentially partitioned to tree branch and foliage, rather than root growth (Dickson 1989, 1991). This phenomenon was demonstrated by Haynes and Gower (1995) after fertilization of 31-year-old red pine (*Pinus resinosa* Ait.) in Wisconsin. Four years after the start of annual fertilizer amendments, litterfall was increased 49 percent and carbon allocation to root and soil processes was decreased 48 percent. In contrast, long-term water and fertility deficits cause an increase in the proportion of carbon partitioned to the root system (Eissenstat and Van Rees 1994). For example, Keyes and Grier (1981) found that the proportion of biomass partitioned to the root system in two stands of 40-year-old Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] was negatively related to soil fertility and site index.

Expansion of tree root systems may be required to offset water and fertility deficits and maximize stand productivity on resource-limited sites in the South. Root growth is affected by growth regulator relations and the availability of carbohydrates, mineral nutrients, and water (Coutts 1987, Dickson 1991, Eissenstat and Van Rees 1994, Klepper 1987). Because these variables are either directly or indirectly influenced by thinning and fertilization, we hypothesize that root system growth and resource uptake can be manipulated by these silvicultural tools. We had two primary objectives in this study: (1) characterize the seasonal root growth and soil environment of plantation loblolly pine (*P. taeda* L.) in response to thinning and fertilization, and (2) evaluate the relationship between tree and root system growth in four stand environments.

MATERIALS AND METHODS

The study was installed in an 8-year-old loblolly pine stand planted at a 1.83-meter (m) by 1.83-m spacing on the Palustris Experimental Forest in Rapides Parish, LA. The soil is a Beauregard silt loam (fine-silty, siliceous, thermic, Plinthaquic Paleudult) (Kerr and others 1980). In April 1988, 12 treatment plots-13 rows of 13 trees each-were established (Haywood 1994). Thinning and fertilization treatments were randomly assigned to the plots in a 2 by 2 factorial design with three replications. Levels of thinning were: the original stocking [2,732 trees per hectare (ha)], and removal of every other row of trees and every other tree in residual rows in November 1988 (721 trees per ha). Levels of fertilization were: no fertilization and broadcast application of 747 kilograms (kg) per ha diammonium phosphate (135 kg N and 150 kg P per ha) in April 1989. The fertilization rate was based on recommendations for

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loblolly pine grown on the nutrient-poor soil in this study (Kerr and others 1980, Shoulders and Tiarks 1983, Tiarks 1982).

Six growing seasons after the initial silvicultural treatments were applied, stand basal areas of the nonthinned and thinned plots were 42 and 25 square meters (m^2) per ha, respectively. In March 1995, the previously thinned plots were thinned from below to 30 percent of maximum stand density index as recommended by Dean and Baldwin (1993), resulting in a residual basal area of 15.6 m^2 per ha. Foliar mineral nutrient concentrations in August 1993 were used to determine a fertilizer recommendation for the previously fertilized plots. Urea, monocalcium phosphate, and potash 1200 kg N, 50 kg P, and 50 kg potassium (K) per ha] were broadcast on the previously fertilized plots in March 1995.

Tree heights and diameters at breast height (d.b.h.) were measured quarterly (Haywood 1994) and outside bark stem volume (Baldwin and Feduccia 1987) was calculated. Two replications were chosen as blocks for measurement of root system growth and the soil environment. Blocks were identified based on the influence of topography on soil drainage. At 14-day intervals in May 1994 through January 1995, and June 1995 through January 1996, new roots [≥0.5 centimeters (cm) long] were cumulatively traced onto acetate sheets attached to five vertical Plexiglas rhizotrons (0.3 x 35.4 x 76 cm) per plot (Sword and others 1996). After each measurement period, a computer image file of each acetate tracing was created and the length of the lines contained in each image file was quantified using GSROOT software (PP Systems Inc., Bradford, MA). Net lateral root elongation was calculated by subtraction and expressed as millimeters per square decimeter (mm dm^{-2}) per day. After each measurement period, root initiation was quantified as the number of independently appearing new roots (20.5 cm long) in the 0- to 5-, 5- to 15-, and 15- to 30-cm depths, and expressed as number dm^{-2} per day.

Soil temperature (°C) was measured by insulated solid state sensors (Sword and others 1996) inserted in the soil at 5, 15, and 30 cm through ports in the rhizotrons. The water content of the soil (percent volume) was measured by time domain reflectometry with one sensor placed at the 15-cm depth through a port in each of three randomly chosen rhizotrons per plot. Soil temperature and Water content were measured at 14-day intervals in May 1994 through January 1995, and June 1995 through January 1996.

Tree height, d.b.h., and stem volume were evaluated by analysis of variance after the 1994 growing season and by analysis of covariance after the 1995 growing season, using a completely random, 2 by 2 factorial experimental design with three replications. Factors were two levels each of fertilization and thinning. Covariates were height, d.b.h., and volume at the end of the 1994 growing season. Net root elongation, soil temperature, and transformed (arcsine of the square root) volumetric soil water content data collected in 1994-95 and 1995-96 were analyzed by a randomized, complete, block-split-plot-in-time design with two blocks. Thinning and fertilization were the whole-plot treatments; time was the subplot treatment. Root initiation in 1994-95 and 1995-96 was analyzed by a randomized, complete, block-split-plot-in-space-and-time design with two blocks. Thinning and fertilization were the whole-plot treatments; time and depth were the subplot treatments. Data were subjected to analyses of variance by measurement date to explain significant time interactions. Together, root growth and soil water content decreased as the growing season progressed. To evaluate this relationship as soil water became less available, Pearson product-moment correlations were calculated for root growth and soil water content in late June through September 1994 (SAS Institute Inc. 1991). Because our time domain reflectometer was inoperable in August through September 1995, we were unable to conduct this analysis in 1995. Main and interaction effects and Pearson correlation coefficients were considered significant at probabilities (Pr) ≤ 0.05 unless otherwise noted, and treatment means were compared with the Least Significant Difference test at Pr ≤ 0.05.

RESULTS

At the end of the 1994 growing season, fertilization significantly increased tree height, and both thinning and fertilization significantly increased d.b.h. and stem volume (table 1). After the 1995 growing season, tree height, d.b.h., and stem volume were not significantly affected by reapplication of the thinning and fertilization treatments.

Maximum rates of root initiation and net root elongation occurred in May through July (figs. 1 and 2). Root initiation was significantly affected by soil depth and by an interaction between time and soil depth in 1994 and 1995 (table 2). Consistently, root initiation in the 0- to 5-cm depth was greater than that at either the 5- to 15-cm or 15- to 30-cm depth; whereas, root initiation at the 5- to 15-cm depth was greater than that at the 15- to 30-cm depth in May and June.

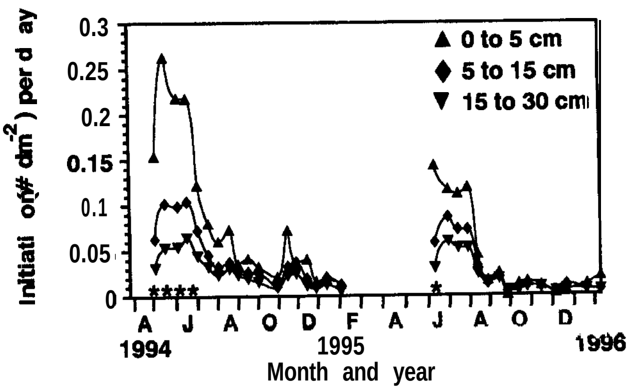

Figure l-Seasonal number of roots per decimeter per day initiated at 0 to 5, 5 to 15, and 15 to 30 centimeters in rhizotrons during 1994 and 1995. Asterisks signify measurement intervals associated with significantly more root initiation at 0 to 5 than at 5 to 15 centimeters, and significantly more root initiation at 5 to 15 than at 15 to 30 centimeters, by the LSD test (Pr ≤ 0.05).

Table 1-Analyses of variance and covariance of juvenile loblolly pine stem growth before and after reapplication of thinning and fertilization on a P-deficient Gulf Coastal Plain site in central Louisiana

Treatment combination	1994—Before treatment reapplication Height	D.b.h.	Volume/tree	1995—After treatment reapplication Height	D.b.h.	Volume/tree
	m	*cm*	*dm^3*	*m*	*cm*	*dm^3*
Not thinned, not fertilized	13.9	13.5	112.5	14.5	13.8	120.6
Not thinned, fertilized	15.0	14.4	140.0	15.9	14.8	161.1
Thinned, not fertilized	13.4	17.4	172.8	14.3	19.0	212.4
Thinned, fertilized	14.7	19.4	229.3	15.6	21 .o	277.6

Source of variation	Analyses of variance df[a]	MS	Pr > F-value	Analyses of covariance df	MS	Pr > F-value
D.b.h. (cm)						
Covariate (C)			.	1	*10.8983*	0.0043
Thinning(T)	1	*59.9534*	0.0001	1	0.8158	0.2932
Fertilization (F)	1	6.1421	0.0054	1	1.1306	0.2228
T x F	1	0.9944	0.1673	1	0.5305	0.3900
(Error)	8	0.4311		7		
Height (m)						
C		.	.	1	*2.8209*	0.0034
T	1	0.5193	0.1706	1	0.1613	0.3332
F	1	4.3010	0.0025	1	0.0090	0.8131
T x F	1	0.0511	0.6492	1	0.1290	0.3836
(Error)	8	0.2291		7	0.1493	
Volume (dm^3 tree-')						
C			.	1	*7649.2760*	0.0017
T	1	16803.2205	0.0001	1	289.2690	0.3680
F	1	284.9786	0.0033	1	420.7903	0.2838
T x F	1	629.4227	0.1916	1	414.0510	0.2874
(Error)	8	309.3901		7	312.3743	

[a] df = degrees of freedom; MS = mean square; Pr > F-value = probability of a greater F-value.

In 1994, the interaction between time and thinning significantly affected root initiation and elongation (table 2). Thinning was associated with stimulated root initiation in May through June 1994, reduced root initiation in November through December 1994 (fig. 3), and increased root elongation during the 1994 growing season (fig. 2). Root initiation was significantly affected by interactions among time, thinning, and fertilization; and time, thinning, and soil depth. In July through early August 1994, root initiation was greater in the nonthinned, fertilized treatment than in the other treatments, and root initiation at the 0- to 5-cm depth on the nonthinned plots was greater than on the thinned plots.

After silvicultural treatments were reapplied in 1995, thinning resulted in significantly greater root elongation (table 2, fig. 2). Root initiation was significantly affected by interactions between time and fertilization, and among time, fertilization, and thinning. In general, root initiation was stimulated 38 percent by fertilization in June through July 1995. In 1995, a significant positive correlation was observed between current annual stem volume increment and mean root elongation in early June through July ($r = 0.6228$, $Pr = 0.0991$) (fig. 4).

Soil temperature at the 5-, 15-, and 30-cm depths was significantly increased by thinning in May through September 1994 and 1995. Thinning significantly decreased soil temperature at the 30-cm depth in November through December 1994, and at the 5-, 15-, and 30-cm depths in November 1995 through January 1996 (fig. 5). In 1994, soil temperature at the 30-cm depth was

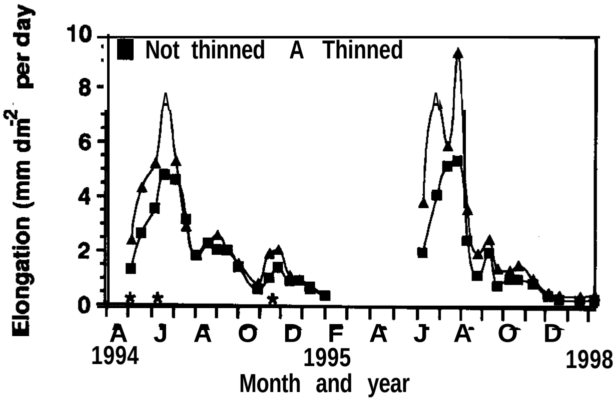

Figure 2—Seasonal net root elongation (millimeters per decimeter) per day in rhizotrons at 0 to 30 centimeters during 1994 and 1995 in response to thinning in November 1988 and March 1995. Asterisks signify measurement intervals in 1994 associated with a significant thinning effect.

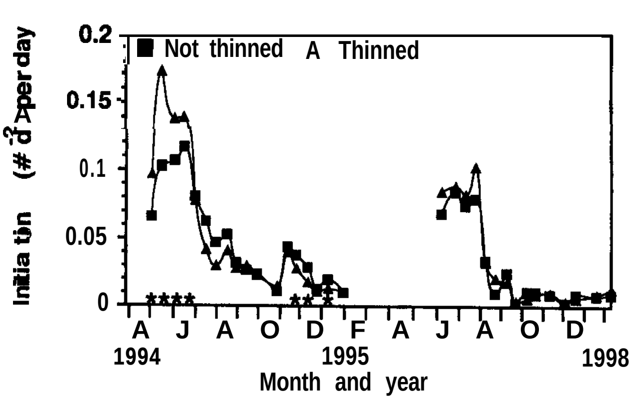

Figure 3-Seasonal number of roots per decimeter per day initiated in rhizotrons at 0 to 30 centimeters during 1994 and 1995 in response to thinning in November 1988 and March 1995. Asterisks signify measurement intervals in 1994 associated with a significant thinning effect.

Table 2-Probability of a greater F-value for the main and interaction treatment effects in the analyses of variance of loblolly pine root initiation rate (number dm^{-2}) per day in the 0- to 5-, 5- to 15- and 15- to 30-cm depths, and root elongation rate (mm dm^{-2}) per day in the 0- to 30-cm depth of the soil during the growing seasons before and after reapplication of thinning and fertilization on a P-deficient Gulf Coastal Plain site in central Louisiana

	1994—Before treatment reapplication		1995—After treatment reapplication	
Source of variation	df[a]	Pr > F-value	df	Pr > F-value
Root initiation (number dm^{-2} /day)				
Block (B)	1	0.1300	1	0.0006
Soil depth (D)	2	0.0037	2	0.0066
Thinning (T)	1	0.3261	1	0.3261
Fertilization (F)	1	0.3490	1	0.5468
T x F	1	0.9178	1	0.6346
T x D	2	0.8565	2	0.8983
F x D	2	0.4225	2	0.6471
T x F x D	2	0.8736	2	0.4874
Time	18	0.0001	14	0.0001
Time x D	36	0.0001	28	0.0001
Time x T	18	0.0001	14	0.1108
Time x F	18	0.1058	14	0.0001
Time x T x F	18	0.0143	14	0.0025
Time x T x D	36	0.0001	28	0.7652
Time x F x D	36	0.9717	28	0.1268
Time x T x F x D	36	0.6204	28	0.9709
Root elongation (mm dm^{-2} /day)				
Block (B)	1	0.2433	1	0.2932
Thinning (T)	1	0.2352	1	0.0192
Fertilization (F)	1	0.4912	1	0.3652
T x F	1	0.8296	1	0.1082
Time	17	0.0001	14	0.0001
Time x T	17	0.0286	14	0.0705
Time x F	17	0.3317	14	0.9625
Time x T x F	17	0.1452	14	0.5070

[a] df = degrees of freedom; Pr > F-value = probability of a greater F-value.

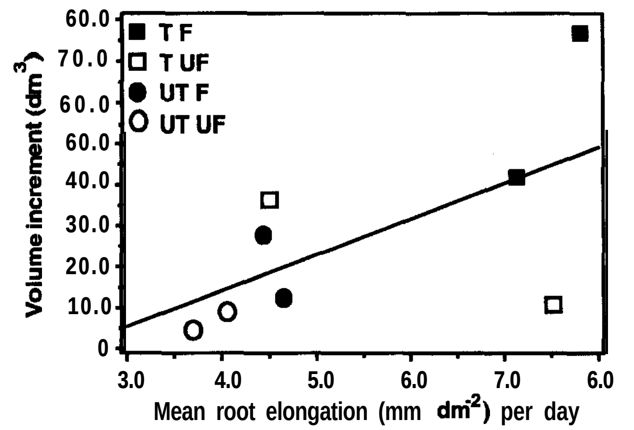

Figure 4--Relationship between the current annual stem volume increment (cubic decimeters) of loblolly pine in 1995 and the mean rate of lateral root elongation (millimeters per decimeter per day) between late June and early August 1995 (r = 0.6228, Pr = 0.0991).

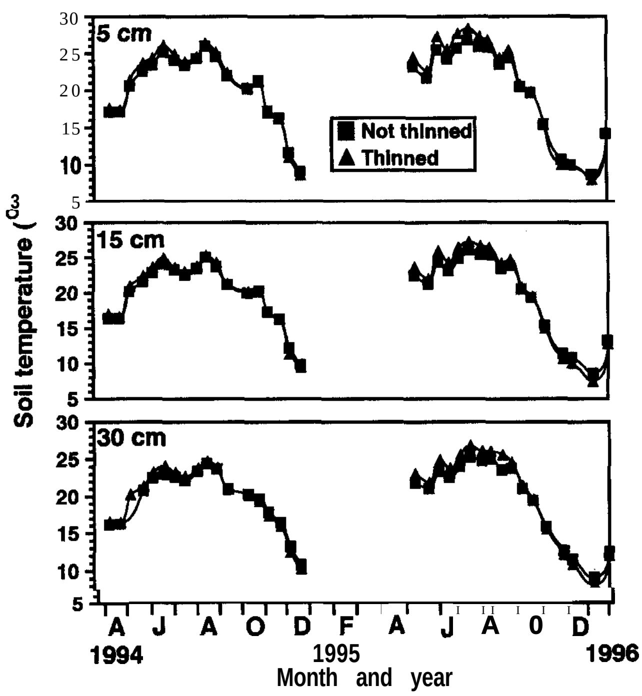

Figure 5-Soil temperature ("C) at 5, 15, and 30 centimeters in rhizotrons during 1994 and 1995 in response to thinning in November 1988 and March 1995.

significantly affected by an interaction between thinning and fertilization. In May through July 1994, soil temperature at the 30-cm depth was 1 .O °C greater on the thinned, nonfertilized plots compared with the other plots. In November through January 1994, soil temperature at the 30-cm depth was 0.7 °C greater on the nonthinned, fertilized plots compared with the other plots.

In 1994, interaction between time and thinning had a significant effect (Pr = 0.0895) on soil water content at the 15-cm depth, with a tendency for greater soil water content at 15-cm in response to thinning (fig. 6). Soil water content at the 15-cm depth in the 1994 growing season was significantly affected by an interaction among time, thinning, and fertilization. In November through December 1994, soil water content at 15-cm was less (14 percent) in response to the nonthinned, nonfertilized treatment compared with the other treatments. In 1995, soil water content at the 15-cm depth was significantly affected by an interaction between time and thinning, with periodic increases in soil water content throughout 1995 on the thinned plots.

Significant positive correlations were found between root elongation and initiation, and soil water content at the 15-cm depth in late June through September 1994. On the nonthinned plots, soil water content at the 15-cm depth was significantly correlated with root initiation at the 0- to 5-cm depth (r = 0.5796, Pr = 0.0005). On the thinned plots, soil water content at the 15-cm depth was significantly correlated with root elongation at the 0- to 30-cm depth (r = 0.5786, Pr = 0.0005), and root initiation at the 0- to 5- (r = 0.6014, Pr = 0.0005), 5- to 15- (r = 0.6032, Pr = 0.0003) (fig. 7), and 15- to 30- (r = 0.6514, Pr = 0.0001) cm depths.

DISCUSSION

In two consecutive years, we observed that new root growth of planted loblolly pine was greatest in May through July, and continued at a reduced rate in August through January. We also found more root growth near the soil surface than deeper in the soil profile. (Sword and others, in press) observed a similar pattern of seasonal root growth at this study site in 1993. Soil temperature, fertility, and moisture availability influence root system growth and development (Eissenstat and Van Rees 1994, Klepper 1987, McMichael and Burke 1996). Therefore, the expansion of loblolly pine root systems may be more sensitive to the surface soil environment in May through July than in other months of the year, and adverse soil environmental conditions in May through July could reduce root system function and soil resource uptake.

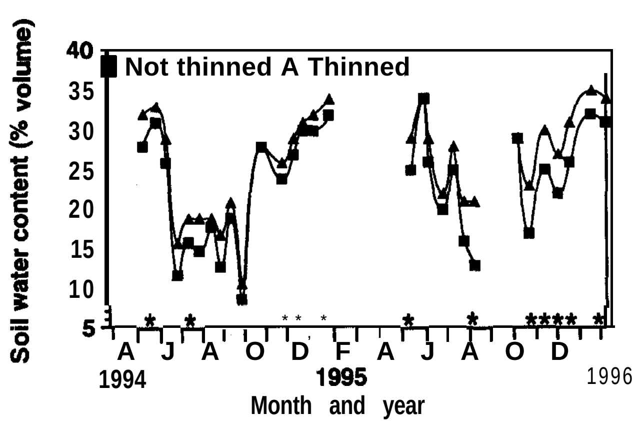

Figure 6-Soil water content (percent volume) at 15 centimeters in rhizotrons during 1994 and 1995 in response to thinning in November 1988 and March 1995. Asterisks signify measurement intervals associated with a significant thinning effect.

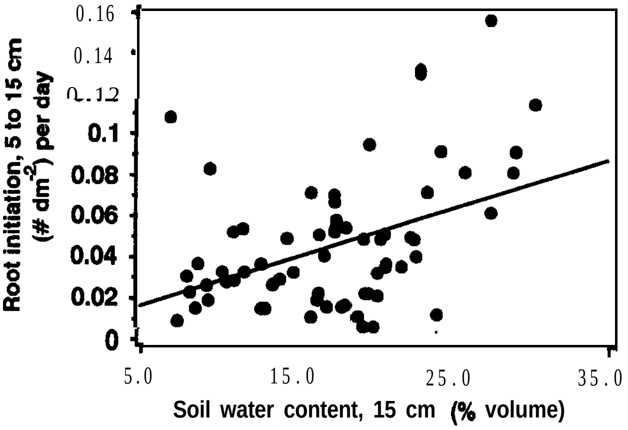

Figure 7—Relationship between the number of roots per decimeter per day initiated in rhizotrons at 5 to 15 centimeters, and soil water content at 15 centimeters (Percent Volume) during late June through September 1994 on the thinned plots (r = 0.6032, Pr = 0.0003).

In 1993, we observed a midsummer decrease in root elongation and initiation that corresponded to reduced soil water content (Sword and others, in press). Between June and September 1994, we found that soil water content decreased 68 percent and root growth and soil water content were significantly correlated. Midsummer water deficits are common in the southern pine region (Allen and others 1990, Dougherty 1996), and if severe enough, water deficits reduce root growth (Brissette and Chambers 1992, Sword 1995). In our study, therefore, water availability after July may have been a regulator of the duration of peak root growth.

We observed more root elongation and initiation on plots maintained at a lower stand density. A similar root growth response was observed at the same site in 1993 (Sword and others, in press). In 1993, light availability in the lower canopy was greater at the lower stand density (Gravatt 1994, Sword and others, in press). Root metabolism depends on glucose derived from either starch stored in root parenchyma or current photosynthate translocated to the root system (Dickson 1991). Thus, we conclude that thinning increased light in the canopy which increased the availability of carbohydrates for root metabolism and, therefore, root growth.

Root elongation on the thinned plots continued to be stimulated after reapplication of the thinning treatment. The positive effect of reduced stand density on root initiation was discontinued, however, by the second thinning. This suggests that the proliferation, but not the elongation of new roots in a forest stand is affected by the number of trees remaining after thinning. Auxin produced in branch apical meristems and translocated to the root pericycle regulates new root initiation (Charlton 1996, Coutts 1987). In our study, tree removal reduced the number of branch apical meristems on the site and, therefore, may have reduced the translocation of auxin to the root pericycle and hindered new root initiation.

In 1993, fertilization did not affect root initiation and only stimulated root elongation on plots that were thinned five growing seasons earlier (Sword and others, in press). By the end of 1994, fertilization had no effect on either root initiation or elongation. Fertilization increases carbon fixation and growth by enlarging leaf area (Teskey and others 1994, Vose and Allen 1988). However in 1994, Yu (1996) observed that 6 years after application, fertilization had no effect on leaf area per tree at this study site. One year earlier, Gravatt (1994) found that foliar concentrations of N on the fertilized and nonfertilized plots averaged 11.0 and 13.0 grams (g) per ha; P averaged 0.90 and 0.58 g per ha. These concentrations approach the boundary between mineral nutrient deficiency and sufficiency for loblolly pine (Allen 1987). We hypothesize that the benefits of N and P fertilization on new root growth subsided after six growing seasons because N and P amendments were either depleted or unavailable. Thus, the leaf area per tree and, therefore, the amount of photosynthate translocated to the root system, was no longer increased by fertilization.

Similar to our observations in 1994, we did not observe a strong positive root growth response to reapplication of fertilizer in early 1995. Starch metabolized in spring originates from photosynthate produced in fall and winter of the previous year (Dickson 1989, Gholz and Cropper 1991). As starch is depleted in roots, current photosynthate sustains root growth (Dickson 1989). Because the fascicle density of first-flush internodes is determined during terminal bud development in the previous year (Stenberg and others 1994), and first-flush fascicle expansion is dependent on starch previously stored in branch parenchyma and current photosynthate (Dickson 1989), the availability of carbohydrates for root metabolism in 1995 had been determined before refertilization. Therefore, a strong root growth response to fertilization in 1995 was not expected. At this study site, Haywood (1994) also found that the tree growth response to the initial fertilization was delayed 1 year.

We observed one root growth response that was inconsistent with our conclusion that root growth was not immediately affected by fertilization. Specifically, fertilization significantly increased root initiation during June through July 1995 by 38 percent. Others have documented an increase in lateral root branching in response to localized areas of high soil fertility (Eissenstat and Van Rees 1994, Mou and others 1995, Pregitzer and others 1993). The isolated increase in new root initiation we observed in response to N, P, and K application may have been caused by a pulse of mineral nutrient availability after fertilization.

A strong positive relationship exists between leaf area and productivity of loblolly pine stands (Stenberg and others 1994, Vose and Allen 1988). In 1995, we found that root elongation during peak root growth was positively related to current annual tree volume increment. We cannot specify whether volume gains were caused by greater root growth, or whether both tree volume and root growth were stimulated by foliage production and carbon fixation. However, the tree volume and root growth responses Of the four treatment combinations in our study intimate that this relationship is regulated, in part, by soil fertility and light availability in the lower crown. We hypothesize that on resource-limited Gulf Coastal Plain sites, positive stand growth responses to fertilization are a result of increased leaf area and carbon fixation together with greater root growth and soil resource uptake. However, these responses to fertilization require a canopy environment and structure conducive to increased carbon fixation.

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REGULATING STAND DENSITY BY PRECOMMERCIAL THINNING IN NATURALLY REGENERATED LOBLOLLY PINE STANDS: EVALUATION OF MANAGEMENT AND ECONOMIC OPPORTUNITIES

David J. Moorhead, Coleman W. Dangerfield, Jr., and M. Boyd Edwards'

Abstract-The economic performance of converting 13-year-old, overstocked (> 3,000 trees per acre), naturally regenerated pine stands using precommercial thinning at a cost of $140 per acre was modeled for 25-, 35-, and 50-year rotations. The stand density was reduced'to 283 trees per acre. Subsequent management scenarios recovered establishment and management costs through final harvest and in combination with periodic commercial thinnings. Indexes of financial performance were 12.3, 17.1, and 15.6 percent Internal Rate of Return; $11.13, $36.25, and $45.65 per acre Annual Equivalent Value; and $139.16, $453.12, and $570.66 per acre in Soil Expectation Value for 25, 35 and 50 year rotations, respectively.

INTRODUCTION

Natural regeneration of loblolly pine *(Pinus taeda L.)* is a common practice, both planned and unplanned, across the South. Landowners may harvest pine from their lands with the goal of allowing natural regeneration to establish the new stand. Typically a seed tree or shelterwood method is employed, leaving mature seed producing pines on each acre after harvest to provide seed for the new crop. Other options include seed, or seedlings in place, or seed from adjacent stands as a natural regeneration source (Edwards 1987b).

While natural regeneration methods can provide a low-cost and effective means to establish new stands, overstocking is common when favorable weather and seedbed conditions occur. Mechanical strip thinning is a recommended practice usually by age 3 to 5. Costs associated with precommercial thinning increase as stands age.

METHODS

Data from a precommercially thinned (PCT) natural regeneration study site on the USDA Forest Service, Hitchiti Experimental Forest, in the Piedmont of Georgia was used to project expected, potential woodflow and financial performance for 25-, 35-, and 50-year rotations.

The stands were established using (1) clearcut method with seed in place, (2) seed tree method, and (3) shelterwood method in 1983 (Edwards 1987b). Following harvest, all hardwood stems 1 inch in diameter at breast height (d.b.h.) and larger were treated by injection with Tordon 101. In the summer of 1996, the stand was precommercially thinned by hand crews using chainsaws to an approximate 12 by 12 foot spacing (302 trees per acre). Following the PCT, measurements of crop tree d.b.h., height, and density were made.

The three management scenarios were modeled using YIELDplus 4.0 (Hepp 1994). Stand inputs from the PCT plots were used in a natural loblolly pine growth and yield simulator. Site index at age 50 was 90 feet (Edwards and Dangerfield 1990). The following financial parameters were set: a 28 percent marginal Federal tax bracket, 8.0 percent before-tax discount rate, $22 per cord for pulpwood, $58 per cord for chip and saw (CNS), and $200 per thousand board feet Scribner for sawtimber. Stumpage prices were inflated at 3.5 percent for pulpwood and CNS, and 4.0 percent for sawtimber over the rotation.

Per-acre management costs included $5 for site preparation burning, $40 for herbicide treatment, and $140 for the PCT. Beginning in 1997, per-acre charges for prescribed burns/fire breaks at 3-year intervals were accessed at $8 for the initial burn, $6 for the second burn, and $5 for the subsequent burns. Total harvest expenses were computed at 12.5 percent of the harvest value, including 10 percent for marketing and 2.5 percent for ad valorem property taxes on timber harvested.

Three management scenarios were examined: a 25-year rotation without thinning, a 35-year rotation with thinning at age 28, and a 50-year rotation with thinning at ages 30 and 40. All thinning treatments were low thinnings to a residual basal area of 65 square feet per acre. Thinnings were set in order to maintain medium to low stand risk to southern pine beetle infestations, and volume removed had to meet a minimum 5 cords per acre to be considered commercially feasible.

RESULTS

Prior to the PCT at age 13, the stand averaged 5,086 stems per acre (3,050 to 8,910). Following the PCT, an average of 283 crop trees remained per acre with average height of 3.85 inches at d.b.h. and 23.24 feet in overall height. These data were used to manually set the initial stand parameters in the model.

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Initial stand conditions present at harvest, residual stand components (if applicable), and harvested stand components for each rotation scenario are presented in table 1. Financial performance (before tax, adjusted for inflation), indicated by the Internal Rate of Return (IRR), Annual Equivalent Value (AEV), and Soil Expectation Value (SEV), is detailed in table 2.

25-Year Rotation

A final harvest was projected for 13 years after the PCT (table 1). Stems averaged 62 feet tall. The stand had a basal area of 83 square feet on 210 merchantable stems per acre. Total volume per acre averaged 25.33 cords, with the chip-and-saw component contributing 5.29 cords per acre.

The investment earned a 12.3 percent IRR, with an AEV of $11.13 per acre. The SEV was $139.16 per acre (table 2).

35-Year Rotation

A commercial thinning was projected at age 28, 16 years after the PCT (table 1). At the first thinning at age 28, the trees averaged 67 feet in height with a basal area (BA) of 98. An average of 83 pulpwood stems per acre were harvested, yielding 10.34 cords per acre.

At final harvest at age 35, trees averaged 77 feet tall. The stand has a BA of 91 in 107 stems. A total of 32.90 cords was projected per acre. The product mix shifted to chip and saw (CNS) and sawtimber with 25.13 cords and 7.77 cords, respectively. The 35-year rotation produced a total of 43.24 cords per acre in the two harvests.

The IRR equaled 17.1 percent with an AEV of $36.25 per acre, and a SEV of $453.12 per acre (table 2).

50-Year Rotation

Two commercial thinnings were projected at ages 30 and 40, 18 and 28 years after the PCT, respectively (table 1). At the first thinning at age 30, the stand was projected to accumulate a BA of 106 on 190 stems averaging 70 feet in height. This thinning produced 13.61 total cords per acre with 9.75 cords of pulpwood, and 3.86 cords of CNS.

The stand was projected to accumulate a BA of 99 by the second thinning at age 40. This harvest removed 12.54 cords per acre. Pulpwood classes had been removed in the first thin and CNS totaled 3.33 cords, with sawtimber totaling 9.21 total cords per acre.

At final harvest at age 50, the stand had accumulated a 90 BA on 55 stems averaging 90 feet in height. This harvest produced 36.49 cords per acre of sawtimber. Overall, a total of 62.65 cords per acre was removed in the three harvests over a 50-year rotation.

The IRR was 15.6 percent. Annual Equivalent Value was projected at $45.65 per acre with a $570.66 per acre SEV (table 2).

DISCUSSION

Many landowners may be hesitant to invest $140 per acre in a 13-year old natural pine stand. However, the financial performance expected following a relatively high investment were promising. Internal rates of return ranging

Table I-Projected per acre stand parameters and woodflow of naturally regenerated loblolly pine at 25-, 35-, and 50-rotations

	Stand condition			Residual component			Harvested component		
Rotation length	Age	Height	PAI[a]	Basal area	Stems	Total cords	Basal area	Stems	Total cords
25 years	25	62	1.0	—	—	—	83	210	25.33
Final harvest totals per acre							83	210	25.33
35 years	28	67	1.1	65	114	21.30	33	83	10.34
	35	77	1.7	—	—	—	91	107	32.90
Final harvest totals per acre							124	190	43.24
50 years	30	70	1.2	65	99	22.28	41	91	13.61
	40	82	1.5	65	55	24.79	34	38	12.54
	50	90	1.2	—	—	—	90	55	36.49
Final harvest totals per acre							165	184	62.65

[a]PAI = Periodic annual increment in cords per acre.

Table 2—Projected financial performance of naturally regenerated loblolly pine at 25-, 30-, and 50-year rotations

Rotation	Internal Rate of Return	Annual Equivalent Value	Soil Expectation Value
	Percent	*-----Dollars per acre*	*----*
25 year	12.3	11.13	139.16
35 year	17.1	36.25	453.12
50 year	15.6	45.65	570.66

from 12.3 to 17.1 percent present attractive investment opportunities. Even with extending the rotation length, income from the periodic thinnings offset the carrying costs of the investment. Over time, SEV increased as the thinnings and final harvests produced greater proportions of more valuable CNS and sawtimber stumpage.

Stands that are densely stocked are expected to stagnate and/or produce only marginal yields (Mann and Lowery 1974). Precommercial thinning is generally recommended at young ages (by age 3) when mechanical equipment can be effectively used to strip-thin at relatively low costs per acre (>$45). Despite the high cost of the PCT, it could be treated as a capital expense in the year of treatment as opposed to a site preparation or reforestation cost.

A PCT is done on an operator select basis, with high-quality crop trees to be favored. Selection criteria should include: preferred species, superior bole form (straightness, single stem, branch angle), absence of bole cankers and other stem damage, and selection of trees with dominant terminals and live crown ratios of > 40 percent. Selection of high-quality crop trees for chain and saw and sawtimber production can justify higher PCT expenses.

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MECHANIZED PRECOMMERCIAL STRIP THINNING OF LOBLOLLY PINE IN NORTH CAROLINA

Carlyle Franklin and Tom Lloyd'

Abstract-Precommercial strip thinning has often been recommended as an economically sound silvicultural practice in natural pine stands. This study demonstrated that this can be true under certain circumstances related to species response to high density, cost of applying the practice, product goals, and prices. Extensive precommercial strip-thinning trials with a specially adapted drum chopper were done in the Coastal Plain and Piedmont of North Carolina in stands 4 to 7 years old. Subsequent measurements were made in treated and control stands at ages 12 to 25 years. Growth and yield projections through one rotation at site indexes of 65, 75, 85, and 95 (base age 50), with and without precommercial thinning, with and without subsequent commercial thinning, and with product merchandizing, obtained the following results. Precommercial thinning could not be economically justified until stand stocking exceeded 5,500 to 6,500 trees per acre, and then only with an aggressive commercial thinning program. In addition, precommercial thinning had to reduce the residual stocking to not more than 2,000 trees per acre by age 10 to obtain maximum internal rates of return. Maximum gains in internal rates of return increased slightly as site index increased from 65 to 95. Maximum gains from precommercial thinning ranged from 3.6 to 4.1 points with aggressive commercial thinning.

INTRODUCTION

Stocking control is one of the most important activities in the silviculture of loblolly pine (*Pinus taeda* L.), especially in natural stands which are often overstocked early in the rotation. Studies of mechanical, precommercial strip thinning in many conifers dates back at least to the late 1940's (Ryans 1988). Interest in this subject continues to be strong (Filip and Goheen 1995, Morris and others 1994). The rolling drum chopper pulled by a rubber-tired skidder has proven to be cost effective in some instances, especially if gathering bars are attached to the yoke to pull in saplings which would otherwise be pushed aside and scarred.* Jennette also suggested that thinning was best accomplished between ages 4 and 6 when the operator could see over the tops of the saplings. Based on measurements of many strip-thinned and control stands in the North Carolina Coastal Plain and Piedmont, we decided to do some silvicultural and economic simulations of precommercial strip-thinning with a drum chopper to develop guidelines for application of the practice. We felt that this was needed because results in the literature suggested that measurements at or before first commercial thinning were often inconclusive (Cain 1993), but later in the rotation precommercial thinning proved to be economically justified (Cain 1995).

METHODS

Growth and Yield Model

For the growth and yield simulations we used "NAT-YIELD," a stand-based simulator developed by Smith and Hafley[3] at North Carolina State University with a grant from the USDA Forest Service, Southern Research Station. This simulator, when run with pine only, yields volumes based on Schumacher and Coile (1960) for natural stands of southern pines. The developers warned that simulations initiated prior to age 20 years might not be reliable, but experience has shown that reliable results can be obtained down to age 10. Therefore, we began our simulations at age 10.

Simulations were run at site indexes (base age 50) of 65, 75, 85, and 95 feet, with and without commercial thinning. Corresponding residual stockings after each successive thinning were 60, 65, 70, and 75 square feet per acre (ft^2/a) respectively, except at the last thinning when residual stocking was 40 (ft^2/a) of basal area to set up a shelterwood regeneration for a rotation ending at age 35 years (table 1). Stockings used at age 10 to begin the simulations were 1, 2, 3. 5, 5, 7. 5, and 10 thousand trees per acre. This implies that residual stocking at ages 4 to 6 years, immediately following strip thinning, was sufficiently higher so that attrition by age 10 yielded the initial stocking used in the simulation. In the case of no strip thinning, it meant that naturally occurring stocking was the stocking specified at age 10.

In measuring many roller chopper, strip-thinned stands, we never found one that had as low as 2,000 tpa at age 10. We found several that substantially exceeded 10,000 tpa without strip-thinning.

Criteria for thinning were (1) a minimum of 500 cubic feet of wood to be removed, and (2) a minimum quadratic stand mean diameter of 6 inches. These seemed to be realistic in terms of the minimum logging chance to attract a logger to a reasonably sized tract. Number of commercial thinnings varied by scenario, decreasing as site index decreased and stocking increased. In fact, some scenarios eligible for thinning, never reached minimums to be thinned out to 35 years.

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[2] Personal communication. 1986. David L. Jennette, Sr. [deceased] Consultant, Timberlands Unlimited, P.O. Box 650, Windsor, NC 27983

[3] Hafley, W.L.; Smith, W.D. Unpublished material. U.S. Department of Agriculture, Forest Service, P.O. Box 12254, Research Triangle Park, NC 27709.

Table 1—Silvicultural parameters used for simulations with "Natyield"

Stocking at age 10 (trees/acre)	1,000	2,000	3,500	5,000	7,500	10,000
Residual basal area by site index	(ft^2) RBA 60 65 70 75					
	(ft) SI 65 75 85 95					
Residual basal area at age 30	40 ft^2 for shelter-wood regeneration					
Top-wood added for sawtimber only	.75 cords per thousand board feet					
Final harvest	35 years					

Economic Analyses

Economic analyses were done using Quick Silver (Vasievich and others 1984). A nominal annual overhead cost of $5 per acre per year was used. The cost used for roller drum chopping was $45 per acre (Dubois and others 1997). Prices used for timber products were the 1996 Southeastern States averages reported by Timber Mart-South (Anon 1996): pulpwood >$23.73 per cord; chip-n-saw >$59.73 per cord; saw timber >$237 per thousand board feet (Scribner) (table 2). Each yield simulation scenario was run with and without the cost of precommercial thinning.

Graphical Analysis

Results were tallied as a single internal rate of return (IRR) for each scenario. These were plotted over trees per acre, strip-thinned versus not strip-thinned within a site index, with or without commercial thinning. Graphical analysis was done as follows (fig. 1A). A horizontal line at the level of highest IRR (19.1) for the "strip-thinned" scenario was drawn from the right margin to its intersection with the line representing the "not strip-thinned" scenario. A vertical line was then extended to intersect the x-axis at the minimum number of trees per acre (6,400) at age 10 necessary to yield a net positive payoff with strip thinning. The maximum possible gain in these scenarios was obtained by subtracting the IRR without strip thinning at 10,000 trees per acre (tpa) (13.6) from the highest IRR with strip thinning (19.1) (usually at 2,000 tpa) (fig. 1A).

Table 2-Activity costs and timber prices for simulations with "Quick Silver'

Cost for strip thinning		$45/acre
Nominal management cost		$5/acre/year
Pulpwood[a] $23.73/cd	Chip-n-saw" $59.73/cd	Sawtimber[a] $237/mbf (Scribner)

[a] Timber Mart-South[0] 1996 S.E. State's average.

Table 3-Minimum number of trees per acre at age 10 for strip-thinning to pay

Site index base -50	With commercial thinning[a]	Maximum gain in IRR[b]
65	5600	5.2
75	5800	5.4
85	6000	5.5
95	6400	5.5

[a] No gains were found without subsequent commercial thinning.
[b] For 10,000 trees/acre without strip thinning versus 2,000 trees/acre with mechanical strip thinning.

RESULTSANDDISCUSSION

Substantial gains in IRR were found for strip-thinned over non- strip-thinned scenarios with subsequent commercial thinning (table 3) (fig. IA-D). Without commercial thinning, the highest IRR between 2,000 and 10,000 tpa never exceeded the lowest IRR without strip thinning, so the conclusion was that without subsequent commercial thinning, mechanical, precommercial strip thinning could not be economically justified (fig. 2A-D).

Systematic sensitivity trials were not run, but limited observations indicated that as the price of pulpwood increased relative to the price of saw timber, strip thinning was less favorable economically. Conversely, as the price of saw timber increased relative to the price of pulpwood, strip thinning was justified even without subsequent commercial thinning, but the threshold minimum number of trees per acre was higher than when subsequent commercial thinning was done. Thus, simulation scenarios of this sort must be done for local growth, yield, and product price combinations to have local applicability.

Another interesting observation was the sharply rising IRR's for scenarios without commercial thinning as 1 0th-year stockings decreased from 2,000 to 1,000 tpa. As stated above, our observations indicated that 1 0th-year stockings lower than 2000 tpa have rarely been achieved with precommercial thinning by drum chopping. Stockings as low as 500 tpa could be achieved with a combination of drum chopping and subsequent hand thinning, as shown by Dangerfield and others (1997) in these proceedings. Our results suggest, and those of others confirm, that a combination of precommercial thinning treatments may hold promise under certain circumstances. This is an area for further research.

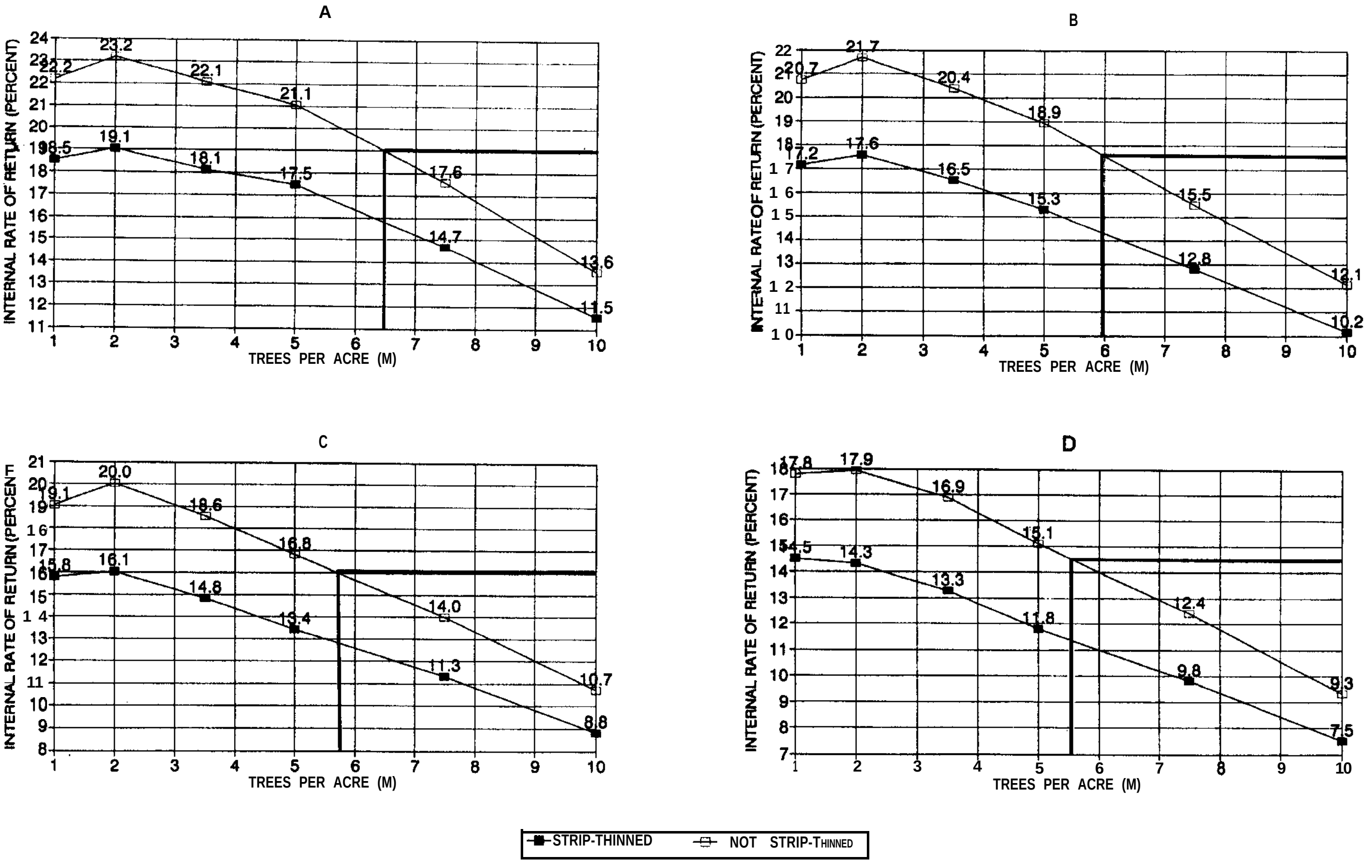

Figure 1—Internal rates of return for natural loblolly pine stands precommercially strip-thinned versus not strip-thinned, at site indexes of 95 (A), 85 (B), 75 (C), 65 (D) (base age 50), with subsequent commercial thinning, arrayed over a range of 10th-year stocking levels from 1,000 to 10,000 trees per acre. The dark horizontal line intersects the "not strip-thinned" line at the maximum IRR with strip thinning. The dark vertical line then intersects the x-axis at the corresponding minimum number of trees per acre to economically justify strip thinning.

Clearly, there are other benefits from precommercial thinning than just the economics of timber production. As other resource values such as wildlife, recreation, and esthetics become more highly valued in approaches to natural resource management, precommercial thinning of stands offers multiple benefits:

- Enhances wildlife habitat by bringing browse and insects back to ground level, allowing more light to reach the forest floor, and increasing internal stand diversity.
- Allows earlier use of prescribed fire in conifer rotations by reducing fuels and providing stand structure conducive to efficient dissipation of heat.
- Increases recreation potential of stands by providing earlier visual and user access, and by creating a more esthetically pleasing forest environment.

Valuation of these benefits may be more difficult than valuation of timber benefits, but such values are nonetheless quite real, and deserve the attention of the natural resource manager.

CONCLUSIONS

Using Southeastern U.S. average timber prices, mechanical precommercial strip thinning of natural loblolly pine stands was economically justified when stocking in the 10th year exceeded about 6,000 tpa, and an aggressive commercial thinning regime was followed. Without commercial thinning, precommercial thinning could not be economically justified. The model is price sensitive and should be applied to local growth, yield, and market conditions before it is applied as a silvicultural decision criterion.

ACKNOWLEDGMENT

Two people played essential roles in this research. David L. Jennette, Sr., now deceased, did hundreds of acres of precommercial thinning in eastern North Carolina in the late sixties and early seventies. We were able to measure those stands as they approached time of first thinning. His knowledge of those stands and of precommercial thinning with a drum chopper was extremely helpful. Our program technician, Gene Nocerino, did yeoman's work in single-handedly inventorying hundreds of acres of strip thinned and untreated stands in the Coastal Plain and Piedmont, under difficult conditions. His dedication is gratefully acknowledged. Thanks are also due to Dr. Tom Lloyd and the USDA FS, Southern Research Station, for providing initial funding to get this project started.

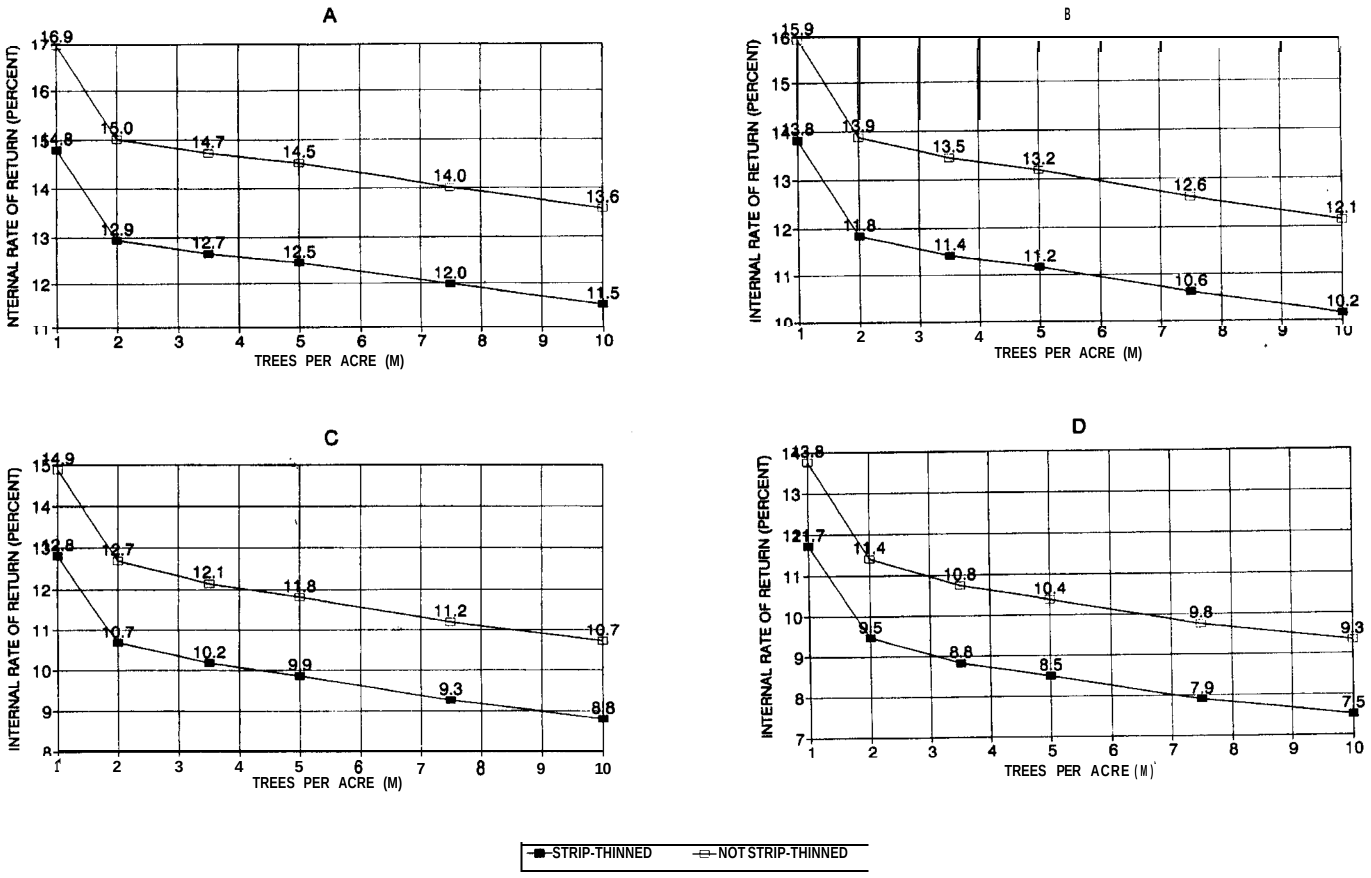

Figure 2—Internal rates of return for natural loblolly pine stands precommercially strip-thinned versus not strip-thinned, at site indexes of 95 (A), 85 (B), 75 (C), 65 (D) (base age 50), without subsequent commercial thinning, arrayed over a range of 10th-year stocking levels from 1,000 to 10,000 trees per acre.

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STUDYING THE EFFECTS OF HARDWOOD STAND MODIFICATION, PERIODIC FLOODING, AND FIRE ON INSECT AND DISEASE COMMUNITIES IN THE LOWER MISSISSIPPI RIVER ECOSYSTEM

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Abstract-The relationship between stand modification and pest organisms (insects and diseases) has been noted in general with few specific studies to evaluate this relationship in the southern hardwoods. As a prerequisite to making the best improvement cut prescription, it is essential to have a perspective on thinning impacts that at present can only be gathered from scattered information. The goal of this study is to better understand the impacts of stand modifications on insect and disease populations. A study of practices in southern pines conducted in 1985 by Nebeker and others will serve as a template. We will examine the relationship of pest organisms to stand modifications such as improvement cuts, clear cutting, periodic flooding (e.g., green tree reservoirs) and burning. To our knowledge, this will be the first such study in southern hardwood stands aimed at understanding this relationship.

Our objectives are threefold. We propose to bring together the literature that reports positive and negative impacts of stand modifications in relation to insects and diseases of hardwoods emphasizing the southern hardwood system. We also propose to follow stand modification procedures in order to document changes in insect and disease populations that lead to degrade or mortality of hardwoods. The organisms of interest primarily include insect borers and various wood decays. The study will be conducted in the Delta National Forest near Rolling Fork, MS, where we will survey pest populations before and after an improvement cutting in a bottomland hardwood stand. In addition, pest population surveys will be conducted in stands thinned within the past 5 years on timber company land in Alabama. The envisioned product will be a document containing pest management recommendations for stand modification practices in southern hardwoods. This will be a great asset in summarizing our understanding of pest population responses to management entries into the southern hardwood ecosystem. It should serve as a benchmark for future studies as well.

INTRODUCTION

There are increasing interests in hardwood forests of the Southern United States. These interests are diverse and far-ranging. There are interests in conservation, wetland preservation, ecosystem preservation, ecosystem management, forest health, and restoration, to mention a few. There is also considerable interest in the sustainable productivity of these forests for fuel, fiber, lumber products, and chemicals. As a result of these latter interests, and in connection with broader ecological interests, the impact from harvesting, periodic flooding (including green tree reservoirs), and fire are of concern.

In a repot-l presented by the National Research Council Committee on Forestry Research (1990), focus was given to research needs in forestry, including a mandate for change. One can generally assume that entry into the forest for improvement cuts-imposed disturbance-may result in various levels of damage. A similar assumption can be stated for periodic flooding and prescribed burning. Damage associated with these events may result in a reduction in long-term productivity. The impact (positive and negative) of insects and diseases as a result of entry into the forest for harvesting purposes is of critical interest. Similar interests also exist in relation to the practice of creating green tree reservoirs for recreational purposes such as hunting.

The forestry practice of thinning (improvement cuts) is of particular interest. While thinning is aimed primarily at improving the value of the residual stems and the stand as a whole, there are other benefits currently gaining recognition, such as risk reduction for insect infestations, disease epidemics, and damage due to abiotic agents. Overstocked and overmature stands are generally more susceptible to insects and disease and thus warrant thinning. The mechanics by which thinning reduces these risks are not completely understood. Observations, however, indicate that thinning can cause positive and/or negative effects depending on how, where, when, and why the stand is thinned. The presence of more than one kind of hazard at any given time and place poses some problems in designing an optimum thinning strategy. Further complicating the situation are the species, stage of development, anticipated direct damages to residual stems, site quality, growth rate, and susceptibility to damaging agents, such as insects, disease, and windthrow.

The magnitude of logging damage is due to the following principal variables: (1) silvicultural (system) used, (2) type of equipment and configuration, (3) species, (4) spacing (density), (5) size class (age), (6) season of harvest (soil moisture conditions), and (7) operator carelessness. The type of damage encountered is generally limited to: (1) limb breakage, (2) bole wounding (upper and lower bole), (3) root wounding, and (4) root breaking. Additional damage includes bending and breaking of whole trees (Nyland and Gabriel 1971). Complete uprooting of trees can also occur. Biltonen and others (1976) reported greater crown damage (but little bole damage) when thinning was done with mechanized equipment than without. Hesterberg (1957) found that 80 percent of broken branches 4 inches or

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greater in diameter developed defects following thinning. Lavallee and Lot-tie (1968) claimed that broken branches 2.5 inches or larger in diameter almost always serve as infection courts in yellow birch after a stand disturbance such as thinning. Berry (1977), working with upland oaks, found that 39 percent of the trees studied had decay. Fire scars were the most important entry courts followed by mechanical wounds, top damage, branch stubs, and parent stumps. Shigo (1966) indicated that broken branches in northern hardwoods lead to wood discoloration and serve as infection courts to decay fungi. Tree species also vary in their susceptibility to thinning-related damages such as yellow birch being more susceptible than sugar maple (Benzie and others 1963). Information concerning the impact of insects in hardwood stands following stand modification procedures is much more limited.

The relationship between thinning and pest organisms has been noted in general with few specific studies to evaluate these relationships. This is especially true for insects. As a prerequisite to making the best thinning prescription, it is essential to have a perspective on thinning impacts which at present can be gathered only from scattered information. A study by Nebeker and others (1985) will serve as a template (general protocol and expected output—publication(s)) for this study.

In the proposed study we will address the influence of stand modification on insect and disease populations associated with bottomland hardwood forests of the South. The stand modification procedures of interest are thinning (improvement cuts), clear cutting, periodic flooding (including green tree reservoirs), and prescribed burning.

The objectives of the study are to:

(1) bring together the literature that reports positive and negative impacts of stand modifications in relation to insects and diseases of hardwoods, emphasizing the southern hardwood ecosystem;
(2) follow stand modification procedures and disturbances in order to document changes in insect and disease incidence, primarily insect borers and wood decays, that lead to degrade or mortality of hardwoods; and
(3) produce a document focusing on pest management recommendations associated with thinning guidelines for southern hardwoods.

Study Area

The primary study area is located on the Delta National Forest. Secondary study sites will be on industrial timberlands in Alabama that have already been thinned within the past 5 years. In addition, other areas being commercially thinned will be noted and surveyed. Preliminary information on the impact of regeneration cutting on insect and disease populations will be made on the Delta Experimental Forest near Stoneville, MS. Of special interest are the impacts (positive and negative) on insect and disease populations of prescribed burning and portions of stands left undisturbed for wildlife refuges within the regeneration area.

Methods

The literature review will consist of computer-assisted searches of data bases available through various libraries. A knowledge base will also be obtained by visiting with and surveying (see survey form) individuals and/or companies that have been involved with hardwood stand modifications.

The survey of the stand to be thinned, on the Delta National Forest, will be conducted during the spring of 1997 and will follow typical forest stand inventory methodology. Site and stand data (tree species, basal area, stand density, age, etc.), linked to fixed plots for determining current stand conditions and for monitoring growth over time, will be collected at each sample point. An assessment of insects and diseases will also be made at each sample point. Emphasis will be on the organisms that may potentially cause degrade or mortality. These primarily include insect borers and diseases of various kinds.

Following the stand modification process, surveys will be conducted to determine the extent of new insect and disease activity as a result of stand entry. These general surveys will be conducted within the year following the treatment and again the following year. Trees with limb breakage, upper and lower bole wounding, and root damage as a result of harvesting will be specifically identified. These trees will be numbered and monitored for signs and symptoms of insect and disease activity.

Analysis

Site and stand data, before and after thinning, will be compared graphically (as percentages) to reflect the changes in species composition, stand density, basal area, and size classes. The occurrence of insects and diseases will be compared in a similar manner and in percentage form. The nature of the data will also lend itself to being expressed in relation to various diversity indexes.

Significance

The relationship between thinning and pest organisms will be documented for southern hardwoods for the first time. A better understanding of the impacts of stand modification on insect and disease populations will be gained. The literature will be brought together that reports impacts of stand modifications in relation to insects and diseases of hardwoods. The results of this study will lead to a document we propose to entitle Stand Modification Practices in Southern Hardwoods-With Pest Management Recommendations.

Harvesting operations often cause widespread damage to the residual stand. Often more than 50 percent of the residual stems are damaged. In one survey, Meadows (1993) found logging wounds on 62 percent of the residual stems following a thinning operation in a river front hardwood stand in Mississippi. The most common types of damage include: (1) branches being broken in the residual canopy (2) upper and lower bole wounding and (3) exposure and breakage of roots. Such wounding serves as infection courts for disease organisms and attraction points for various insects that can lead to degrade and potential mortality of the residual stems. In addition, disease propagules such as fungal spores, bacteria, and viruses may be introduced into trees through wounds created by insects, birds, or mammals, The subsequent reduced vigor of individual trees may also reduce the overall health of the residual stand, making it susceptible to further insect and disease attack.

Changes in stand structure as well as exposure to periodic flooding when water remains standing for various lengths of time can influence ecosystem functions. Food sources, especially nectar, for parasites of hardwood insect pests may be reduced as a result of these events. Insects, especially those that have one or more life stages in the ground or duff, may be affected. This is of concern if it is one of the natural enemies of an insect pest affecting the system. Having such information will further our understanding of this ecosystem and the changes in the system associated with stand intervention and periodic disturbances.

Managers of bottomland and upland hardwood stands typically remove trees with hollow bases, large disfiguring cankers, and/or many scars caused by wood-boring insects. They reason is that by removing these trees they are creating growing space for better quality residual trees, and are reducing the presence of insects and diseases in the stand. On the surface, these assumptions appear biologically sound. Our research is intended to provide the scientific basis for supporting and perhaps modifying these underlying assumptions that are already in practice. This will be a great asset in extending our understanding of entries into and disturbances of the southern hardwood ecosystem.

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SURVEY

We solicit the assistance of forest managers in providing information, published or unpublished, concerning increases or decreases in insect and/or disease activity associated with the general purpose of this study. We are extremely interested in actual observations concerning insects and/or diseases associated with partial cutting, improvement cutting, logging damage, periodic flooding, or fire in the southern bottomlands.

Name: ______________________________

Address: ______________________________

Phone: ______________________________

Work: ______________________________

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We appreciate your assistance.

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UPLAND VS. BOTTOMLAND SEED SOURCES OF CHERRYBARK OAK

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Abstract-The influence of seed sources (upland vs. bottomland) on first-year height increment, groundline diameter increment, leaf number, seedling emergence, and survival percentages of cherrybark oak (*Quercus pagoda Raf.*) was investigated on a bottomland, a terrace, and an upland planting site. Cherrybark oak acorns were collected from open pollinated trees at nine bottomland and eight upland stands across an east-west transect in central Mississippi. The acorns were sown on a bottomland site and a terrace site in Carroll County, and on an upland site in Winston County in central Mississippi. The soils at the planting sites are classified as Oaklimeter silt loam (coarse-silty, mixed, thermic Fluvaquentic Dystrochrepts), Loring silt loam (fine-silty, mixed, thermic Typic Fragiudalfs), and Maben fine sandy loam (fine, mixed, thermic Ultic Hapludalfs), respectively.

First-year results showed that upland and bottomland seed sources did not differ for seedling emergence, survival, height increment, groundline diameter increment, and leaf number. However, large planting site and stand variations in some measured traits were detected. Planting sites varied with respect to seedling emergence, survival, height, ground line diameter, leaf number, and leaf number per centimeter of height. The terrace planting site generally was best. Stands (acorn collection sites) varied significantly for laboratory germination, height increment, and leaf number. Three of the highest germination values came from the Upper Coastal Plain and Blackland Prairie Soil Resource Areas of Mississippi. However, acorns coming from the stands in the Mississippi River Delta resulted in the poorest value for speed and completeness of germination. Acorns from a stand in the Upper Thick Loess Soil Resource Area of Mississippi had the largest height growth, and acorns from a stand in the Upper Coastal Plain Soil Resource Area of Mississippi demonstrated the highest leaf number. There were only small changes between height rank and leaf number rank of stands. Tallest first-year heights were generally associated with the greatest number of leaves. There was no pattern of change among stands from east to west for the traits of height and leaf number, except germination value. First-year results suggest that topographic position of seed sources is not important to regeneration success.

INTRODUCTION

Cherrybark oak (Quercus pagoda Raf.) is one of the most valuable red oaks in the lower Mississippi River valley because of its fast growth, clear bole, and value for wildlife. The tree occurs naturally from eastern Texas north along the Mississippi River to southern Illinois and Indiana, and east to southern Virginia (Fowells 1965). It occurs on a range of sites from dry-mesic uplands to floodplains.

Even though cherrybark oak genetic investigations have been conducted in recent decades (Dicke and Toliver 1987, Greene and others 1991, Randall 1973), unknown seed source is still a prevailing concern for private individuals and seed dealers. Most acorns for seedling production and direct seeding are collected from upland sites, although most of the artificial regeneration is being done on floodplain sites in the South. This could pose a problem for survival and growth of the seedlings.

The objectives of this study were to investigate factors affecting survival and growth of acorns of cherrybark oak including: (1) upland and bottomland seed sources, *(2)* variation among topographical position of planting sites, and (3) variation among stands from which acorns were collected.

MATERIALS AND METHODS

Planting Stock

Four to 10 cherrybark oak trees from natural stands on nine bottomland and 8 upland sites were chosen for acorn collection on an east-west transect across central Mississippi (fig. 1). "Bottomland (B)" and "upland (U)" sites represent two topographic positions. Bottomland sites are in the floodplain and subject to brief periods of flooding each year. Acorns were collected from those open pollinated trees in the fall of 1995, and were immersed in water to remove empty or defective "floaters." The "full" acorns collected from trees at one site were mixed in equal numbers from each tree to provide a stand mix. These acorns were placed in sealed, zip-lock plastic bags, and stored in a cooler at 3C until the first week of March 1996, when they were manually sown in paired seed spots. The depth of seed placement was about 5 centimeters. A total of 8,160 acorns were sown at three planting locations, excluding borders.

Test Locations

Trials were planted on a bottomland site and on two upland sites, one of which was a terrace site, in central Mississippi (fig. 1). The bottomland and terrace planting sites were located in Carroll County, MS (latitude: 33°18' N, longitude: 89°40' W, T.17 N and R.6 E). The upland planting site was situated in Winston County, MS (latitude: 33°15' N, longitude: 89°06' W, T.16 N and R.12 E). The planting sites in Carroll County were old fields. The planting site in Winston County was an opening in a pine-hardwood forest on a south slope. The soils at the planting sites were classified as Oaklimeter silt loam, moderately well drained (coarse-silty, mixed, thermic fluvaquentic Dystrochrepts); Loring silt loam, moderately well drained (fine-silty, mixed, thermic Typic Fragiudalfs) (USDA Soil Conservation

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Service 1990), and Maben fine sandy loam, well drained (fine, mixed, thermic Ultic Hapludalfs) (USDA Soil Conservation Service, unpublished), respectively.

Experimental Design

A randomized complete block design was used. Every planting site had four blocks. In a block there were 17 adjacent plots representing stands. The acorns from each stand were sown in 2 rows with 10 planting positions in each row in a plot. In other words, 20 seeded. positions were installed in a plot. There were two acorns planted at each planting position, and positions were spaced at 3 by 3 meters. Two border rows were installed around each block. Blocks were randomly assigned in a planting location, and then plots (acorn sources of stands) were randomly assigned within a block. All effects in the population model were considered random because the entire population was of interest. Inference can be made from this experiment for the entire population of cherrybark oak.

Weed Control

Weeds were controlled in the first year by mowing and disking between trees and with direct spray application of herbicide. After sowing (but just before seedling emergence) a tank mixture of Gramoxone® and Goal® was sprayed in a 1.5-meter band for every planting row to control the early emergent weed species. The dosage was 56.2 milliliters Goal®/liter (5.8 liters/hectare) and 22.43 milliliters Gramoxone Extra®/liter (2.3 liters/hectare). After seedlings emerged, Fusilade® 2000 was sprayed two times at 30-day intervals as 12 milliliters/liter (1.2 liters/hectare), including 3 milliliters surfactant/liter. In addition, glyphosate was applied two times as a directed spray on weed species at the dosage of 22.45 milliliters/liter (5.9 liters/hectare) by putting a 45-centimeter PVC pipe around the seedlings. A piece of aluminum foil was placed on the top of pipes to prevent drift of glyphosate onto the oak seedlings.

Data Collection and Analysis

Traits measured on every seedling were height, groundline diameter, leaf number per seedling, seedling emergence, and survival. Height and groundline diameter were measured in millimeters. In the case of multiple stems, the height of the tallest stem was recorded. Seedling emergence counts were made on June 15, July 15, early August, and early September 1996. When the seedling had two leaves, it was scored as emerged. Where two seedlings survived at a flagged position, one of them was randomly chosen and the other was removed in October 1996. All final measurements were taken in the first week of October 1996. Survival was determined from this final measurement.

Differences between seed sources and among stands were evaluated by analysis of variance on a plot-mean basis. A format of the analysis of variance table is shown in table 1. A Satterthwaite-F (pseudo-F) test (Steel and Torrie 1980) was used for the "planting sites and topographic positions of stands" sources of variation. All analyses were performed using SAS statistical procedures (SAS Institute Inc. 1988).

Table 1 -Format of analysis of variance for cherrybark oak seed source trails on two upland sites and a bottomland site

Source of variation	df	Expected (MS)
Total (corrected)	203	
Planting sites (L)	2	$a^2_{SB(L)} + 17\alpha^2_{B(L)} + 4\alpha^2_{SL} + 68\alpha^2_{L}$
Blocks within L. (B/L)	9	$\alpha^2_{SB(L)} + 17\alpha^2_{B(L)}$
Stands (S)	16	$\alpha^2_{SB(L)} + 4\alpha^2_{SL} + 12\alpha^2_{S}$
Topographic positions of stands (T)	1	$\alpha^2_{SB(L)} + 4\alpha^2_{SL(T)} + 12\alpha^2_{S(T)} + 68\alpha^2_{TL} + 204\alpha^2_{T}$
Stands within T.(S/T)	15	$\alpha^2_{SB(L)} + 4\alpha^2_{SL(T)} + 12\alpha^2_{S(T)}$
Stands * P. sites (S*L)	32	$\alpha^2_{SB(L)} + 4\alpha^2_{SL}$
T*L	2	$\alpha^2_{SB(L)} + 4\alpha^2_{SL(T)} + 68\alpha^2_{TL}$
S/T*L	30	$\alpha^2_{SB(L)} + 4\alpha^2_{SL(T)}$
S*B/L	144	$\alpha^2_{SB(L)}$

Laboratory Germination Test

The test was run at the Forestry Sciences Laboratory, Starkville, MS, which is maintained by the Southern Research Station of the USDA Forest Service. Germination of oak acorns was tested by the "cut and peel" method, as in standard testing procedures (AOSA 1978, Bonner 1984). Fifty acorns were used from each stand for the test, and the whole test was replicated four times. The acorns were cut in half and the pericarps were removed.

The germination test was accomplished in a germination chamber. Kimpak (cellulose paper wadding) was used as germination medium. Light was furnished for the 8-hour "day' portion of the cycle. Night and day temperatures in the cabinet were set on 20 °C and 30 "C, respectively. A 3-centimeter space was left between acorns on the Kimpak in labeled germination trays. An acorn was scored as germinated when plumule and root development were observed. The test was run until the last acorn germinated. Germination counts were made at the same time every day. Fungal infected and ungerminated acorns were also counted. Germination percentage and germination value (GV) were calculated. Czabator's formula was used to quantify the germination value of acorns from different stands (Czabator 1962).

RESULTS AND DISCUSSION

Upland vs. Bottomland

Results supported the null hypothesis that there was no difference between upland and bottomland seed sources for the measured traits in the first year (table 2). Therefore, the collection of acorns from upland sites for planting on

Table 2-Mean squares and F-test results for field emergence and laboratory germination, survival percentage, height, groundline diameter, leaf number, and leaf number per centimeter of height for 1-year-old cherrybark oaks; upland vs. bottomland seed sources

		Mean squares[a]						
Sources of variation	df	Field emerg	Lab. germ	Surv	Hght	Grnd line diam	Leaf #	Leaf # per cm height
Planting sites	2	23455**	—	9683**	23299**	18**	493**	0.7**
Blocks within P. sites	9	302.4**	—	325.3	4980.3	0.8*	16.9	0.1**
Topographic position of stands (Topo)	1	200.8	0.5	0.8	3847.5	0.2	11.4	0.03
Stands within Topo	15	293.4	394*	248.4	2736*	0.4	16.6**	0.02
P. sites * Topo	2	426.7	—	300.7	2406.8	0.1	0.1	0.004
P. sites* stands within Topo	30	185.0*	—	187.7	1351 .o	0.2	5.0	0.03
Stands* blocks within P.sites	144	102.8	—	252.6	3017.6	0.4	10.8	0.03
Blocks	3	—	58.9	—	—	—	—	—
Stands * blocks	48	—	183.6	—	—	—	—	—

[a] Where,* indicates the calculated F was significant at the alpha = 0.05 level, and ** indicates the calculated F was significant at the alpha = 0.01 level.

bottomland sites should not cause any problem in seedling emergence, survival, and first-year growth of the seedlings. However, later problems as the stand develops cannot be predicted based on these first-year results.

Great genetic variation in species that occur naturally in disjunct populations can generally be expected (Zobel and Talbert 1984). A possible explanation for this lack of significant variation between upland and bottomland seed sources in close proximity to each other is that migration prevents the evolution of bottomland and upland ecotypes by natural selection. Similarly, Larsen (1963) found, in his investigation of the effects of water soaking on acorn germination of four southern oaks, that susceptibility to flooding injury was not significantly different between “dry site” species and “bottomland site” species. In contrast, results from a northern red oak study by Kubiske and Abrams (1992) clearly demonstrated that xeric and mesic seed sources showed ecotypic differences in leaf morphology, photosynthesis, and water relations during drought in the first year, even though seed sources came from neighboring sites in central Pennsylvania.

Variation Among Planting Sites

Significant variation was found among planting sites in mean field emergence, survival, height, groundline diameter, total leaf number, and leaf number per centimeter of height (table 2). Emergence was 55 percent at the terrace, 24 percent at the bottomland, and 22 percent at the upland planting site (table 3).

Lowest field emergence at the upland planting site might have been caused by consumption of acorns by small mammals and birds, although digging and other clear evidence of acorn destruction in the field were not observed. Munns (1921) has proposed that the moisture content of soil affects the germination of forest tree seeds. A fluctuation in water content on either side of what is called “the optimum range of soil moisture for germination” would cause a decrease in germination. Therefore, the poor field emergence at the upland and bottomland planting sites might have been caused by too little and too much soil moisture during a critical period of acorn germination. Some studies have reported that waterlogged soils inhibit oak germination (Briscoe 1961, Hosner 1957). In this study, the bottomland planting site was flooded several times from the nearby Big Black River in March through June 1996. This might have reduced the germination at the bottomland planting site. After the germination period, however, seedling survival percentages at the bottomland and terrace planting sites were very similar (even slightly higher on the bottomland site), and about 24 to 25 percent higher than seedling survival on the upland planting site (table 3). Dry soil conditions during the summer after acorn germination might be responsible for these results.

Table 3-Overall means of cherrybark oak of field emergence, survival, height, groundline diameter, and leaf number on the bottomland, terrace, and upland planting sites

Traits measured	Overall mean of P. sites			
	Bottomland	Terrace	Upland	Overall avg.
Field emergence (percent)	23.68	55.26	22.43	33.79
Survival (percent)	86.17	85.46	64.98	78.87
Height (mm)	175.54	185.38	150.43	170.44
Groundline diameter (mm)	2.82	3.12	2.10	2.68
Leaf number	12.63	14.48	9.28	12.15

Much has been written about the effects of flooding on acorn germination and seedling survival of cherrybark oak, but there is little on the effects of summer drought. Cherrybark oak seedlings are classified as intolerant to flooding (Hosner and Boyce 1962, McKnight and others 1980, Pezeshki and Chambers 1985). Under water saturated soil conditions, leaf moisture deficits apparently induced the early death of cherrybark oak seedlings due to reduced water uptake resulting from root mortality (Hosner and Boyce 1962). However, findings of Pezeshki and Chambers (1985) contradicted this. Water deficits did not result from flooding, based on the leaf xylem pressure potential measurements in cherrybark oak under controlled environmental conditions. Flooding causes stomatal closure, lower transpiration rates, and reduction in net photosynthetic rate in cherrybark oak (Pezishki and Chambers 1985). These factors might have contributed to failure on the bottomland planting site, because seedling height, groundline diameter, and leaf number were higher on the terrace planting site than the seedling means on the other two planting sites (table 3). The bottomland planting site was ranked second for the same traits. Hosner and Boyce (1962) reported that 60-day periods of saturated soil under controlled environmental conditions did not affect the height growth of cherrybark oak seedlings. Drought at the upland site seems a big problem. The lowest values of the measured traits at the upland planting site may indicate the importance of available water in the soil during the growing season.

Stand Variation

Significant variations were found among stand means averaged over the three planting sites for laboratory germination, height, and leaf number (table 2). Stands within topographic positions varied for mean germination value when germinated under controlled laboratory conditions ($p=0.023$) (table 2). This source of variation was not significant in the field tests, probably because of the planting site-by-stand-within-topographic-position interaction and because measurements were taken at long intervals.

The mean germination values of acorns of stands ranged from 88 (stand 9B) to 57 (stand 158) in the laboratory test. Acorns from stand 9B had approximately 35 percent more germination speed and completeness than stand 15B. Stand differences of this magnitude could be important. Large gain for germination speed and completeness can be obtained from choosing the best stands for acorn collection.

While three of the highest germination values came from stands 9B and 13B (the Upper Coastal Plain Soil Resource Area of MS) and 10B (the Blackland Prairie Soil Resource Area of MS), which were bottomland stands, acorns of the two stands 3B and 15B from the Mississippi delta had the lowest germination values (fig. 2). There was a pattern of change among stands from east to west. Acorns from the two west stands (3B and 15B) demonstrated the poorest germination values. These two delta sources also slowly completed the germination process. Low germination values of acorns of those two stands might be due to selfing, because the stands are isolated from other cherrybark oak stands.

Pettry (1977) has said “Mississippi may be divided into ten major soil resource areas, each containing soils, topography, and climatic factors that make it distinct from the other land areas.” Those soil resource areas of Mississippi are Delta, Upper and Lower Thick Loess Areas, Upper and Lower Thin Loess Areas, Upper Coastal Plain, Lower Coastal Plain, Blackland Prairie, Interior and Coastal Flatwoods (fig. 1). Based on this division, the stands coming from the Upper Coastal Plain Soil Resource Area were above average for germination value (fig. 2).

The cause of different stand values for acorn germination in the laboratory study is not known. Possible reasons include kind of reserve food materials (such as fats and carbohydrates), different temperature requirements for germination, or differences in degree of dormancy. Kramer and Kozlowski (1979) attributed the seed dormancy of oaks to physiological embryo dormancy. Vogt (1974) in northern red oak found a decrease of an abscisic-acid-like germination inhibitor and the increase of a gibberellin-like germination promoter during stratification. In the germination of acorns of some stands this type of mechanism may have been involved.

After one growing season, significant variation among stands within topo positions occurred for height increment ($p=0.049$) (table 2). The mean height of seedlings of stands ranged from 139 to 194 millimeters in the field. Seedlings of stand 2U, located in the Upper Thick Loess Soil Resource Area, were the tallest (fig. 2). There was no pattern of change among stands from east to west for this trait. Other researchers also found significant differences among provenances in cherrybark oak (Dicke and Toliver 1987, Greene and others 1991, Randall 1973).

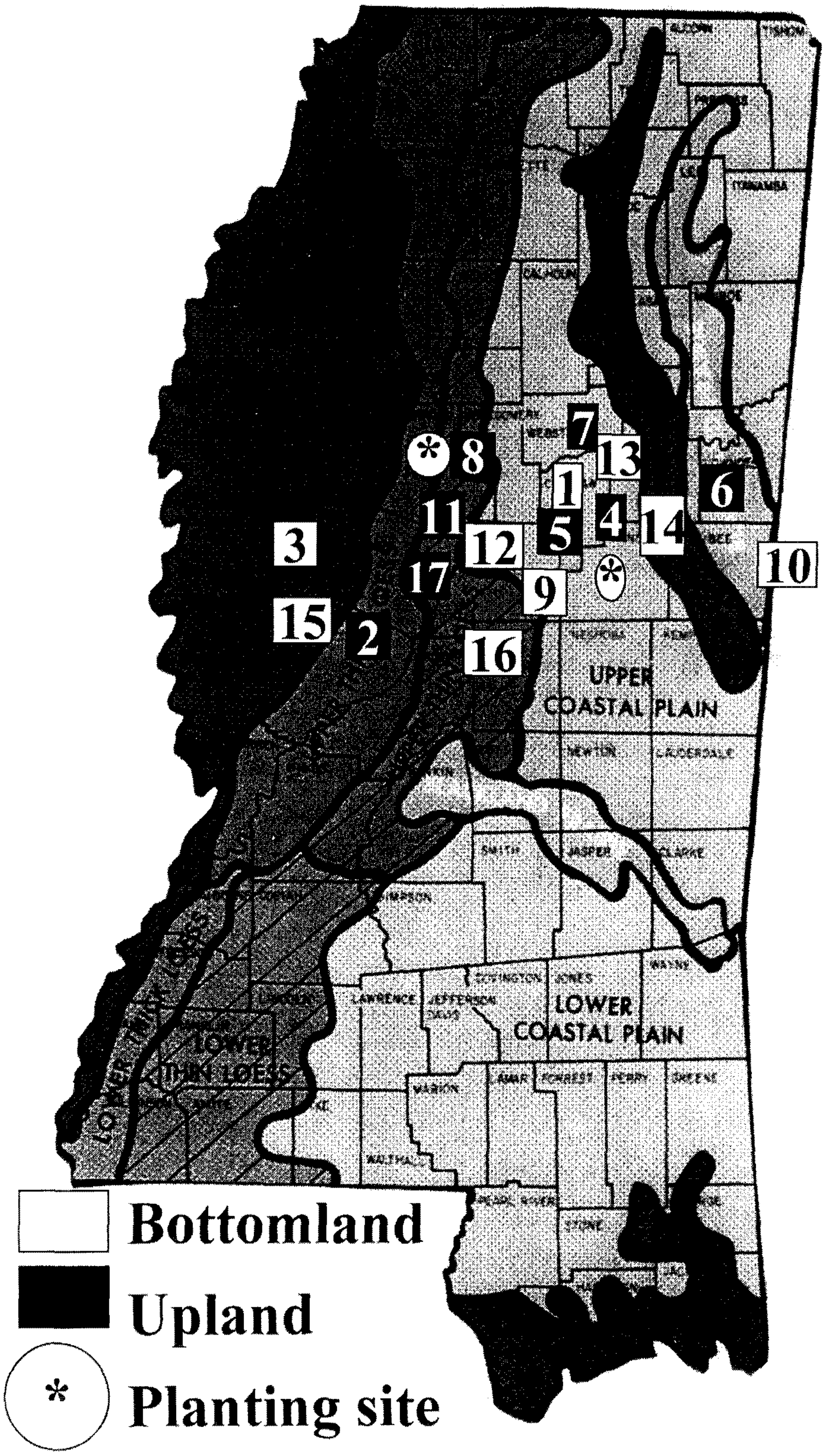

Figure l-Acorn collection and planting sites in Mississippi (Pettry 1977).

Stands within topographic positions varied relative to mean leaf number ($p=0.002$) (table 2). The mean leaf number of seedlings of stands ranged from 14 (stand 4U) to 10 (stand 15B) in the field. There was no pattern of change among stands from east to west for leaf number of seedlings (fig. 2). Stand rankings for leaf number were similar to rankings for height. Although stands within topographic positions were significant for leaf number, the leaf number per centimeter of height was not significantly different (table 2). Taller seedlings had more leaves.

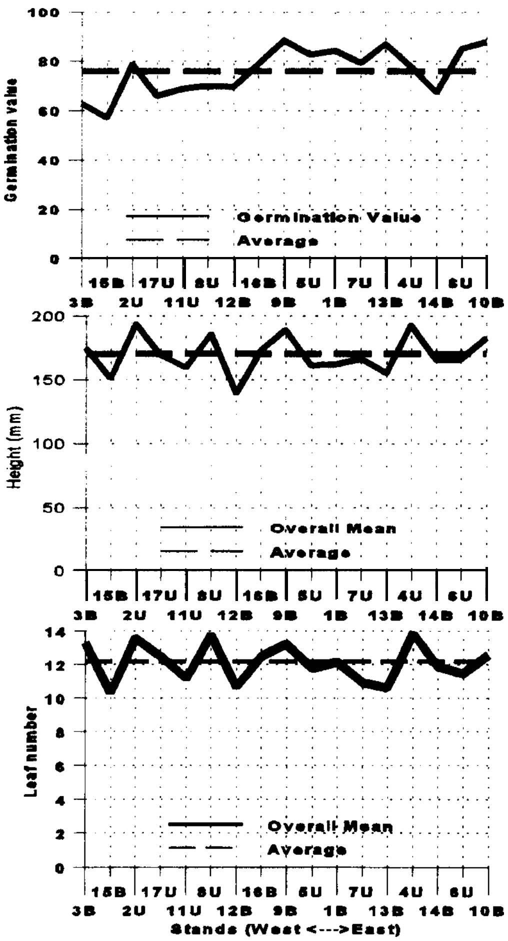

Figure 2-Mean germination value of acorns, mean height increment and leaf number of seedlings from 17 cherrybark oak stands across an east-west transect in central Mississippi.

McGee (1968) reported that there was a high correlation between seed source and number of leaves per seedling in northern red oak. He partially attributed this high correlation to the high number of multiple stems produced by one particular seed source.

Planting-Sites-by-Stands within Topographic Position Interaction

The only interaction between planting sites and stands within topographic positions was for mean percent field emergence ($p=0.0043$) (table 2). Stands 4U and 6U (fig. 1) ranked 15th and 17th at the bottomland planting site, 4th and 17th at the terrace planting site, and 2nd and 3rd at the upland planting site, respectively. Stands 1 B and 12B ranked 2nd and 6th at the bottomland planting site, 11th and 16th at the terrace, and 16th and 17th at the upland planting site, respectively. The two upland stands moved to the high ranks as they changed bottomland to upland planting sites, while the two bottomland stands moved to the lowest ranks as they changed from bottomland to upland planting sites. These were the four extreme stands for rank changes and probably were responsible for the significant interaction. However, this pattern was not true for all stands from the same topographic position (topographic position by site was not significant). Therefore, no definitive conclusion can be drawn about matching stand origin with the topographic position of the planting site.

CONCLUSION

There was no significant variation between upland and bottomland seed sources. Acorns from upland and bottomland sites had similar first-year performance when planted on either type of site. However, large variation among planting sites occurred with respect to seedling emergence, survival, first-year height increment, first-year groundline diameter increment, and leaf number. The terrace planting site was generally best. The differences among planting sites may be due to moisture content of soils during germination and during the summer. There was variation among stands within the two topographic positions for laboratory germination, height increment, and leaf number. Acorns from the two delta stands had the lowest germination value. There was no pattern of change among stands from east to west for height and leaf number, except germination value of acorns. Much of the variability among stands was random with regard to location. Poor rank correlations among planting sites contributed to interactions between planting sites and stands within topographic positions for seedling emergence in the field. Some stands moved to the high ranks as they changed the planting site from bottomland to upland, while some stands moved to the lowest ranks as they changed the planting site from bottomland to upland. The results obtained in this study indicate that topographic position of stands where acorns were collected does not influence the first-year regeneration success. Planting-site selection and collection of acorns from healthy stands with a large cherrybark oak component (for good cross pollination) are probably more important for the success of reforestation.

ACKNOWLEDGMENT

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REGENERATION EFFICIENCY OF BAREROOT OAK SEEDLINGS SUBJECTED TO VARIOUS NURSERY AND PLANTING TREATMENTS

Kirk D. Howell and Timothy B. Harrington[1]

Abstract-Seedlings of cherrybark oak (Quercus *falcata* var. *pagodifolia* Ell.) and northern red oak (Quercus *rubra* L.) from five seedbed densities were outplanted using three root-handling treatments. Using a cost-over-benefit evaluation technique, the components of cost (seedling cost, seedling weight, and planting rate) and performance (survival, diameter, and height) were analyzed concurrently. In general, seedlings from low seedbed densities were lowest in cost, but those from high seedbed densities were highest in performance. The dug-hole method of planting was more costly to implement than the two compression methods of planting, yet it showed some improvement in seedling performance over the compression methods. The evaluation of regeneration efficiency indicated that the performance advantage gained from growing seedlings at low seedbed densities and planting them by the dug-hole method did not overcome the high costs of treatment implementation.

INTRODUCTION

Artificial regeneration technology strives to minimize regeneration costs and maximize seedling performance—regeneration efficiency. The dilemma of unsatisfactory oak regeneration is a result of the failure to balance the competing objectives of cost and performance. The challenge for today's forester is to improve the one without compromising the other.

Commercial oak species of the Southern United States are typically regenerated naturally with shelterwood systems (Loftis 1990). However, artificial regeneration (i.e., hand-planting) of oak is seldom considered because adequate seedling performance in the field is difficult to obtain (Boyette 1980). Oak nursery culture today places much emphasis on a seedling's ability to survive and grow after planting. Since stem caliper is indicative of root mass (Coutts 1987), a stem diameter of 12 millimeters has been recommended to maximize field performance of oak (Johnson 1988).

Nursery technology of oak has yet to produce affordable stock that is easily planted and demonstrates strong seedling performance. If regeneration costs were not a significant component of a silvicultural system, it would be justifiable to plant large saplings or small trees instead of seedlings. However, contemporary nursery cultural practices seem to produce seedlings at their plantable limits, such as with oaks. Moreover, planting small oak seedlings should be less expensive and less exhausting, although they will not have the stem caliper and root bulk likely to promote high survival and growth (Johnson 1988).

Bulky oak root systems are encouraged within current nursery practices. In this scenario, there are two approaches that can be utilized in order to properly plant the seedling. Either some sort of corrective strategy (i.e., field pruning) must be performed or the planting hole must be opened to a sufficient size. If neither of these is performed, root deformation (i.e., root balling or j-rooting) will occur. Some have suggested that root deformation may not be deleterious to a seedling's short- or long-term performance (Haase and others 1993). Root deformation is not condoned, although it is obviously more acceptable than to plant seedlings at a shallow depth. Perhaps some sort of root restriction strategy, such as variation in seedbed density, may be practically applied within future nursery cultural practices.

This study's objectives were to: (1) observe the effects of seedbed density on root morphology and subsequent root-handling treatments, (2) analyze costs and benefits, and (3) determine treatment(s) of maximum regeneration efficiency.

METHODS

Seeds of cherrybark oak (Quercus *falcata* var. *pagodifolia* Ell.) and northern red oak *(Quercus rubra* L.) were purchased in November 1992, stored at 5 °C until sowing, and sown at Whitehall Forest, Athens, GA, in December 1992. In November 1993, the seedlings were lifted and placed in cold storage. In December 1993, the northern red oak seedlings were planted on a sloping, shelterwood site having a basal area of 22 square meters per hectare located at Bent Creek Experimental Forest, Asheville, NC. The cherrybark oak seedlings were planted on a level shelterwood site having a basal area of 9 square meters per hectare managed by T&S Hardwoods, Inc., Milledgeville, GA.

A randomized, complete block design was employed, where seedlings from each of the five seedbed densities were subjected to three root-handling treatments with four replications of four seedlings per treatment (240 seedlings per species). The five nursery densities were 100, 169, 256, 400, and 529 seedlings per square meter. The three root-handling treatments were root balling (j-rooting), heavy root pruning (9 centimeters from the root collar), and dug-hole planting (no root pruning or balling).

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Measurements

The main establishment cost variables were seedling price (dollars), seedling weight (grams), planting rate (seconds per seedling). Another variable, considered only in total cost estimation, was site preparation cost. Stem heights (centimeters) and ground-line diameters (millimeters) were taken at planting, and in October 1994 and 1995.

Analyses

Data were analyzed using analysis of variance (ANOVA, SAS Institute, Inc. 1988) and Tukey's test for means comparisons of main effects. All analyses were conducted with a 95 percent significance level. If the interaction between main effects was significant, the data were reanalyzed via one-way ANOVA. Initial size was used as a covariate.

The conservative land value ($827 per hectare for the cherrybark oak site; $1,217 per hectare for the northern red oak site) provided an assessed cost for bare forest land, designated to continue as such (Georgia Department of Revenue 1996). Site preparation was not required at the Indian River site; however, a herbicide application was needed for understory control at Bent Creek at an estimated cost of $69 per hectare.

The estimated purchase price for bare-root oak seedlings (about $100 per 1,000 seedlings) was obtained for oak stock grown at a density of 256 seedlings per square meter. Based on their density in proportion to the 256-per-square-meter density, seedlings from 100, 169, 400, and 529-per-square-meter densities were priced at $256, $151, $64, and $48 per 1,000, respectively. At an assumed hourly rate of $15 per hour, planting 240 seedlings took 2.2 hours for cherrybark oak, and 2.0 hours for northern red oak, at a spacing of 1.8 meters by 1.8 meters (2,989 stems per hectare), for a total planting cost of $415 per hectare ($139 per 1,000 seedlings) and $380 per hectare ($127 per 1,000 seedlings) for cherrybark oak and northern red oak, respectively. Half of the total planting cost was equally assigned to each of seedling weight and planting rate, because weight and rate both affect planting time.

The following equations were used to calculate adjusted cost, benefit, and cost-over-benefit for each measurement year, respectively:

$$C=Cb*(1+i)**t$$

$$B=TPH*S*\Sigma((3.14159*(r**2)*h)/2)$$

$$COB=C/B$$

where

C is compounded total cost (dollars per hectare),
Cb is total cost (dollars per hectare),
i is an assumed interest rate (i=8 percent),
t is the time period of cost compounding (t=2 years),
B is stand volume (cubic decimeters per hectare),
TPH is trees per hectare,
S is proportion of surviving stems,
r is individual-tree stem radius (decimeters),
h is individual-tree height (decimeters), and
COB is cost-over-benefit (dollars per cubic decimeter).

The COB ratio is similar to the inverse of the benefit-cost ratio (Clutter and others 1983). The COB index, however, retains the units to provide a basis for meaningful comparisons among other regeneration treatments not considered in this study. The treatment with the lowest COB value, if significantly different from the other treatments, was considered optimum.

RESULTS

Seedlings from the two highest seedbed densities were lightest in weight for both species (table 1). The dug-hole method of planting was significantly slower ($p \leq 0.05$) than the other planting methods for both species. Second-year survival and diameter of cherrybark oak seedlings from 100-per-square-meter density were significantly greater than those of the highest density. Northern red oak survival results indicated that trimmed seedlings from the 529-per-square-meter density and dug-hole seedlings from the 256-per-square-meter density were significantly greater than dug-hole seedlings from the 400-per-square-meter density. Second-year diameters and heights did not differ significantly among treatments.

Total cost differed significantly among density and root-handling treatments for both species (table 2). The lowest density and dug-hole planting had the largest significant values for total cost at year 2 for both species. Second-year benefit (stand volume) for the lowest seedbed density was significantly greater than those of the other seedbed densities for cherrybark oak, while year-2 benefits did not differ significantly among treatments for northern red oak.

Second-year COB values for seedling cost (table 3) were significantly greater for the density of 100 per square meter versus other densities for both species. The highest density had a significantly lower second-year, seedling transport COB value than the other densities for northern red oak. Second-year COB values for planting rate indicated that the dug-hole method was significantly greater than those of the other root-handling treatments for both species. Second-year total cost COB values did not differ significantly among treatments.

DISCUSSION

Seedlings from low seedbed densities in our study were smaller than was expected, since fertilization was not included in the nursery culture. Smaller, lighter-weight seedlings, grown in high density seedbeds, allowed the planter to carry more seedlings to the planting location, reducing planting costs. Moreover, hoedad planting required the least amount of time for hole preparation, lowering planting costs. Therefore, while a treatment's benefit may not be greatly increased with time, lowering costs can serve to improve a treatment's chances of being selected as optimum.

Since weight tends to be positively correlated with volume, seedling transport COB values should be expected to increase with decreasing density. In fact, costs (determined by weight) divided by yield (determined by the parabaloid

Table I-Second-year costs and benefits for cherrybark and northern red oaks

		Cherrybark oak						Northern red oak					
		costs			Benefits			costs			Benefits		
Density	Treat-ment	SC^a	ST^a	P^b	S^a	D^a	H^{ns}	SC"	ST^a	P^b	S^{a*b}	D^{ns}	H^{ns}
529	Balled	48	7	18	33	5	33	48	9	17	56	4	19
	Trimmed			8	31	5	41			16	100	4	21
	Dug-hole			65	56	4	28			55	88	5	21
400	Balled	64	8	17	56	4	31	64	10	17	81	4	20
	Trimmed			18	50	4	36			16	75	4	21
	Dug-hole			63	69	4	25			54	44	5	19
256	Balled	100	14	20	56	4	31	100	11	15	67	4	18
	Trimmed			21	39	4	35			13	63	5	23
	Dug-hole			62	75	5	34			54	100	5	24
169	Balled	151	19	17	42	6	42	151	14	17	81	5	18
	Trimmed			16	63	5	34			14	81	5	22
	Dug-hole			58	46	5	39			57	83	5	18
100	Balled	256	14	17	58	5	39	256	21	16	69	6	22
	Trimmed			18	67	5	41			15	75	4	16
	Dug-hole			63	58	6	40			64	50	5	19

SC=seedling cost (dollars per 1000 seedlings); ST=seedling transport (grams per seedling); P=planting rate (seconds per seedling); D=diameter (millimeters); H=height (centimeters); S=survival (percent); a=density treatments differed ($p<0.05$); b=root-handling methods differed ($p<0.05$); ns=insignificant.

Table 2—Second-year costs (costs in dollars/hectare) and benefits for cherrybark and northern red oaks

		Cherrybark oak					Northern red oak				
		costs			Benefits		costs			Benefits	
Density	Treat-ment	SC[a]	ST[a]	P[b]	Tc[a,b]	dm^3/ha	SC"	ST[a]	P[b]	Tc[a,b]	dm^3/ha
529	Balled	165	150	120	1410	5.3	165	165	135	1995	2.4
	Trimmed			150	1410	4.2			120	1980	5.1
	Dug-hole			480	1770	3.8			450	2370	6.5
400	Balled	225	165	135	1485	3.6	225	165	150	2070	3.8
	Trimmed			135	1485	4.2			135	2055	3.9
	Dug-hole			480	1830	4.2			450	2430	2.9
256	Balled	345	270	150	1740	3.3	345	195	120	2205	3.0
	Trimmed			165	1740	3.8			105	2160	5.0
	Dug-hole			450	2025	7.1			465	2340	12.6
169	Balled	525	360	135	1980	7.1	525	255	135	2445	4.1
	Trimmed			120	1965	6.6			120	2415	4.8
	Dug-hole			435	2280	6.5			420	2550	4.4
100	Balled	900	270	135	2265	7.2	900	345	135	2895	5.0
	Trimmed			135	2295	8.1			120	2880	2.1
	Dug-hole			465	2580	13.7			525	3060	3.8

TC=total costs; a=density treatments differed ($p<0.05$); b=root-handling methods differed ($p<0.05$); ns=insignificant.

Table 3—Second-year cost-over-benefit means for cherrybark and northern red oaks

		Cherrybark oak				Northern red oak			
		COB				COB			
Density	Treatment	SC"	ST^{ns}	P^b	TC^{ns}	SC"	ST^a	P^b	TC^{ns}
		-Dollars per cubic centimeter-				-Dollars per cubic centimeter—			
529	Balled	94	88	74	794	99	100	83	1171
	Trimmed	67	54	52	560	38	39	25	438
	Dug-hole	50	50	151	544	35	36	95	482
400	Balled	65	47	37	430	63	50	39	573
	Trimmed	89	76	50	600	82	59	54	748
	Dug-hole	176	166	353	1455	150	120	297	1571
256	Balled	127	110	54	140	190	116	64	1185
	Trimmed	191	177	77	975	142	60	52	866
	Dug-hole	49	37	65	289	44	25	54	312
169	Balled	109	76	27	412	143	67	37	655
	Trimmed	96	65	22	359	126	57	28	571
	Dug-hole	120	84	100	526	187	97	162	978
100	Balled	168	58	25	434	255	114	43	839
	Trimmed	119	39	17	305	472	186	65	1515
	Dug-hole	284	72	152	816	406	163	231	1480

a=density treatments differed ($p<0.05$); b=root-handling methods differed ($p<0.05$); ns=insignificant.

volume yield equation) should be linearly related. In our study, cherrybark oak followed this linear trend, but northern red oak gave spurious results.

Benefits, unlike costs, have potential to increase linearly, exponentially, or remain constant. In our study, benefit was expressed in terms of total stem volume, but it also may be expressed on an individual-seedling basis. Thus, the importance of the yield equation is evident: it combines the variables and ranks them according to their relative effect on merchantable production (survival >> diameter > height).

To be considered profitable, growth in benefit for a given treatment should exceed the growth in cost, which is fixed by the given interest rate (8 percent in our study). Cherrybark oak was more profitable in time than was northern red oak, due to an average 36 percent increase in yield over 2 years, compared to an average 10 percent increase for northern red oak. Moreover, additions of extraneous costs (i.e., land costs) to total costs seem to distort the cost influence within COB analysis, and to diminish the cost influence from the variables of interest within COB analysis.

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PHOTOSYNTHESIS AND BIOMASS ALLOCATION IN OAK SEEDLINGS GROWN UNDER SHADE

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Abstract-Northern red oak *(Quercus rubra* L.) (NRO) and white oak (Q. *alba* L.) (WO) acorns were sown into wooden plots and grown under 30 percent shade screen (30 percent S) or 70 percent shade screen (70 percent S). Seedlings grown under full sun were the controls (C). At the end of the first year, the 30 percent S NRO had 30 percent greater seedling dry weight (DW) than C seedlings. No growth differences existed between these two treatments after 2 years. Compared to C, 70 percent S NRO had a 40 percent lower net photosynthetic rate (A), twofold less seedling DW and leaf number, and fourfold less lateral root DW after 2 years. Dry weight biomass allocation to lateral roots increased from 17 percent at the end of the first growing season to 22 percent after 2 years for both the C and 30 percent S NRO. The 70 percent S seedlings, however, allocated only 8 percent DW to lateral roots for both years. White oak seedlings responded similarly to shade as NRO seedlings. The 70 percent S WO had 30 percent lower A and fourfold less lateral root DW than the controls after 2 years. At the end of the second year, DW biomass allocation to lateral roots was 12, 7, and 5 percent, respectively, for C, 30 percent S, and 70 percent S WO seedlings. The impact of shade (reduced light intensity) on seedling growth of both oak species was discussed in terms of A, photoprotection, and DW biomass allocation.

INTRODUCTION

For the last three decades various silvicultural practices have been suggested to improve the success of natural and artificial regeneration of northern red oak *(Quercus rubra* L.) (NRO) on high-quality mesic sites. Several factors have been implicated in the less-than-satisfactory results of NRO regeneration. Competition for light between NRO seedlings and other hardwood species (such as *Acer saccharum* Marsh., *A. rubrum* L., and *Liriodendron tulipifera* L.) is the one most commonly mentioned in the literature (Barton and Gleeson 1996, Loftis and McGee 1993). Indeed, full-sun-grown NRO seedlings have higher net photosynthetic rates (A) than shaded seedlings (Crunkilton and others 1992, Kubiske and Pregitzer 1996, McGraw and others 1990). Yet, there still exist controversial results on the effects of shade on NRO growth. For example, Gottschalk (1985, 1987) reported that NRO seedlings receiving 70 percent of full sunlight grew better than seedlings receiving 8 to 57 percent or 94 percent of light. Similar contradictions exist for other *Quercus* species. Jarvis (1964) concluded that sessile oak *[Q. petraea* (Matt.) Liebl.] is intolerant to light intensity greater than 56 percent, whereas Gross and others (1996) reported that root collar diameters were smaller in sessile and pedunculate oak *(Q. robur* L.) seedlings grown under 50 percent shade for 3 years.

Even when oak seedlings are outplanted on clearcut sites, their poor initial growth results in their becoming overtopped by herbaceous vegetation and other faster growing hardwood species. Use of large size nursery stocks in the artificial regeneration practice has been suggested as a method of improving slow initial growth (Farmer 1975, Foster and Farmer 1970). Kormanik and others (1994) reported a nursery protocol that produced large-size oak seedlings as compared to seedlings used in various studies (Farmer 1979, Gottschalk 1985, Teclaw and Isebrands 1993). Nevertheless, shelterwood planting has been recommended as an alternative to outplanting oak seedlings on clearcut sites for various reasons (Loftis and McGee 1993, Teclaw and Isebrands 1993). However, these shaded oaks did not have fast growth even Several years after release (Loftis and McGee 1993).

Chlorophyll bleaching has been reported to occur in shade leaves as Well as in sun leaves formed from shade buds in the released understory plants. In other words, the sudden improvement of light intensity and quality resulting from overstory canopy removal actually imposes damage to the released plants. During the last decade, it has been well documented that under conditions when absorbed light energy cannot be fully utilized for photochemical reactions in photosynthesis, the xanthophyli cycle-dependent and pH-dependent dissipation of excessive energy prevents photo-oxidative damage to chlorophyll, chloroplasts, and cells. Of the three carotenoid pigments in the xanthophyll cycle, zeaxanthin (Z) and antheraxanthin (An) can dissipate excess energy but violaxanthin (V) cannot. Under light conditions, the de-epoxidation of V to Z via the intermediate An is catalyzed by de-epoxidase in the presence of ascorbate and low thylakoid lumen pH. Thus, the xanthophyll pool size and the ratio between Z+An and Z+An+V have been used to describe a leaf's photoprotection capacity (Demig-Adams and Adams 1996). Indeed, several reports showed that shaded leaves have lower levels of xanthophyll cycle pigments and smaller ratio of Z+An to Z+An+V as compared to sun leaves (Demig-Adams and Adams 1996, Faria and others 1996). The objectives of this study are to use the protocol of Kormanik and others (1994) to grow NRO and white oak (Q. *alba* L.) (WO) seedlings under different shade conditions and to evaluate the effects of shade on photosynthesis and biomass allocation.

MATERIALS ANDMETHODS

Seedling Growth and Harvest

In January 1993, 16 acorns of NRO or WO were sown into 1 meter by 1 meter by 0.6 meter wooden plots at a depth

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of 1 centimeter below soil surface. Seedlings began to emerge by mid-March. The study was a complete random design with three treatments and two replications. A total of 12 plots were used for each species. In early April, a layer of neutral density screen was draped over a wooden frame 3.3 meters in height. Four plots were enclosed in each frame with a 0.6-meter distance between plots and a 0.8-meter distance between plots and the screen. The extent of shade was created by screens of different densities. Maximal photosynthetic active radiation, measured by a LiCor quantum sensor, for 30 percent shade (30 percent S) and 70 percent shade (70 percent S) treatments was 1100 $\mu E/m^2.s$ and 550 $\mu E/m^2.s$, respectively. The full sun control (C) had greater than 1800 $\mu E/m^2.s$. A gap of 0.3 meters was left between the ground and the lower edge of the screen to help air circulation. Seedlings were watered and fertilized according to the protocol of Kormanik and others (1994). The screen was lifted after leaf abscission in December 1993 and placed back in early April 1994.

In early December of 1993, seedlings were harvested from two of four plots for each species in each treatment. Care was taken to minimize root loss during harvest. Seedlings were separated into stems (with branches), leaves, taproots, and lateral roots. Each seedling component was oven dried at 95 °C until constant weight was obtained. Leaf area was measured with a portable CID Leaf Area Meter. The rest of the seedlings were grown for another year and harvested in December 1994. Dry weight for each seedling component was obtained.

Photosynthesis and Leaf Pigments

A portable LiCor 6200 Infrared gas analyzer was used to measure net photosynthetic rate (A) from recently mature leaves still attached to seedlings. In early September 1994, developing leaves of elongating flushes and mature leaves of the latest mature flushes from NRO seedlings grown under full sun were harvested throughout a day and immediately frozen in liquid N_2. Procedures for leaf pigment extraction and analysis were modified from the method by Gilmore and Yamamoto (1991). Ethanol (95 percent) and $CaHCO_3$ were used to extract pigments. A Dionex Al- 450 High Performance Liquid Chromatograph with a 4.5 millimeter by 25 centimeter Zorbax non-endcapped Cl 8 column was used. The gradient system used was as followed: 0 to 6 minutes, eluent A (acetonitrile : methanol, 80 percent : 20 percent); 6 to 9 minutes, eluent A to eluent B (methanol : ethyl acetate, 68 percent : 32 percent); 9 to 15 minutes, eluent B. Flow rate was 2 milliliters per minute for both eluents. Pigments were detected at 445 nanometers. Retention times (in minutes) are: neoxanthin 2.4, violaxanthin 2.8, antheraxanthin 3.7, lutein 4.7, zeaxanthin 5.0, chlorophyll b 9.4, chlorophyll a 11 .0, a-carotene 13.9, and p-carotene 14.1.

RESULTSANDDISCUSSION

Seedling Growth

Growth parameters of NRO and WO seedlings grown under different shades were presented in tables 1 to 4. Regardless of treatments, mean seedling size and weight for both species in this study are much greater than those reported in the literature (Farmer 1975, 1979; Gottschalk 1985, 1987; Teclaw and Isebrands 1993). The NRO seedlings were similar in size to the "1-O large" seedlings classified by Johnson and others (1984). Because this study was designed for 2 years, the planting density used was about one-fourth of the prescribed density by Kormanik and others (1994).

The screen used in this study only decreased light intensity but did not change light quality. The 30 percent S grown NRO were significantly greater in total leaf area per seedling, total seedling dry weight (DW), and stem plus branch DW than the controls in 1993 (table 1). Although not statistically

Table l-Effects of shade on first-year growth of northern red oak seedlings

Variable measured	Full sun	30% shade	70% shade	p-Value
Height (cm)	100.7a[a]	139.5a	100.8a	.0513
Groundline diameter (mm)	14.5a	16.4a	11.7b	.0063
FOLR number[b]	16.4a	17.8a	13.8a	.4209
Taproot DW[c] (g)	62.6a	70.1a	38.913	.0077
Lateral root DW (g)	28.5a	34.2a	9.4a	.0671
Leaf DW (g)	34.9a	38.5a	23.2a	.0403
Leaf number	53.2a	50.1a	34.5a	.1925
Leaf area (cm^2)	3237.0b	4590.0a	3381 .Ob	.0016
Average leaf area (cm^2)	66.3a	93.2a	98.8a	.0795
Stem and branch DW (g)	48.1b	85.2a	34.5b	.0009
Seedling DW (g)	174.1b	228.0a	105.9c	.0029

[a] Least-square means for a given variable are not significantly different at the 0.05 experimentwise level using the Bonferroni approach when each pairwise contrast is tested at the 0.05/3 = 0.0167 level.
[b] First-order lateral root.
[c] Dry weight.

significant, these 30 percent S seedlings were generally larger in each growth parameter than C except for leaf number. This trend was less obvious for the second year (table 2). The 30 percent shade screen probably provided a cooling effect on the oaks during hot weather of the 1993 summer, thus resulted in more growth than controls. Northern red oak grown at 23 °C/23 °C (day/night) for 4 months had 60 percent greater seedling DW than those grown at 29 °C/23 °C (Farmer 1975). Hodges and Gardiner (1993) also reported that full-sun-grown *Q. pagoda* Raf. seedlings were smaller than those under 53 percent sun, but larger than seedlings grown under 27 and 8 percent sun.

Northern red oak seedlings of 70 percent S were consistently smaller in taproot and total seedling DW than controls for both years. At the end of the second year, effects of 70 percent shade on decreasing DW growth were significant in all seedling components with the exception of average individual leaf DW (table 2). Fewer leaves and larger individual leaf were observed in 70 percent S seedlings as compared to C and 30 percent S seedlings. Similar effects of shade on leaf number and area were reported with pedunculate oak (Ziegenhagen and Kausch 1995). The specific leaf weight for C, 30 percent S, and 70 percent S seedlings were 10.8, 8.4, and 6.9 mg/cm^2, respectively. Greater average leaf area, smaller specific leaf weight, and thinner leaf have been observed in several oak species grown under shade (Ashton and Berlyn 1994, Carpenter and Smith 1981, Farmer 1975).

Unlike NRO seedlings, the 30 percent S treatment did not increase WO growth over that of C (tables 3, 4). Lateral

Table 2—Effects of shade on growth of northern red oak seedlings for 2 years

Variable measured	Full sun	30% shade	70% shade	p-Value
Height (cm)	142.7a[a]	171.5a	160.6a	.3566
Groundline diameter (mm)	23.1a	22.9a	17.8a	.0281
Taproot DW[b] (g)	195.2a	186.6a	92.6b	.0176
Lateral root DW (g)	120.6a	122.0a	23.8b	.0053
Leaf DW (g)	52.3a	56.9a	38.5b	.0145
Leaf number	157.3a	140.8a	74.3b	.0019
Average leaf DW (g)	0.34a	0.42a	0.53a	.0171
Stem and branch DW (g)	154.5ab	177.0a	114.2b	.0275
Seedling DW (g)	522.6a	542.5a	269.1 b	.0063

[a] Least square means for a given variable are not significantly different at the 0.05 experimentwise level using the Bonferroni approach when each paitwise contrast is tested at the 0.05/3 = 0.0167 level.
[b] Dry weight.

Table 3—Effects of shade on first-year growth of white oak seedlings

Variable measured	Full sun	30% shade	70% shade	p-Value
Height (cm)	36.9a[a]	45.7a	37.5a	.2657
Groundline diameter (mm)	9.3a	9.9a	7.4b	.0133
FOLR number[b]	10.0a	9.4a	7.8a	.1649
Taproot DW[c] (g)	33.9a	37.1a	19.5a	.0619
Lateral root DW (g)	3.1a	2.7ab	1.5b	.0280
Leaf DW (g)	8.6ab	10.2a	6.4b	.0264
Leaf number	45.0a	53.8a	42.1a	.0811
Leaf area (cm^2)	965.0a	1309.0a	893.0a	.0573
Average leaf area (cm")	21 .Oa	24.9a	21.3a	.3242
Stem and branch DW (g)	11.3ab	14.9a	7.1b	.0278
Seedling DW (g)	56.9a	64.8a	34.4a	.0353

[a] Least-square means for a given variable are not significantly different at the 0.05 experimentwise level using the Bonferroni approach when each paitwise contrast is tested at the 0.05/3 = 0.0167 level.
[b] First-order lateral root.
[c] Dry weight.

Table 4-Effects of shade on growth of white oak seedlings for 2 years

Variable measured	Full sun	30% shade	70% shade	p-Value
Height (cm)	95.0a[a]	98.6a	101 .Oa	.9420
Groundline diameter (mm)	18.1a	17.3a	14.0a	.1235
Taproot DW[b] (g)	120.3a	108.6a	62.4a	.0734
Lateral root DW (g)	36.3a	30.2ab	7.6b	.0215
Total leaf DW (g)	25.2a	24.3a	13.3a	.1352
Regular leaf DW (g)	15.1a	19.4a	8.4a	.0567
Recurrent leaf DW (g)	10.1a	4.9a	4.9a	.3454
Total leaf number	149.8a	154.7a	72.4a	.1268
Regular leaf number	131.0a	144.0a	60.7a	.0964
Recurrent leaf number	18.8a	10.7a	11.7a	.9233
Avg regular leaf DW (g)	0.11a	0.14a	0.14a	.0513
Avg recurrent leaf DW (g)	0.54a	0.46a	0.42a	.2837
Stem and branch DW (g)	80.0a	90.7a	52.7a	.2701
Seedling DW (g)	261.8a	253.8a	136.0a	.1095

[a] Least square means for a given variable are not significantly different at the 0.05 experimentwise level using the Bonferroni approach when each pairwise contrast is tested at the 0.05/3 = 0.0167 level.
[b] Dry weight.

root DW growth was consistently less in 70 percent S seedlings than C for both years (tables 3, 4). In 1994, we noticed that some WO recurrent flushes had individual leaves with much greater area than most leaves. These extra large-area leaves (recurrent leaves) were threefold to fivefold greater in DW than the regular leaves (table 4). Control seedlings seemed to have more recurrent leaves than shaded seedlings. The specific leaf weights for C, 30 percent S, and 70 percent S seedlings in 1993 were 8.9, 7.8, and 7.2 mg/cm^2, respectively. Similar to NRO, WO seedlings grown under shade had fewer leaves, smaller individual leaf DW, and less total leaf area (tables 3, 4).

There were great variations in seedling size even within a wooden plot. The effects of shading on growth can be masked by these variations. When percents of DW allocated to each seedling component were examined, it was clear that DW allocation to lateral roots was affected the most by shading with both oak species in both years (table 5). It has been reported that shading decreased oak DW allocation to root system (Gottschalk 1987, Hodges and Gardiner 1993, Ziegenhagen and Kausch 1995). Our study probably is the first to show that shading decreased DW allocation to lateral roots but not taproots in oaks. Messier and Puttonen (1995) reported shading decreased DW allocation to fine-root biomass in *Betula pubescens* Ehrh. and *B. pendula* Roth

Table 5-Effects of shade on percent dry weight biomass allocation within oak seedlings

	Full sun		30% shade		70% shade	
Variable measured	1 year	2 year	1 year	2 year	1 year	2 year
Northern red oak						
Lateral root	16.9	22.0	14.9	20.5	8.3	8.3
Taproot	37.2	39.9	32.1	38.1	38.5	37.3
Stem and branch	27.0	27.9	36.2	30.5	31 .0	39.8
Leaf	18.9	10.2	16.8	10.9	22.2	14.6
White oak						
Lateral root	5.2	11.7	4.3	10.7	4.5	4.9
Taproot	61.1	50.1	57.4	46.8	57.4	50.9
Stem and branch	19.2	28.3	22.0	32.5	19.5	35.3
Leaf	14.5	9.9	16.3	10.0	18.6	8.9

grown under pine stands of different light availability. Thus, the underplanted oak seedlings with decreased lateral root growth would probably become less and less competitive for water and nutrient with established trees in the stands. High mortality of outplanted oaks in mixed hardwood stands as compared to that of pine stands and clearcut site planting has been observed by Kormanik and others (in press).

Photosynthesis

In this study, NRO A was not affected by the 30 percent shade treatment in either year (table 6). However, there was at least 30 percent decrease in A in 70 percent S NRO seedlings as compared to the controls. Effect of shade on decreasing A was more obvious with WO seedlings. Decreased oak A by shading, with or without change in light quality, has been reported in many studies (Crunkilton and others 1992, Kormanik and others (in press), Kubiske and Pregitzer 1996, McGraw and others 1990).

If leaf number and area were taken into consideration, the estimated A for 70 percent S NRO and WO seedlings were about 70 and 30 percent, respectively, of the controls for 1994 (table 6). These estimated A values are close to the value of 50 percent less seedling DW for both species grown under 70 percent S (tables 2, 4). Although WO has similar A to that of NRO, the slower growth by WO seedlings can be explained by the fact that WO seedlings have fewer leaves and smaller individual leaf area than NRO (table 6). Similar A's for WO and NRO were reported by Barton and Gleeson (1996) and Sung and others (1995).

Photoprotection

Levels of pigments in developing and mature leaves from full sun-grown NRO seedlings are presented in table 7. Mature leaves had twice as much chlorophyll a plus chlorophyll b (Chl a+b) as developing leaves. No significant differences in the levels in all the carotenoid pigments, expressed on the mol Chl a+b basis, were observed between developing and mature leaves (table 7). Only the xanthophyll cycle pigments exhibited diurnal patterns in both types of leaves. The Z+An to Z+An+V ratio was low in the dark and very high around noon. Values presented in table 7 were comparable to those found with cork oak leaves (Faria and others 1996). Judged from the xanthophyll pool size (Z+An+V) and the ratio between Z+An and Z+An+V, it is obvious that the photoprotection mechanism is more active in developing leaves than in mature leaves. Similarly, sun cork oak leaves are more photoprotective than shade leaves (Faria and others 1996). The effects of shading on the xanthophyll pool sizes and the diurnal patterns of Z+An to Z+An+V ratio will be examined for NRO and WO seedlings grown under different types of stands in the future.

CONCLUSIONS

Northern red oak and white oak seedlings grown under 70 percent shade had lower net photosynthetic rate, fewer leaves, and less specific leaf weight, seedling dry weight, and dry weight allocation to lateral roots as compared to those grown with full sun. Like most plants, developing and mature northern red oak leaves exhibit diurnal xanthophyll cycle for photoprotection. Greater dry weight growth with northern red oak seedlings than white oak is associated with the former having more and larger leaves. With the presence of large leaves on some of the recurrent flushes in white oak seedlings, dry weight growth can be increased because recurrent leaves have a higher

Table 6—Effects of shade on oak net photosynthetic rate (A)

Light level	1993 Average A[a] $\mu mol/m^2.s$	1993 Estimated A[b] $\mu mmol/seedling.h$	1994 Average A $\mu mol/m^2.s$		1994 Estimated A $\mu mmol/seedling.h$
Northern red oak					
Full sun	10.1	11.76	10.5		18.34[c]
30% shade	10.3	17.02	10.4		25.40
70% shade	6.6	8.03	6.3		12.72
White oak:			(Regular)	(Recurrent)	
Full sun	10.2	11.89	11.5	15.1	13.40[d]
30% shade	8.9	14.71	9.7	10.7	11.11
70% shade	6.5	7.91	5.7	6.8	4.16

[a] Average of photosynthetic rates measured between June and October.
[b] Derived from average A x leaf area per seedling.
[c] Leaf area per seedling was calculated using the same specific leaf weight (g/cm^2) obtained from seedlings harvested in 1993.
[d] Derived from sum of estimated A for regular leaf and for recurrent leaf.

Table 7-Levels of chlorophyll and carotenoids in developing and mature leaves from northern red oak seedlings grown under full sun

	Time of day					
Pigment	5am	9 am	11 am	2 pm	5 pm	9 pm
Developing leaf[a]						
Chl a+b, mol/m^2	174.3	143.4	168.1	163.1	147.2	165.1
Zeaxanthin (Z)[b]	5.1	21.8	33.8	33.8	41.7	8.5
Antheraxanthin (An)	4.8	17.0	17.8	22.8	26.8	8.4
Violaxanthin (V)	78.1	35.6	14.3	27.1	21.3	82.3
Z+An+V	88.0	74.4	65.9	83.7	89.8	99.2
Lutein	122.9	116.0	115.0	130.3	122.2	124.6
Neoxanthin	58.5	60.5	57.8	56.0	57.9	54.4
a-Carotene	1.8	2.4	2.3	2.6	2.2	1.6
p-carotene	50.8	49.6	47.7	48.7	49.2	47.8
Total Carotenoid	322.1	302.9	288.7	321.3	321.3	327.6
Z+An/Z+An+V ratio	0.11	0.52	0.78	0.68	0.76	0.17
Mature leaf[c]:						
Chl a+b, mol/m^2	394.3	336.4	363.7	354.8	363.4	360.2
Zeaxanthin (Z)	4.6	8.3	12.5	29.1	16.8	6.7
Antheraxanthin (An)	4.8	8.8	8.2	11.4	9.3	5.9
Violaxanthin (V)	52.7	50.7	25.2	19.4	14.9	50.7
Z+An+V	62.1	67.8	65.9	59.9	51 .o	63.3
Lutein	92.7	94.7	84.4	99.4	84.3	94.4
Neoxanthin	57.0	56.1	53.1	60.7	50.1	57.8
a-Carotene	1.1	1.1	1.4	1.4	1.1	1.1
p-carotene	56.5	56.7	53.1	61.5	50.9	57.4
Total Carotenoid	269.4	276.3	258.0	282.8	237.5	273.9
Z+An/Z+An+V ratio	0.15	0.25	0.62	0.68	0.71	0.20

[a] Average of four developing leaves from an elongating flush. Flushes of similar developmental stages were used for analysis throughout the day. All leaves were between 5 and 20 percent of average mature leaf size.

[b] All carotenoid pigments are in mmol/mol Chl a+b.

[c] Average of three mature leaves from the latest mature flush; different sets of leaves were used throughout the day.

net photosynthetic rate than regular leaves. Use of large-size planting stock and outplanting these seedlings on clearcut sites should improve success of artificial regeneration of oak species.

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EARLY GROWTH OF SHELTERED AND UNSHELTERED CHERRYBARK OAK ESTABLISHED BY PLANTING 1-O BAREROOT AND 1-O CONTAINERIZED SEEDLINGS, AND BY DIRECT-SEEDING

John A. Mullins, Edward R. Buckner, George Hopper, and Gordon G. Percell[1]

Abstract-Early growth of sheltered (TUBEX® tree shelters) and unsheltered cherrybark oak (*Quercus falcata* var. *pagodaefolia* Ell.) seedlings was compared in this study. Seedlings were established by: (1) direct seeding, (2) hand planting two types of containerized seedlings;-those grown in (a) Rootrainer® books (20 cubic inch volume) and (b) greenhouse-forced seedlings grown in large tree-pots (150 cubic inch volume)-and (3) conventional hand planting of bareroot seedlings. With the exception of the greenhouse-forced seedlings that were not sheltered, tree shelters were applied to each seedling type. After five growing seasons, mean height and diameter at breast height (d.b.h.) of all trees was 8.8 feet and 2.2 inches, respectively. There were no significant differences in 5-year heights or diameters between sheltered and unsheltered seedlings. However, the comparative rates of growth of sheltered and unsheltered seedlings reversed after the sheltered seedlings emerged from the shelter tops. During 1993, height growth of the sheltered seedlings, before they emerged from the shelters, was significantly greater than that of unsheltered seedlings for all establishment methods. Except for direct-seeded seedlings, height growth during 1995 and 1996 was significantly greater for previously unsheltered seedlings. Deer-browse was not a factor in this study. After five growing seasons, minimal differences in height and d.b.h. resulted from very different patterns of growth for sheltered and unsheltered cherrybark oak seedlings. Establishment by conventional bareroot seedlings and/or by direct seeding was not improved by the use of shelters or enhanced seedling types.

INTRODUCTION

Cherrybark oak is the most valuable bottomland oak native to Tennessee. It produces a higher percentage of high grade lumber than other species of bottomland red oaks. Attempts to use cherrybark oak in plantation culture have been disappointing. While survival has been satisfactory, early growth of transplanted seedlings is generally slow.

Tree shelters have been utilized by the British Forestry Commission since 1979 to improve survival and growth of planted oak trees (Tuley 1985). The initial cost of installing shelters-$4 to $6 each-(Smith 1993, Kays 1995) has limited their application to high-value species.

Lantagne (1991) found that rapid early height growth of sheltered northern red oak (Q. *rubra* L.) enabled seedlings to grow more quickly into dominant and codominant crown positions in a regenerating clearcut. Similar early height growth would allow planted cherrybark seedlings to overtop and suppress competing vegetation, a primary cause of slow growth. This study evaluates using tree shelters to stimulate early growth of cherrybark oak. Shelters were tested on seedlings established (1) as bareroot planting stock, (2) in containerized seedlings, and (3) by direct seeding. As a comparison, very large, greenhouse-produced, containerized seedlings were also planted.

METHODS

The study was established on The University of Tennessee Agricultural Experiment Station at Jackson, TN, on a previously cropped agricultural field, which was seeded to wheat as an interim cover crop. Soils in the study area are Grenada silt loam, eroded, gently sloping terrace phase (Tglossic Fragiudalf, fine-silty mixed thermic). The study design was an incomplete block with 10 replications of eight treatments. Each treatment plot consisted of six planting spots on an 8 foot by 8 foot spacing.

Cherrybark oak acorns were collected in Shelby County, TN, during the fall of 1990, by Tennessee Division of Forestry (TDF) personnel. The acorns were held in cold storage at the TDF nursery. In mid-January 1991, a sample from the bulk seedlot was separated by water flotation. Ten pounds of sound acorns were selected for this study. Five pounds of this sample were kept at the TDF nursery and used to produce the barerooted seedlings. Standard nursery practices were followed. The remaining acorns were maintained in cold storage until divided into thirds and utilized to produce seedlings under each of the following cultural systems:

Greenhouse-Forced Containerized Seedlings

Acorns were removed from cold storage on January 20, 1991, imbibed in water for 15 hours, and kept moist in a bucket until germination. Each day, all germinated acorns were transplanted into Zarn® tree containers (4 inches by 4 inches by 16 inches) filled with a pine bark growing media. Seedlings were grown under supplemental lighting (14-hour day length), watered as required, and fertilized weekly with a 200-parts-per-million solution of a 20-20-20 water soluble fertilizer. Temperatures suitable for growth were maintained using steam heat in winter and evaporative cooling during spring and summer.

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Containerized Seedlings

Containerized seedlings were produced using the same methods as the greenhouse-forced containerized seedlings with the following exceptions: acorns were removed from cold storage March 30, 1991, and, after germination, were seeded into Hillison® Rootrainer Books filled with a 1 :1 :1 ratio of peat moss, vermiculite, and perlite.

Direct-Seeding

On March 26, 1991, the remaining acorns were removed from cold storage and direct-seeded into their assigned field Plots the following day. Two acorns were placed by hand in the bottom of a l-inch-deep dibble bar slit at each Planting spot and the slit was closed by foot pressure. The seeding dates for the containerized and direct-seeded seedlings were selected such that their emergence would coincide with that of the acorns sown in the nursery. In mid-June the less vigorous seedling was removed from each direct-seeded spot.

The containerized seedlings and the forced greenhouse seedlings were outplanted into assigned field plots in early October 1991. Barerooted seedlings were lifted on December 18, 1991, and stored until outplanted January 20, 1992.

Shelter Installation

Four-foot Tubex® tree shelters were installed during the spring of 1992 on assigned plots of bare-rooted, containerized and direct-seeded seedlings before they broke dormancy, with the following exceptions: (1) those direct-seeded seedlings designated for shelters at planting time (shelters were installed in early June 1991), and (2) the large greenhouse-forced seedlings were not sheltered. Eight treatments were evaluated:

(1) Bareroot seedlings with shelters and,
(2) without shelters.
(3) Containerized seedlings with shelters and,
(4) without shelters.
(5) Direct-seeded with shelters and,
(6) without shelters and also,
(7) with shelters installed at seeding.
(8) Greenhouse-forced seedling without shelters.

Control of competing vegetation was accomplished by mowing and directed spray applications of Roundup@ herbicide around each seedling as required. Total height to the nearest 0.1 foot was measured after barerooted seedlings were planted, in 1991, and after their second, fourth, and fifth growing seasons. Diameter at breast height (d.b.h.) was measured after the fifth growing season. Data were analyzed with a randomized incomplete block model using Proc Mixed (SAS 1996). Least-square means were calculated and compared using pairwise t-tests ($P < 0.05$).

Age of the direct-seeded seedlings does not include their initial growing season in the field, so their "age" compares with the other seedling types that were produced in the nursery and/or greenhouse.

RESULTS

Initial Seedling Size

Seedling size after out-planting for seedlings grown under the various cultural systems is given in table 1. At the end of the initial growing season, height of direct-seeded seedlings that were sheltered (0.58 feet) was significantly ($P<0.05$) greater than that of unsheltered direct-seeded seedlings (0.44 feet).

Unsheltered Seedlings

Two years after outplanting, greenhouse-forced seedlings were the tallest of the seedling types at 4.1 feet, which was significantly taller than bareroot (2.3 feet), containerized (2.2 feet), and direct-seeded (1.9 feet) (table 2). By the fourth year these differences in total seedling height had disappeared. There were no significant differences among the d.b.h.'s of unsheltered seedlings.

Shelter Effects

After two growing seasons, both the sheltered bareroot and the containerized seedlings were significantly taller (5.0 feet, and 5.1 feet, respectively) than unsheltered seedlings (2.3 feet, and 2.2 feet, respectively) (table 2). However, the early height advantage of the sheltered seedlings, both bareroot and containerized, had disappeared after the fourth growing season. There were no significant differences in d.b.h. between sheltered and unsheltered seedlings (both bareroot and containerized) after five growing seasons.

Seedlings established by direct-seeding with shelters installed at planting, were significantly taller (3.6 feet) after two growing seasons than both the unsheltered seedlings (1.9 feet) and those having shelters installed after their initial growing season (2.5 feet). Similar to the sheltered

Table I-Initial height and groundline diameter (after planting) of cherrybark oak seedlings produced by the indicated cultural systems (all seedlings 1 -year-old)

Cultural system	Mean height	Mean groundline diameter
	Feet	*Inches*
Bareroot nursery	1.25	0.19[a]
Direct-seeded	0.44	0.12
Containerized	1.15	0.28
Greenhouse forced	3.50	0.39
Direct-seeded w/o shelter	0.44 a[b]	0.12
Direct-seeded w/shelter	0.58 b	0.11

[a] Measured after planting at ground-line (root collar measurement would have been larger).
[b] Mean heights of unsheltered direct-seeded seedlings and direct-seeded seedlings sheltered in the initial growing season differ significantly at $P<.05$.

Table 2-Height after 2, 4, and 5 years, and diameter at breast height (d.b.h.) at 5 years for sheltered and unsheltered cherrybark oak seedlings established by bare-root, direct-seeded, containerized, and greenhouse-forced stock

		Age			
Seedling type	Shelter	2 yrs	4 yrs	5 yrs	
		--- Height (ft) ---			--- D.b.h. (in) ---
Bareroot	No	2.3 d[a]	6.7 a	8.7 a	0.9 a
Bareroot	Yes	5.0 a	6.9 a	6.6 a	1.0 a
Containerized	No	2.2 d	5.8 a	8.5 a	0.9 a
Containerized	Yes	5.1 a	6.5 a	8.6 a	1.0 a
Direct-seeded	No	1.9 d	6.7 a	8.5 a	0.9 a
Direct-seeded	Yes (1)[b]	3.6 c	6.1 a	8.3 a	0.9 a
Direct-seeded	Yes	2.5 d	7.3 a	9.5 a	1.1 a
Greenhouse-forced	No	4.1 b	7.0 a	9.7 a	1.1 a

[a] Means within columns not followed by the same letter differ significantly at $P < 0.05$.
[b] Direct-seeded seedlings sheltered in the initial growing season.

and unsheltered treatments with both bareroot and containerized seedlings, total height differences had disappeared by the end of the fourth growing season.

Incremental Height Growth

Bareroot and container seedlings-Height growth of sheltered seedlings during the second growing season (while seedlings were still within the shelters) for both bareroot (2.1 feet) and containerized (1.8 feet) planting stock, was significantly greater than that of unsheltered seedlings (0.8 feet and 0.7 feet, respectively) (table 3). During the fourth growing season after all seedlings had emerged from the shelters, this pattern of growth had reversed, and unsheltered seedlings, from both bareroot (2.1 feet) and containerized (1.7 feet) stock had significantly greater height growth than did the sheltered seedlings (0.6 feet, and 0.4 feet, respectively) (table 3). After seedlings emerged from the shelters they developed crowns comparable to that of unsheltered seedlings during the first two growing seasons. While the sheltered

Table 3-Annual increment at indicated ages for sheltered and unsheltered cherrybark oak seedlings by establishment method

		Age		
Seedling type	Shelter	2 yrs	4 yrs	5 yrs
		-------- Annual increment (ft) --------		
Bareroot	No	0.8 cd	2.1 a	1.9 bd
Bareroot	Yes	2.1 a	0.6 b	1.8 d
Containerized	No	0.7 d	1.7 a	2.5 ac
Containerized	Yes	1.8 b	0.4 b	1.9 bd
Direct-seeded	No	1.0 c	2.2 a	2.1 bcd
Direct-seeded	Yes	1.4 c[a]	2.2 a	2.5 ab
Direct-seeded	Yes(1)[b]	2.2 a	0.5 b	2.0 bd
Greenhouse-forced	No	0.3 d	1.9 a	2.8 a

[a] Means within columns not followed by the same letter differ significantly at $P < 0.05$.
[b] Direct-seeded seedlings sheltered the first growing season.

seedlings were developing a crown above the shelter, there was a marked decrease in their height growth. During the fourth growing season the annual height growth of unsheltered seedlings (2.5 feet) was significantly greater than that of the sheltered seedlings, both for containerized (1.9 feet) and bareroot (1.8 feet).

Direct-seeded seedlings-Annual height growth in the second growing season, of direct-seeded seedlings which were sheltered when seeded (2.2 feet) was significantly greater than either seedlings that remained unsheltered (1 .0 feet) or seedlings sheltered after their initial growing season (1.4 feet). As with the bareroot and container seedlings, this early pattern was reversed for the fourth growing season and disappeared in the fifth.

CONCLUSIONS

At the end of five growing seasons in the field, there were no significant differences in total height due to either shelters or seedling type. The early height growth advantage observed for sheltered seedlings was not evident at the end of this study. The development of a crown above the shelters took precedence over continued height growth, allowing the previously unsheltered seedlings to catch up. Establishment of cherrybark oak in west Tennessee by the conventional method, hand-planting bareroot seedlings, or by direct-seeding was not improved upon by either the use of shelters or by the use of containerized seedlings.

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ESTABLISHMENT OF PAULOWNIA PLANTATIONS USING FLOAT TRAY SEEDLINGS

Jeffrey W. Stringer'

Abstract-This study was designed to determine the effectiveness of using float tray seedlings, a relatively inexpensive type of containerized plug seedling, in establishing Paulownia *tomentosa* plantings. Cultural treatments including a control, hardwood bark mulch, a soil mixture, and a combination mulch/soil mixture were tested with and without l-foot-tall tree shelters to determine their effects on growth and survival of *P. tomentosa* over a 3-year period. Tests were completed on four sites: three sutface-mined sites and one alluvial bottom site in eastern Kentucky. Results showed an initial seedling survival rate of < 25 percent when seedlings were planted without a shelter and without a soil amendment. One-foot reusable tree shelters in combination with a soil amendment treatment produced significantly greater survival across all sites ($P<0.05$). After 3 years, survival was greater than 75 percent on a number of the sites tested. This study indicates that this type of planting stock can be considered as a viable option in the establishment of paulownia plantations.

INTRODUCTION

Since the mid-1970's, relatively high prices have been paid for *Paulownia tomentosa* trees and logs meeting export grade requirements (Stringer and Graves 1994). These prices spurred the development of both scientific and commercial projects involving the establishment and growth of paulownia plantations (ex. Beckjord 1984, Dong and van Buijtenen 1994, Stringer 1986). These projects have shown that *Paulownia* spp. can be used for a variety of different forestry applications and sites ranging from surface mine reclamation on relatively marginal sites to reforestation of highly productive alluvial bottomland sites.

Economic analysis of growing Paulownia for both domestic and export markets indicated that reasonable returns could be expected (Hardie and others 1989, Kays and others 1988, Johnson and others 1992). Rotation lengths were estimated to be between 10 and 20 years, and greater than 30 years for the production of logs meeting the requirements for domestic and export markets, respectively (Graves 1993). Rates of return, as is the case with all such analyses, are higher when initial establishment costs are kept to a minimum. However, initial efforts in plantation establishment of the genera used high-cost nondormant, containerized planting stock. The production, handling, planting, and initial care of this type of planting stock can be problematic, especially for large scale plantings. Low-cost alternatives, such as root cuttings (Stringer 1994a, b) and small plug-type planting stock, can be used to dramatically reduce establishment and maintenance costs. This study was designed to determine the effectiveness of using float tray seedlings, a relatively inexpensive type of containerized plug seedling, in establishing *Paulownia fomentosa* plantings on both marginal surface mine sites and an alluvial bottomland site.

METHODS

Tests were completed on four sites: three surface mined sites, and one alluvial bottom site in the Eastern Coalfield Region of Kentucky. All sites were dominated by Kentucky 31 tall fescue (*Festuca elatior* var. KY-31). The surface mined sites were generated through standard overburden handling procedures and grass and legume revegetation practices associated with contour mining for coal. Spoil material was composed of 3-year-old sandstone and shale overburden (pH > 5.8). The three sites included a north and south facing slope (slope percent 20 to 30) and a flat, highly compacted, contour bench. Soils on the alluvial bottomland site were mapped as a Grigsby series (coarse-loamy, mixed, mesic Dystric Fluventic Eutrochrept). These soils are typically loamy to fine-loamy, deep, and well-drained, formed from mixed alluvium from sandstone, siltstone, and shale.

Each site contained one replicate planting. A complete randomized block design (three blocks per site) was used to establish each replicate planting. Each block contained four main treatment plots consisting of eight trees. The plots had one of the following treatments: hardwood bark mulch, incorporated soil mix, combination of mulch and soil mix, and a control. The composted and ground hardwood bark mulch was applied 2.5 centimeter deep in a 1 -meter square around each planting spot. The soil mix involved the mixing of potting soil in a 1 :1 ratio with existing media in a hole 30-centimeters deep and 20 centimeters around each planting site. Each treatment plot was split into two subplots and the four trees in one of the randomly selected subplots received a 25-centimeter-tall $\text{Tubex}_{(TM)}$ tree shelter.

Float tray seedlings, a type of containerized plug seedling, were originated from a mixed collection of seed from nine local mother trees. Seeds were taken from cold storage and pretreated to initiate rapid germination, and sown onto standard potting mix in a seedling flat. The flat was covered with polyspun material to provide adequate moisture and light for germination (Stringer 1986). One-week-old seedlings were transplanted to 200-cell $\text{Styrofoam}_{(TM)}$ float trays and subjected to a 16-hour day length.

Previously existing vegetation on all planting sites was killed with glyphosate (Accord,,,) applied at the recommended rate. Five-week-old float tray seedlings were hand planted in early May and each of the treatments and shelters were applied at this time. No other cultural

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treatments were applied during the first growing season. Seedlings at all test sites were coppiced 2.5 centimeters above the groundline at the end of the 2nd growing season.

Survival and total height were measured 1 month after planting and at the end of the each growing season for 3 years. Standardized residual plots were used to determine variance homogeneity to locate potential outliers. Bonferroni's inequality was used to inflate "a priori" p-values for outliers and t-tests used to remove outliers. ANOVA (Type III SS) and LSD (t) and Wilcoxon 2-sample t-tests were employed to determine among treatment and among site differences ($P<0.05$). Survival percent was determined for each subplot and an arc sin transformation used for analysis (Steel and Torrie 1980). Comparisons among primary (soil amendments) and secondary (shelters) treatment effects were completed on data pooled over all planting sites as well as for within planting sites.

RESULTS AND DISCUSSION

Analysis of data pooled over all sites showed a significant difference ($P<0.01$) in survival between sheltered versus nonsheltered seedlings within all primary treatments except the control (fig. 1). This pattern was consistent throughout the experimental period and across all sites. Survival of nonsheltered seedlings among treatments was not significantly different, averaging approximately 25 percent after 2 years (fig 1 c). This indicates a significant additive effect of the combination of tree shelters and a mulch and/or soil mix treatment. While mean survival for the soil mix treatment was less than that of the mulch or the combined treatment, no significant difference was found among them. Survival was not increased by using a combination of soil mix and mulch.

Data pooled over all sites showed first-year height growth averaged approximately 0.5 meter (fig 2a). A significant difference in seedling height after 1 year was found between sheltered versus nonsheltered seedlings across all treatments except for the soil mix treatment. However, the impact of the shelters on height growth was relatively short-lived. No significant differences in height, among treatments or between sheltered versus nonsheltered seedlings, were found after the first growing season (figs. 2b and 2c). After 2 years, total height averaged 1.71 meters over all treatments. Between the second and third growing season, trees were coppiced. The third-year data represent l-year coppice growth averaging 2.81 meters for all trees. The second-year coppicing produced sprouth growth of a magnitude sufficient to establish a single main stem of the minimum length requirement of 2 meters for current export markets.

The short-lived effect of the shelters on height growth is probably a result of the fact that the trees emerged from the top of the l-foot shelters during the first month after outplanting. While no significant difference in height between sheltered versus nonsheltered seedlings were found, there was a trend for the sheltered coppice sprouts to be taller than nonsheltered sprouts (fig. 2c). This may have been due to the extension in the length of the growing season provided to the coppiced trees by the shelters. Anecdotal observation found that sprouting initiated within the shelters approximately 1 to 2 weeks before sprouting of the nonsheltered trees. The difference in timing of coppice initiation may be have been responsible for the trend.

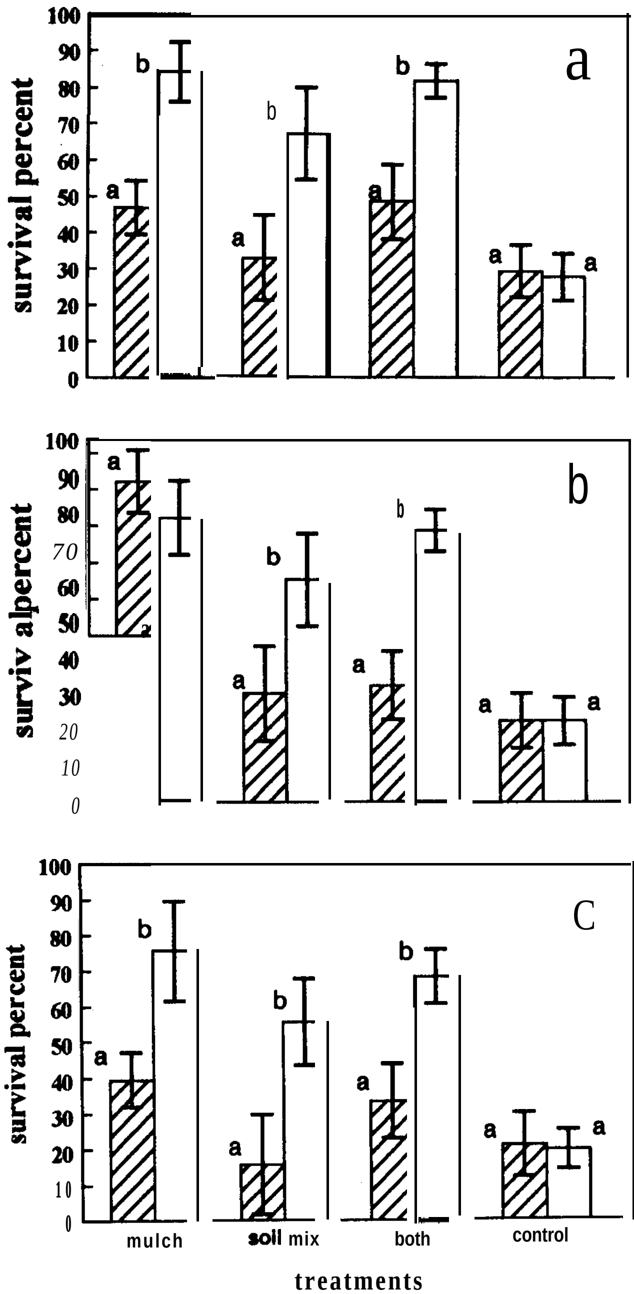

Figure l-Survival percent of *Paulownia tomentosa* float tray seedlings. Bars (open=sheltered seedlings and lined=nonsheltered seedlings)and standard error bars represent data pooled over all sites for: (a) one month, (b) 1 year, and (c) 2 years. Bars with different letters represent significant differences ($P<0.05$) both within and among treatments.

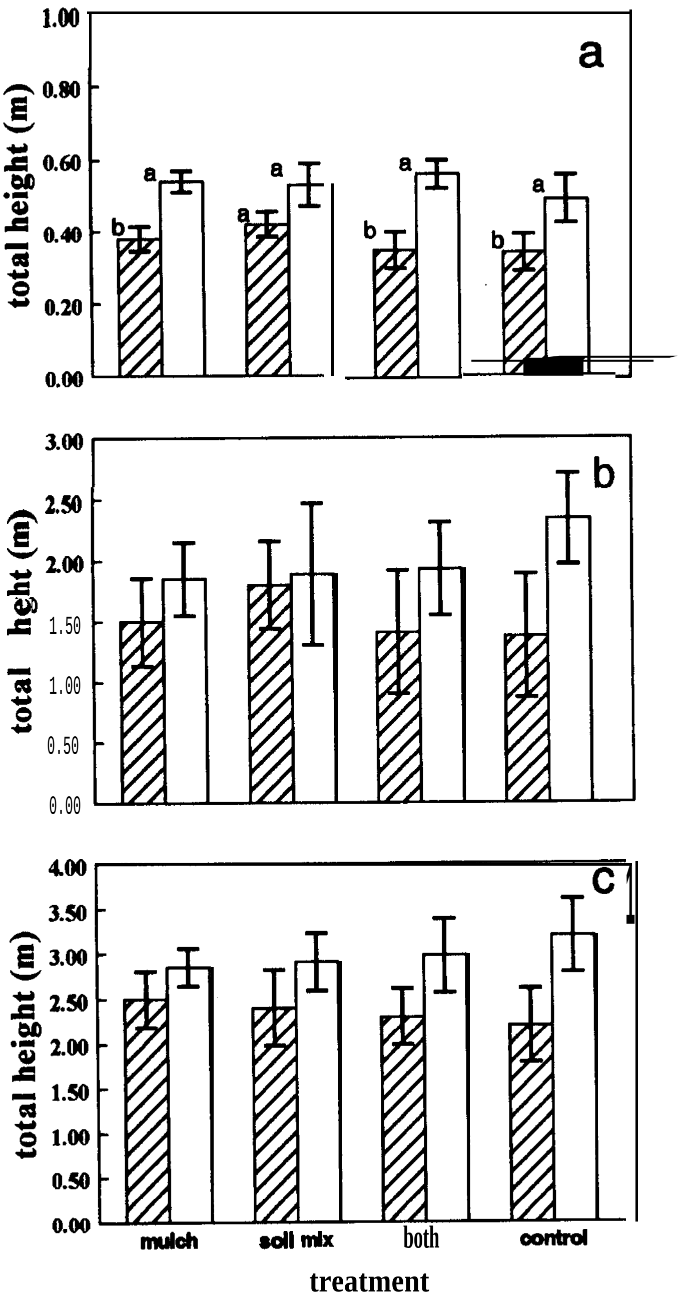

Figure 2—Total height of *Paulowina tomentosa* float tray seedlings. Bars (open=sheltered seedlings and lined=non-sheltered seedlings)and standard error bars represent data pooled over all sites for: (a) 1 year, (b) 2 years, and (c) 3 years. Bars with different letters represent significant differences (P<0.05) both within and among treatments.

After the first year there was a significant difference in height growth among sites (fig. 3). The seedlings on the flat surface-mined site, while exhibiting height growth equivalent to seedlings on the other sites during the first year, did not increase in height in subsequent years. This is consistent with other findings relating to tree growth on similar, highly compacted, surface-mined sites.

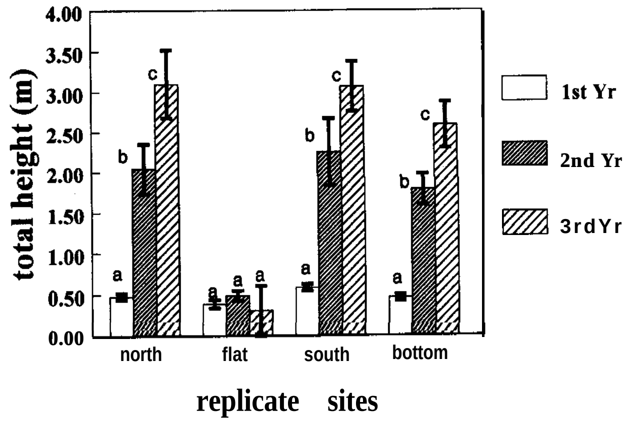

Figure 3-Differences in total height of *Paulowina tomentosa* float tray seedlings among test sites. Bars (open=sheltered seedlings and lined=nonsheltered seedlings) and standard error bars represent data pooled within sites. Bars with different letters represent significant differences (P<0.05) among years or sites.

Results of analysis of the data within a replicate site showed similar results to those obtained from analyzing the data pooled over all sites. Figure 4 shows an example using 2-year height data from the south facing surface-mined site. No significant difference in total height between sheltered versus nonsheltered seedlings or among treatments was found.

CONCLUSIONS

Results of this experiment indicate that float tray seedlings can be used to establish *Paulownia tomentosa* on sloping surface-mined lands as well as alluvial bottoms in eastern Kentucky. Without further testing, flat, highly compacted, surface-mined sites should be avoided. These data also show that environmental support in the form of tree shelters and soil amendments was required to ensure adequate initial survival of float tray seedlings. Results showed an initial seedling survival rate of < 25 percent

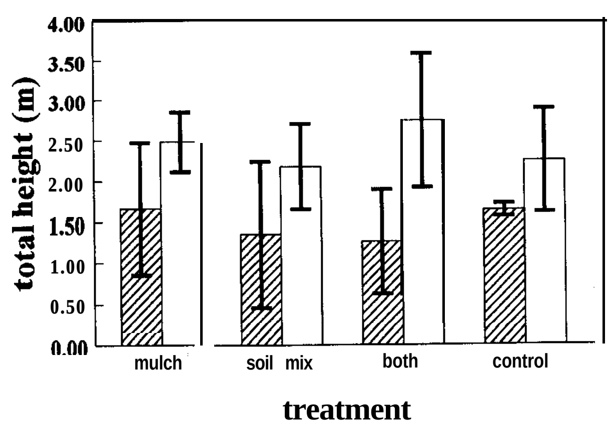

Figure 4-Total height of e-year-old *Paulowina tomentosa* float tray seedlings growing on a south facing surface-mined site in eastern Kentucky. Bars (open=sheltered seedlings and lined=nonsheltered seedlings)and standard error bars represent data within one site.

when planted without environmental support, regardless of site. Survival was improved significantly on all sites with the use of i-foot-tall tree shelters and a soil amendment with a number of sites having > 80 percent survival. However, shelters and the soil amendment treatments had limited effect on long-term height growth. While the sites used in this study were in eastern Kentucky, the wide range of site qualities and rooting media involved in this study suggest that the recommendations developed from this study may have broad application.

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USE OF COVER CROPS IN SHORT-ROTATION HARDWOOD PLANTATIONS

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Abstract-This study investigates the effects of cover crops on the growth and biomass yield of sweetgum (*Liquidambar styraciflua* [L.]) planted as a short-rotation woody crop at a 1.5 by 3 meter spacing. Four cover crops, winter rye grass (*Lolium multigeonum* L., a winter annual grass); tall fescue (*Fescuta eliator* L., a growing-season perennial grass); crimson clover (*Trifolium incarnatum* L., a winter annual legume); and interstate sericea (*Lespedeza ameata* L., a growing-season perennial legume), were tested at two different strip widths (1.22 and 2.44 meters) as well as a control with complete competition control. Height and ground-line diameter of trees were measured on a monthly basis. The cover crops and strip widths significantly affected height, ground line diameter, and volume index of sweetgum. Lespedeza and tall fescue significantly affected ground-line diameter, height, and volume index over rye and control. Crimson clover significantly affected ground-line diameter over control and volume index over rye grass and control. Rye grass and control were not significantly different from each other. Sweetgum ground-line diameter, height, and volume index were significantly affected by the strip widths. The greatest reduction was at the 2.44 meter (8 feet) strip width. The reduction in diameter and volume index by strip width was more significant than for height.

INTRODUCTION

Hardwoods are preferred over pines as short-rotation intensive culture (SRIC) species because of their rapid juvenile growth rates and ability to coppice. Unlike conventional forestry, individual tree size and form are not a major consideration for SRIC. More important factors are initial survival, rapid early growth rates, high annual energy and biomass yields, coppice survivability, and subsequent vigor. For these reasons and because the species is adaptable to many sites, sweetgum has become an important species considered for SRIC management. Sweetgum (*Liquidambar styraciflua* L.) is one of the most important commercial hardwoods in the southeast and is put to a great many uses such as lumber, veneer, plywood, slack cooperage, railroad ties, pulpwood and fuel (USDA 1974).

Biomass resources have been historically important for energy supplies. They offer an excellent renewable alternative to fossil fuels. The biomass resources include agricultural residues, long-rotation woody plantings, thinning material, logging residues, wood wastes and residues from production of paper and forest products, and specialized wood and herbaceous crops developed specifically for energy production (Hohenstein and Wright 1994). The overall energy use has increased by 167 percent during 1949 to 1990, wood energy use has increased by 108 percent, while wood energy use represents 82 percent of the total biomass energy use (U.S. DOE 1993).

The research on wood energy-crops is leading forestry into a new era of more intensive silviculture because there will be a greater need for large, renewable woody biomass plantations for conversion to gasoline and gaseous fuels. The wood consumption of a biomass conversion facility will be in the range of 200,000 to 1 million dry megagrams per year (1 megagram = 1 metric ton = 1 .1 English tons), similar to the demand of a pulp mill (Ranney and others 1987). Under such a scenario, intensive culture of hardwoods appears to fit this need very well (Farnum and others 1983).

The high-yield biomass energy crops could be produced on most of the U.S. land currently under food crops production. The Department of Agriculture reported 162 million hectare (Mha) of cropland in the United States in 1991. Out of this base, 137 Mha were either used to produce crops, were planted but not harvested, or were summer fallowed. The remaining 25 Mha were idled either through Annual Acreage Reduction programs or through Conservation Reserve Program (U.S. DOE 1991).

The short-rotation intensive culture (SRIC) hardwoods are presumed to protect soil exceptionally well after first growing season. Under SRIC conditions, mean annual rate for productivity of 12 to 16 megagrams per hectare (5.4 to 7.1 tons per acre) is considered an acceptable range. Eventually, a goal of up to 20 dry megagrams per hectare (about 9 tons per acre) may be achieved. SRIC crops would be an excellent compromise for obtaining economic returns from the Conservation Reserve Program (Food Security Act, 1985) land while providing needed soil protection as well (Ranney and others 1987). Hardwood SRIC is not feasible without good weed control, which is usually accomplished through agricultural-type site preparation and herbicide use until canopy closure (Kennedy, 1984).

The objective of this study was to determine the feasibility of cover crops use for erosion protection during the early phase of stand development. The study examined both erosion protection and sweetgum growth reduction by various cover crop regimes. This paper is concerned only with the effects of cover crops on sweetgum growth.

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METHODS

Site Description

The experiment was established at the Winfred Thomas Agricultural Research Station in Hazel Green, AL, 9 miles north of Alabama A&M University campus. The soil is classified as a Decatur and cumberland silt loam, undulating phases, with 2 to 6 percent slope with good natural drainage. The site has previously been occupied by corn cultivation. Each plot measures 21.34 meter by 7.62 meter (65 by 25 feet) separated by a 3.05 meter (10 feet) buffer. Each plot is surrounded by a 20 to 25 centimeter (8 to 10 inch) high soil berm. There are nine plots in each of three replications.

Cover Crops and Sweetgum Planting

The four types of cover crops planted are: (a) winter annual - *rye* grass (*Lolium multigeonum* L.) variety Kino seeded @ 25 pound per acre + wheat (*Triticum aestivum* L.) @ 40 pound per acre, (b) perennial grass • tall fescue (*Fescuta eliator* L.) variety Kentucky 31 seeded @ 15 pound per acre + Wheat (*Triticum aestivum* L.) @ 40 pound per acre, (c) winter annual legume - crimson clover (*Trifolium incarnatum* L.) variety Big bee seeded @ 25 pound per acre (all three planted on November 3, 1994), and (d) perennial legume -interstate sericea (*Lespedeza ameata* L.) variety seeded @ 30 pound per acre (planted on May 17, 1995). The cover crop strip widths between sweetgum rows were maintained at 1.22 meter (4 feet) and 2.44 meter (8 feet) as well as a control with no cover crop. One-year-old seedlings of sweetgum were transplanted as a short rotation woody crop on March 21 to 27, 1995 at 1.5 by 3.0 meter (5 by 10 feet) spacing with 35 sweetgum plants in each plot, 315 plants per replication, and 945 plants in three replications.

Measurements

For the first 2 years of plant growth, monthly measurements of height and ground-line diameter (gld) were recorded from May to September 1995 and 1996, with dormant period information as of February 1996, to compare plants performance under different cover crop regimes.

Study Design and Data Analysis

The experiment in a Split Plot design with one level of nesting. The cover crops per plot are the main treatments, cover crop's strip width treatments are split with 15 trees nested. The data were analyzed using the GLM procedure of Statistical Analysis System for analysis of variance and means separated by Tukey's Studentized Range Test.

RESULTS AND DISCUSSIONS

Effects of Cover Crops

Ground line diameter-The ground line diameter (gld) was significantly affected by the cover crops. Rye grass was not significantly different from control. The crimson clover, lespedeza, and tall fescue significantly reduced gld in comparison to the control. Among cover crops, crimson clover and rye grass were not significantly different, similarly crimson clover, lespedeza, and tall fescue were not significantly different from each other; however, both lespedeza and tall fescue were significantly different from rye grass. The highest gld was observed under control, followed by rye grass, crimson clover, tall fescue, and lespedeza (table 1). Gld was affected early in the first year, becoming statistically significant by July of the first growing season (fig. 1). At this time, crimson clover had significantly reduced gld compared to control. Crimson clover continued to be the only cover crop to significantly reduce gld throughout year 1.

Table I-Effects of cover crops on sweetgum during the growing seasons of 1995 and 1996[a]

Sr. no., year, and cover crop	Ground line diameter	Height	Volume index (D2H)
	------- cm	-------	--- cm3 ---
First growing season			
(1) Control	2.30a	100.86a	551.88a
(2) Crimson clover	1.84b	93.45a	343.6213
(3) Rye grass	2.14a	98.03a	468.13ab
(4) Lespedeza	2.06ab	101.41a	454.73ab
(5) Tall fescue	2.14a	103.80a	488.12ab
Second growing season			
(1) Control	4.64a	201.34a	4430.07a
(2) Crimson clover	3.99bc	190.51ab	3219.37b
(3) Rye grass	4.30ab	199.56a	3782.06a
(4) Lespedeza	3.78c	173.00c	2629.44c
(5) Tall fescue	3.84c	180.29bc	2783.40bc

[a] Means (year-wise) within same column effects followed by the Same letter are not significantly different at 5 percent level.

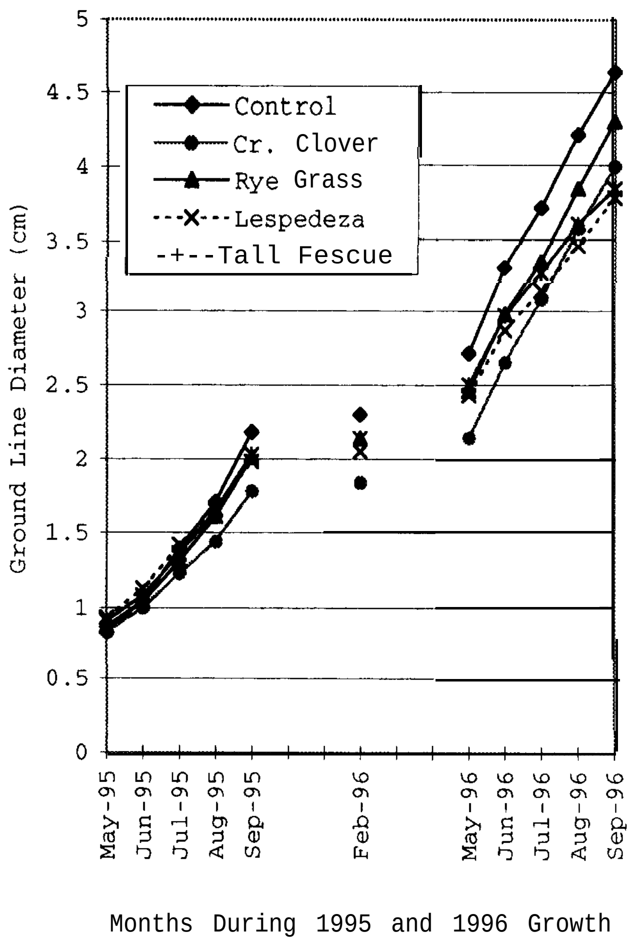

Figure l-Effects of cover crops on sweetgum ground-line diameter.

Winter annual cover crops tended to reduce growth to a greater extent than perennial cover crops during the first year. During the second growing season, however, this relationship changed. Both tall fescue and lespedeza exerted a greater growth reduction than clover or rye grass. The effect increased throughout the growing season and by the end of the growing season the gld curves for trees grown with perennial cover crops were diverging from the rest. These results indicate that winter annual cover crops exert their greatest influence on sweetgum growth during their first year, whereas growing season perennials take longer to influence growth. This may be due to the early effects of the winter annuals during the first year after planting. Because these cover crops were already well established when the trees were still undergoing planting shock, competition by these crops resulted in greater growth reduction.

Using legumes as cover crops did not increase gld over grasses during the first growing seasons. This indicates that benefits of the legumes, by way of fixing nitrogen into soil, did not result in any increase in growth. Apparently, competition for moisture during first 2 years of growth was the dominant competitive effect of cover crops.

Height-The height of trees with crimson clover and rye grass was not significantly different than control; however, lespedeza and tall fescue were significantly lower from control. Among cover crops, crimson clover and rye grass were not significantly different, the crimson clover and tall fescue were not significantly different, similarly lespedeza and tall fescue were not significantly different from each other. However, both lespedeza and tall fescue were significantly different from rye grass. The maximum height was recorded under control, followed by rye grass, crimson clover, tall fescue, and lespedeza (table 1). No significant differences were observed during the first year of growth (fig. 2). Height first became significant in the second growing season, and rye grass was not significantly different from control. Lespedeza and tall fescue were not significantly different, but are significantly different from control and rye grass (fig. 2).

Volume index-The volume index closely paralleled diameter growth. The rye grass and control were not significantly different. The crimson clover, tall fescue, and lespedeza were significantly different from control. Among cover crops, the crimson clover and tall fescue were not significantly different, similarly lespedeza and tall fescue were not significant; however, crimson clover, lespedeza, and tall fescue were significantly different from rye grass. Crimson clover and lespedeza were also significantly different. The highest volume index was observed with control, followed by rye grass, crimson clover, tall fescue, and lespedeza (table 1). A review of fig. 3 reveals that at the end of the second growing season the volume index curves resulting from each cover crop are diverging.

Effects of Strips Widths

Ground line diameter-Gld first became statistically significant in August of the first growing season (fig. 4). Both strip widths became significantly different from

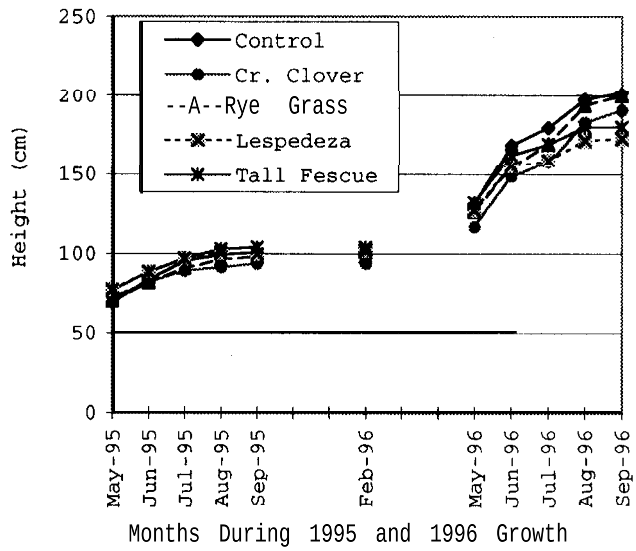

Figure 2—Effects of cover crops on sweetgum height.

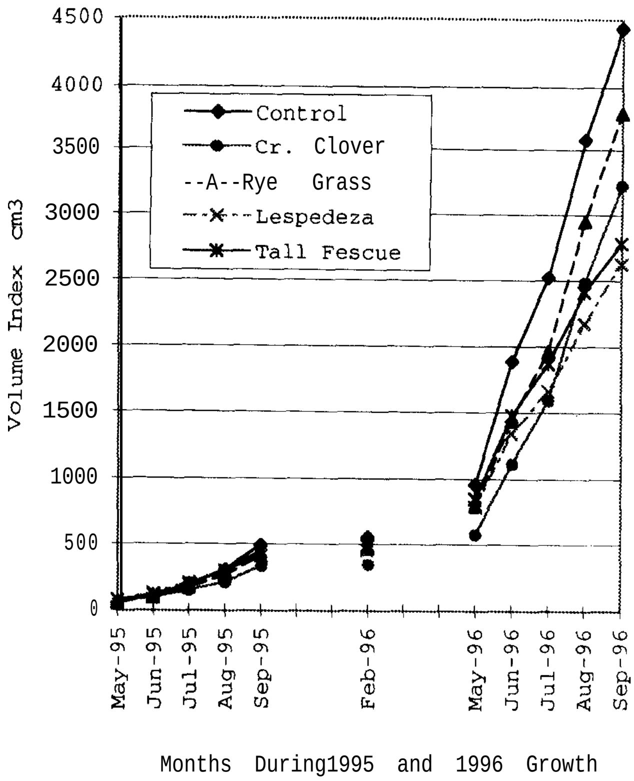

Figure 3-Effects of cover crops on sweetgum volume index.

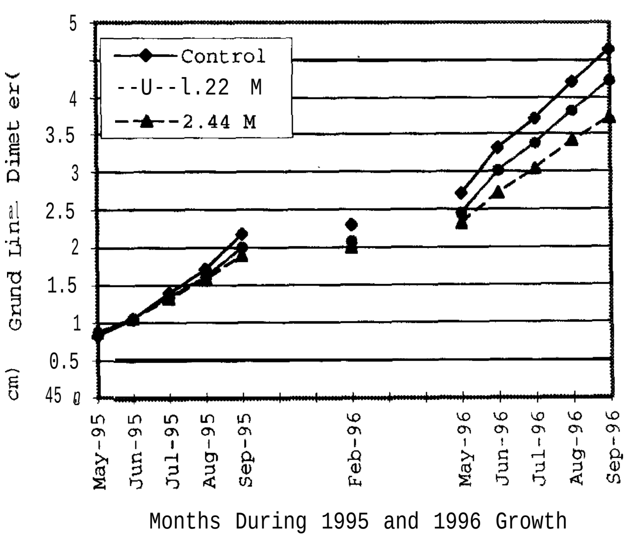

Figure 4—Sweetgum ground-line diameter affected by strip width of cover crops.

control during the first growing season. This relation became more apparent during second growing season when 1.22 meter (4 feet), 2.44 meter (8 feet) and control became statistically different from each other beginning early second growing season (fig. 4). Maximum gld was suppressed by 2.44 meter (8 feet) strip width, followed by 1.22 meter (4 feet) and control.

Height-The height was not significantly affected by strip widths during the first growing season (table 2). However, during the second growing season 2.44 meter strip width significantly reduced height over both 1.22 meter strip width and control (table 2). The height for the first time became statistically different in June 1996, and onwards, the same may be seen from diverging graph lines in fig. 5.

Volume index-The volume index was significantly affected by strip widths of cover crops. Volume index was not found to be significant during the first growing season (table 2). The volume index was, however, observed as significant for the first time early second growing season, when all the three strip widths were observed to be significantly different from each other, and this trend was maintained (fig. 6).

CONCLUSION

Sweetgum growth was significantly affected by all cover crops and at each strip width. During the first growing season, winter annual cover crops tended to reduce growth more than perennial. This trend, however, was reversed during the second growing season. The perennial cover crops showed increased growth reduction during second growing season. The legumes did not benefit sweetgum over grasses and, in fact, reduced growth to a greater extent than grasses.

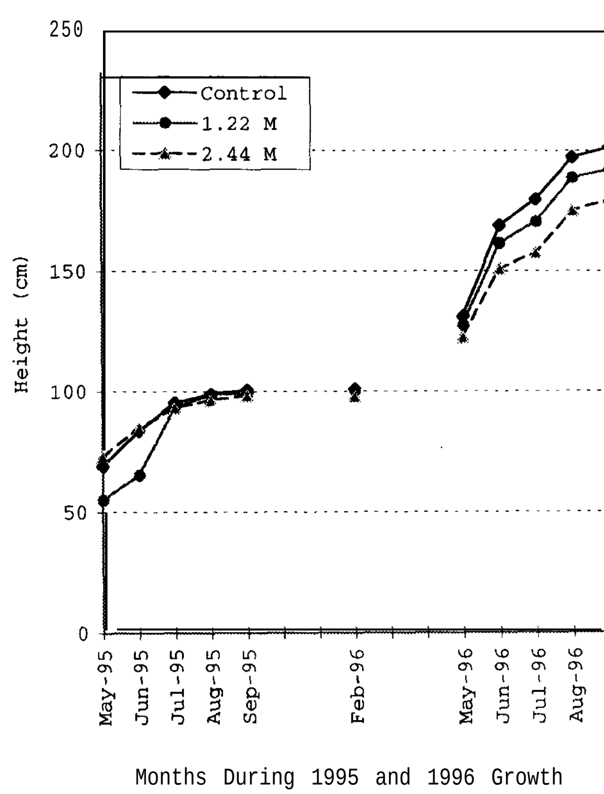

Figure 5—Sweetgum height affected by strip width of cover crops.

Table 2-Effects of strip widths of cover crops on sweetgum during the growing seasons of 1995 and 1996[a]

Sr. no., year, and cover crop	Ground line diameter	Height	Volume index (D2H)
	------- cm -------		--- cm3 ---
First growing season			
(1) Control (no cover)	2.30a	100.86a	551.88a
(2) 1.22 meters	2.08b	100.37a	462.48a
(3) 2.44 meters	2.00b	97.99a	415.07a
Second growing season			
(1) Control (no cover)	4.63a	201.34a	4430.34a
(2) 1.22 meters	4.23b	192.15a	3559.47b
(3) 2.44 meters	3.72c	179.53b	2646.52~

[a] Means (year-wise) within same column effects followed by the same letter are not significantly different at 5 percent level.

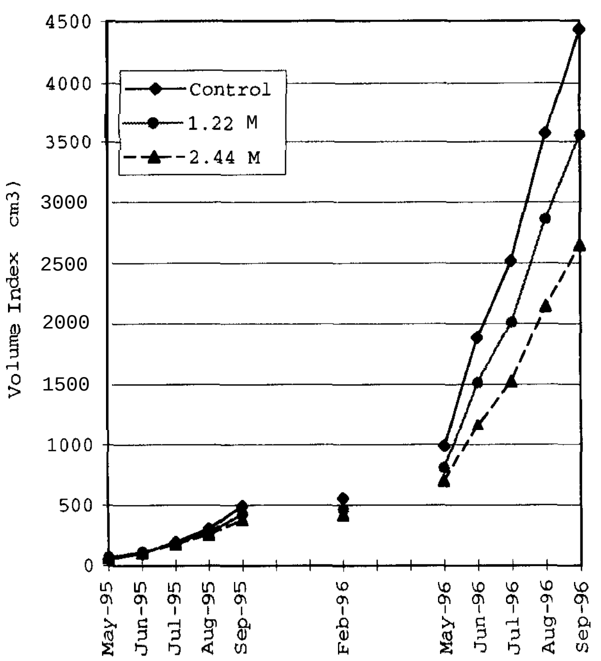

Figure 6—Sweetgum volume index affected by strip width of cover crops.

With regard to strip widths, these data show that the narrower the cover crop strip (wider the competition-free zone around the sweetgum rows) the better the growth of sweetgum trees. In this study, the 1.22 meter strip width, which provided 0.92 meter of competition-free area on each side of the sweetgum trees, still caused a competition-induced reduction in sweetgum growth. However, this growth reduction was less significant than that using wider cover crop strips.

ACKNOWLEDGMENT

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EFFECT OF SEEDLING SIZE AND FIRST-ORDER-LATERAL ROOTS ON EARLY DEVELOPMENT OF NORTHERN RED OAK ON MESIC SITES

Paul P. Kormanik, Shi-Jean S. Sung, Donald J. Kass, and Scott Schlarbaum[1]

Abstract-Northern red oak (*Quercus rubra*) seedlings were placed in three grades based on number of first-order-lateral roots. The grades were poor, medium, and good and had numbers of 0 to 6, 7 to 11 and ≥ 12, respectively. Eighty seedlings from each group were either underplanted or established in an adjacent clearcut on a high-quality mesic site in North Carolina. There were 240 seedlings outplanted on each area. The poor-graded seedlings were initially smaller than the medium and good seedlings with heights and root collar diameters of about 67 centimeters and 7.4 millimeters; 115 centimeters and 11.3 millimeters; and 138 centimeters and 13.4 millimeters, respectively. Survival was better overall with the underplanted seedlings at year 7, with the poor, medium, and good seedlings surviving at 75, 78, and 96 percent, respectively. Growth was unsatisfactory for all three grades. Survival on the clearcut was affected by a 17-year-locust (*Magicicada septendecim* L.) infestation and heavy stump sprout competition. Survival of the poor, medium, and good seedlings were 59, 63, and 66 percent, respectively. Height and stem caliper were very good for the medium and good seedlings. Only 3 seedlings from the O-6 grade were free to grow at age 5, while 29 of the seedlings in the good grade were free to grow.

INTRODUCTION

Scores Of manuscripts have reported on attempts to obtain northern red oak (Quercus *rubra*) regeneration on desirable mesic sites where the species is an important economic and ecological component of the forest. The basic tenets of most Of this northern red oak research have been reported by Sanders (1971, 1972; Sanders and Graney 1993). That is, for this species to be a significant component of a future stand, they must be represented by specific numbers and size classes in the understory when the current stand is harvested. Stand structure is regulated by thinning of either (or both) the canopy and the understory to encourage the establishment and development of the smaller oak regeneration before the residual stand is harvested (Loftis 1983, 1990). Many of the regeneration attempts that have shown promise of providing adequate oak regeneration are on the more xeric sites, where northern red oak may not be the desirable oak species. Stable oak communities are not difficult to obtain or to maintain on xerophytic sites where site index is ≤60 (base age 50) (Lorimer 1993).

Kellison (1993) reported that obtaining oak regeneration is not a universal generic problem but, rather, is a specific problem of northern red oak on high-quality mesic sites. This serious problem is complicated by ignoring the effect of edaphic and environmental factors on the competitor species of this important oak species. The pertinent issue may be the desire to develop a generic management protocol that is simultaneously politically correct, scientifically sound, and universally applicable to all *Quercus* species regardless of edaphic and environmental constraints. This “Holy Grail” is unlikely to exist and if research and management continues to search for it, then Kellison’s (1993) prediction of northern oak becoming the “California Condor” of the eastern deciduous forest may indeed become a reality.

Natural versus Artificial Regeneration

Oak research at the Institute for Tree/Root Biology (ITRB) was initiated a decade ago when we began screening northern red oak open-pollinated, half-sib progeny for first-order lateral roots (FOLR) development. The ultimate purpose of the research was to develop a seedling grading system to be used for assessing the future competitive ability of individual outplanted seedlings. We first had to develop a nursery protocol to grow high quality seedlings of this species, since a consistently reliable method had not been reported for any species of oak (Williams and Hanks 1976). Only a few organizations were even considering an option of artificially regenerating northern red oak because emphasis was on natural regeneration. The primary management emphasis was on mensurational aspects of stand manipulation, such as timing of thinning or removal of overhead canopy, rather than on the biological requirements of the species. (Loftis 1990, Johnson and others 1989).

Timing of regeneration cuts for northern red oak is difficult because of the periodic occurrence of good seed years and reduced acorn crop as the stand ages and passes its peak reproductive years. However, following a good seed year on most sites, small newly germinated northern red oak seedlings can be found in great numbers for several years (Loftis 1990). Few of these will survive on mesic upland sites for sunlight is usually significantly lower than the compensation point required by northern red oak seedling (Hodges and Gardiner 1993). Similar reliance on periodic acorn crops for seedling production in nurseries severely limits artificial enrichment planting opportunities that should accompany natural regeneration. Absence of a ready source of acorns has severely limited planned research on this species but recent results on acorn production from seed orchards have been encouraging.[2]

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Development of Northern Red Oak Seedlings

We will not include a discourse on acorn production but will assume the acorn has germinated. After germination, seedlings may survive a few years but light intensity near the forest floor on mesic sites is often below the compensation point for northern red oak. Seedlings seldom develop more than 2 or 3 leaves and the terminal buds remain very small. However, because of small openings in the canopy and sporadic understory, individuals can survive for a number of years under these suboptimal light conditions. They frequently break bud several weeks before canopy closure and may be able to partially replenish root reserves depleted during bud break. Although complete information is lacking, those seedlings reaching more than 1 meter in height might be considered advanced reproduction that can benefit from partial release. These partially released trees may develop slowly and after 9 years have a basal diameter increase of 0.86 centimeter with insignificant height growth (Loftis 1990). Thus, before as well as after this release, growth is far from satisfactory and newly germinated species like yellow poplar (*Lirodendron tulipfera*) or the already established competing vegetation rapidly overtops all but the tallest of the slower growing northern red oak seedlings. However, northern red oaks are notoriously slow to respond to initial release, and the heavy competition on mesic sites is far more severe than on the xeric sites. Thus, initial clearcutting or a series of release and regeneration cuts to release this species may be unsatisfactory as long as the reproduction is being overtopped.

The purpose of this study was to determine how large northern red oak seedlings stratified by FOLR numbers react to competition in a clearcut and an understory planting on a high-quality mesic site.

METHOD

Two adjacent areas on the USDA Forest Service's Grandfather Ranger District on the Pisgah National Forest, 12 miles northwest of Marion, NC, were used in this study. The site index for yellow poplar was approximately 100 (base age 50). The main crown canopy was a mixture of northern red oak, white oak (Q. *alba*), red maple (*Acer rubrum*) and yellow poplar. The clearcut area to be used for enrichment planting was a small segment of a larger harvested area.

The area to be underplanted was immediately across the road and consisted of the same species composition as the clearcut area. For the underplanting, basal area was reduced by 30 percent to 20.44 square meters per hectare (88 square feet per acre) primarily by removing the intermediates and suppressed trees from the canopy level as well as those individuals occurring in the subcanopy level.

Acorns were collected from the Forest Service's Wataqua seed orchard in eastern Tennessee. The seedlings were grown at the ITRB Whitehall Experimental Nursery during the 1989 growing season, using the hardwood nursery protocol reported elsewhere (Kormanik and others 1994a). The seedlings were harvested during February 1990 and outplanted in March 1990.

When lifted, the seedlings were placed in one of three groups, poor, medium, and good, based upon FOLR numbers. FOLR numbers were defined as roots with basal diameter exceeding 1 millimeter along the first 30 centimeters below the root collar. The poor, medium, and good groups had FOLR numbers of 0 to 6, 7 to 11, and ≥ 12, respectively. Root collar diameters (RCD), and heights, were recorded for each seedling. Each lateral root was trimmed to approximately 13 centimeters and taproots were pruned to 30 centimeters before seedlings were outplanted.

Eight blocks were laid across the contour and 10 trees from each grade were shovel planted at 1.5 meters by 3.1 meters spacing in adjacent rows. The design was a split-split plot with eight blocks. Each block contained 10 trees from each grade, giving a total of 240 seedlings per treatment. The spacing was maintained with only minor adjustments. All standing trees in the clearcut area were felled before planting but no subsequent vegetation control measures were taken. Mechanical control in the underplanting area removed subcanopy trees as well as trees overlapping naturally regenerated northern red oak seedlings. Essentially no subcanopy remained after basal area reductions had been completed.

Survival data were obtained after the first growing season in 1990. Survival, RCD, and HGT were also obtained after the fifth year (1994). Competing vegetation density was recorded from three positions in each block during the fifth-year remeasurement. Five artificially regenerated trees were excavated after the fifth growing season from both the clearcut and underplanting areas to examine root development characteristics. Survival, diameter at breast height (d.b.h.), and heights were also obtained after the seventh growing season (1997).

RESULTS AND DISCUSSION

Two unanticipated factors significantly affected the results. The first was a massive infestation of the 17-year locust (*Magicicada septendecim* L.) that severely damaged almost all 240 seedlings in the clearcut toward the end of the second growing season. Very few naturally regenerated or coppiced trees were affected in the clearcut and none of the oak seedlings in the understory planting were attacked. The second factor was that the intense competition from untreated stumps of Carolina silverbell (*Halesia carolina*), red maple, and yellow poplar seedlings proved to be more significant than anticipated.

Seedling Survival

Survival following the first season was 100 percent in both the clearcut and understory plantings for all three FOLR groups of seedlings. The second year, locust damage was so extensive on seedlings in the clearcut that their long-term survival appeared to be in doubt. Many stems were severely damaged over half to two-thirds of their heights by the end of the second growing season. In the understory, all seedlings from all three FOLR grades were intact (table 1). A total of only 20 trees had not survived in the understory at age 5. Of these 20, 16 were in the poor (0 to 6) FOLR group, two in the medium (7 to 11) group, and two

Table I-Northern red oak survival by first-order-lateral root groupings[a] from clearcut and understot-y plantings

Survival rate	Clearcut			Understory		
	Good	Medium	Poor	Good	Medium	Poor
1 st year	100	100	100	100	100	100
5th year	68	66	63	96	96	96
7th year	66	63	59	96	78	75

[a] Good = ≥12; medium = 7-11; poor = 0-6.

in the good (212) group. When stands were remeasured after the seventh growing season, more mortality had occurred in both the medium and poor FOLR grades but essentially all in the good grades were still surviving in the understory (table 1).

Mortality in the clearcut was more severe (table 1) due to the result of both the intense competition from stump sprouts and the residual effect of the locust damage. Survival did not change between the fifth and seventh year in the clearcut planting area.

Growth, Vigor, and Competitive Status of Regeneration

Most of the naturally regenerated oak seedlings were less than 30 centimeters tall when the study was initiated and few of these were found by age 7. Although we did not make an exhaustive survey, newly developed seedlings were rarely observed. We do not know whether this situation occurred due to limited mast production or insufficient sunlight for seedling development. In neither the understory planting nor the clearcut area, would natural northern red oak regeneration development have been sufficient to be more than a minor component on this high-quality mesic site. Artificial regeneration, however, has altered this possibility through at least age 7.

Underplanting

The original basal area reduction has been effective through the seventh year, in that no low or mid-crown canopies have developed. However, even the best FOLR grade seedlings have not developed satisfactorily. Height growth has been minimal and RCD increases through the fifth year have remained essentially unchanged from their initial caliper; the seventh year d.b.h. measurements are tracking that of the RCD development (figs. IA, 1 B). The poor (0 to 6) FOLR group of seedlings remains the smallest and is spindly, although some-those taller than 1.0 meter-might be considered "advanced" reproduction. Characteristic of all underplanted seedlings, regardless of FOLR grade, is that only a few leaves develop annually. Even on the largest seedling, we have seldom observed more than 20 to 30 leaves. Tip dieback has occurred Several times on most of the seedlings and is not associated with any particular FOLR grade. Low vigor of the poor and medium FOLR grades appeared to be related to the mortality that occurred between the fifth and seventh year. The seedlings within a specific grade were uniform in size and appear to be related to their initial sizes.

Trees excavated after year 5 showed that FOLR numbers had declined for each seedling examined. This was relatively unexpected. Underplanting or shelterwood regeneration assumptions are that the released seedlings will develop a vigorous root system and be competitive when the stand is harvested. As reported in other species, unfavorable edaphic or environmental conditions such as low light intensity can result in a reduction in FOLR numbers and vigor with a preferential carbon allocation to the taproots at the expense of the lateral roots (Sung and others 1996; Kormanik and others 1994b; Sung and other, in press). This may be the situation here since photosynthetic active radiation was at least 1500 $\mu E/m^2/s^2$ in the original clearcuts but less than ca. 5 percent in the understory.[3]

At age 7, the mean height increases since underplanting for the good, medium, and poor FOLR grades were 50, 40, and 30 centimeters, respectively (fig. IA). The tallest seedlings were 280,200, and 170 centimeters for each FOLR grade, respectively. In the understory, FOLR grades had little effect upon RCD increments through the fifth year and the poor FOLR grade had few seedlings large enough to obtain d.b.h. measurements at the seventh year (fig. 1 B).

Clearcut

Large differences were observed in all growth parameters among FOLR root grades in the clearcut area. Survival was not related to root grade and seedling size per se. All seedlings remained free to grow during their first year, but competition for sunlight became intense between years 2

[3] Data on file at the USDA Forest Service, Institute for Tree/Root Biology, Athens, GA 30601.

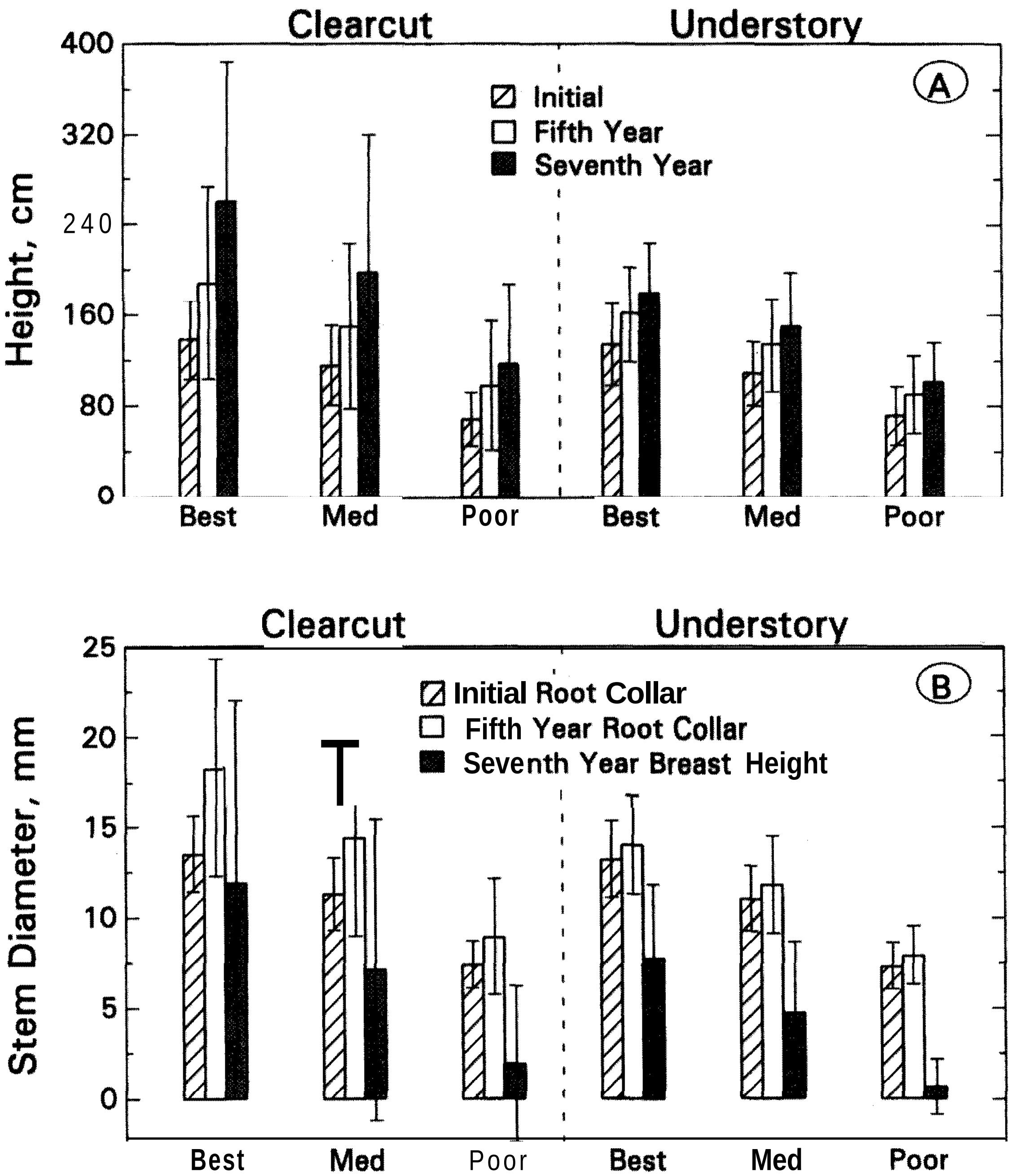

Figure l-Initial-, fifth-, and seventh-year diameters and heights of root graded (Good = ≥12 first-order-lateral roots; medium =7-11 first-order-lateral roots; poor = O-6 first-order-lateral roots) northern red oak in a clearcut and adjacent underplanting. Figure 1 A heights; 1 B diameters.

and 5 as stump sprouts and other seedlings rapidly developed. When the first remeasurement was made at year 5, evidence of significant dieback of many stems was clearly visible as a direct result of the second growing season attack by the 17 year cicada. At age 5, seedling sizes and competitive position were closely related to original FOLR grade, with the poorest grade trailing far behind the better two grades (figs. 1 A, 16). At that time, only 3 seedlings were free to grow in the poor grade, but 15 of the medium and 29 of the best grade were in this category. This latter number, 29, is especially significant as it represents about 50 percent of the surviving seedlings in this good FOLR grade. The tallest seedlings at ages 5 and 7 were strikingly different for each FOLR grade. At age 5, the poor, medium, and good FOLR grades' tallest seedlings were 235, 455, and 510 centimeters, respectively (see footnote 3). Only the medium and good grades continued to be free to grow at age 7. Many were beginning to experience severe competition from the faster growing Carolina silverbell and yellow poplar seedlings, and red maple sprouts.

At age 5, a thorough survey of competition in the clearcut revealed that the planted oaks were competing with 126,800 stems per hectare of 14 different deciduous hardwood species. However, it was the sprouts of the three above-mentioned species and the yellow-poplar seedlings that had become the major competitors and had affected oak development the most. Vegetation was not resurveyed at age 7, but stem numbers did not appear to have declined from age 5.

During the seventh year, when crown competition in the clearcut area became intense, the number of leaves on the oak seedlings was quite high with 200 to 400 leaves being common on the better seedlings. The effect of leaf number was most evident during the initial 3 years when essentially all larger seedlings were free to grow. Northern red oak seedling development during the first 2 to 3 years is especially important and is dependent upon full sunlight for optimum establishment. We found that during years 1 and 2, major carbon allocation with northern red oak is directed to root maintenance and development with little stem elongation occurring. Without early establishment of an adequate root system, subsequent top growth is severely restricted and newly released or outplanted seedlings are soon overtopped.

Many of the naturally regenerated oak seedlings had died or had been suppressed by faster growing competitors between years 2 and 7. The reason is clear for this mortality and what was observed in this study is probably true on other mesic sites. The established oak seedlings did not immediately respond to release and few seedlings produced more than 3 to 5 leaves the first or second year. Growth during this first year was negligible as others have reported (Pope 1993). Newly germinated herbaceous vegetation, other tree species, and many sprouts soon overtopped these naturally regenerated northern red oak seedlings. By the second growing season, most of these naturally regenerated seedlings were completely overtopped and received phtosynthetic active radiation of less than 5 percent of full sunlight.

The large artificially regenerated seedlings essentially remained free to grow until the third and fourth years except when planted adjacent to stumps that sprouted Vigorously. During this early period, the surviving seedlings developed a large root system that was not observed in underplanted individuals. The advantage of the large seedlings was quite obvious. The newly germinated competitors started at ground level and they seldom were more than 60 to 80 centimeters tall the first year. This was well below the height of the medium and good planted oak seedlings. Even the stump sprouts resulted in minimal competition during years 1 and 2 when the artificially regenerated oaks were establishing their root system. Thus, an early major, limiting factor of northern red oak characteristically encountered on high-quality mesic sites was moderated, i.e., access to full sun. However, it is expected that at least one release will be needed to sustain development of these free-to-grow individuals.

CONCLUSION

Large northern red oak with FOLR numbers 27 can be used effectively for enrichment planting on high-quality mesic sites following clearcutting. Large seedlings effectively compete against Severe competition from newly germinated seedlings and other herbaceous vegetation, but by age 7 may need release from the more rapidly growing stump sprouts and yellow poplar seedlings. Planting immediately adjacent to untreated stumps of yellow-poplar, red maple, and Carolina silverbell can result in severe competition and mortality. Few individuals from the poor FOLR grade (0 to 6) Were in a Competitive position after year 2. Treatment of stumps adjacent to artificially regenerated seedlings may prove beneficial but was not tested.

Underplanted individuals released to a basal area of 20.44 square meters per hectare had a better survival rate than those in the clearcut, but grew little during these first 7 years. The seedlings repeatedly died back regardless of initial sizes and FOLR numbers. Excavation at age 5 from the understory, revealed most of the original FOLR have senescenced and root mass was smaller than when initially outplanted due to mortality of the FOLR.

Neither artificial nor natural regeneration techniques may prove effective for regenerating northern red oak on mesic sites unless mechanical or chemical competition control accompanies use of large nursery-grown seedlings. It is questionable whether advanced natural regeneration can be relied upon on mesic sites with the shelterwood method of regenerating this species.

ACKNOWLEDGMENT

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PREHARVEST HERBICIDE METHOD TO DEVELOP COMPETITIVE OAK REPRODUCTION IN UPLAND OAK STANDS OF THE MOUNTAINS AND PIEDMONT OF NORTH CAROLINA—7-YEAR RESULTS

Donald J. Kass And Warren G. Boyette[1]

Abstract-To promote development of small advanced upland oak reproduction, two variations of understory and midstory basal area reduction were applied to medium quality sites (site index 70 to 80) of mixed oak stands in the piedmont and mountains of North Carolina. Seven-year measurements indicate some increase in survival, diameter, and heights in the treated plots as compared to the untreated plots. However, in practical terms, the slight increases in diameter are not enough to increase the likelihood that the oak seedlings would be competitive should these stands be harvested now. More time will be required on medium-quality sites for the small oaks to develop to a larger size. This extended timeframe may be a serious obstacle to implementation of the practice by the private landowner.

INTRODUCTION

Once harvested, upland oak stands on medium and good sites are not regenerating to a viable component of oak species. The upland oak resource is widespread and valuable, especially for timber and wildlife. Any technique or practice that shows promise of enhancing the oak regeneration component is needed. A large number of advanced, well-developed oak seedlings are usually required to ensure adequate regeneration (Sander and Clark 1971, Johnson 1975, Loftis 1983). An Oak Shelterwood method for the mountain cove sites seems to develop large, advanced, northern red oak regeneration on very good sites (Loftis 1990b, 1992). It is important to determine whether this method works as well on medium-quality sites, which are common in the piedmont and mountains.

In this study, two variations of basal area reduction were applied to mixed oak stands on medium quality sites in the piedmont and mountains of North Carolina. The purpose of the study was to: (1) compare the effectiveness of the oak shelter-wood and another silvicultural technique in advancing small upland oak reproduction to a larger, competitive size; and (2) determine the rate of small oak reproduction development, by species, following treatment.

METHODS

Three stand treatments were utilized in the study.

(1) Control. No treatment.
(2) Oak Shelterwood. Kill the understory and midstory and, if necessary, some of the least desirable overstory trees in order to remove at least 25 percent but no more than 40 percent of the total basal area.
(3) Kill Suppressed Stems. Kill the understory, midstory, and suppressed trees in the overstory without regard to how much basal area was removed.

The "hack and squirt" method of herbicide application was used to kill the targeted trees. Trees down to 0.8" d.b.h. (1-inch class) were treated.

Five study locations were established between 1986 and 1988. Elevations of the study sites ranged from a high of 3,200 feet in Avery (two sites) and Polk counties to 1,100 feet in Caldwell County to a low of 300 feet in Chatham County. Each of the stands had a large proportion of mature oak in the overstory along with yellow-poplar (*L. tulipifera*), hickory (*Carya spp*), black gum (N. *sylvatica*), and red maple (A. *rubrum*). Understory species included dogwood (C. *florida),* sourwood (0. *arboreum*), hemlock (*T. canadensis),* redbud (C. *canadensis),* and red maple. Site indices ranged from 70 to 80 for oak at age 50. The study locations represent the range of typical hardwood stands found in the North Carolina mountains and piedmont on medium-quality upland sites.

Initial average stand basal area levels ranged from 134 to 145 square feet. The average levels of basal area reduction for the two herbicide treatments were very similar. The Oak Shelterwood treatment averaged 33 percent removal with a range of 22 to 38 percent, and the Kill Suppressed Stems treatment averaged 27 percent with a range of 19 to 45 percent.

The study design was randomized block. Treatment plot dimensions were 100 feet by 100 feet. Each location had two replications (blocks) of each treatment; circular 1/10-acre plots were centered inside the treatment plot from which a maximum of 50 oak seedlings were identified, tagged, and measured. The measured seedlings were representative of the oak species and stem sizes present on the plot as advanced reproduction.

The following parameters were recorded for each seedling: species, basal diameter (measured just above the root collar), height, and competitive status (such as being overtopped by other vegetation adjacent to it or whether it was single or multiple stemmed). Later measurements also included any original stem die back and new Stem development. Measurements were taken at 1, 2, and 7 years after establishment. Basal diameter was recorded

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only at 1 and 7 years. All surviving stems at 7 years following treatment were included in the survival analyses but immediately overtopped stems and stems with multiple leaders or that had died back were excluded from the diameter and height growth analyses.

Five common oak species were represented in the study. Northern red oak (Q. *rubra)* was most prevalent followed in order by white oak (Q. *alba),* scarlet oak *(Q. coccinea),* chestnut oak *(Q. prinus)* and black oak *(Q. velutina)* (fig. 1). Northern red oak and scarlet oak occurred on all study sites. White oak and black oak were present on four of five locations and chestnut oak occurred on three of the five.

Most of the initial advanced oak reproduction was quite small. The largest proportion, 72 percent, was in the 0.1-inch diameter class and only 13 percent was 0.3 inch or larger in diameter (fig. 2).

Initial heights tended to increase with increasing basal diameters, and average beginning heights were similar for each species. Of the five species, all but chestnut oak averaged less than 1 foot tall when the basal diameter was under-O.3 inches (table 1).

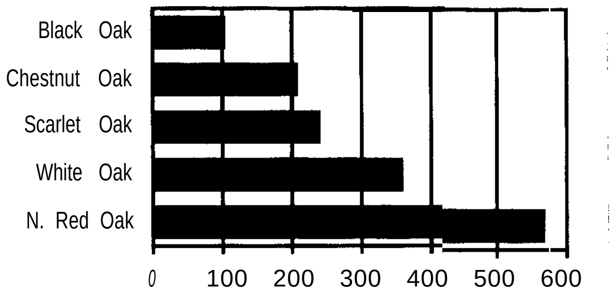

Figure I-Initial number of seedlings by species for all treatments combined.

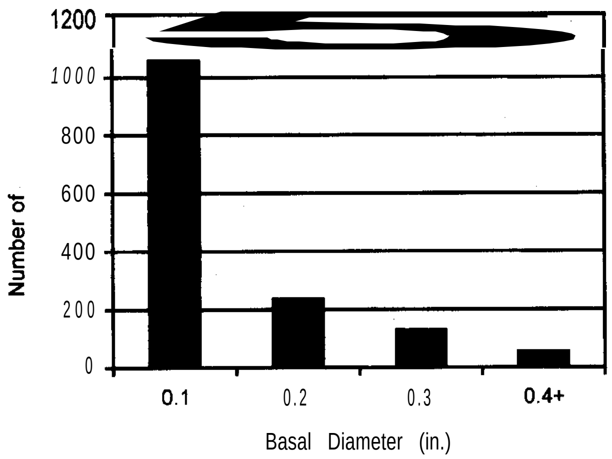

Figure 2-Basal diameter distribution of initial seedlings for all treatments combined.

Table I-Average initial height by initial basal diameter class and species for all treatments combined

Oak species	Initial basal diameter class 0.1	0.2	0.3	0.4+	Average
	-Height (*in*)-				
Black	5	7	13	28	7
Chestnut	6	13	16	29	9
Northern red	6	10	15	24	8
Scarlet	6	9	11	-	7
White	6	10	16	31	10
Average	6	11	15	28	8

RESULTSANDDISCUSSION

Similar Response by Species

Survival and growth response was similar for the five oak species (table 2). For all treatments combined, survival ranged from 66 to 78 percent. Loftis (1992) found that white oak responded more slowly to release than did black, scarlet, northern red, and chestnut oaks. However, when white oak data were excluded, the basal diameter increases were essentially unchanged for the herbicide treatments. For height growth, white oak was intermediate among the five species. Height growth was slightly more variable among the species than was basal diameter growth.

Survival

Seven-year seedling survival for all species combined increased with increasing initial seedling basal diameter and with an understory treatment to augment sunlight reaching the forest floor (table 3). The control treatment showed a significantly lower average survival than the herbicide treatments. This result is in agreement with the observation of Loftis (1992) that oak seedlings under full shade gradually die in the understory if not exposed to

Table 2-Average survival, basal diameter, and height increases for all treatments combined

Oak species	Survival	Diameter increase	Height increase
	Percent	*Inches*	
Black	75	.08	3.6
Chestnut	78	.06	1.4
Northern red	68	.07	2.3
Scarlet	66	.06	2.7
White	75	.08	3.1

Table 3-Average survival after 7 years by initial diameter class and treatment[a]

Treatment	Initial basal diameter				
	0.1	0.2	0.3	0.4+	Average
	----- Survival rate (percent) -----				
Control	43	69	7%	92	*53a*
Oak Shelterwood	73	91	94	100	*78b*
Kill Suppressed Stems	79	94	89	100	*83b*

[a] Average percents followed by a different letter are statistically different according to Duncan's Multiple Range Test (P=0.05).

increased sunlight. No significant difference in survival was detected between the herbicide treatments. The adverse impact of shade was most dramatic on the smallest seedlings, which are typically the most prevalent in upland hardwood stands on medium-quality sites. For the control treatment only about 40 percent of the seedlings in the 0.1-inch diameter class were surviving after 7 years, whereas nearly 70 percent in the 0.2-inch class were surviving.

Changes in Basal Diameter

For all species combined, the herbicide treatments produced a significant increase in basal diameter over the control treatment (table 4). In practical terms, though, the overall advantage of 0.05 inches is only modest at best. In fact the 0.08-inch increase in basal diameter for the treated plots is only one-half that predicted by Loftis (1990b) for the oak shelterwood treatment on medium-quality sites.

Nonetheless, the oak seedlings are developing slowly into larger seedlings. As the seedlings increase in diameter, the proportion in the 0.1 -inch class has decreased for all three treatments, while the number of seedlings in each of the other diameter classes has increased. The proportion of increase for the herbicide treatments is larger than the control for each diameter class (fig. 3).

Table 4-Average basal diameter increase by treatment[a]

Treatment	Diameter increase
	---- *Inches* ----
Control	0.03*a*
Oak Shelterwood	0.08*b*
Kill Suppressed Stems	0.08*b*

[a] Numbers followed by a different letter are statistically different according to Duncan's Multiple Range Test (P=0.05).

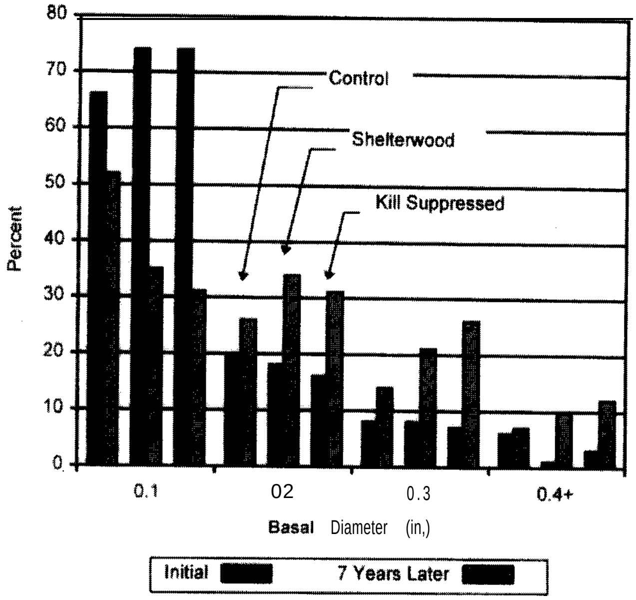

Figure 3-Proportion of seedlings by treatment in each diameter class initially and 7 years after treatment. (For each basal diameter class, Control, Shelterwood, and Kill Suppressed are grouped from left to right).

Changes in Height

For the five species combined there was a significant though small increase in average height growth for the herbicide treatments compared to the control (table 5). The advantage was consistent as the herbicide treatments outperformed the control in each diameter class. However, this net advantage of 2 inches for the herbicide treatments likely is of little practical importance.

The changes in oak seedling height are probably less important than changes in diameter, since the majority of seedlings would be knocked down during logging and would have to resprout from the stump. Nevertheless, height growth does give some indication of how the seedlings are developing since, generally, taller seedlings have larger basal diameters.

Table 5—Average height increase by treatment[a]

Treatment	Average height increase
	---*Inches*----
Control	la
Oak Shelterwood	*3b*
Kill All Suppressed Stems	*3b*

[a] Average height increases followed by a different letter are statistically different according to Duncan's Multiple Range Test (P=0.05).

Non-Oak Understory Redevelopment

No measurements were taken to quantify the subsequent development of the non-oak seedlings in the understory that were too small at study establishment to treat (less than 0.5inches d.b.h.). These were mostly eastern white pine (*P. strobus*), Fraser magnolia (*M. fraseri*), eastern hemlock, dogwood, sourwood, blackgum, red maple, and American holly (*I. opaca*). It is now obvious that these seedlings have developed and grown to the point where they will soon begin shading and suppressing the oak seedlings. Unless the oaks begin to develop faster, it may be necessary to retreat some of the areas to control these competitors.

Another occasional problem observed on treated seedlings outside the measurement plots was the development of honeysuckle (*Lonicera japonica*). Where present, the honeysuckle was stimulated by the increased sunlight and in some cases has developed into a thick mat, entangling and pulling down the small oak seedlings.

SUMMARY AND CONCLUSIONS

Providing sunlight to the small advanced oak reproduction by either of the herbicide treatments significantly improved survival. All five oak species responded in a similar manner. Even white oak, generally acknowledged to be the slowest grower of the upland oaks, responded similarly to the other oaks. The herbicide treatments also provided significant, but small, improvement in basal diameter and height growth. There was no difference in survival or growth response for the two herbicide treatments. Both herbicide treatments removed similar average amounts of stand basal area though the oak shelterwood removal rates were more consistent. Survival of the oak reproduction improved with increasing initial basal diameters for both the herbicide and control treatments, though the herbicide treatments showed consistently higher survival in each initial diameter class.

In practical terms the herbicide treatments were most effective at reducing mortality of the oak seedlings. Though the improved growth response did advance some seedlings into larger diameter classes, the response was only half that predicted by Loftis (1992) for the oak shelterwood. The slow response was especially telling for the small advanced reproduction. After 7 years, very little of the small advanced reproduction, that in the 0.1 and 0.2 basal diameter classes and less than 1 foot in height, has grown enough to be competitive once the overstory is removed. Typically, this small reproduction is the common size found on most upland oak stands on medium-quality sites.

IMPLICATIONS

For the private landowner, these silvicultural techniques may not be practical unless there are very large amounts of advanced oak regeneration already present and there is a willingness to wait a long time for the seedlings to develop. More than 7 to 10 years may be needed for the small advanced reproduction to develop. A complicating factor is that the non-oak competitors are also developing alongside the oak, and additional control measures may be required to keep the oak seedlings from becoming suppressed. Most landowners may not find it feasible to invest in silvicultural treatments more than 10 years in advance of a harvest. Based on these study results, on medium-quality sites, the landowner will either have to wait longer for the oak reproduction to reach an average minimum threshold size, or accept fewer oaks per acre in the next stand.

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GROWTH AND PROTECTION OF SELECTED NORTHERN RED OAK SEEDLINGS PLANTED ON OLD FIELD SITES

B. Diane Graveline, G.R. Wells, Scott E. Schlarbaum, and H.A. Fribourg[1]

Abstract-High-quality northern red oak (Quercus *rubra* L.) seedlings have been produced at the Tennessee Division of Forestry nursery in Etowah, TN, through the efforts of the University of Tennessee Tree Improvement Programs and the USDA Forest Service. In an effort to begin establishing planting guidelines for these oaks, seedlings from 10 different genetic families were lifted in spring 1995 and visually graded according to size, stem form, bud set, and root characteristics. The selected 1+0 northern red oak seedlings were planted on formerly established grass plots on nine marginal soils at five branch experiment stations in Tennessee. White-tailed deer (*Odocoileus virginianus* Zimmermann) browsed these seedlings heavily, regardless of location. A quantitative measure of browse damage was developed for this study. Due to the confounding effects of damage by deer on the 1995 marginal soils study, another study was initiated in spring 1996 to determine whether graded seedlings could be protected from white-tailed deer when planted on old field sites. Four commercial repellents, Deer-Away Big Game Repellent[R], Hinder Deer and Rabbit Repellent[R], Nortech's Tree Guard[TM], and Pro-Tee Garlic Sticks were applied to field-planted 1+0 northern red oak seedlings from six different genetic families. Six treatments, including Tubex[R] 1.2-meter tree shelters and an untreated control, were replicated three times at separate plots on an area known to have a high deer population, the Chuck Swan Forest and Wildlife Management Area in Union County, TN. Two months after planting, damage by deer was evident in all treatments except for seedlings in tree shelters. Three months after planting, the most heavily browsed seedlings were in the control plots, the Tree Guard plots, and the Pro-Tee Garlic Stick plots. Response to treatments will be evaluated through the second growing season.

INTRODUCTION

Northern red oak *(Quercus rubra* L.) is a highly desirable species for timber production, for providing habitat and mast for wildlife, and for recreational opportunities. However, oak stands, particularly those of red oak, on good to excellent sites are increasingly being replaced by less desirable species after harvesting (Crow 1988, Johnson 1984, Lorimer 1992, McGee and Hooper 1970).

Oak mortality contributes to the decreased stocking level of northern red oak in Tennessee and the Southern Appalachians. In Tennessee, forest resource reports from 1991 show the amount of growing stock that dies has doubled since 1990, and nearly two-thirds of the increase in mortality is occurring in oaks, mostly red oaks (Nebeker and others 1992).

Attempts to artificially regenerate northern red oak are often met with limited success (Loftis 1979). The principal cause is the failure of northern red oak seedlings to exhibit rapid juvenile height growth. This lack of early growth does not allow northern red oak to compete with faster growing vegetation (Beck 1970, Olson and Hooper 1972, Russell 1973). In addition to the problem of slow juvenile growth, seedlings that were commonly planted were smaller and were graded based only on aboveground characteristics. Research has shown that nursery practices of grading bare-root hardwood seedlings based only on shoot characteristics (e.g., height and diameter) have not provided adequate planting stock (Thompson and Schultz 1995). The morphological grading of northern red oak seedlings based on root system characteristics, as well as those of the shoot, could greatly increase growth and survival of planted seedlings (Johnson 1992, Kormanik 1986, Ruehle 1986, Stroempl 1985, Thompson and Schultz 1995). The regeneration problems with northern red oak may be remedied to some extent by producing quality seedlings that can be used to increase the oak component in forest stands and for reforestation purposes.

The objective of this research was to determine whether graded 1+0 northern red oak seedlings from different genetic families would survive and grow on soils unsuitable for cultivated row crops. The potential of many sites for northern red oak possibly could be determined since the soils, selected in a previous study (Fribourg and others 1989), are representative (i.e., droughty, eroded, poorly drained, etc.) of marginal soils found throughout the State. Should families show a range of responses, genotypes could be isolated that will perform best on various soils.

Following extensive damage to oak seedlings by white-tailed deer (*Odocoileus virginianus* Zimmermann) at all planting locations, an attempt was made to quantitatively record damage done by deer. A second study was then established in spring 1996. This study was designed to determine whether graded 1+0 northern red oak seedlings planted on old field sites could be protected from deer and, if so, whether seedlings from different genetic families would show varying responses to different treatments.

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METHODS

1995 Marginal Soils Study

Acorns were collected from the USDA Forest Service northern red oak seedling orchard in Carter County, TN. Seedlots were collected from nine mother trees (pollen parent seed source unknown). Acorns were planted at the Tennessee State nursery in Etowah in February 1994 at a density of 280 acorns per square meter. Seedlings were grown without undercutting or top-pruning. They were lifted in the fall of 1994 and overwintered in cold storage.

Before outplanting in spring 1995, seedling stock was graded by number of first-order lateral roots (FOLR), stem form, and bud set. Approximately two-thirds of the seedlings were culled at the nursery. Larger seedlings having a minimum of six FOLR were selected for planting. Tap roots were pruned when dormant to 30.5 centimeters, and FOLR were pruned to 15.2 centimeters.

Seedlings were then outplanted in an incomplete block design on formerly established grass plots on nine marginal soils at five University of Tennessee branch experiment stations (table 1). Since the number of families per replication and soil series was determined by available space, all nine families were not planted in each replication or at every location. Families were assigned to the five locations favoring nearby seed sources over distant ones. Seedlings were planted in five rows of eight seedlings per family on a 1.8- by 2.4-meter spacing. Because of seedling size, augers were used to ensure holes were big enough to accommodate the large root systems. Height and root collar diameter (RCD) measurements were taken after outplanting. Measurements of height were made to the nearest 0.1 centimeter, and diameter was measured to the nearest 0.01 millimeter. Glyphosate herbicide was sprayed around each seedling 1 month after planting. Data for survival and field measurements were analyzed using the General Linear Model analysis of variance procedure of the Statistical Analysis System (SAS Institute, 1985) and comparisons were made using Tukey's Studentized (HSD) Range test.

In a study done by Meyers and others (1989) with planted northern red oak, browse damage was a factor, but no quantitative measurement of the effect of browsing on height growth or survival was made. For this study, a deer damage rating system was developed to assess quantitatively the severity of browse damage, and possibly to determine whether there were location or family differences. For maximum efficiency, no further measurements were taken. Instead, seedlings were assigned a subjective rating of 0 to 4, based on an ocular estimate of the deer browse damage. Seedlings were rated in mid-July 1995 and again in summer 1996. Seedlings that were unbrowsed received a rating of 4, seedlings that had 25 percent or less damage were rated 3 (lightly browsed), seedlings that received damage from 26 to 75 percent (heavily browsed), received a rating of 2, and seedlings damaged from 76 to 99 percent (severely browsed) were rated 1. Seedlings rated 0 (completely defoliated) appeared to be dead at the time of assessment, but may be capable of resprouting.

Table l-Northern red oak outplanting locations by family and experiment station for 1995 marginal soils study

Experiment station and soil series	Families	Replications
Ames Plantation	2,3,4,7,9	
Lexington (APL)		3
Alamo (APA)		3
Memphis (APM)		3
Ruston (APR)		2
Cumberland Forest	1,4,5,6,10	
Wolftever (CFW)		2
Philo (CFP)		2
Oak Ridge	1,2,4,7, 0	
Armuchee (ORA)		4
Tullahoma	2,4,7,9,10	
Dickson (TFD)		3
West Tennessee	2,3,4,7,9	
Collins (WTC)		3

1996 Deer Repellent Study

Northern red oak seedlings for the 1996 study were sown, planted, and graded at the State nursery under the same protocol as was presented for the marginal soils study above. Seedlings were lifted in fall 1995 and overwintered in cold storage. They were planted in spring 1996 on 18 old field plots located at the Chuck Swan Forest and Wildlife Management Area in Union County, TN. This area is known to have a large deer population, and incidence of browse damage was expected. Four commercial repellents, Deer-Away Big Game Repellent^{R}, Hinder Deer and Rabbit Repellent', Not-tech's Tree Guard^{TM}, and Pro-Tec Garlic Sticks were applied to field-planted 1+0 northern red oak seedlings. Tree Guard has not been approved for use in Tennessee, but permission was obtained for its use for research purposes. Two other treatments were Tubex^{R} 1.2-meter tree shelters and an untreated control. All six treatments were replicated three times on seedlings from six genetic families, with two families in each replication.

Seedlings were planted in late March on a 3- by 3-meter spacing in two rows of eight seedlings each. Initial height and RCD were measured, and deer repellent treatments were applied at that time. Glyphosate herbicide was sprayed around each seedling 1 month after planting. Seedlings treated with spray applications of Hinder, Deer-Away, and Tree Guard were retreated 50 days after planting when new growth averaged 10 centimeters. Missing garlic sticks were also replaced. Seedlings were monitored closely for signs of browse damage the first 2 months after planting, and browse damage ratings (as described for the 1995 study) were recorded for each seedling at the time of retreatment. Browse damage ratings were then recorded three more times throughout May and June. Data for survival and field measurements of the seedlings were analyzed using the same procedure as was presented for the 1995 study.

RESULTS

1995 Marginal Soils Study

Seedling survival--Overall survival rates declined from 94 percent in the first year to 58 percent at the end of the second growing season (table 2). Survival in the second growing season was good and ranged from 85 to 90 percent at three Ames Plantation locations on the Alamo (APA), Memphis (APM), and the Ruston (APR) soil series sites.

There were no significant differences in first-year survival by browse damage level among browsed seedlings rated 3, 2, or 1 (99, 99, and 96 percent). Survival of 72 percent for seedlings rated 0 (totally defoliated) was less than survival at all other damage level ratings. Seedlings that had been completely defoliated by deer had the highest mortality. Variation in survival that could be attributed to browse damage was significant in both growing seasons at the same p level ($p = 0.0001$). Second-year survival was 100 percent for seedlings given a rating of 3 (lightly browsed). Of the seedlings rated 0 in 1995, 96 percent did not change rank when rated in 1996 and mean survival dropped to 3 percent.

Seedling growth-Seedlings planted at the Ames Plantation Memphis series location (APM), which served as the control and is not a marginal soil, outperformed seedlings at all other locations (fig. 1). Significant differences (p c 0.05) in height growth occurred between seedling groups rated 3 and 2 in both the first and second growing seasons (table 3). There were no differences between seedling groups rated either 0 or 2 in the first year. Seedlings with the smallest increase in height, those

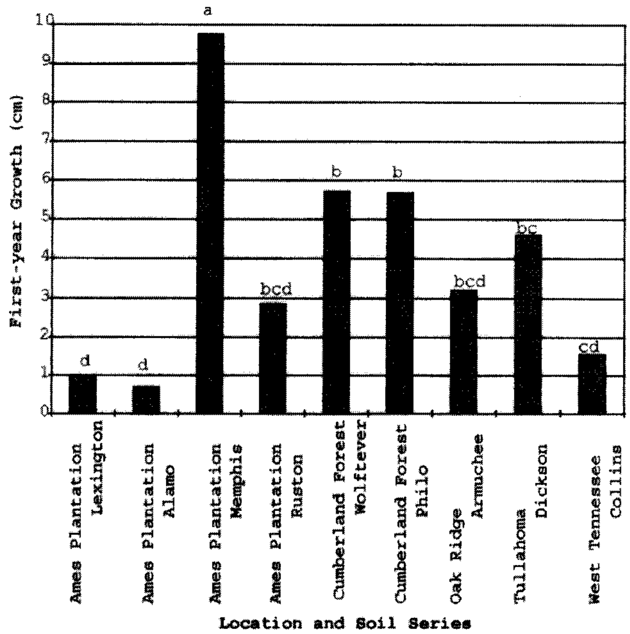

Figure l-First-year mean height growth of selected 1+0 northern red oak planted on marginal soils in 1995. Bars with the same letter are not significantly different (p c 0.05) using Tukey's Studentized Range (HSD) Test.

Table 2—Mean survival of 1+0 northern red oak seedlings after outplanting on marginal soils

Experiment station and soil series	Year[a] 1995	1996
	-----Percent-----	
Ames Plantation		
Lexington (APL)	92ab	78bc
Alamo (APA)	97a	90a
Memphis (APM)	98a	88ab
Ruston (APR)	91 ab	85ab
Cumberland Forest		
Wolftever (CFW)	95a	29e
Philo (CFP)	98a	62d
Oak Ridge		
Armuchee (ORA)	92ab	28e
Tullahoma		
Dickson (TFD)	86b	68cd
West Tennessee		
Collins (WTC)	97a	9f
Mean	94	58

[a] Means within a column with the same letter are not significantly different ($p<0.05$) using Tukey's Studentized Range (HSD) Test.

Table 3-Annual and cumulative incremental height, and diameter growth of 1+0 northern red oak planted on marginal soils, by four deer damage levels

Damage level	First yea?	Second year	Cumulative (2 yrs)
	----------- *Height* -----------		
0=Defoliated	2.3bc	-12.6c	-9.lc
1=Severe	0.9c	-17.4c	-15.3c
2=Heavy	3.0b	2.2b	7.3b
3=Light	7.4a	19.5a	26.3a
Mean	3.8	0.4	5.1
MSD[b]	1.9	12.0	12.4
	---------- *-Diameter-* ----------		
Defoliated	0.52a	0.06c	0.31 b
Severe	0.50a	-0.19c	0.58b
Heavy	0.48a	1.43b	2.10b
Light	1.09a	3.47a	4.66a
Mean	0.68	1.39	2.13
MSD	0.61	1.31	2.46

[a] Means within a column with the same letter are not significantly different ($p<0.05$) using Tukey's Studentized Range (HSD) Test.
[b] Minimum Significant Difference ($p<0.05$).

rated 0 and 1 (completely defoliated and severely browsed), were not different in 1995 and 1996. These results are similar to those found by Auchmoody and Walters (1992), who demonstrated that the height of planted seedlings was affected more by browsing pressure than by light if unprotected from deer.

There were no differences in diameter growth among any of the damage ratings the first year. In the second year, seedlings rated 1 and 0 were not different from each other. Seedlings rated 2 and 3 showed the largest increase in diameter (1.4 and 3.5 millimeters, respectively) and were different from each other and from seedlings rated 0 or 1.

1996 Deer Repellent Study

Seedling survival-Just as in the 1995 study, first-year survival was high. Family, treatment, and damage rating variables were not different (p c 0.05) in survival the first year. Survival across all treatments was 98 percent. Survival of seedlings with a damage level of 1 (85 percent) was different from that of seedlings rated 2, 3, or 4 (99, 100, and 98 percent). There were no seedlings rated 0 in this study.

Seedling growth-Differences in height growth attributed to treatment were apparent (p c 0.05). Protection provided by Tree Guard was limited. Garlic Sticks and Deer-Away seemed to be most effective early on. When browse damage percentages were compared among the six treatments (fig. 2), tree shelters clearly surpassed all other deer repellent treatments. Seedlings in tree shelters had substantial increases in height the first year, and were different from all other treatments. The increased height growth of seedlings in shelters was similar to the results of Lantagne and others (1990) with northern red oak planted in a Michigan clearcut. Height growth ranged from 0.6 centimeters in the control to 52.8 centimeters for seedlings in tree shelters (table 4). Level of browse damage was also significant for height growth (p = 0.0425). Seedlings rated 4 (unbrowsed) had a mean height growth of 33.2 centimeters

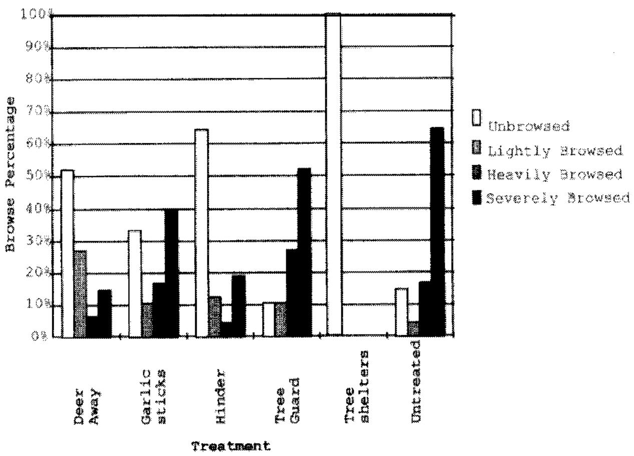

Figure 2-Comparison of four levels of browse damage among six treatments applied to selected 1+0 northern red oak planted at Chuck Swan Forest and Wildlife Management Area.

and were significantly different from seedlings rated 3, 2, or 1. However, this rapid growth for the unbrowsed seedlings can be attributed to the increased growth of seedlings in the tree shelter treatment. Seedlings rated 3 and 2 were not different from each other (12.9 and 5.4 centimeters), but were different from seedlings rated 4 or 1. Seedlings that received a rating of 1 (completely defoliated) did not increase in height and were, in fact, shorter than when they were planted. However, only 6 percent of the seedlings fell into this category.

Diameter growth across all treatments was 1 .O millimeter. The largest increase in diameter was recorded in the Deer-Away treatment (1.4), and the smallest was in the Garlic Stick plots (0.6). Seedlings in tree shelters had the second largest increase in diameter, and apparently diameter growth occurred even when seedlings had large increases in height. Larger select seedlings planted in shelters are not only protected from browse, they may be less spindly and have the possible advantage of removal from the shelter in two growing seasons.

DISCUSSION

Seedlings at a few locations grew well in 1995, but overall performance was discouraging. Loftis (1979) has reported that height growth of less than 30.5 centimeters per year is considered poor, and even at the location where best results were obtained, mean growth in the 1995 study was less than 10 centimeters in the first year. Growth rates were unacceptably slow, damage by deer was widespread, and mortality was high in the second year.

Extensive damage to seedlings by deer was recorded in both the 1995 and 1996 studies. When browse damage became apparent in 1995, Pro-Tee Garlic Sticks were applied to seedlings at every location in early June, except for those planted at Tullahoma. Browse damage to the seedlings at this location became apparent approximately 1 month later. Garlic Sticks were applied at that time. Since repellents were applied to seedlings at Tullahoma after browse damage had already occurred, protection may have been minimal. Gillingham and Bunnell (1989) conducted research on the feeding habits of black-tailed deer *(Odocoileus hemionus columbianus* Richardson) and found that memory may play an important role in the foraging activities of deer. The results of the marginal soils study would suggest that some form of protection from deer is needed at planting time, and should be applied before feeding habits are established.

Presently, outside of Pennsylvania, published evidence on the effects of deer browsing on oak has been very limited. Lorimer (1992) stated that researchers have found that establishing hardwood plantations is often like "setting the table for deer," and more evidence is needed on the effects of moderate deer browsing on growth rates of oak. Seedlings planted for the deer repellent study in 1996 were protected initially, and several repellent treatments seemed to deter further browsing. From planting time until budbreak, no browse damage was recorded, and even in the untreated plots deer did not begin to browse the

Table 4-Height and diameter growth of 1+0 northern red oak planted at Chuck Swan Forest and Wildlife Management Area by treatment and deer damage level

Treatment	Mean[a]	Damage level			
		Severe	Heavy	Light	Unbrowsed
		Height (cm)			
Deer Away	9.6bc	-25.5	8.7	7.6	15.5
Garlic Sticks	5.6bc	-7.5	6.3	10.8	5.5
Hinder	13.1b	—	8.2	16.9	12.8
Tree Guard	5.8bc	0.00	5.4	10.8	—
Tree Shelters	52.8a	—	—	56.0	52.7
Untreated	0.6c	-6.7	2.5	—	—
Mean[b]	15.4	-8.3c	5.4b	12.9b	33.2a
		Diameter (mm)			
Deer Away	1.44a	0.06	1.32	1.57	1.57
Garlic Sticks	0.57c	0.32	0.54	0.64	1.50
Hinder	1.09ab	—	0.79	1.09	1.18
Tree Guard	0.78bc	0.10	0.69	1.70	—
Tree Shelters	1.14ab	—	—	1 .00	1.15
Untreated	0.94abc	0.87	0.96	—	—
Mean[b]	1.01	0.55b	0.80ab	1.28a	1.25a

[a] Means within a column with the same letter are not significantly different ($p<0.05$) using Tukey's Studentized Range (HSD) Test.
[b] Means with the same letter within rows are not significantly different.

seedlings until approximately 6 weeks after planting. Seedlings that were treated with some form of deer repellent outperformed unprotected ones. No seedlings were completely defoliated in the 1996 study, and there may be two possible reasons for this outcome: deer did not become accustomed to browsing the seedlings because protection was applied at planting time or, because it is a wildlife management area, plenty of other food sources were available.

CONCLUSIONS

Results from both studies indicate that browse damage ratings assigned to northern red oak seedlings are helpful in identifying which ones are expected to respond and recover, and which seedlings are more likely to die. In areas where browse pressure is a concern, protection from deer in the first few years after planting is crucial to the early growth and development of northern red oak seedlings. The increased growth rate and excellent early performance of these select seedlings in tree shelters deserves further study.

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NATURAL ESTABLISHMENT OF WOODY SPECIES ON ABANDONED AGRICULTURAL FIELDS IN THE LOWER MISSISSIPPI VALLEY: FIRST- AND SECOND-YEAR RESULTS

James A. Allen, John McCoy, and Bob D. Keeland[1]

Abstract-The natural establishment of woody seedlings on abandoned agricultural fields was investigated at sites in Louisiana and Mississippi. Series of disked and undisked plots originating at forest edges and oriented in cardinal directions were established on fields at each site. During the first 2 years, seedling recruitment was dominated by sweetgum, sugarberry, and elms at both sites. Seedling establishment was strongly affected by direction from mature forest and disking, and to a slightly lesser degree by distance from mature forest. Slightly under half of the variation in seedling numbers per plot was explained by the effects of direction, distance, and disking, indicating that other factors also may play an important role in seedling recruitment.

INTRODUCTION

A typical restoration project in the Lower Mississippi Valley region involves the establishment of two to three overstory tree species, usually oaks (esp. *Quercus nuttallii, Q. phellos, Q. nigra*, and *Q.* pagoda), either by planting 1-year-old bare-root seedlings or by direct seeding acorns. The techniques used to reforest former agricultural lands have been described in more detail elsewhere (Allen and Kennedy 1989).

It is generally assumed that establishment of other woody species will occur through natural dispersal and that a mixed-species forest will develop over time. There is, however, evidence that a mixed-species forest does not always develop, at least during the first 25 to 50 years. For example, Haynes and Moore (1988) noted that while some reforestation sites in the Lower Mississippi Valley appeared to have a desirable degree of species diversity, others did not. Also, although Allen (1990) found that average stocking of invader species on 10 reforestation sites was fairly high overall, most of the established trees were within 60 meters of mature forest (Allen, in press). Among the factors suggested by Haynes and Moore (1988) as possible causes of the reduced establishment of invading woody species was the lack of available seed sources, which may be largely a factor of distance and direction to mature forest or trees.

Land managers responsible for restoration could benefit from information on patterns of natural invasion of woody species. On sites where natural invasion is expected to be slow, planting species other than oaks may prove beneficial. On sites where natural invasion is expected to be more rapid, it might be cost effective to plant only oaks and rely on natural regeneration to provide the desired species diversity. The problem-and the justification for this study-is that it is not yet clear which sites (or portions of large sites) will have adequate natural invasion.

METHODS

This study is being conducted on two sites: (1) a former farm located in Sharkey County, MS, (the Sharkey Site) and (2) Lake Ophelia National Wildlife Refuge (NWR), near Marksville, LA. Most of the Sharkey Site was transferred to the U.S. Fish and Wildlife Service from the Farmers Home Administration in 1993. A small portion on the southern end Of tract was transferred to the USDA Forest Service (Delta National Forest).

The Sharkey Site is approximately 820 hectares and is located about 8 kilometers east of Anguilla, MS. Most of the site has been cleared since the early 1960's. A recent on-site inspection by a Natural Resource Conservation Service employee found most to be Sharkey clays. On the highest sites, there are small areas of Dundee silt loams and Forestdale silty clay loams.

Lake Ophelia NWR is located on the Red River floodplain in east central Louisiana (Avoyelles Parish). The 5,990-hectare refuge is characterized by meandering channels, shallow sloughs, oxbow lakes, cypress-tupelo swamps, and bottomland hardwoods. The overall configuration of the area is a combination of ridges and swales with only slight changes in elevation. Soils in the area are roughly 50 percent Tensas silty clays and 40 percent Sharkey clays. Much of the refuge is currently open land that is still farmed, or land that was cleared and is now in various stages of reverting back to forest. The refuge is prone to both backwater flooding and shallow flooding from local precipitation (U.S. Fish and Wildlife Service 1988).

In the fall of 1994, a series of transects was laid out at each site in cardinal directions, originating at the edges of mature forests and proceeding into recently abandoned agricultural fields. Each transect consists of one disked and one undisked section, each 30 meters by 150 meters. Within each section a series of eight 0.01-hectare (10 by 10 meters) plots were established at 20-meter intervals; plot mid-points range from 5 meters to 145 meters from the forest edge. Where possible, three transects were established in each of the four cardinal directions at each study site. Limitations on the

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availability of suitable sites resulted in the following exceptions: (1) only two west-facing transects could be established at the Sharkey Site, and (2) only two north-facing and no east-facing transects could be established at Lake Ophelia NWR. A total of 19 transects and 304 plots was established.

All the transects at Lake Ophelia and the north-facing transects at the Sharkey Site were on fields farmed less than 1 year prior to their establishment. These fields were essentially devoid of competing vegetation prior to the 1995 growing season. The remainder of the transects on the Sharkey Site were established in fields that had been out of production for 1 or 2 growing seasons. The transects on these fields were bush-hogged prior to plot establishment.

Woody vegetation established on the plots was measured in the late fall of 1995 and 1996. A complete census of woody stems was made on each plot. Two l-square meter subplots were located within each main plot to characterize herbaceous vegetation. Ocular estimates of percent cover were made for total cover and cover for each of the most common herbaceous species.

A four-way analysis of variance was performed on the 1996 data to test for the effects of direction, distance, disking, and site on the number of seedlings established per plot. All four factors were treated as fixed effects. Because the mean number of seedlings per plot was small (<10 in both years) and many plots had no seedlings, a square root transformation (of the number of seedlings per ptot + ½) was employed (Steel and Torrie 1980). Statistical analysis was performed using the GLM procedure of the Statistical Analysis System (SAS, Release 6.11). Only descriptive statistics are presented for herbaceous vegetation.

RESULTS AND DISCUSSION

Herbaceous Vegetation

At Lake Ophelia NWR, where all fields were in their first year after abandonment in 1995, annuals (e.g., *Sida rhombifolia*) were an important component of the herbaceous vegetation. The importance of annuals declined in 1996 at Lake Ophelia NWR, and perennials such as *Aster* spp. and *Solidago* spp. grew in overall importance (table 1). At the Sharkey Site, where most fields had been abandoned for a longer period, perennials were dominant in both years.

Broad similarities between the two study sites were evident, but there were also some potentially important differences. Johnson grass *(Sorghum halepense),* for example, was an important component of the vegetation at the Sharkey Site, especially in 1995, but was relatively uncommon at Lake Ophelia NWR (table 1).

Most herbaceous species were found on both disked and undisked plots, but their relative importance often varied. Disking eliminated raised planting rows, which, because of their slightly higher elevation, offered drier microsites than adjacent furrows. Disking therefore favored species more tolerant of soil saturation (e.g., *Iva annua),* while drier-site species (e.g., *Andropogon glomeratus)* were more common on undisked plots (table 1).

Table l-Importance value (IV200; relative frequency + relative cover) for selected herbaceous species by study site, year, and disking

	Lake Ophelia NWR				Sharkey Site			
	1995		1996		1995		1996	
Species	Disk	No Disk	Disk	No Disk	Disk	No Disk	Disk	No Disk
Aster spp.	25.3	31.6	65.7	56.4	45.4	38.5	61.3	53.9
Andropogon glomeratus	2.2	3.7	11.8	29.8	4.5	10.8	2.7	7.5
Desmanthus illinoensis	0.0	0.0	0.0	0.0	7.8	6.5	17.0	16.1
Iva annua	25.1	22.0	58.6	31.9	25.4	22.7	27.2	18.6
Sida rhombifolia	24.0	25.9	0.0	0.0	1.4	1.4	0.0	0.0
Solidago spp.	10.4	8.7	20.1	28.1	24.6	29.9	33.8	44.7
Sorghum halepense	5.7	4.1	6.4	3.7	50.1	53.7	24.1	26.9
Xanthium struimarium	27.3	16.7	1.5	0.4	0.0	0.0	0.0	0.0
Other species	80.0	87.3	35.9	49.7	40.8	36.5	33.9	32.3

Overall Seedling Abundance

A total of 1,071 woody seedlings were censused on the two sites in 1995 for an overall average of 351 seedlings per hectare. Most of the seedlings (727) were classified as sprouts from seedlings already established on the Sharkey Site fields that had been abandoned for more than one growing season. Fifteen woody species or species groups were found, of which sweetgum *(Liquidambar styraciflua)* and elms (*Ulmus* spp.) were the most common (table 2), followed by sugarberry (*Celtis laevigata*) and persimmon *(Diospyros virginiana)*. Oaks (Quercus spp.) and other heavy-seeded species were relatively uncommon.

By the end of the 1996 growing season, the mean number of seedlings increased to 605 per hectare. Most species increased in abundance in the second year; the few with large declines were relatively rare species (table 2).

The general pattern of seedling abundance and species composition was similar at the two study sites. At the end of the 1996 growing season, there was no significant difference in overall seedling abundance between the two sites (table 3). The same three species or species groups (sugarberry, sweetgum, and elms) were the most common at both sites, although their relative abundance differed. Elms were the most common seedlings on the Sharkey Site and sugarbery was by far the most common on Lake Ophelia (table 2). In addition to the large number of sugarbery seedlings at Lake Ophelia NWR, other notable differences between the two sites include the total absence of boxelder (*Acer negundo)* and the smaller number of persimmon at Lake Ophelia NWR.

Effects of Direction from Mature Forest

The orientation of transects with respect to adjacent mature forest had a significant effect on seedling establishment (table 3). Significantly more seedlings were found per plot on the east- and, to a lesser degree, north-facing transects than along those facing south and west (fig. 1). This pattern is not unexpected, given the prevailing wind patterns in the region, which are affected by both the west-to-east jet stream and frequent fronts moving northeast from the Gulf of Mexico.

Effects of Distance from Mature Forest

The effect of distance from the forest edge was not significant at the 0.05 level (table 3; fig. 2a). A more rapid decline in the number of seedlings with distance from the forest edge has been found in other studies (Harper 1977; Hughes and Fahey 1988; Allen, in press). We suspect that the more typical pattern is obscured in our case by the relatively high number of seedlings that may have been

Table 2-Mean number of woody species seedlings (excluding vines) found per hectare by study site and year

Species	Sharkey Site 1995	Sharkey Site 1996	Lake Ophelia 1995	Lake Ophelia 1996	Total 1995	Total 1996
Acer negundo	52.4	48.2	0.0	0.0	30.1	27.9
Acer rubrum	12.6	21.0	5.4	15.6	9.6	18.8
Amorpha fruticosa	0.0	0.5	0.0	0.0	0.0	0.3
Celtis laevigata	55.6	95.3	48.4	248.5	52.6	159.6
Cephalanthus occidentalis	0.0	17.5	3.2	3.2	1.2	11.6
Cornus spp.	0.0	0.0	0.0	4.7	0.0	2.0
Crataegus spp.	12.6	14.8	6.2	33.6	9.9	22.7
Diospyros virginiana	31.1	65.2	25.7	23.5	28.9	47.7
Forestiera acuminata	.0	0.0	2.2	0.0	1.0	0.0
Fraxinus spp.	14.8	31.1	0.7	17.3	8.9	25.2
Gleditisia spp.	1.2	1.7	0.0	0.0	0.7	1.0
Ilex decidua	14.1	19.8	0.0	0.0	8.1	11.6
Liquidambar styraciflua	138.6	118.6	44.5	110.2	98.8	115.0
Planera aquatica	0.0	0.0	0.7	0.0	0.3	0.0
Platanus occidentalis	0.0	0.0	1.5	0.7	0.7	0.3
Quercus spp.	8.4	6.9	14.8	19.5	11.1	12.1
Salix nigra	0.0	1.7	0.0	0.7	0.0	1.2
Ulmus spp.	134.6	174.4	28.2	112.4	89.7	148.2
Total per acre	476.0	616.7	181.5	589.9	351.6	605.2

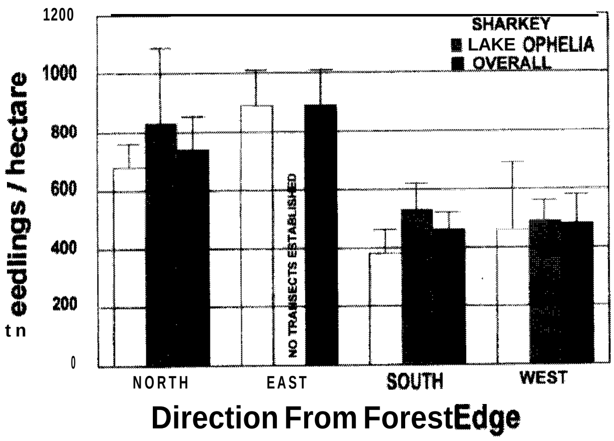

Figure l-Second-year seedling establishment (mean ± 1 SE) in relation to direction of transect orientation from adjacent forest.

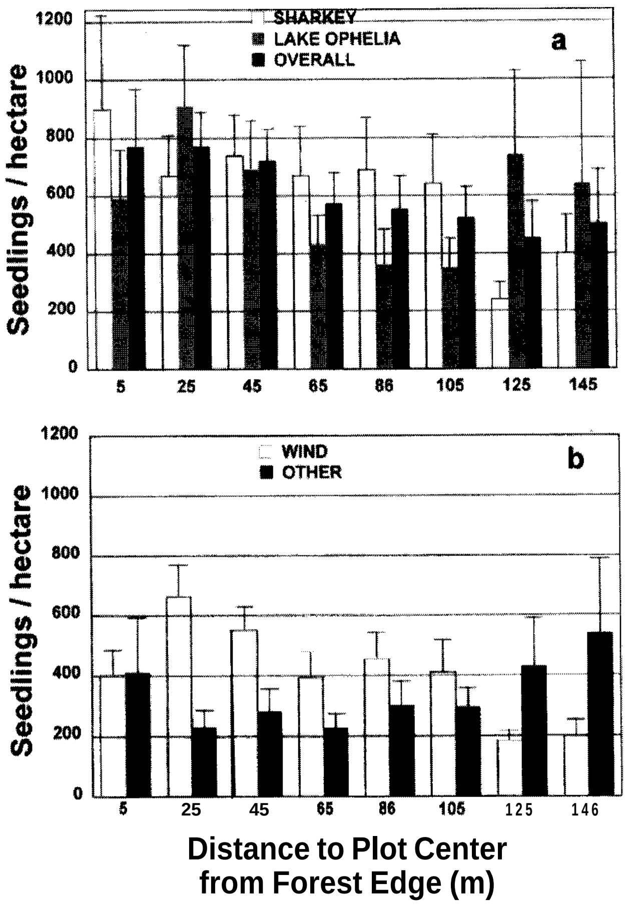

Figure 2-Second-year seedling establishment (mean ± 1 SE) as affected by (a) distance from forest edge and (b) distance and means of seed dispersal.

dispersed by water or animals. Species believed to be dispersed primarily by means other than wind are more common than wind-dispersed seedlings at the farthest distances evaluated (fig. 2b). The high standard errors for the other than wind-dispersed seedlings at 125 meters and 145 meters from the forest edge are caused by high numbers of seedlings found in several plots where localized clumps of sugarberry (possibly due to wracking) occurred, mainly at Lake Ophelia NWR.

Effects of Disking

Disking had a very pronounced effect on seedling establishment (table 3). More than twice as many seedlings

Table 3-Analysis of variance table for the effects of direction from mature forest, distance from mature forest, disking, and site on the mean number of seedlings per plot

Source	DF	Type III Sum of Squares	F Value	P
Direction (DIR)	3	33.473	8.08	0.0001
Distance (DIS)	7	19.023	1.97	0.0613
DIR*DIS	21	28.523	0.98	0.4854
Disking (DISK)	1	57.044	41.31	0.0001
DIR*DISK	3	9.461	2.28	0.0803
DIS*DISK	7	2.950	0.31	0.9509
DIR*DIS*DISK	21	33.483	1.15	0.2959
Site	1	2.757	2.00	0.1593
DIR*SITE	2	5.004	1.81	0.1661
DIS*SITE	7	15.683	1.62	0.1311
DIS*DIS*SITE	14	27.112	1.40	0.1549
DISK*SITE	1	12.183	8.82	0.0034
DIR*DISK*SITE	2	4.707	1.70	0.1847
DIS*DISK*SITE	7	7.096	0.73	0.6433
DIR*DIS*DISK*SITE	14	14.514	0.75	0.7210

were found on undisked plots than on disked plots (fig. 3). The large soil clods and possibly a soil surface more prone to drying and high temperatures may be major factors responsible for lower seedling establishment on disked plots. The higher microsites found on the undisked plots were probably also a very significant factor. The tendency for seedlings to be found on the raised planting rows, rather than in the adjacent furrows, was especially evident at Lake Ophelia NWR. Although there were differences in herbaceous vegetation between disked and undisked plots, it appears that the effect of disking on availability of suitable microsites was more important than vegetation differences in its effect on woody species establishment.

The only significant interaction found in the 1996 data was for disking by site (table 3). We attribute this to the wetter conditions prevailing at Lake Ophelia NWR, which probably made small differences in microsite even more critical. The greater response of seedling establishment to disking for Lake Ophelia NWR is evident in figure 3.

Other Factors Affecting Seedling Establishment

The four-way ANOVA model had an R^2 of 0.49, indicating that slightly over half of the variation observed in seedling establishment was due to factors other than those

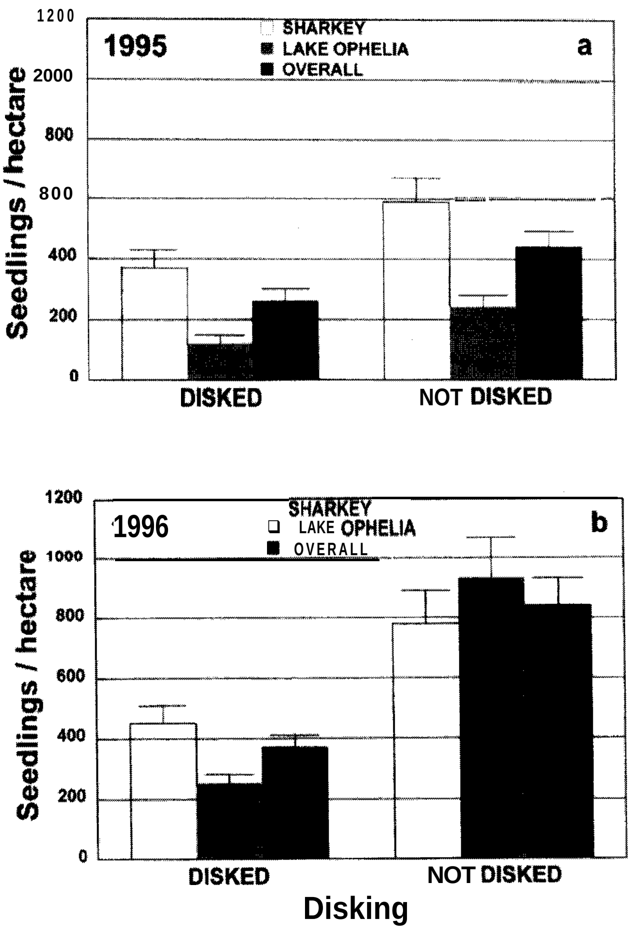

Figure 3-Seedling establishment (mean ± 1 SE) as affected by disking in (a) 1995 and (b) 1996.

evaluated. Other factors that may be important-besides the inevitable measurement error associated with finding seedlings in dense herbaceous vegetation-include differences (1) in time since abandonment, (2) in species composition of the adjacent forests, and (3) in microsite characteristics within and amongst fields. Another factor that may be important is the pattern of fields versus forest in the vicinity of each transect, which probably influences localized wind speed and turbulence, as well as perhaps having an impact on the total number of seed available for dispersal at any given site.

CONCLUSIONS

Fields at both study sites are going through a pattern of old-field succession that appears to be typical for the region, and which may eventually result in bottomland forest stands of moderately high species diversity. It is clear, however, that the general course of old-field succession is being affected by factors such as the distance and direction of the field from mature forest, and by whether or not the field has been disked.

There are several implications of this research for resource managers involved in bottomland hardwood forest restoration. First, the overall emphasis on planting heavy-seeded species with limited dispersal capabilities, such as oaks and hickories (*Carya* spp.), appears to be fairly well-justified. It is likely that species diversity within restored stands could be increased substantially, however, with supplemental plantings of other species. Supplemental plantings may be most effective in fields oriented to the west and south of mature forest and at distances of greater than about 60 to100 meters from forest edges. Sweetgum, elms, and sugarberry generally establish in sufficient numbers, but almost all other species found in bottomland systems might be good candidates for supplemental plantings. Disking appears to be a mixed blessing. Disking usually enhances survival and growth of planted seed or seedlings (Haynes and others 1995), but, especially on wetter sites, it may temporarily reduce the natural establishment of other seedlings.

ACKNOWLEDGMENT

The authors would like to thank the staffs of the Yazoo NWR Complex, Lake Ophelia NWR, and the Delta National Forest for providing access to the two study sites and carrying out the site preparation required for installation of the study. We would also like to thank Robert LaFleur, Wayne Norling, Monica Moore, Matt Sevier, Chris Wells, and Parker Day for assistance in plot establishment and data collection. Drs. Darren Johnson and James Baldwin provided statistical advice.

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RIVERFRONT HARDWOOD REGENERATION 1 YEAR FOLLOWING COMPLETE AND PARTIAL OVERSTORY HARVESTING

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Abstract-Emphasis on bottomland hardwood regeneration research has focused on the oaks (Quercus spp.). Information is needed on the regeneration dynamics of other bottomland hardwood species including those associated with the riverfront hardwood type. Therefore, a study was established in 1995 to follow the long-term establishment and development of bottomland hardwood regeneration. Two harvesting methods, clearcutting and selection cutting, along with an unharvested control were established in the winter of 1995/1996. First-year results showed that harvesting and growing season flooding had an impact on first-year survival and growth. One species, sugarberry (*Celtis laevigata*), responded well to the harvesting treatments. All other species responded less favorably.

INTRODUCTION

In the past 15 to 20 years research in bottomland hardwood regeneration has focused on oak (*Quercus* spp.) species (Clark 1993, Hodges and Janzen 1987). Evidence for this includes the number of bottomland hardwood papers presented at recent biennial southern silvicultural research conferences (Brissette 1993, Edwards 1995) and the number of oak-specific symposiums (Loftis and McGee 1993). While oaks constitute an important component of southern bottomland hardwood forests, other commercially important tree species exist (Putnam and others 1960). These species include those of the riverfront hardwood association, namely cottonwood (*Populus deltoides*), green ash (*Fraxinus pennsylvanica*), sweet pecan (*Carya illinoensis*), and sugarberry (*Celtis laevigata*). Given the importance of an increasing understanding of bottomland hardwood ecosystem structure and function, information is needed on the regeneration dynamics of nonoak species. Therefore, a study was initiated to: (1) determine the response of advanced riverfront hardwood regeneration to two levels of harvesting, (2) determine the composition and development of new riverfront hardwood regeneration following two levels of harvesting, and (3) test a regeneration evaluation model recently developed for coastal plain bottomland hardwood types (oak types).

METHODS

The study site is located on Pittman Island in Issaquena County, MS, adjacent to the Mississippi River and approximately 3 miles south of the Arkansas border. This island is located within the unprotected portion of the Mississippi Alluvial Plain (inside the levees); therefore, it is subjected to periodic flooding. Topography is ridge/swale with differences in elevation of approximately 3 to 5 meters in extreme cases. Soils are primarily of the Commerce silt loam and Sharkey clay series (Mr. Johnny Lack, Anderson-Tully Company, personal communication). Tree species composition is of the riverfront hardwood association including sugarberry (62 percent), sweet pecan (8 Percent), boxelder (*Acer negundo;* 8 percent), American elm (*Ulmus americana;* 8 percent), green ash (3 percent), and Nuttall oak (Q. nuttallii, 2 percent).

TWO treatments, clearcutting and selection cutting, were installed in the winter of 1995/1 996. Each treatment, plus an unharvested control, were located on 20-hectare treatment plots and replicated three times in a partially randomized design (no two treatment plots could share a common border) for a study area of 180 hectares. In the clearcutting treatment, all commercial stems were removed during the logging operation. A followup treatment consisted of felling all stems ≥5 centimeters diameter at breast height (d.b.h.) to create a complete, or biological, clearcut. In the selection harvest, tree marking was done according to Anderson-Tully Company guidelines. Combinations of single-tree and group selection harvesting were conducted to remove approximately one-third to one-half of the basal area. Tree species favored for continued management included green ash, Nuttall oak, sweet pecan, and sugarberry.

Prior to harvest, sixteen 0.1 -hectare circular plots were systematically established within each treatment plot. Within each O.l-hectare plot, a O.Ol-acre (0.004 hectare) circular regeneration plot was established, on either the east or west end of the larger plot. An English-unit plot dimension was necessary to test the regeneration results with a regeneration evaluation model recently developed for Coastal Plain bottomland hardwoods (Hart and others 1995). All seedlings ≥30 centimeters (1 foot) in height were measured for height, ground-line diameter, previous growing season linear stem growth, topographic location (ridge, swale, or transition between the two), and vigor (good, medium, or poor). These seedlings were also flagged and distance/azimuth measured for future relocation and measurement. First-year postharvest measurements were conducted during the winter of 1996/1997 (designated as 1996) and included any new seedlings in the 230 centimeters size class. Survival and density retention were calculated based on the two sets of measurements. Density retention was defined as the percentage of seedlings ≥30 centimeters tall in 1996 compared to those present in 1995. A density retention Of 100 percent indicates 100 percent survival with no recruitment of new seedlings ≥30 centimeters tall, or the recruitment of new seedlings into this size class was equal to the mortality of seedlings measured prior to harvest. Data were analyzed using analysis of variance. Duncan's

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multiple range test was used to separate treatment means if significant differences (alpha=0.05) were found in the analysis of variance.

RESULTS AND DISCUSSION

Survival and Density Retention

Survival rate of seedlings measured in 1995 was 39 percent. This low rate survival was the result of both harvesting and a June 1996 flood that inundated the site for 3 weeks. Harvesting effects were apparent as survival was lowest in the clearcuts (15 percent) and highest in the controls (68 percent) with the partial harvest having an intermediate value (35 percent) (table 1). A similar pattern of survival was reported by Lowe (1996) in the Neches River floodplain in east Texas. Surprising, though, was the low survival rate in the controls where no harvesting took place. Seedlings ≥30 centimeters were considered well-established, advanced regeneration; therefore, they were expected to have low mortality in the controls. Flooding during the 1996 growing season represented the fourth straight year of growing season flooding inside the levee system of the Mississippi River. These floods inundated seedlings after they had leafed out, placing them under considerable stress. Most of the seedlings measured prior to harvest were classed as poor in vigor, due probably to both low light levels and the previous three years of growing season flooding.

While survival was low, especially in the harvest treatments, density retention was good, indicating a high recruitment of seedlings into the ≥30 centimeters size class (table 1). Although not significantly different, a pattern of greater harvest intensity resulted in higher mean density retention. This pattern was the inverse of survival. Lowe (1996) also reported an inverse pattern between survival and density retention, with lowest survival and greatest density retention occurring in the greatest harvesting intensity (clearcuts). High rates of density retention were particularly evident with sugarberry, especially in the harvest treatments (table 2). Sugarberry is a noted root and stump sprouter following harvesting (Kennedy 1990). Care was taken during the 1996 measurements to use only the tallest seedling when multiple root and stump sprouts were present around individual sugarberry stumps. Numerous recent sugarberry germinates (usually 3 to 6 centimeters in height) were observed during the fall following the 1995 and 1996 growing seasons. Obviously, some of these seedlings and/or the seedlings germinating from buried seed following the June 1996 flood contributed to this high recruitment of sugarberry seedlings into the ≥30 centimeters size class. All other species with a least 20 seedlings per treatment plot showed a similar pattern of survival, but not density retention, as sugarberry (table 2). Noteworthy was the low survival of green ash, a premier timber species on the Mississippi Alluvial Plain.

Height and Linear Stem Growth

Average height of seedlings was 64 centimeters prior to harvest. Linear stem growth, which reflected the growth in stem length from the previous year's terminal bud, was 8 centimeters across the study site. This low stem growth is typical of advanced bottomland hardwood regeneration growing underneath closed canopies (Janzen and Hodges 1987, Lockhart and others 1991). Average seedling height was 51 centimeters 1 growing season after harvest (table 1). Reductions in seedling height from the previous growing season can be attributed to stem dieback and mortality. While actual seedling height decreased, linear stem growth tripled for seedlings growing in the harvesting treatments (table 1). Greater growth compared to controls was most likely due to the higher light levels reaching the forest floor and the greater vigor associated with root and stump sprouts.

CONCLUSIONS

Conclusions, based on 1 -year postharvest results, are:

(1) harvesting does have an impact on regeneration survival and composition 1 year following harvesting,

Table l-Survival, density retention, and linear stem growth (LSG) for seedlings ≥1 foot in height by harvest treatment on Pittman Island, Issaquena County, MS

		Harvest treatment		
Description	Unit	Clearcut	Selection	Control
Survival	Percent	15a[a]	35 b	68 c
Density retention	Percent	142	90	73
Height (1995)	Centimeter	62	64	67
Height (1996)	Centimeter	48	52	52
LSG (1995)	Centimeter	8	9	7
LSG (1996)	Centimeter	34 a	32 a	10 b

[a] Numbers followed by different letters within a row are significantly different at the alpha=.05 level.

Table 2—Survival (Surv.) and density retention (DR.) for seedlings ≥30 centimeters in height for selected species by harvest treatment on Pittman Island, Issaquenna County, MS

Species	Clearcut Surv.	Clearcut DR.	Selection Surv.	Selection DR.	Control Surv.	Control DR.
	Percent					
Sugarberry	16	224	34	129	73	75
Green ash	9	11	24	27	57	60
American elm	11	22	33	33	58	65
Deciduous holly	18	35	50	66	131	86
Swamp privet	5	47	50	69	93	93

(2) growing season flooding also appears to have an impact on advanced regeneration survival,
(3) sugarberry has the capacity to respond rapidly to harvesting, and
(4) 1 -year postharvest results are probably not reliable to predict future regeneration composition in lands inside the levees of the Mississippi River.

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AN EVALUATION OF HARDWOOD REFORESTATION METHODS ON PREVIOUSLY FARMED LANDS IN CENTRAL ALABAMA

D. Ramsey Russell, Jr., John D. Hodges, and Andrew W. Ezell[1]

Abstract-First-year growth and survival of 1-O oak seedlings were measured to determine the effectiveness of operational-scale mechanical subsoiling, planting methods, and grass control methods in establishing oak on previously farmed lands in central Alabama. First-year seedling height growth was improved by a mechanically subsoiled treatment. Machine-planted seedlings had significantly greater first-year growth and survival than hand-planted seedlings. A two-pass application of Fusilade 2000™ resulted in significantly greater first-year growth in height, and discing significantly increased first-year survival in a field that possessed a heavy grass sod.

INTRODUCTION

Bottomland hardwood forests are among the most productive timberland and wildlife habitats in the United States. This resource has numerous economic, ecological, and aesthetic values to society. The consumption of forest products has increased 140 percent since 1975, and hardwoods comprise about one-fifth of the 370 million cubic meters consumed annually in the United States (Anonymous 1997). Hardwood growth currently exceeds hardwood removals, but may not be readily available for harvests (Abt and others 1994).

Tremendous agricultural potential led to the clearing of about half the original eastern hardwood forest by the late 1930's, and the pace of clearing hardwood bottomlands escalated throughout the 1970's. Many of these hardwood bottomlands were better suited for forest than for agriculture because of periodic inundation (Allen and Kennedy 1989). Currently, there are opportunities to reforest these agricultural lands on a cost-share basis under the auspices of the Farm Bill and its amendments. In the South, about 73,700 hectares have been enrolled for reforestation under State and Federal cost-share programs, and it is projected that as many as 110,000 hectares will be reforested by the year 2005.[2]

Artificial regeneration is the only means of establishing oak on areas that are void of an existing oak component. In the South, artificial regeneration implies either direct seeding or seedling planting (Kennedy 1992), but there is limited information regarding the ensured, future success of bottomland oak species on agricultural lands. The establishment method is complex and several years may elapse before planting success can be adequately appraised. Development and evaluation of practical oak reforestation techniques are needed (Lea and Fredrick 1989).

The fracturing of a soil hardpan by mechanical subsoiling or discing is an effective means of increasing tree growth by mitigating the adverse effects of soil compaction (Woodrum 1982, Morris and Lowery 1988, Nix 1989), a phenomenon commonly associated with heavy equipment trafficking. Subsoiling increases the amount of soil exploited by seedling roots, results in greater uniformity of seedling depth, and may increase soil moisture availability (Miller 1992). Increased planting uniformity reportedly increases the survival of machine-planted pine seedlings as compared to hand-planted pine seedlings (South and Mexal 1984). Studies are inconsistent with respect to which of the two planting methods is generally best as a means of establishing pine (*Pinus* spp.) (Wakely 1954, McNab and Bredemuehl 1983, Xydius and others 1983). Ninety-one percent of nonindustrial and public plantings are currently performed by independent contractors (Long 1991).

Interference from competing vegetation may be the most consistent factor contributing to oak establishment failures on old field sites (Bey and others 1975, von Althen 1977). Increased early growth rates of oaks after vegetation control have been noted (Aust and others 1985, Krinard and Kennedy 1987).

The purpose of this research was to evaluate mechanical subsoiling, hand and machine planting, and techniques of controlling competing vegetation on fields with heavy grass sods as suitable methods of reforesting recently abandoned farmlands to oak. This study was comprised of three independent experiments that were conducted on an operational basis.

METHODS

The study was incorporated into a planting activity encompassing approximately 1,011 ha that is part of the Tennessee Tombigbee Waterway Wildlife Mitigation Project administered by the U.S. Army Corps of Engineers. The study area was located in the Alluvial Floodplains Province and surrounded by the Hilly Coastal Plains Province (Hodgkins and others 1976) in northeastern Lowndes County, near Whitehall, AL. Primary land-use prior to 1996

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[2] Personal communication. 1997. Callie Schweitzer, Reforestation Forester, U.S. Department of Agriculture, Forest Service, Stoneville Hardwoods Laboratory, Stoneville, MS 38776.

consisted of cotton production. Fallow cotton fields, hay fields, and forestland comprised remaining land usages.

Operational-scale treatments consisted of mechanical subsoiling, discing, two-pass herbicide applications, and machine seedling plantings. Operational-scale treatments were performed by an independent contractor under agreement with the State of Alabama Department of Conservation and Natural Resource Game and Fish Division. Experimental plot size was 1616 square meters. Seedlings were spaced on a 3.66-meter grid. Plot size and seedling Spacing facilitated the planting of 100 seedlings Per plot, but only the interior 64 seedlings were measured to eliminate edge bias. Response variables were seedling growth in height and diameter, and percent survival. Preseason seedling heights and diameters were measured prior to active stem growth in the third week of April 1996. Postseason seedling heights and diameters were measured in the fourth week of September 1996.

Subsoiling Experiment

The mechanical subsoiling experiment was located in a former cotton field on an upland site with Bama soil series (fine-loamy, silicous, thermic Typic Paleudults). The site possessed a traffic pan within 30.5 centimeters of the soil surface. Experimental plots were arranged in a split-plot design. Mechanical subsoiling and control comprised whole-plot experimental treatments. Split-plot experimental variables consisted of machine-planted 1-O cherrybark oak (*Quercus pagoda),* water oak (Q. *nigra*), and white oak (*Q. alba*) bareroot seedlings. Treatments were randomly assigned to experimental plots, and each treatment combination was replicated four times. The ripping procedure was implemented by welding a metal shank about 61 centimeters in length to the trencher of a continuous-furrow mechanical tree planter and traversing the site 6 weeks prior to planting. Treatment seedlings were planted directly into the subsoiled trench.

Planting Method Experiment

A factorial design was used to compare the effectiveness of hand and machine planting methods. Experiment treatments consisted of topographic site, oak species, and planting method. Soils at the upland site are of the Bama soil series. The terrace site consisted of Annemaine soil series (clayey, mixed, thermic Aquic Hapludults). Soils at the floodplain site were of lzagora soil series (fine-loamy, silicous thermic Aquic Paleudults). Seedlings were 1-0 bareroot cherrybark and water oak. Treatments Were randomly assigned to experimental plots and each planting method-species combination was replicated three times On the upland, terrace, and floodplain sites. Machine and hand plantings were performed January-February 1996.

Grass Control Experiment

A completely randomized design was used to evaluate techniques for controlling competing vegetation on a hayfield site that had a heavy grass sod. The experiment was situated on a low terrace site with Annemaine soil series. Experimental treatments were discing immediately prior to planting, a one-pass over-the-top band application of Fusilade 2000™ in June, discing before planting and a one-pass over-the-top band application of Fusilade 2000™ in June, a two-pass over-the-top band application of Fusilade 2000™ in June and again in July, and an experimental control. Herbicide application rate was 2.62 liters Of Fusilade 2000™ per hectare with an 80 percent nonionic surfactant. The two-pass herbicide treatment was replicated three times. All other treatments were replicated four times. Seedlings were machine planted and consisted entirely of 1-O bareroot cherrybark oak.

RESULTS

Subsoil Experiment

Preseason seedling heights were greater ($p = 0.0129$) in the control than in the subsoil treatment. Mean preseason height of treatment seedlings was 34.8 centimeters versus 36.7 centimeters for control seedlings. Mechanical subsoiling increased ($p = 0.0155$) the first-year height growth of oak seedlings. First-year seedling diameter growth and percent survival did not differ ($p = 0.0919$ and $p = 0.9188$, respectively) between treatments. First-year height growth of cherrybark oak seedlings was greater ($p = 0.0317$) in the mechanical subsoil treatment than in control. First-year height growth of water oak ($p = 0.0518$) and white oak ($p = 0.0892$) did not differ between treatments (table 1).

Planting Methods Experiment

Machine-planted seedling heights (mean = 42.1 centimeters) were greater ($p = 0.0066$) than hand-planted seedling heights (mean = 36.8 centimeters) at preseason sampling. Machine planting increased the first-year height growth ($p = 0.0002$), first-year diameter growth ($p = 0.0013$), and first-year survival ($p = 0.0001$) of cherrybark and water oak seedlings (table 2). Average height growth was lower on the terrace site (mean = 9.8 percent) than on the upland (mean = 34.2 percent) and floodplain (mean = 25.3 percent) sites. Mean diameter growth differed among upland (mean = 72.9 percent), terrace (mean = 24.6 percent), and floodplain (mean = 51.7 percent) sites.

Percent diameter increase of water oak was greatest on upland and floodplain sites. Percent diameter increase of cherrybark oak was greater ($p = 0.0077$) on the upland than on the floodplain site. Water oak did not exhibit differential survival among topographic sites, but survival Of cherrybark oak was less ($p = 0.0019$) on the upland than on the floodplain and terrace sites. Survival of Water oak seedlings was generally greater than survival of cherrybark oak seedlings.

Machine planting resulted in greater ($p = 0.0169$) seedling survival on the upland and terrace sites than did hand planting, but seedling survival did not differ significantly between planting methods on the floodplain site. Machine-planted water oak had greater survival than hand-planted water oak, and machine-planted cherrybark oak had greater survival than hand-planted water oak. Hand-planted water oak had greater ($p = 0.0006$) survival than hand-planted cherrybark oak. No differential survival was detected between hand-planted water and machine-planted cherrybark oak seedlings (fig. 1).

Table l-First-year height growth (cm), diameter growth (mm), and percent survival (mean ± standard error) of 1-O cherrybark, water, and white oak seedlings in response to mechanical subsoiling; relative percent height growth and percent diameter growth are in parentheses; means in a row with unlike letters differ significantly at the 0.05 probability level

Response	Subsoil treatment	Control
Cherrybark oak		
Height growth	11.9 ± 0.68	7.7 ± 1.0
	(35.6 ± 1.8)a	(21.3 ± 2.9)b
Diameter growth	2.8 ± 0.21	2.4 ± 0.4
	(59.3 ± 3.5)a	(54.7 ± 8.7)a
Survival	73.5 ± 2.72a	74.8 ± 3.8a
Water oak		
Height growth	26.9 ± 3.0	16.5 ± 1.8
	(70.3 ± 8.8)a	(39.7 ± 3.9)a
Diameter growth	5.7 ± 0.8	4.1 ± 0.3
	(139.3 ± 23.5)a	(91.1 ± 6.4)a
Survival	96.4 ± 0.4a	94.0 ± 1.5a
White oak		
Height growth	18.6 ± 2.5	14.4 ± 1.3
	(57.8 ± 8.5)a	(44.7 ± 4.8)a
Diameter growth	4.5 ± 0.7	3.6 ± 0.4
	(99.8 ± 18.1)a	(85.2 ± 12.2)a
Survival	98.4 ± 0.6a	98.8 ± 1.2a
Total		
Height growth	19.2 ± 2.2	12.9 ± 1.3
	(54.5 ± 5.7)a	(35.2 ± 3.6)b
Diameter growth	4.4 ± 0.5	3.4 ± 0.3
	(99.5 ± 13.3)a	(77.0 ± 6.9)a
Percent survival	89.4 ± 3.5a	89.2 ± 3.4a

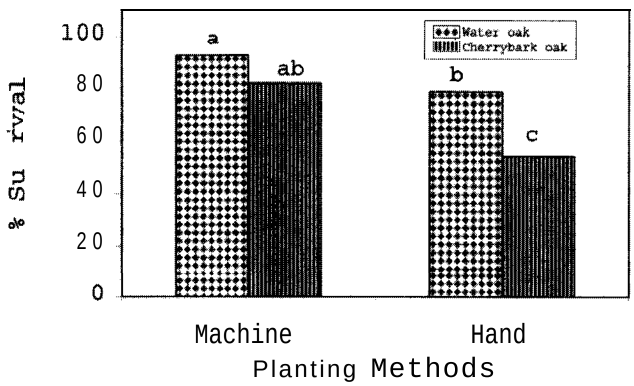

Figure l-First-year survival of cherrybark and water oak seedlings in machine- and hand-planting treatments in central Alabama. Survival means with unlike letters differ significantly at the 0.05 probability level.

Grass Control Experiment

Pre-season seedling heights were greater (p = 0.0001) in disced (alone [mean = 33.3 centimeters] and in combination with one-pass herbicide treatment [mean = 33.4 centimeters]) plots than in two-pass herbicide plots

Table 2-First-year height growth (cm), diameter growth (mm), and survival (mean ± standard error) of hand- and machine-planted 1-O cherrybark and water oak; relative percent height growth is in parentheses; growth means in a row with unlike letters differ significantly at the 0.05 probability level

	Planting method	
Response	Hand	Machine
Height growth (cm)	4.9 ± 1.6	12.8 ± 2.4
	(11.9 ± 3.4)a	(34.4 ± 6.5)b
Diameter growth (mm)	1.7 ± 0.3	2.7 ± 0.4
	(38.1 ± 7.9)a	(61.5 ± 8.9)b
Percent survival	59.8 ± 4.9a	87.0 ± 2.3b

(mean = 29.5 centimeters). The application of a split, two-pass herbicide treatment resulted in greater (p = 0.0064) first-year height growth than other grass control methods and control. Discing, alone and in combination with one-pass herbicide treatment, resulted in greatest (p = 0.0023) first-year seedling survival. First-year seedling survival did not significantly differ among one- and two-pass herbicide treatments and control (table 3). However, actual percent seedling mortality that had occurred prior to the implementation of herbicide treatments was not documented, and it is possible that seedling mortality had occurred prior to chemical treatment application.

DISCUSSION

Mechanical subsoiling significantly increased seedling height growth. Diameter growth increased at the 0.10 probability level, but mechanical subsoiling did not affect first-year seedling survival. Increased height and diameter growth on this upland site is attributed to the disruption of the existing traffic pan and to increased planting depth, both of which may have increased exploitable soil, increased moisture availability, and subsequently increased root growth and development. Apparently, moisture stress was not so severe as to limit first-year seedling survival. After three years, Miwa and Schoenholtz[3] observed no difference- between Nuttall oak (Q. *nuttallii*) seedling growth in mechanically subsoiled and control treatments on a Mississippi alluvial floodplain site, because moisture availability may generally be much greater on floodplain than on terrace and upland sites. Mechanical subsoiling may be neither appropriate nor necessary in all instances.

Increased first-year height and diameter growth of machine-planted seedlings can be attributed to greater planting depth, as confirmed by significantly lower

[3] Personal communication. 1997. Stephen Schoenholtz, Associate Professor, Mississippi State University, Mississippi State, MS 39762.

Table 3—First-year height growth (cm), diameter growth (mm), and survival (mean ± standard error) of 1-0 cherrybark oak seedlings after grass control treatments; means in a column with unlike letters differ significantly at the 0.05 probability level

Treatment	Height growth	Height change	Diameter growth	Diameter change	Survival rate
	cm	*Percent*	*Mm*	*Percent*	*Percent*
Disc	-0.1 ± 1.0	-0.1 ± 1.0a	0.6 ± 0.2	13.1 ± 4.9a	78.5a
1-herbicide[a]	1.87 ± 1.1	5.8 ± 3.3a	5.8 ± 3.3	17.2 ± 6.1a	52.8b
2-herbicide[b]	5.20 ± 1 .1	18.5 ± 5.3b	- -	—	46.6bc
Disc and herbicide	0.66 ± 0.3	1.93 ± 1.0a	0.49 ± 0.1	11.2 ± 3.3a	71 .0a
Control	1.25 ± 0.4	4.12 ± 1.3a	0.46 ± 0.3	10.5 ± 7.0a	52.9bc

[a] Treatment consists of a one-pass application of Fusilade 2000™.
[b] Treatment consists of a split, two-pass application Fusilade 2000™ performed by State of Alabama planting contractor.

preseason seedling heights and diameters, and to the greater planting uniformity afforded by the mechanical planter, both of which potentially increase soil moisture availability. Soils on terrace sites usually have well developed agrillic and fragipan horizons. The growth and development of hardwoods are generally not as good on these as on floodplain sites due to the inherent leaching of nutrients, the presence of a well-developed fragipan, and less favorable soil moisture conditions (Hodges 1995). Relative to the floodplain and terrace sites, less competing vegetation was observed on the upland site. Significantly less seedling growth on the terrace than on the upland and floodplain sites was expected. Differential survival of cherrybark oak among topographic sites may underscore the site-specific sensitivity of this species.

Light is a dominant limiting factor for oak development under dense forest canopies, but soil moisture may also limit oak establishment (Hodges and Gardiner 1992). Crow (1988) identified “large, well-developed, well-established” root systems as the key factor to rapid seedling growth, and other studies have demonstrated the responsiveness of oak seedlings to soil moisture stress (Larson and Whitmore 1970, Larson 1980).

Discing, alone or in combination with a single herbicide application, increased first-year survival. The split, two-pass herbicide treatment, however, resulted in about twice the first-year height growth of seedlings than in any other grass control treatment. Zutter and others (1986) report soil moisture and first-year height and diameter growth of loblolly pine as negatively correlated with the level of herbaceous vegetation, and first-year pine growth most highly correlated to soil moisture level in late August when soil moisture was lowest. Mechanical alteration of the heavy grass sod by discing may have created a soil environment favorable to early-season root development. Both the increased survival of seedlings in disced plots, and the increased height growth of seedlings in the Split, two-pass herbicide treatment are attributed to increased moisture availability. The striking differences in seedling response between these two treatments, however, possibly reflects the timing of competing vegetation removal.

CONCLUSIONS

In this study, increased mechanical manipulation of the soil improved seedling growth. It is suggested that one reason for improved growth is greater moisture availability due to greater planting depths in the subsoiled areas and by machine planting. In addition, this study demonstrates that mechanical subsoiling, machine planting, and grass control techniques may be practical methods of establishing oak on previously farmed lands on an operational scale.

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INFLUENCE OF SOIL SERIES AND PLANTING METHODS ON FIFTH-YEAR SURVIVAL AND GROWTH OF BOTTOMLAND OAK RE-ESTABLISHMENT IN A FARMED WETLAND

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Abstract-Bottomland hardwood forest restoration often depends on reestablishment of bottomland oak species. Success, using either planted seedlings or acorns, has been inconsistent and may require several years before it can be accurately assessed. In 1991, a study was initiated on a farmed wetland in the Lower Mississippi Alluvial Valley to evaluate effects of soil series and planting methods on reestablishment of cherrybark oak (Quercus pagoda Raf.), Nuttall oak (*Quercus nuttallii* Palmer), Shumard oak (*Quercus shumardii* Buckl.), and water oak (*Quercus nigra* L.). A randomized complete block design with four replications was used to test performance of the four oak species established by direct seeding or planting of bareroot seedlings on three common soil series (Sharkey, Forestdale, and Dundee). Overall survival and growth after five growing seasons was not affected by soil series. Survival of trees originating from planting as bare-root seedlings was significantly greater than that for trees direct-seeded for Nuttall, cherrybark and water oaks, whereas for Shumard oak there was no significant difference between planting methods. Height and groundline diameter of trees planted as bare-root seedlings after 5 years was greater than height of direct-seeded trees for all four oak species. After 5 years, Nuttall oak had a 72 percent overall survival rate, mean height of 169 centimeters, and mean groundline diameter of 27 millimeters; followed by water oak (59 percent, 115 centimeters, and 15 millimeters); Shumard oak (55 percent, 76 centimeters, and 11 millimeters); and chertybark oak (52 percent, 67 centimeters and 10 millimeters). Survival of each species, whether planted as bare-root seedlings or by direct seeding, produced stocking that surpassed Federal Wetland Reserve Program standards for tree reestablishment. This suggests that mixed-species plantings using these four oak species can be successfully established on sites with similar soils and hydrologic conditions.

INTRODUCTION

The importance and multiple values of forested wetlands have generally been recognized only within the past 2 decades (Mitsch and Gosselink 1993). Studies show that in most of the United States more wetland area was destroyed than was required to be restored or created, resulting in net losses of these valuable ecosystems (Kentula and Others 1993). For example, about 2.4 million hectares of forested wetlands were converted to other land uses (mainly agriculture) in the United States between 1950 and 1970 (Lugo and others 1990). Loss of bottomland hardwood (BLH) forests in the Lower Mississippi River Alluvial Valley (LMAV) is estimated at about 6.5 million hectares since European settlement, and most of the remaining BLH forests in LMAV are fragmented and have lost many of their original values (Mitsch and Gosselink 1993). Almost 12.4 million hectares, less than one-third of that prior to European settlement, of forested wetlands remain in the South with about 2 million in the floodplain of the LMAV (Stanturf and Shepard 1995). Rudis (1995) stated that clearing of forested wetlands for nonforest land use is frequently done because of their suitable agricultural conditions, including rich alluvial soils and adequate moisture.

This large amount of loss has caused increasing efforts to restore and protect wetlands in recent years (Mitsch and Gosselink 1993). Since 1980, numerous restoration and protection projects have been supported by both public and private programs. These include the Conservation Reserve Program and the Wetland Reserve Program (WRP). The purpose of these programs is to establish an adequate vegetative cover in fragmented ecosystems and to mitigate fish and wildlife habitat losses (Stanturf and Shepard 1990). The LMAV has the most restoration projects applied to former BLH forest sites that were cleared since the 1950's and converted to farmland (Clewell and Lea 1990). However, according to Clewell and Lea (1990), there have been relatively few intentional creation or restoration efforts to compensate for lost forested wetlands in the Southeastern United States, and most of them are too young to be assessed. In addition, some limitations need to be addressed for successful efforts on restoration of BLH forests. Allen and Kennedy (1989) mentioned the following problems identified from BLH forest restoration projects: (1) site selection and the possible need for site preparation, (2) the question of which species on which type of soil, and (3) choosing a planting technique-direct seeding or planting of seedlings. Furthermore, Hook (1987) explained that relationships between hydroperiod and site requirements of some species, including oaks and other heavy-seed species that inhabit mixed BLH wetlands, are not well understood. These limitations and lack of information on restoration suggest a need for information related to species-site interactions and choice of planting methods. The overall objective of this study is to assess impacts of soil series and planting methods on fifth-year survival and growth of four bottomland oak species in a reestablishment effort in the LMAV.

METHODOLOGY

This study is located in Yazoo County, MS, and is a part of the Lake George Wildlife Wetland Restoration Project established by the U.S. Army Corps of Engineers in 1991. It comprises about 3,300 hectares that were originally forested and are being incrementally replanted with trees to replace crop production. The project site is bounded by two

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fragmented forest ecosystems: the Delta National Forest and the Panther Swamp National Wildlife Refuge. One of the major objectives of the overall Lake George Project is to reestablish a BLH forest in order to connect these two fragmented forests.

Three soil series that commonly occur in the LMAV were evaluated in this study: (1) Dundee (fine-silty, mixed, thermic, Aeric Ochraqualfs) soils are at the higher elevations and have a brown surface soil and a brownish silty clay subsoil, (2) Forestdale (fine, montmorillonitic, thermic, Typic Ochraqualfs) soils are at lower elevations than Dundee soils and are grayer and more poorly drained than Dundee soils, and (3) Sharkey (very fine, montmorillonitic, nonacid, thermic, Vertic Haplaquepts) soils are at lowest elevations, are poorly drained, and have dark-colored, clayey profiles (Scott and others 1975). Miwa (1993) has reported physical and chemical properties of these soil series as they occur at the study site.

Four bottomland oak species commonly used on restoration and reforestation projects in the South were evaluated: cherrybark oak (Quercus pagoda Raf.), Nuttall oak *(Quercus nuttallii* Palmer), Shumard oak *(Quercus shumardii* Buckl.), and water oak *(Quercus nigra* L.). Water oak, cherrybark oak, and Shumard oak are desirable species that can be regenerated on the ridges in bottomlands, whereas Nuttall oak is suitable in the flats of bottomlands (Ezell and Hodges 1994). Seedlings grown in the nursery for 1 year were obtained from Delta View Nursery in Leland, MS, and from the Mississippi Forestry Commission Nursery in Winona, MS. They were hand-planted at 3 by 3 meter spacing in December 1991 (Miwa 1993). Acorns of cherrybark, Shumard, and water oak were collected near Starkville, MS, whereas Nuttall oak acorns were collected in the Mississippi Delta region. All acorns were hand-planted at 3 by 3 meter spacing with two acorns per location at a depth of 5 to 8 centimeters in March 1992 (Miwa 1993). Survival, height, and groundline diameter were measured at the end of the first and second growing seasons, in 1992 and 1993, respectively, and reported by Miwa (1993). Fifth-year survival, height, and groundline diameter were measured in October 1996.

A randomized complete block design with split-split plots was applied to compare treatments. Four blocks (replications) were established at the restoration site. Treatments within this design were as follows: (1) main treatment plots made up of one of three common soil series (Dundee, Forestdale, and Sharkey), (2) four oak species (cherrybark oak, Nuttall oak, Shumard oak, and water oak) randomly assigned to split plots, and (3) two planting methods (direct seeding and seedling planting) randomly assigned as split-split plots. Analysis of variance (ANOVA) was used to test null hypotheses at the 0.05 significance level. (Schlotzhauer and Littell 1987). To compare our treatment means, ANOVA with Least Significant Difference (LSD) to test for means separation was used. Arcsin transformations were applied to survival data to normalize their distributions (Aster and Seidman 1991).

RESULTS AND DISCUSSION

Effects of Soil Series

Fifth-year survival of cherrybark, Nuttall, Shumard, and water oaks was not affected by soil series (table 1). Survival pooled across both planting methods ranged from 50 percent for cherrybark oak on Dundee soils to 73 percent for Nuttall oak on Sharkey soils (table 1). These survival rates, which are pooled for seedlings and acorns planted on 3 by 3 meter spacing, result in fifth-year stocking that ranges from 556 trees per hectare for cherrybark oak on Dundee soils to 811 trees per hectare for Nuttall oak on Sharkey soils. This range exceeds the required 309 trees per hectare for satisfactory stocking of BLH species on WRP restoration sites at the end of three growing seasons. Lack of soil series effects suggests that differences in soil physical and chemical properties among the three soil series reported by Miwa (1993) did not significantly influence survival of oak species after 5 years.

Height and groundline diameter were not different among the three soil series after 5 years for Nuttall, Shumard, and water oak (table 1). However, for cherrybark oak, height (83 centimeters) and groundline diameter (12 millimeters) on Sharkey soil were significantly larger than height (46 centimeters) and groundline diameter (6 millimeters) on Forestdale soil, but did not differ significantly from height (73 centimeters) or groundline diameter (11 millimeters) on Dundee soil (table 1). The relatively strong performance of cherrybark oak on Sharkey soil was unexpected. Krinard (1990) stated that cherrybark oak develops best on loamy,

Table I-Effect of soil series on fifth-year survival and size of four planted oak species at the Lake George Wetland Restoration Site in Yazoo County, MS[a]

	Oak species			
Soil series	Cherrybark	Nuttall	Shumard	Water
Survival rate (pct)				
Dundee	50 a[b]	69 a	55 a	58 a
Forestdale	52 a	73 a	57 a	63 a
Sharkey	53 a	73 a	54 a	57 a
Height (cm)				
Dundee	73 ab	189a	86 a	130a
Forestdale	46 b	142a	65 a	94 a
Sharkey	83 a	177 a	75 a	121 a
Diameter (mm)				
Dundee	11 ab	30 a	14 a	17 a
Forestdale	6 b	23 a	10 a	13 a
Sharkey	12 a	27 a	11 a	15a

a Values are means of four plots.
b For each oak species and response variable, means followed by different letters are significantly different at the 0.05 level according to Fisher's protected LSD test.

wolf-drained soil and is uncommon on clay soil such as Sharkey, which is poorly drained. Our results suggest that moisture relations on Sharkey soil at this site did not differ as a limiting factor for oak survival or growth compared with moisture relations on Dundee or Forestdale soils. Furthermore, flooding has not been observed on the study plots, suggesting that excess water and poor drainage often associated with Sharkey soils did not occur on this site.

Effects of Planting Method

Evaluation of planting-method effects was pooled across soil series because there was no interaction between planting method and soil series. Survival of planted seedlings of cherrybark, Nuttall, and water oak was 74, 79, and 67 percent, respectively, and was significantly higher than 29, 65, and 51 percent survival, respectively, resulting from direct seeding (table 2). Similarly, fifth-year survival of planted seedlings of Shumard oak was 61 percent compared with 50 percent for seedlings from direct seeding. However, this difference was not significant at the 0.05 level. These results show the consistent advantage of planted seedlings for enhanced survival when compared with direct seeding. However, even direct-seeded cherrybark oak with 29 percent survival produced a stocking of 322 trees per hectare, which is greater than minimum stocking requirements for WRP sites.

Fifth-year height and diameter were significantly greater on planted seedlings than on seedlings from direct-seeded acorns among all four oak species (table 2). Mean height and diameter of planted cherrybark, Shumard, and water oak seedlings were at least three times greater than seedlings from direct seeding, whereas size of planted

Table 2-Effect of planting method on fifth-year survival and size of four planted oak species at the Lake George Wetland Restoration Site in Yazoo County, MS[a]

Planting Method	Oak species: Cherrybark	Nut-tall	Shumard	Water
Survival rate (pct)				
Planted seedling	74 a[b]	79 a	61 a	67 a
Direct seedling	29 b	65 b	50 a	51 b
Height (cm)				
Planted seedling	102a	215 a	114 a	182a
Direct seedling	33 b	124b	37 b	48 b
Diameter (mm)				
Planted seedling	15a	38 a	18 a	25 a
Direct seedling	4 b	16b	5b	6 b

[a] Values are means of four plots.
[b] For each species and response variable, means followed by different letters are significantly different at the 0.05 level according to Fisher's protected LSD test.

Nuttall oak seedlings was approximately two times greater than seedlings from direct seeding (table 2). Allen (1989) conducted a study using Nuttall, water, Shumard, and cherrybark oak species in the Yazoo National Wildlife Refuge Complex in Washington County, MS, and found that both height and diameter growth of planted seedlings were higher than for seedlings from direct seeding. Stanturf and Kennedy (1996) also reported that planted seedlings of cherrybark oak were significantly larger than direct-seeded cherrybark oak seedlings after 5 years.

Comparison of Species

Species comparisons of survival, height, and groundline diameter were pooled across soil series since there was not a species-soil series interaction. Nut-tall oak had the highest fifth-year survival and largest size for either of the two planting methods (table 3). For planted seedlings, Nuttall oak had 79 percent survival followed by cherrybark, water, and Shumard oak with 74, 67, and 61 percent survival, respectively. For direct seeding, Nuttall oak had 65 percent survival followed by water, Shumard, and cherrybark oak with 51, 50, and 29 percent, respectively (table 3). This result concurs with other studies that have compared oak species for artificial regeneration of BLH forests (Johnson and Krinard 1988, Johnson and Krinard 1989).

Fifth-year height and groundline diameter of Nut-tall oak for both planted seedlings and seedlings from direct seeding were significantly greater than the other three species (table 3). Trees originating as planted seedlings had

Table 3-Comparison of fifth-year survival and size of four oak species using two planting methods at the Lake George Wetland Restoration Site in Yazoo County, MS[a]

Oak species	Planted seedling	Direct seeding
Survival (pct)		
Cherrybark oak	74 a[b]	29 c
Nuttall oak	79 a	65 a
Shumard oak	61 b	50 b
Water oak	67 ab	51 b
Height (cm)		
Cherrybark oak	102 c	33 c
Nuttall oak	215 a	124a
Shumard oak	114 c	37 bc
Water oak	182 b	48 b
Diameter (mm)		
Cherrybark oak	15 c	5 b
Nut-tall oak	38 a	16a
Shumard oak	18 c	5 b
Water oak	25 b	6 b

[a] Values are means of four plots.
[b] For each planting method and response variable, means followed by different letters are significantly different at the 0.05 level according to Fisher's protected LSD test.

heights of 215 > 182 > 114 = 102 centimeters for Nuttall, water, Shumard, and cherrybark oak, respectively. Trees originating from direct seeding had heights of 124, 48, 37, and 33 centimeters for Nuttall, water, shumard, and cherrybark oak, respectively (table 3). Groundline diameter for planted and direct-seeded oak species followed the same patterns as height (table 3).

These results indicate that Nuttall oak has the most successful establishment and growth 5 years after planting on this site. This supports findings that Nuttall oak grows well on alluvial clay soils in the LMAV region (Filer 1990). However, cherrybark, Shumard, and water oak have adequate survival to meet the WRP stocking goal of 309 trees per hectare for both planted seedlings and seedlings originating from direct seeding. The slower growth rate of these three species in comparison to Nuttall oak indicates that they are not as well adapted as Nuttall oak to soil conditions on this site.

CONCLUSIONS

Based on fifth-year survival and size, Nuttall, cherrybark, Shumard, and water oak can be grown on any of the three soil series studied on this site, since soil series did not significantly affect measured response variables of the oak species. This result indicates that mixed-species plantings using these four oak species can be successfully established on similar sites. However, Nuttall oak showed best survival, height, and groundline diameter among the four species for either planting method. Furthermore, flooding has not occurred on this site during the course of this study and has, therefore, not been a limiting factor in association with poorly drained Sharkey soils.

Planted seedlings had better survival and size than seedlings established by direct seeding, suggesting that maximum establishment success and growth rates can be achieved with planted seedlings. However, direct-seeded seedling survival was sufficient to produce adequately stocked 5-year-old stands of all species according to WRP standards. This suggests that direct seeding can be successful on sites similar to this study if rapid early growth rate is not a primary objective.

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POCOTALIGO SWAMP FOREST PLANTING DEMONSTRATION PROJECT

William H. Conner, Roy Todd, and L. Wayne Inabinette[1]

Abstract-Prior to logging in the late 1950's and 60's, the Pocotaligo Swamp represented a typical baldcypress-water tupelo (*Taxodium distichum-Nyssa aquatica*) riverine forest in south-central South Carolina. Regeneration of the swamp forest following logging was poor, due to permanent flooding conditions caused by logging access roads and the dense, mat-like growth of aquatic vegetation that occurred throughout the swamp. Efforts have been undertaken to restore portions of the swamp near Manning, SC. Three hundred fifty baldcypress seedlings were planted at four sites in May 1995. First-year survival was 76 percent and average height growth was 20 centimeters. Second-year survival was 64 percent and average height growth was 50 centimeters. In January 1996, an additional 249 root-pruned baldcypress and 73 containerized water tupelo were planted in three of the areas. Survival of the 1996 planted baldcypress was 80 percent and average height growth was 44 centimeters. Sixty-three percent of the water tupelo survived with an average height growth of 25 centimeters. Indications are that baldcypress and water tupelo can be successfully planted in the Pocotaligo Swamp if they can be protected from beaver herbivory. Long-term monitoring of these seedlings, along with additional plantings, will provide valuable information on restoration of flooded freshwater wetland sites.

INTRODUCTION

Forested wetlands were once viewed as obstacles to development, reservoirs of disease, and haunts of terrible monsters (Hammer 1997). Even with these perceptions, however, Europeans quickly recognized that cypress (refers to both baldcypress [*Taxodium distichum* (L.) Rich] and pondcypress (*T. distichum* var. *nutans*) when used like this) wood was very rot resistant, strong, and easily worked, and efforts to establish a timber trade with Louisiana began around 1700 (Mancil 1980). Harvesting in these wet swamps was seasonal in nature until the invention of the pullboat in 1889. Pullboats and the expansion of the railroad system (Sternitzke 1972), combined with a massive national campaign by cypress dealers (Burns 1980), resulted in a logging boom during the period 1890 to 1925. Production of cypress lumber increased from 1.17 million m^3 in 1899 to over 2.36 million m^3 in 1913 (Mattoon 1915, Betts 1938). By 1925, nearly all of the virgin timber had been cut and most of the mills closed. In 1933, only about 10 percent of the original standing stock of cypress remained (Brandt and Ewel 1989), but some cypress harvesting continued throughout the Southern United States on a smaller scale.

The Pocotaligo Swamp, located in Clarendon and Sumter Counties, SC, is a 12,141- hectare braided stream system once dominated by baldcypress and water tupelo (*Nyssa aquatica* L.) forests. In the 1950's and early 1960's, most of the swamp was logged. Numerous access roads were constructed to remove the timber, criss-crossing the swamp in numerous places and blocking stream channels. Normal water flow patterns were disrupted and much of the swamp became permanently flooded. Although baldcypress and water tupelo can both survive and grow in flooded areas (Brown 1981, Conner and others 1981, Wilhite and Toliver 1990), their seeds do not germinate under flooded conditions, and young seedlings are killed by a few days Of submergence (Demaree 1932). As a result, much of the Pocotaligo Swamp never returned to a closed canopy forest but is now dominated by scrub-shrub stands with scattered trees. Freshwater marsh communities composed of pennywort (*Hydrocotyle ranunculoides* L.), cattail (*Typha latifolia* L.), and alligatorweed [*Alternanthera philoxeroides* (Mart.) Gris.] cover the swamp floor.

The Pocotaligo Swamp Restoration Committee was created in 1988 to provide leadership in the restoration of the swamp's natural ecosystem. In 1994, demolition experts blew 115 channel gaps in the old access roads, thus improving water flow in the swamp and lowering water levels approximately 1 foot. Planting began in 1995 in an effort to show landowners that trees could be planted in the swamp to restore the area to its former forested condition. This paper describes the preliminary efforts to reestablish baldcypress and water tupelo in the swamp.

METHODS

Four areas were selected in the upper Pocotaligo Swamp north of Manning for planting. In May 1995, a total of 357 baldcypress seedlings was planted at these sites. The seedlings were 2-year-old bareroot stock from the South Carolina Forestry Commission and were planted with a dibble in 2 to 3 feet of standing water. In January 1996, an additional 249 two-year-old baldcypress seedlings and 73 containerized water tupelo seedlings were planted in two of the areas. Because of the difficulty of planting seedlings in standing water, the baldcypress seedlings were root-pruned (lateral roots removed and the tap root cut at 8 inches) and planted by pushing the tap root into the soft sediment. Numbered, half-inch PVC pipe sections were used to mark the location of each seedling. Height measurements were made for each seedling when planted and at the end of the 1995 and 1996 growing seasons.

RESULTS AND DISCUSSION

First-Year survival of baldcypress was similar for the 1995 planting (76 percent) and the 1996 planting (80 percent; table I), indicating that root pruning was not detrimental to

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Table I-Survival and height of baldcypress and water tupelo seedlings planted in Pocotaligo Swamp, SC

Year planted	Species	Survival rate 1995	Survival rate 1996	Height 1995	Height 1996
		- - - - Percent - - - -		- - - - - - Centimeters - - - - - -	
1995	Baldcypress	76	64	96 (1.2)[a]	146 (2.5)
1996	Baldcypress	—	80	—	110 (2.2)
1996	Water tupelo	—	63	—	86 (3.4)

[a] Number in parentheses represents ± 1 SE.

seedling survival. Survival of water tupelo seedlings (63 percent) was less than that of baldcypress and may have been due the smaller size of the container-grown seedlings (starting height of 68 centimeters vs. 86 centimeters for baldcypress) and the deep water in which they were planted. Second-year survival of the 1995-planted baldcypress declined to 64 percent, mainly as a result of beaver clipping the seedlings. Beaver moved into the area in 1996, and freshly cut seedlings were observed when the height measurements were made. Other researchers in South Carolina have had similar problems with beaver (McLeod and others 1996). In Louisiana, nutria (*Myocastor coypus*) have long been detrimental to baldcypress planting efforts (Blair and Langlinais 1960, Conner 1988, Hesse and others 1996). The use of plastic (Allen 1995, McLeod and others 1996) and PVC (Myers and others 1995) treeshelters has proved beneficial in preventing beaver and nutria from clipping seedlings.

First year height growth [average = 19.8 ± 1 centimeters (±1 SE)] of 1995-planted baldcypress was significantly less than second-year height growth (average = 50.8 ± 2.0 centimeters; fig. 1). First-year height growth of the 1996-planted baldcypress was 44.0 ± 1.6 centimeters (fig. 2). There may be many explanations for the lower first-year height growth of the 1995-planted seedlings. However, most plants that have developed under drained conditions (nursery-grown) experience some degree of root dieback upon flooding, regardless of their ability to tolerate flooded conditions (Hook and Brown 1973, Sena Gomes and Kozlowski 1980, Syvertsen and others 1983, Topa and McLeod 1986). Lateral roots may either die back to the tap root or to the primary lateral from which they originated, and thick, succulent, relatively unbranched roots (soil water roots) may be initiated from the point of dieback in root systems undergoing acclimation to flooding (Hook and others 1970). By pruning the root systems of the 1996-planted seedlings, the die back phase was eliminated and new roots developed immediately as was been shown by Conner (1995).

First-year height growth of 1996-planted water tupelo averaged 25.0 ± 3.0 centimeters, and there was a significant difference between the two areas planted. In one area, water tupelo height growth was 18.7 ± 3.1 centimeters compared to 31.9 ± 4.8 centimeters in the other area (fig. 2). This difference is probably due to the difference in the amount of competition in the two areas. One area was densely populated with cattail, and was so thick it was difficult to find the seedlings even with the PVC stakes.

CONCLUSIONS

Today, there are numerous opportunities to reestablish forested wetlands on disturbed sites. Root-pruned seedlings allow for the quick and easy insertion of seedlings into flooded sediments. Early growth and survival are adequate to reestablish forests as long as beaver does not become too much of a problem. Treeshelters may be one way to prevent herbivory problems with newly planted seedlings. The impacts of root pruning on long-term survival and growth are unknown and require further study.

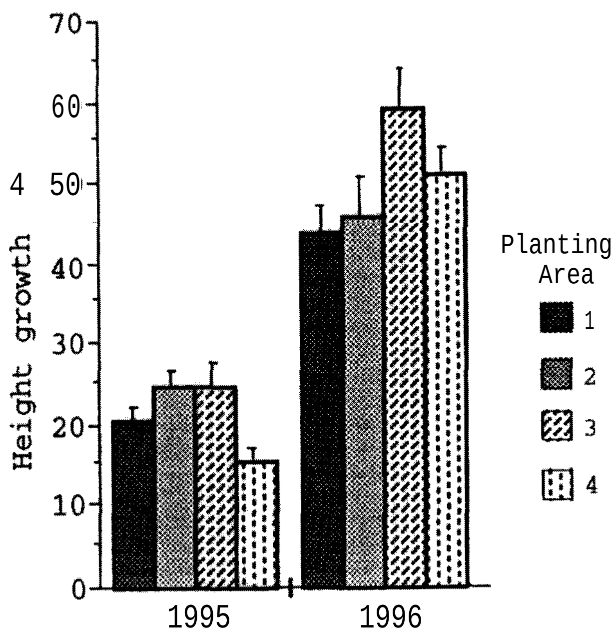

Figure I-Height growth (cm) of baldcypress seedlings planted in 1995 in four areas of the Pocotaligo Swamp.

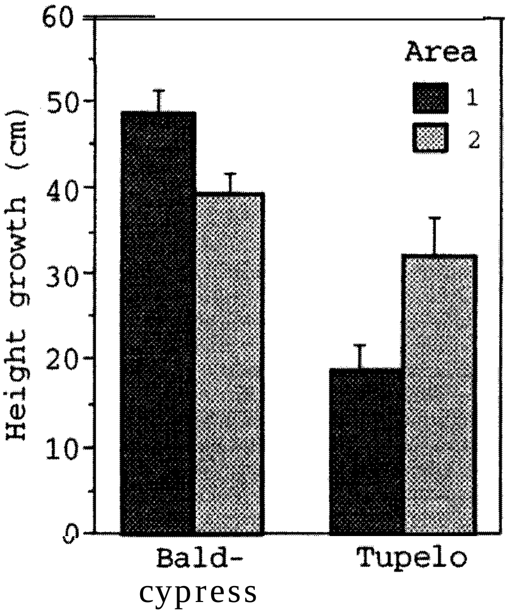

Figure 2-Height growth (cm) of baldcypress and water tupelo seedlings planted in 1996 in two areas of the Pocotaligo Swamp.

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WATER RELATIONS AND MORPHOLOGY OF NUTTALL OAK SEEDLING SPROUTS

Emile S. Gardiner'

Abstract-Seedling sprouts are considered the most reliable source of oak regeneration in bottomland hardwood forests. This is because rapid shoot growth encouraged by a high root/shoot ratio provides oak seedling sprouts a competitive opportunity in regenerating stands, To learn more about the physiological mechanisms supporting this rapid shoot growth, a greenhouse study was designed to determine whether altered water transport rates facilitated the rapid shoot growth of Nuttall oak (Quercus *nuttallii* Palmer) seedling sprouts. In February 1996, sixty 1-O seedlings were established in 15-liter pots containing a potting soil mix. Shoots were clipped on half of the seedlings about 5 centimeters above the root collar to promote sprout development. Measurements of stem growth, biomass accumulation, leaf physiology and sap flow indicated that physiological functions of Nuttall oak seedling sprouts were probably moderated after a balance was restored between root system size and shoot size of the sprout.

INTRODUCTION

Seedling sprouts, a form of coppice reproduction, develop from dormant buds above the root collar following damage or dieback of the terminal shoot (Johnson 1993, Kramer and Kozlowski 1979). Under repetitive shoot dieback and resprouting, the seedling sprout develops a high root:shoot ratio which can facilitate a quick growth response when released (Johnson 1993). Seedling sprouts are especially important to bottomland oak *(Quercus* spp.) species, because oaks typically follow a regeneration strategy that relies on accumulating advance reproduction in a regeneration pool (Johnson 1993). A regeneration pool well-stocked with advance oak reproduction is required to ensure successful oak replacement after stand disturbance.

Since sprouts serve as an important source of oak regeneration, some research has focused on revealing the physiological mechanisms underlying the rapid shoot growth observed for this form of reproduction (Lockhart and Hodges 1994, Kruger and Reich 1993a, 1993b). However, except for leaf-level aspects, few studies have examined the influence of the high root:shoot ratio of a seedling sprout on its water relations (Blake and Tschaplinski 1986, Kruger and Reich 1993b, Syvertsen 1994). This study was designed to determine whether altered water transport rates facilitate the rapid shoot growth of seedling sprouts. To determine this, a greenhouse study was designed with the objectives of: (1) quantifying shoot growth, (2) quantifying sprout morphology in terms of biomass accumulation, and (3) describing the sap flow patterns of oak seedling sprouts.

METHODS

Experimental Material

Sixty 1-O Nuttall oak (Q. *nuttallii* Palmer) seedlings were potted in 15-liter polyethylene pots with a 50:50 (volume:volume) sphagnum peat and sand mixture (pH = 4.2). Pots were placed in a greenhouse and given a single application of 20-20-20 Osmocote (Grace Sierra, Milpitas, CA 95035) time release fertilizer. Soil was watered as needed to maintain field capacity in all pots during the entire growing season. To promote sprout development, 30 randomly selected seedlings were shoot-clipped with pruning shears about 5 centimeters above the root collar. Plants were grown under ambient light in the greenhouse for about 9 months between February and October 1996.

Measurements

To quantify sap flow of the experimental plants, four randomly selected seedlings and sprouts were fitted with Dynagage SGA1 0-WS stem-flow gauges and monitored with a Flow32 Sap-flow Datalogger System (Dynamax, Incorporated, Houston, TX 77099). The Dynamax sap-flow system uses an energy balance method to estimate velocity of sap flow from known inputs of continuous heat supplied to the stem flow gauge. Sap flow was monitored on the eight plants for a 3-week period in September. These measurements were planned for earlier in the growing season, but the stem flow gauges used in this study required a minimum shoot diameter of 10 millimeters, and experimental material did not attain this size until late in the growing season. While sap flow measurements were in progress, air temperature, relative humidity, and photosynthetically active radiation were monitored in the greenhouse with a LI-COR LI-1000 data recorder and appropriate sensors.

During the 3-week sample period, three cloud-free days were selected as sample days to quantify leaf physiology of the experimental plants. On each of these three days, measurements of net photosynthesis and transpiration were made on eight randomly selected seedlings and sprouts. Net photosynthesis was measured with an ADC LCA3 Portable Photosynthesis System (Analytical Development Company Limited, Hoddesdon, England), while stomatal conductance and transpiration rate were measured on these same plants with a LI-COR, LI-1600 Steady State Porometer (LI-COR, Incorporated, Lincoln, NE 68504). All gas exchange measurements were performed on leaves from the terminal flush of selected plants between 1000 and 1100 hours solar time.

Height and root-collar diameter were measured on all seedlings before clipping and after the g-month growing

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period. Following 9 months of growth, all 60 plants were harvested and separated into root, stem, and leaf biomass. All biomass components were oven dried at 50 °C for 7 days before measuring dry weights to the nearest 0.01 gram with an analytical balance. Root:stem ratios were computed by dividing root biomass with stem biomass for each plant.

Statistical Analyses

Analysis of variance for a completely random design was used to test for a treatment effect on plant height, root-collar diameter, biomass accumulation, and root:stem ratio. Leaf physiology variables were also analyzed according to a completely random design, but sample day (replication) served as a source of variation in the model. A similar model was used to analyze treatment effects on sap flow. Analysis of variance was performed on the daily accumulation of sap flow of gauged plants on three cloud-free days during the 3-week sample period. All statistical tests were conducted at the 0.05 probability level.

RESULTSANDDISCUSSION

Seedling Growth

Before shoot clipping, seedlings of both treatments were about 39 centimeters tall with a root-collar diameter greater than 5 millimeters (table 1). All clipped seedlings resprouted from dormant buds above the root collar, and no seedling mortality was observed during the experimental period. After the g-month experimental period, shoot clipping did not significantly affect height or root-collar diameter of plants (table 1). Thus, if relative growth is considered, it is obvious that sprout shoots grew considerably more than seedlings. The height increment of seedlings was 41 centimeters, while the height increment of sprouts was 86 centimeters. These height increments equate to 100 percent and 1700 percent relative growth rates, respectively.

Table I-Initial and final height and diameter (mean ± SE) for Nut-tall oak seedlings and seedling sprouts grown in a greenhouse for 9 months (n=30)

Measurement	Seedlings	Sprouts
Height (in centimeters)		
Initial[a]	38.8 ± 0.5 a	38.8 ± 0.7 a
Final'	79.5 ± 5.0 a	91.2 ± 6.2 a
Diameter (in millimeters)		
Initial[c]	5.4 ± 0.2 a	5.8 ± 0.2 a
Final[d]	11.4 ± 0.2 a	11.8 ± 0.4 a

[a] Treatment means followed by the same letter in a row are not different. P > F = 0.9693.
[b] P > F = 0.1478
[c] P > F = 0.2004
[d] P > F = 0.4010

Other investigations into the growth of oak seedling sprouts are in accord with these findings. For example, the height of white oak (*Q. alba* L.) seedlings was not influenced by shoot clipping for two of three half-sib families studied by Kormanik and others (1995). In another field study, Lockhart and others (1993) found relative height and diameter growth of cherrybark oak (Q. *pagoda* Raf.) natural regeneration was increased by shoot clipping, so that sprouts attained the same size as intact seedlings within 4 years after clipping. Similarly, Kruger and Reich (1993b) reported that a compensatory growth response by sprouts diminished any effect of shoot removal from northern red oak *(C?. rubra* L.) seedlings that were clipped while dormant. However, results from this study and others cited here indicate the increase in relative growth rate exhibited by shoot-clipped oak seedlings may not be maintained beyond the initial height of the seedling.

Biomass Accumulation

For both seedlings and sprouts, roots composed the largest component of plant biomass, and leaves contributed the least to total plant mass (table 2). There was no observable effect on plant morphology 9 months after shoot clipping, as differences in biomass accumulation were not detected for any of the plant components (table 2). As a result, root:stem ratios for both seedlings and sprouts averaged about 2.9 ± 0.13 (mean ± standard error) (P > F = 0.8954) at the end of the experimental period. Root:stem ratio increased during the growing season from a pretreatment value of 1.4 ± 0.05.

The rapid growth often observed on sprout shoots of many tree species is often linked to an increased sink demand of the developing stem. If shoot removal completely eliminates the photosynthetic surface of oak seedlings, initial sprout development is supported by carbohydrate reserves translocated upward from the roots (Kruger and Reich 199313). For natural regeneration of cherrybark oak, stored carbon reserves and Current

Table 2—Biomass accumulation (mean ± SE) by Plant component for Nuttall oak seedlings and seedling sprouts grown in a greenhouse for 9 months (n=30)

Component	Seedlings	Sprouts
	----------- Grams ------------	
Roof	74.1 ± 2.1 a	77.4 ± 2.6 a
Stem[b]	27.2 ± 1.6 a	29.9 ± 2.0 a
Leaf[c]	18.7 ± 1.2 a	21.8 ± 0.9 a
Total[d]	119.9 ± 3.8 a	129.1 ± 4.1 a

[a] Treatment means followed by the same letter in a row are not different. P > F = 0.3199.
[b] P > F = 0.3079
[c] P > F = 0.0583
[d] P > F = 0.1099

photosynthates produced by developing leaves were used to meet the demands of the developing shoot (Lockhart 1992). The lack of a treatment effect on the biomass distribution and total mass of plants in this study is particularly noteworthy. Apparently, sink demands of developing shoots were met and sprouts shifted into a carbon allocation pattern similar to that of intact seedlings at some point during the g-month growing period. Root:stem ratios indicated that both seedlings and sprouts followed a carbon allocation pattern which favored biomass accumulation in roots. Northern red oak seedlings that received a dormant season shoot-clipping reportedly behaved in a similar manner (Kruger and Reich 1993b).

Leaf Physiology

Several existing studies have documented that increased rates of photosynthesis, stomatal conductance, and transpiration support the sink demands of the developing sprout shoot (Kruger and Reich 1993a, Tschaplinski and Blake 1989a, 1989b). It is argued that the high sink demand of the developing sprout shoot maintains the increased photosynthetic rate of leaves by reducing assimilate accumulation which may serve as a feedback mechanism limiting photosynthesis (Tschaplinski and Blake 1989b). Contrary to these published studies, the sampled Nuttall oak sprout leaves did not show elevated rates of photosynthesis, stomatal conductance, or transpiration (table 3). However, it is probable that enhancement of leaf physiology would have occurred while sprout shoots were in a stage of vegetative growth. Unfortunately, seedlings and sprouts had entered into a lag phase of shoot development prior to sampling for leaf physiology variables.

Table 3-Leaf physiology and sap flow (mean ± SE) for Nuttall oak seedlings and seedling sprouts grown in a greenhouse for 9 months

Process measured	Seedlings	Sprouts
Photosynthesis[a] ($\mu mol\ m^{-2}\ s^{-1}$)	12.47 ± 0.7 a	11.9 ± 0.6 a
Stomatal[b] conductance ($cm\ s^{-1}$)	0.80 ± 0.06 a	0.88 ± 0.05 a
Transpiration[c] ($\mu g\ cm^{-2}\ s^{-1}$)	6.9 ± 0.4 a	7.4 ± 0.4 a
Sap flow[d] (grams per day-')	439.2 ± 26.7 a	493.9 ± 24.9 a

n=8 with three replications for leaf physiology, n=4 with three replications for sap flow

[a] Treatment means followed by the same letter in a row are not different. P > F = 0.4828.

[b] P > F = 0.3189

[c] P > F = 0.2990

[d] P > F = 0.1538

Sap Flow

Figure 1 presents sap flow of gauged seedlings and measured environmental variables in the greenhouse on a representative sample day. Similar diurnal patterns of water ascent were observed for seedlings and sprouts with peak flow rates of about 60 grams of water per hour occurring near solar noon (fig. 1). Analysis of the daily accumulated sap flow of gauged plants indicated that shoot clipping did not influence the sap ascent rate of sprouts near the end of the g-month experimental period (table 3). Daily water transport through the stems of seedlings and sprouts was about four times the dry weight of the plant. Results were similar when sap flow rates were weighted by leaf area of individual sample plants (data not shown).

Few studies have examined the water relations of seedling sprouts. Blake and Tschaplinski (1986) proposed that the rapid growth of sprouts resulted from releasing the plant from water stress. They demonstrated that partial shoot removal improved water relations of poplar (*Populus deltoides* Bartr. X *Populus nigra* L. cv. DN22) seedlings within 5 days of clipping. Increased transpiration rates and water potential were attributed to an increase in the root:shoot ratio rendered by the clipping. Shoot-clipping may have temporarily improved water availability to sprouts

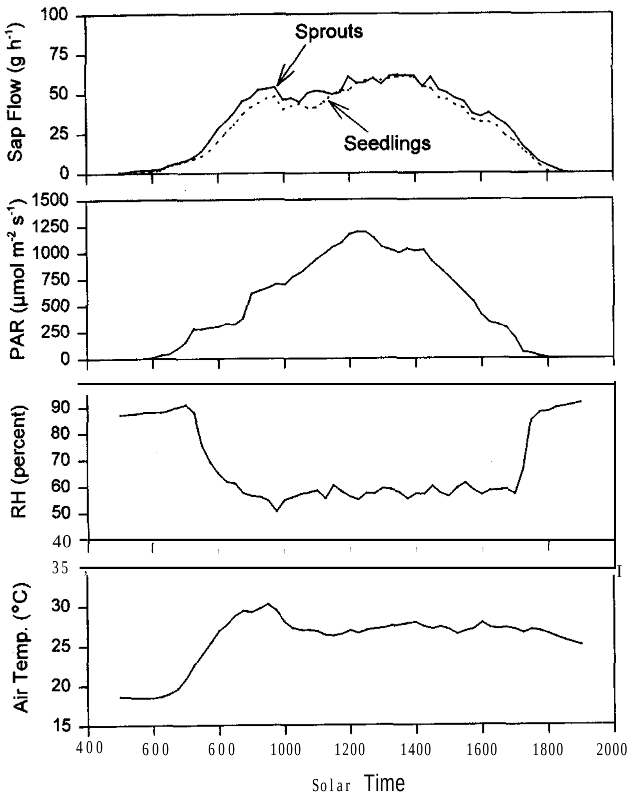

Figure I-An example of the diurnal pattern of sap flow for Nuttall oak seedlings and seedling sprouts measured in a greenhouse on September 22, 1996. Sap flow lines represent the average of four plants for each reproduction type, and photosynthetically active radiation (PAR), relative humidity (RH), and air temperature in the greenhouse are presented for the sample day.

in this Study, but this was not evident from sap flow measurements. Perhaps, sampling sprouts during a period of vegetative growth would have been more revealing.

CONCLUSIONS

Results from this study may be best explained in light of the growth pattern typically exhibited by oak seedlings. Oak seedlings exhibit relatively conservative semideterminant shoot growth patterns that are characterized by recurrent flushing (Dickson 1991). Bud expansion begins, leading to stem elongation, and leaf expansion follows stem elongation. Formation of a new bud occurs after leaves are fully expanded, and then the shoot enters into a lag phase or quiescent growth phase (Hanson and others 1986). During periods of vegetative shoot growth, leaf physiology is enhanced and assimilates are translocated upward in response to the sink strength of the developing shoot (Dickson 1991). In contrast, during the lag phase, photosynthesis is moderated and assimilates are translocated to the lower stem and roots (Dickson 1991). It is believed that this downward transiocation of assimilates during the lag phase serves to restore starch reserves of the plant depleted during the flush episode (Dickson 1991). And, it serves to restore the water balance of the plant by contributing to root extension (Dickson 1991, Kruger and Reich 1993b). Thus, it appears that oak seedlings maintain a balance between the size of the root system and the size of the shoot (Kruger and Reich 1993a, 1993b).

In this study, it is assumed that shoot clipping created a root:shoot imbalance. From the literature, it may also be assumed that leaf physiology was enhanced to meet the demands of the sink strength of the sprout. Along with this, there may have been a shift in the water relations of the sprouts, possibly even sap flow rates. However, the root:shoot imbalance was corrected before sampling began. Prior to sampling, sprouts set bud and entered into a lag phase for the remainder of the experimental period. Once plants entered the lag phase, photosynthesis presumably was moderated. And, if water transport was increased during the development of the sprout shoots, it too was moderated upon shoot development. From this research, it appears that the physiological invigoration of sprouts often reported in the literature is not maintained by Nuttall oak regeneration once a balance between root system size and shoot size is restored.

However, it should be brought out that results reported for this greenhouse experiment may not be directly comparable to what occurs under field conditions with natural oak reproduction. In this study, both reproduction types were vigorous plant material that received ample water, sunlight, and an adequate nutrient supply. In the field, the relative difference between sprouts and seedlings may be greater in terms of morphology or anatomical characteristics such as vessel size. For example, suppressed seedlings may have a vascular System that is not able to support rapid movement of water to developing foliage. If vessel size is typically larger in sprouts than in seedlings, sprouts may have an advantage when responding to release. It would be beneficial to focus additional research in this area on reproduction growing in a natural environment.

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EFFECTS OF FLOODING REGIME, MYCORRHIZAL INOCULATION AND SEEDLING TREATMENT TYPE ON FIRST-YEAR SURVIVAL OF NUTTALL OAK (Quercus *nuttallii* PALMER)

Virginia Burkett and Hans Williams'

Abstract-Three different types of Nuttall oak (Quercus *nuttallii* Palmer) seedlings were planted on floodprone, former cropland in Mississippi, Louisiana, and Texas. The three types of 1+0 seedlings planted at each site in January and February of 1995 were bareroot seedlings, seedlings grown in 164 square centimeters plastic containers, and container-grown seedlings inoculated with vegetative mycelia of *Pisolithus tinctorious* (Pers.) Coker and Couch. Seedlings at the Mississippi site were planted in a split-plot design at three different elevations, which provided three different natural flooding treatments. Seedlings at the other two sites were planted in a Latin square design at a single elevation. Significant differences in the survival and condition of the seedlings during the first growing season were observed at the Louisiana site, favoring the inoculated container-grown seedlings over the other two stock types. First-year seedling survival at the site in Texas, which had the best drainage of the three sites, was not significantly different between treatments. Small mammals clipped 98 percent of the container-grown seedlings at the Mississippi site.

INTRODUCTION

Bottomland hardwood forested wetlands are characteristically exposed to soil saturation and periodic or continuous flooding at various times of the year. Depth to the permanent water table and timing, frequency, and duration of flooding play key roles in the occurrence and growth rate of hardwood species from seed germination, in early seedling survival, and in growth during establishment (Kennedy and Johnson 1984). Seedling survival can be strongly influenced by root morphology, which affects nutrient and water accumulation. Oak seedlings grown in containers develop more primary lateral roots and secondary roots than bareroot seedlings (Dixon and others 1981a).

The roots of forest seedlings are commonly ingrown with mycorrhizal fungi that penetrate the surrounding soil and provide access to a much greater soil volume than uninfected roots. The presence of mycorrhizal fungi may be especially important to seedling growth on harsher sites (Read 1991), because they enhance the transport of nutrients, water, and organic materials to the seedling. Dixon and others (1981a, b) found that leaf area, number of primary lateral roots, and carbohydrate reserves were increased in container-grown black oak seedlings that were inoculated with *Pisolithus tinctorious,* (Pers.) Coker and Couch, a common mycorrhizal fungus associated with many southern forest species.

Pisolithus tinctorius, an "ectomychorrizal" fungus which forms a mantle or sheath on the root surface, has been Used effectively to enhance pine (*Pinus*) seedling growth and survival (Marx and others 1977). Mycorrhizal fungi are obligate plant symbionts; flooding, cropping, and fallow have been shown to reduce their populations. Despite the assumption that wetland plants are non-mycotrophs, wetland species generally develop mycorrhizae when soils become relatively dry (Allen 1990). The influence Of seasonal flooding and soil anoxia on mycorrhizal development and functions in hardwood forests is poorly understood.

The purpose of this study was to determine the relative importance of seedling type and mycorrhizal inoculation in the growth of Nuttall oak seedlings for wetland reforestation.

METHODS

Seedling Culture

Common nursery practices were used to cultivate the container and bareroot seedlings used in these experiments. Thirty pounds of Nuttall oak seed were obtained from a seed source in the Delta area of Mississippi in late April of 1994 and placed in cold storage at 1.7 °C. The acorns were soaked overnight in a 5-gallon bucket of tap water; 111 acorns that floated were discarded. The remainder were placed in 18 plastic bags and refrigerated at 1.7 "C. Bags were turned and opened to check for spoilage three times each week through May 26, 1994, when 2,222 acorns were individually sown in 164-centimeter^3 plastic seedling cones (Ray Leach "Cone-tainer" Nursery, Canby, Oregon).

A 1 :1 homogeneous mixture of autoclaved peat moss and construction-grade vermiculite was used as a planting medium for the container stock. A total of 2,222 seeds were sown, thoroughly watered, and placed in a greenhouse at Stephen F. Austin State University. By July 18, a total of 1928 container seedlings had been produced and moved into an outdoor shadehouse. They were fertilized biweekly and watered as needed.

On July 6, 1994, every other tray of seedlings in the shadehouse was removed and inoculated with vegetative mycelial inoculum of *P. tinctorius.* One-half (5 grams of

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fungal mycelia) of a commercially available inoculum kit was applied in a drench following procedures recommended by the distributor (Mycorr Tech, Inc., Pittsburgh, PA). Seedlings were inoculated again on August 30 and December 21, 1994. The inoculated seedlings were maintained on separate tables in the shadehouse but otherwise treated the same as the noninoculated stock.

Bareroot seedlings (46 centimeters or larger) were obtained from the same seed source and seed lot as the container-grown seed.

Morphological Analysis Prior to Planting

On January 5, 1995, 50 seedlings of each container seedling type (container with inoculation and container without inoculation) were selected using a random numbers table. They were gently removed from their containers and soaked in tap water for 1 hour to loosen the potting medium. After washing, the exposed root systems were submerged in tap water overnight so that they would not dry out.

For the preplanting comparison of bareroot Nuttall oak seedlings with those grown in containers, 250 bareroot seedlings were obtained from the seed/seedling source in Mississippi. They were lifted from the nursery bed on January 3, 1995, and transported overnight in sealed shipping bags to Stephen F. Austin State University, where they were placed in cold storage at 1.7 "C. On January 6, 1995, 50 bareroot seedlings and the container seedlings that were harvested the prior day were brought into the laboratory for morphological and biomass measurements. Weight of aboveground and belowground plant material was measured using a Mettler PC 8000 analytical balance (Mettler Instrument Corp., Heightstown, NJ). Root volume was measured using a displacement procedure described by Burdett (1979). Stems and roots were placed in a drying oven at 60 "C. When a constant weight was reached, the dry weights of stem and root tissue were recorded.

For all statistical analyses used in these experiments the level of significance was established at a = 0.05. A one-way analysis of variance (ANOVA; using Proc GLM of the Statistical Analysis System, SAS Institute Inc. Cary, NC) was used to test for fixed treatment effects on seedling morphology prior to planting. If significant differences were found between at least two of the three seedling types, means were compared using Duncan's multiple range test (Freund and Wilson, 1993).

Field Trials

Yazoo National Wildlife Refuge, MS-Field experiments that involved the testing of seedling treatment and flooding regime were conducted at Yazoo National Wildlife Refuge (NWR) in the Delta Region of west-central Mississippi. The planting site was located on a tract of farmed wetlands that was recently annexed to the Yazoo NWR in Sharkey County, MS, 2.5 kilometers east of the community of Anguilla. A 1994 soil survey of the tract indicated that the soil type at this site is Sharkey clay (very fine, montmorillonitic, nonacid, thermic Vet-tic Haplaquept). The Sharkey soil contains montmorillonitic clay that, when dry, develops cracks that are from 2 to 10 centimeters wide and several centimeters deeper than wide (Soil Conservation Service 1962).

The field is roughly rectangular in shape, with a manmade drainage ditch running the entire length of the east side, from north to south along its long axis. The field has a very gentle slope (< 2 percent) dipping to the east, toward the drainage ditch. An RDS WL-80 water level recorder (Remote Data Systems, Inc., Wilmington, NC) was placed near the study plots on a wooden pile on the west side of the drainage ditch.

An elevation survey of the field was conducted to identify three elevation contours that would best represent three natural flooding regimes (i.e., whole plots): frequently flooded, less frequently flooded, and not flooded. The three elevations relative to mean sea level are 28.1 meters, 28.8 meters, and 29.4 meters. Four 22.8-meter by 7.6-meter whole plots (i.e., replications) were laid out lengthwise along each of the three elevations, with a 7.6-meter spacing between each plot. Each whole plot was subdivided into three 7.6-meter by 7.6-meter subplots, oriented parallel to the elevation gradient. Each of the three seedling treatments was assigned at random to one of the subplots or "split plot" within each whole plot.

Container seedlings were transported in a covered van from the university to the site on January 9, 1995. Bareroot seedlings were lifted from the nursery bed on January 9 and transported in sealed shipping bags directly to the planting site at Yazoo NWR on January 10, 1995. Thirty seedlings were planted with a planting shovel on January 10 and 11, 1995, in each subplot on a 1.5-meter by 1.5-meter spacing arrangement.

Plant competition at each of the three elevations on August 19, 1995, was compared by describing the percentage cover by species and overall height in a 1 -square meter plot located between each whole plot at each elevation.

Alazan Bayou Wildlife Management Area, TX-The Alazan Bayou Wildlife Management Area (WMA), owned and managed by the Texas Parks and Wildlife Department (TP&W), is located in northeastern Texas, approximately 10 miles north of Lufkin in Nacogdoches County. The WMA includes approximately 800 hectares of former pasture and bottomland hardwood forests, mostly located along Alazan Bayou. A relatively low and flat mowed area on the southern end of the tract was selected for the field trials at Alazan Bayou WMA. The 1980 soil survey of Nacogdoches County indicates that the site is Mantachie sandy loam (fine loamy, silicious, acid thermic Aeric Fluvaquent; Dolezel and Fuchs 1980).

There was only one main factor of interest at the Alazan Bayou site: seedling treatment at three fixed qualitative levels (bareroot, container, and container with inoculation). Three 22.8-meter by 7.6-meter blocks (i.e., reps), numbered 1, 2, and 3, were laid out in a north-to-south direction. Each of the blocks was split into three equal size Plots (7.6 meters by 7.6 meters), oriented in an east-to-west direction. For Block 1, each of the seedling treatments was randomly assigned to the plots. The seedling treatment assigned to the westernmost plot of Block 1 was then assigned to the middle plot of Block 2; the seedling treatment assigned to the middle plot of Block 1 was assigned to the easternmost plot of Block 2; and so forth, Creating a 3 by 3 Latin Square design. The order of experimentation was restricted, that is, blocked in two directions: rows and columns.

Ninety bareroot seedlings were selected at random from those that had been placed in cold storage at the university on January 4, 1995. Ninety container seedlings of each treatment type were selected at random from those that remained in the shadehouse. Seedlings were planted with planting shovels in rows in each plot on a 1.5-meter by 1.5-meter spacing arrangement on February 9, 1995.

To compare the morphology of seedlings at the end of the first growing season, three randomly selected seedlings were dug up from each of the nine plots with a planting shovel on January 30, 1996. The procedures that were used to measure all variables but root area were the same as those used in the preplanting analysis of seedlings. For root area measurements, lateral roots were removed with a small scalpel and scanned with the Li-Cor Portable Area Meter (LI-3000 A, Lincoln, NE).

Bayou Macon Wildlife Management Area, LA-Bayou Macon WMA in northeast Louisiana, owned and managed by the Louisiana Department of Wildlife and Fisheries, is located east of Bayou Macon between State Highways 2 and 582, approximately 15 kilometers west of the Mississippi River. The predominant cover type is bottomland hardwood forest, but 644 hectares had been clearcut and used for agricultural purposes before the land was purchased by the State. The soil type at the Bayou Macon WMA planting site is Sharkey clay[2] (Allen and others 1988).

The experimental design at the Bayou Macon WMA was the same as that used at the Alazan Bayou site in Texas. Seedling treatment was the only factor of interest. Seedlings were planted with planting shovels on December 14, 1995.

Data analyses-Analysis of variance (using Proc GLM, SAS) was used to test for treatment effects on seedling height and other continuous response variables measured in-situ at each site. The responses were transformed, if necessary, to meet the assumptions of homogeneity for the error terms of the model. If significant differences Were found between treatments, means that involved two populations (e.g., flooded and nonflooded plots) were compared using the least significant difference or LSD test (Fisher 1960). Duncan's multiple range test was used to compare means from three different populations (e.g., three different seedling types).

For the analysis of the morphology of the 1+1 seedlings harvested at Alazan Bayou WMA, a multivariate analysis of variance (MANOVA, SAS) was performed on those responses which appeared correlated; otherwise, a univariate analysis was performed. Prior to MANOVA, each variable was tested for homogeneous variance assumptions and normality. Means were compared using Duncan's multiple range test when significant differences were found.

Categorical data analyses (using Proc Catmod, SAS) were used to compare rates of survival, dieback, herbivory, and basal sprouting among seedling treatments and flooding regime. If normality assumptions were not met by the categorical model, a binomial test of proportions was used to test for differences between treatments. Contrasts were used to compare means where significant differences were found.

RESULTS

Morphological Differences Prior to Planting

All morphological measurements indicated significant differences between the 1+0 bareroot and the container seedlings prior to planting (table 1). The bareroot seedlings had a significantly larger stem biomass and root collar diameter than the inoculated and noninoculated container seedlings. The initial height of the average bareroot seedling was approximately 10 percent higher than that of the container seedlings. The root systems of the bareroot seedlings were also significantly larger than those of the container seedlings, but the container seedlings had roughly twice as many primary lateral roots. The only significant morphological difference found between the two container seedling treatments prior to planting was the number of primary lateral roots greater than 0.5 millimeters. The inoculated container seedlings had 17 percent more primary lateral roots than the container seedlings that were not inoculated (table 1).

Table l-Morphology of the three types of Nuttall oak seedlings prior to planting at the three field sites (means within a row having a common superscript are not significantly different, a = 0.05)

Inoculated variable	Bareroot	Container	Container
Stem height (cm)	70.4[a]	60.3[b]	65.6[b]
Stem dry weight (g)	12.95[a]	4.52[b]	4.65[b]
Root dry weight (g)	11.30[a]	7.51[b]	7.41[b]
Stem diameter at root collar (mm)	13.0[a]	9.0[b]	9.0[b]
Root volume (ml)	11.55[a]	3.50[b]	3.71[b]
Primary lateral roots	16[c]	30[b]	35[a]

[2] Personal communication. June 17, 1996. Floyd Hooker, NRCS, Lake Providence, LA.

Yazoo National Wildlife Refuge

The planting site at Yazoo NWR was partially flooded twice during the first growing season. The lowest elevation, 28.1 meters mean sea level, was flooded continuously from March 8 to March 23, 1995 and again from April 26 to May 1, 1995. This flooding exposed the seedlings at the lowest elevation to 21 days of flooding. The middle planting elevation was flooded for only five days (March 16 to 20) during the first flood event and seven days (April 24 to 30) during the second event. The highest planting elevation, 29.4 meters mean sea level, did not flood during either event.

The predominant plant species that naturally invaded the planting site at the lowest elevation was *Iva* annua, which covered an average 75 percent of three 1 -square meter plots sampled on August 17, 1995. No other species had more than 5 percent cover at any elevation in the canopy of the competing vegetation at the lowest elevation., Competition in the middle plots was more diverse, with *Iva annua* and *Sorghum halepense* (Johnson grass) occupying 45 percent and 25 percent of the upper canopy, respectively. The upper plots were heavily dominated by a dense growth of Johnson grass, which covered an average of 90 percent of each meter quadrant sampled.

Early in the first growing season (June 1, 1995) average survival (aboveground) of both types of container-grown seedlings exceeded 96 percent at all three elevations. At that time, survival of the bareroot stock averaged 45 percent, 27 percent, and 31 percent at the highest, middle, and lowest elevations, respectively. Survival through the end of the first growing season was difficult to compare among treatments because only 18 of the 720 container-grown seedlings had not been clipped by rodents. The container seedlings at the higher elevation were the first to be clipped, probably because there was more protective cover for rodents under the dense growth of Johnson grass. *Iva annua,* which dominated the competition at the lower elevation, reached comparable height but has a canopy structure that allows much higher light penetration at ground level.

Alazan Bayou Wildlife Management Area, TX

The survival and development of basal sprouts in seedlings during the first growing season at Alazan Bayou was not significantly different among the three seedling treatments (table 2). The categorical data analysis did detect significant effects of seedling treatment on shoot dieback, which was generally confined to the upper 10 centimeters of the stem. One third of the bareroot seedlings experienced partial dieback, compared to an average 67 percent dieback in both types of container stock (table 2).

Live stem length was significantly higher in the container-grown seedlings, even though they were more prone to partial shoot dieback (table 3). Root biomass and stem diameter were significantly higher in the bareroot seedlings. The inoculated container seedlings had a significantly higher number of first-order lateral roots than did the other seedling types, but there were no significant differences in the area of the primary lateral roots in the three types of seedlings. The total volume of taproot and lateral roots in the bareroot seedlings was greater than that of either container seedling type (table 3).

Table 2-Percentage of seedlings that survived, exhibited basal sprouts, and partially died back at the Alazan Bayou WMA in NE Texas during the first growing season (means within a row having common superscript are not significantly different, a = 0.05)

Variables	Bareroot	Container	Inoculated container
Survival	94.08[a]	97.31[a]	97.318
Basal sprout	5.91[a]	1.61'	2.80[a]
Partial dieback	33.33[b]	66.66[a]	68.18[a]

Table 3-Morphology and biomass of seedlings after first growing season at Alazan Bayou WMA in NE Texas (means within a row having same superscript are not significantly different, cc = 0.05)

Variables	Bareroot	Container	Inoculated container
Stem length (cm)	57.1[b]	71 .7[a]	66.1 [a,b]
Stem biomass (g)	3.38[a]	2.92[a]	2.94[a]
Root biomass (g)	4.12[a]	2.63[b]	2.53[b]
Stem diameter (mm)	11.0[a]	10.2[b]	9.8[b]
Root volume (ml)	6.2[a]	4.5[b]	4.6[b]
Lateral root area (cm^2)	9.17[a]	9.17[a]	9.04[a]
Tap root length (cm)	17.2[b]	21 .4[a]	18.3[b]
Primary lateral roots (#)	33[b]	39[a,b]	46[a]

Bayou Macon Wildlife Management Area, LA

Seedling height, the only continuous variable measured at the end of the first growing season at Bayou Macon WMA, was significantly different among all three seedling treatments. The inoculated container seedlings were 20 percent and 79 percent taller than the noninoculated container and bareroot stock, respectively (table 4). The categorical data analyses did not detect any significant differences in basal sprouting or dieback among seedling treatments. Both types of container seedlings experienced greater herbivory by deer than the bareroot seedlings, but the differences were significant only between the bareroot and non-inoculated container seedlings (table 4). Survival among the inoculated container seedlings was 97 percent, which was significantly higher than that of the noninoculated container and bareroot stock (i.e., 88 percent and 79 percent, respectively) (table 4).

Table 4-Comparison of mean first-year height and survival among seedlings planted at Bayou Macon WMA in NE Louisiana (means within a row with same superscript are not significantly different, $\alpha = 0.05$)

Seedling treatment	Height	Survival rate	Deer browse
	Cm	-Percent-	
Bareroot	32.8"	78.8^{b}	3.4^{b}
Container	48.8^{b}	87.5^{b}	15.6^{b}
Inoculated container	58.7^{a}	96.6'	$7.3^{a,b}$

DISCUSSION

Morphological differences between the 1+0 bareroot and container-grown seedlings were significant and can be used, in part, to explain the differences in the survival and condition of the seedlings during the first growing season after planting. The root systems of the bareroot stock consisted primarily of a large taproot with roughly half as many primary lateral roots as the container-grown seedlings. This lack of root surface area has implications for reduced water and nutrient uptake, which may have offset the growth potential advantages associated with the larger biomass and height of the bareroot seedlings.

Differences in first-year survival among the three seedling types at Yazoo NWR were difficult to evaluate because most of the container seedlings were clipped at or near the root collar by rodents. Few container-grown seedlings sprouted after they were clipped in mid-August. However, both the bareroot and container-grown seedlings may resprout during the second growing season.

Morphological differences between seedling types diminished greatly after the first growing season at Alazan Bayou WMA, which had the most efficient natural drainage of the three sites. In addition, height growth among seedlings had shifted, favoring the container stock, even though partial dieback was more prevalent among the container stock. There was no significant difference in survival among the seedling types at this site. However, the noninoculated container seedlings grew significantly taller than the bareroot seedlings, despite the greater rate of partial dieback. The high rate of partial dieback among both types of container-grown seedlings could be related to one or more of the following factors: a higher demand for water associated with their more highly developed root systems, increased vulnerability of their more slender stems to damage by ice and freezing temperatures, and, possibly, the indirect effects of biweekly fertilization.

After the first growing season, the number of lateral roots in the bareroot stock was no longer significantly lower than that of the noninoculated container stock, but the number of lateral roots in the inoculated container seedlings was significantly higher than the other two seedling types. The noninoculated container seedlings grew significantly taller than the bareroot stock, but both types of container seedlings were twice as prone to dieback as the bareroot stock.

At Bayou Macon WMA, the drainage of local precipitation from the field was very slow, but it was not inundated by backwater flooding. The significance of the improved survival among the inoculated container stock at Bayou Macon WMA is possibly related to the more highly developed root system of these seedlings, which was induced by confinement in Containers, frequent watering and fertilization, and more extensive mycorrhizal development.

CONCLUSIONS

Seedling Culture clearly influenced the morphology of the root systems in the three types of seedlings used in these experiments. The highly fibrous root system of the container-grown seedlings may present potential advantages when planted at sites that are prone to drought and/or flooding. Inoculation of the container seedlings with vegetative mycelia of *P. tinctorious* slightly, but significantly, enhanced root fibrosity.

During the first growing season at Alazan Bayou WMA, the morphological differences between seedling types diminished. At this site, which had the most efficient drainage of the three planting sites, there were no significant differences in seedling survival among the three seedling types. The container-grown seedlings were twice as prone to dieback as the bareroot seedlings; however, their overall height growth was greater. Height growth was also greater among the container-grown seedlings at the Louisiana site. At Bayou Macon WMA, where drainage was poor but there was no long-term inundation, significant improvements in first-year survival and growth among the inoculated container stock could be attributed to seedling culture and related differences in root morphology. At Yazoo NWR, loss of stem tissue in 98 percent of the container-grown seedlings to small mammals precluded a meaningful comparison of first-year survival among the three treatments.

Seedling sprouting and survival during the second and third growing seasons should provide further insight into the relative importance of seedling type. The first year after planting, however, appears to be a very critical period in which seedling morphology, flooding, and herbivory have significant impacts on growth and survival, especially on sites that are prone to flooding.

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INFLUENCE OF HYDROLOGY ON ARTIFICIAL REGENERATION OF OAKS IN THE MISSISSIPPI DELTA

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Abstract-Artificial hardwood regeneration on hydric agricultural sites, commonly known as farmed wetlands, has had little success in the Lower Mississippi Alluvial Valley, which consists of Mississippi, Arkansas, and Louisiana. A commonly held belief is that the failures are often the result of flooding events which occur on these sites. The objective of this study was to determine the influence of hydrology on the establishment and growth of two species of oak seedlings in four different, artificially controlled, flooding regimes planted at two dates on a farmed wetland site. Nuttall oak (Quercus *nuttallii*, Palmer) planted in December had the highest survival rate and leaf area measurements with regard to all flooding regimes, while willow oak (Q. *phellos*, L.) planted in March had the lowest survival rate, leaf area, and height growth in all flooding regimes.

INTRODUCTION

Of an estimated 24 million acres of bottomland hardwood forest present at the time of European colonization in the Lower Mississippi Alluvial Valley, commonly referred to as the Mississippi Delta, only 7.9 million acres of nonfederal forested wetlands remained as of 1993 (Cubbage and Flather 1993). These forested wetlands were cleared because of the higher value placed on agricultural products, and flood control structures were put in place to protect the agricultural crops.

Many of the forested wetlands that were cleared for agricultural production were not suitable for row crops because of backwater flooding characteristic to this area. Backwater flooding occurs when the water level of the Mississippi River rises higher than the water levels of streams and rivers inland. When this occurs, flood control structures prevent the inland waterways from flowing into the Mississippi River and many sites in the Delta are flooded. As a result, Federal, State, and private land managers have expressed interest in reforesting these farmed wetland areas rather than continuing to take annual economic losses from row crop destruction.

Bottomland hardwood forests are important economically for their timber production and hunting and fishing revenues. They also provide necessary ecological functions and supply noncommodity values (Wharton and others 1982, Wilkinson and others 1987). Some of the ecological functions of wetlands are nutrient cycling, biogeochemical cycling, and hydrologic cycling (Walbridge 1993).

Under the legislation of the Federal Agriculture Improvement and Reform Act of 1996, specifically the Wetlands Reserve Program, lands that are classified as farmed wetlands may be reforested through the help of the Federal Government by different economic programs (Federal Agriculture Improvement and Reform Act 1996). As a result of this support, many flood-prone sites in agricultural production have been and will continue to be reforested. Two methods of artificial regeneration are commonly used in the South. They are direct seeding and seedling planting (Johnson 1989, Johnson and Krinard 1985). Both are used on sites where no oak component exists.

On these open agricultural fields, light is not the limiting factor at time of planting of oak seedlings (Hodges and Gardiner 1992). Depending on when it occurs and the duration, flooding can influence the performance of oak seedlings (King 1995, Kozlowski and Pallardy 1979, Malecki and others 1983, Pezeshki and Chambers 1985, Streng and others 1989). Physiological functions such as stomatal conductance and photosynthesis are altered by flooding conditions and can affect the growth of oak seedlings. Kozlowski and Pallardy (1979) determined that flooding induced stomatal closure for *Fraxinus pennsylvanica* (green ash), which reduced the rate of photosynthesis. Pezeshki and Chambers (1985) found that stomatal conductance and net photosynthesis of *Quercus pagoda* (cherrybark oak) seedlings were significantly lower in flooding periods compared to preflooding conditions, indicating that this species encountered stress caused by flooding. Physiological conditions as affected by hydrology may lead to seedling stress that can hinder growth responses and survival (Pezeshki and Chambers 1985).

This study was designed to provide information on techniques for artificial regeneration of oaks on these types of hydric agricultural sites.

METHODS

Study Site

The study area is in the Lower Mississippi Alluvial Valley, more specifically in Sharkey County, MS, on the U. S. Fish and Wildlife Service, Yazoo National Wildlife Refuge. The area is known as the Sharkey Research Site. It was chosen because it was in agricultural production of soybeans and cotton prior to the installation of the research project, and it contained the characteristics of a farmed wetland.

The site is usually inundated during the dormant season (December - March), but it also floods for frequent periods during the early part of the growing season (April and

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May). This was an important characteristic in choosing the site for this research because many of the farmed wetlands in the valley are subject to flooding during the early part of the growing season. The growing season for this site occurs from February to October (Soil Conservation Service - USDA 1991).

The soil type is Sharkey clay (very fine, montmorillonitic, nonacid, thermic, Vertic Haplaquepts) (Soil Conservation Service - USDA 1975). It is currently classified as a hydric soil (Soil Conservation Service - USDA 1991). Because it is a montmorillonitic soil, the physical properties are altered by shrinking and swelling of the soil particles due to moisture level changes. These changes in the soil may prevent formation of traffic pans.

Study Objectives

The objectives of this research were to determine, for two oak species (Nut-tall oak and willow oak); (1) the influence of hydroperiod on seedling establishment and development, and (2) the influence of planting date on seedling survival and growth.

Null Hypothesis

The general null hypothesis was that hydrologic conditions were not the controlling factor for successful regeneration of planted Nuttall and willow oak seedlings on these particular sites. Specific null hypotheses were as follows: (1) season of planting does not influence the success of the two species of planted red oak seedlings, and (2) flooding regimes do not have an effect on the performance of the two species of planted red oak.

Study Design

The study design was a randomized complete block design with split plots. Three levee impoundments, or replications, of 93 meters * 179 meters were constructed to hold water to mimic flooding. Water levels in the impoundments were controlled by pumps and a series of pipes and valves. This design permitted an evaluation of the effects of timing and duration of flooding on establishment of the red oak seedlings.

Within each impoundment, four flooding regimes were installed. They were as follows: (1) No-Flooding-control; (2) Winter/Spring flooding with no crown inundation-l 0 centimeters flood depth, January 20, 1996 to May 10, 1996; (3) Winter/Spring flooding with crown inundation-91 centimeters flood depth, January 20, 1996 to May 10, 1996, (4) Spring flooding with crown inundation after leafout—91 centimeters flood depth, May 10, 1996 to May 25, 1996.

Within each flooding regime, four treatments or experimental plots were installed. The treatments were Nuttall oak planted in December 1995, willow oak planted in December 1995, Nuttall oak planted in March 1996, and willow oak planted in March 1996. Each treatment plot size was 80 square meters. Each treatment consisted of 90 seedlings planted on a 0.6 meter * 0.6 meter scale. Seedlings for this study were purchased from a local vendor. This scale size was chosen because of the research area size limit. The close planting scale had no effect on seedling growth responses in the first 2 years of the study. All treatments were hand-planted in the same manner at both planting dates using hardwood planting shovels. This method of planting was chosen because the shovels had a broad head allowing for more space for the roots to expand. On this type of site, this method is used on an operational scale.

The response variables were seedling root/shoot ratios, seedling growth by height and groundline diameter, leaf area, and percent survival. Preseason height and diameter and root/shoot ratio measurements of seedlings were taken before dormancy broke for seedlings at both planting dates. Leaf area measurement dates were staggered throughout the 1996 growing season. First lateral, first flush, second lateral, second flush, third lateral, and third flush leaf area measurements were recorded when the seedlings were in their respective lag phase (Hanson and others 1986). Percent survival, root/shoot ratio, and height and diameter were recorded at the end of the growing season in November 1996.

RESULTS

Results are based on first-year, post-growing season data. Root/shoot ratios did not differ between flooding regimes ($p=0.1648$). Across all four flooding regimes (table 1), Nuttall December and Nuttall March seedlings had higher postseason root/shoot ratios ($p=0.0377$) than willow oak seedlings planted in March but not higher than willow oak planted in December ($p=0.2994$).

Height growth was significantly greater for No Flooding and Winter/Spring No Crown flooding vs. Winter/Spring Crown flooding and Spring flooding ($p=0.0095$). Nuttall December had significantly more height growth vs. the remaining three treatments ($p=0.0007$) (table 1). As shown in table 1, negative measurements were recorded for height growth due to stem dieback, which is common in oak seedlings. Diameter growth was greater for No-Flooding ($p=0.0146$) than Winter/Spring Crown flood, but there was no difference between Winter/Spring No Crown flood and Spring flooding ($p=0.2739$). Nuttall December and Nuttall March had significantly larger diameters ($p=0.0103$) than willow December and willow March (table 1).

Seedlings in the No Flooding regime had significantly higher leaf areas ($p=0.0263$) than seedlings in the remaining three flooding regimes, and the seedlings in the Winter/Spring No Crown flood had higher leaf area than those subjected to Spring flooding. Nuttall December was significantly higher ($p=0.0001$) than the remaining three treatments for leaf area. Willow December and willow March did not differ (table 1).

Percent survival was significantly higher ($p=0.0104$) for No Flooding, Winter/Spring Crown, and Winter/Spring No Crown compared to Spring flooding. For treatments, Nuttall December was significantly higher ($p=0.0001$) than the other three. Willow December and Nuttall March did not

Table 1-First-year average root/shoot ratio (R/S), height growth (HG), diameter growth (DG), leaf area(LA), and survival rate for Nuttall and willow oak seedling treatments for No Flooding, Winter/Spring No Crown flood, Winter/Spring Crown flood, and Spring flooding regimes (p=0.05)

Treatment	R/S	HG	DG	LA	Survival rate
		cm	*mm*	*cm^2*	*Percent*
Nuttall December	1.9a	4.7a	1.3a	3,526.5a	82.6a
Willow December	1.5ab	-7.0b	0.4b	1,854.5c	68.9b
Nuttall March	1.7a	-4.0b	I.la	2,705.8b	69.8b
Willow March	1.3b	-7.9b	0.3b	1,319.7c	33.1c

differ in survival rates. Willow March had the lowest survival rate (table 1).

DISCUSSION

In this study, Nuttall planted in December and March had the highest root/shoot ratios compared to the other treatments (table 1) and with all flooding regimes (tables 2 and 4). This species is typically found on lower sites which flood more frequently in the valley (Johnson 1975). Roots and shoots are interdependent throughout the life of a woody plant (Kozlowski 1971). Feedback between the root and shoot acts as a system of regulation for plant growth and development (Davies and Zhang 1991). There are three fundamental carbon allocation patterns in woody plants (Dickson 1991, Kozlowski 1992). They are determinate shoot growth, indeterminate shoot growth, and semideterminate shoot growth. Semideterminate shoot growth is common with *Quercus.* In this type of shoot growth, periodic flushes take place with intermediate lag stages (Hanson and others 1986). During the lag stages, reserves are stored in the roots. The results of this study indicate that more growth occurred in the Nuttall oak planted in December and March compared to the willow oak planted in December and March. Johnson (1975) found growth of Nuttall oak to be best on low sites where water stood into the early part of the growing season.

Height and diameter growth were both higher for No Flooding because the stresses of hydrology did not hinder the growth of both species of seedlings. According to Hook (1984), the shallower the water level, the less amount of stress the seedling has to overcome before it can grow.

Leaf area and survival were related in the measurements taken for this study. Higher leaf areas resulted in higher survival rates (table 1). These results indicated that Nuttall planted in December had higher leaf areas than Nuttall planted in March. This was one reason survival rates were significantly higher for Nuttall planted in December compared to the other treatments for all flooding regimes. Because these seedlings had more leaf area, more photosynthesis could be carried out, which increased

Table 2-First-year average root/shoot (R/S), height growth (HG), diameter growth (DG), leaf area (LA), and survival rate for Nuttall oak seedlings planted in December 1995 per flooding regime

Flooding regime	R/S	HG	DG	LA	Survival rate
		cm	*mm*	*cm^2*	*Percent*
No Flooding	2.2	11.8	2.0	4,385.0	87.7
Winter/Spring No Crown flood	1.5	8.3	1.5	4,002.4	84.6
Winter/Spring Crown flood	2.1	-1.4	-0.1	2,951.5	78.5
Spring flooding	1.8	0.1	1.7	2,767.3	80.3

Table 3-First-year average root/shoot (R/S), height growth (HG), diameter growth (DG), leaf area (LA), and survival rate for willow oak seedlings planted in December 1995 per flooding regime

Flooding regime	R/S	HG	DG	LA	Survival rate
		cm	*mm*	*cm²*	*Percent*
No Flooding	1.8	-4.1	0.2	2,367.9	82.0
Winter/Spring No Crown flood	1.6	-2.2	0.2	1,736.1	71.3
Winter/Spring Crown flood	1.2	-11.7	0.6	2,024.2	72.5
Spring flooding	1.3	-10.1	0.6	1,289.8	49.6

Table 4-First-year average root/shoot (R/S), height growth (HG), diameter growth (DG), leaf area (LA), and survival rate for Nuttall oak seedlings planted in March 1996 per flooding regime

Flooding regime	R/S	HG	DG	LA	Survival rate
		cm	*mm*	*cn?*	*Percent*
No Flooding	1.9	1.9	1.5	3,870.8	74.8
Winter/Spring No Crown flood	1.3	-1.3	1.0	3,282.4	75.3
Winter/Spring Crown flood	1.8	-5.6	1.2	2,437.7	84.4
Spring flooding	1.9	-11.1	0.8	1,232.5	44.6

Table 5—First-year average root/shoot (PUS), height growth (HG), diameter growth (DG), leaf area (LA), and survival rate for willow oak seedlings planted in March 1996 per flooding regime

Flooding regime	R/S	HG	DG	LA	Survival rate
		cm	*mm*	CI??	*Percent*
No Flooding	1.1	-9.5	0.4	2,087.7	41.1
Winter/Spring No Crown flood	0.8	-2.9	0.5	631.6	31.4
Winter/Spring Crown flood	1.2	-12.5	-0.4	1,209.7	29.1
Spring flooding	2.0	-6.8	0.8	1,349.9	30.8

survival rates. Higher leaf area measurements existed in the No Flooding, Winter/Spring No Crown, and Winter/Spring Crown. The Spring flooding regime had the lowest ($p=0.0104$) survival rate with the lowest leaf area. The seedlings in the Spring flooding regime were damaged the most. According to Kozlowski and Pallardy (1997), flooding during the growing season is more damaging than dormant season flooding. The spring flooded seedlings were flooded after leafout occurred. The seedlings lost their leaves in the flooding event, therefore additional energy was required for the seedlings to start the process of initial shoot growth again after the water level was dropped. This may have caused the seedlings to use additional reserves in the roots. By doing this, they may not have had enough reserves in the roots to carry on root growth.

CONCLUSIONS

In this study, by analyzing the first-year results, we see that Nuttall oak seedlings planted in December withstood the stresses brought on by flooding very well with regard to survival, leaf area, and height growth in all flooding regimes (table 2). The No-Flooding regime, Winter/Spring No Crown flooding, and Winter/Spring Crown flooding had Significantly higher rates of survival for both species at both planting dates compared to the Spring flooding regime. The Spring flooding proved to be most detrimental to the seedlings and, as shown in tables 2, 3, 4 and 5, willow oak seedlings did not perform as well as Nuttall oak seedlings for both planting dates in each flooding regime.

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FIRST-YEAR SURVIVAL AND GROWTH OF BAREROOT, CONTAINER, AND DIRECT-SEEDED NUTTALL OAK PLANTED ON FLOOD-PRONE AGRICULTURAL FIELDS

Hans M. Williams and Monica N. Craft'

Abstract-Container and 1-O bareroot Nuttall oak (*Quercus nuttallii*, Palmer) seedlings were hand-planted, and acorns were direct- seeded, in a Sharkey soil (very fine, montmorillonitic, nonacid, thermic, Vertic Haplaquepts). The seedlings and seed were planted in January, February, March, and June, 1993. Flooding, to a depth of 2 meters, occurred on the study site from late March to late May. Seedlings planted in June were not flooded. Regardless of planting date, mean first-year survival for container seedlings was greater than 80 percent. Overall mean survival for bareroot seedlings was about 40 percent and direct-seeding survival was 30 percent. Bareroot seedling survival was about 60 percent when seedlings were planted in January or February, but fell below 25 percent when seedlings were planted in March and June. The reduction in bareroot survival was attributed to long-term cold storage. Mean first-year total height of container, bareroot, and direct-seeded seedlings was 46 centimeters, 34 centimeters, and 15 centimeters, respectively. However, stem dieback resulted in shorter seedlings after the first year in the field. Container seedlings were slightly shorter than when planted, but bareroot seedlings averaged 22 centimeters shorter. Greater survival and flexibility with regard to planting schedules may justify the use of container seedlings on flood-prone sites.

INTRODUCTION

Federal programs such as the Wetlands Reserve Program administered by the Natural Resource Conservation Service, and mitigation for wetland loss required by the U.S. Clean Water Act have initiated the increase in bottomland hardwood wetlands restoration in the Southeastern United States. Usually, the objective is to restore the wildlife and water quality wetland functions. Timber production, while enhancing the value of these reforested sites, is a secondary objective. Agricultural fields that flood in most years are ideal restoration sites because the presence of hydrology increases the opportunity for many wetland functions to occur. In addition, restoration costs may be reduced because little site preparation is needed prior to planting.

Flooding usually occurs in the Southeastern United States during the winter and early spring, which coincides with the conventional planting season. Consequently, this desirable flooding can cause significant problems during reforestation. Flood timing can disrupt seedling delivery and planting schedules, prolong cold storage of seedlings, or create difficult planting conditions. The long-term, complete inundation of newly planted flood-tolerant bottomland hardwood seedlings may reduce survival (Kozlowski and others 1991).

In 1991, the U.S. Army Corps of Engineers, Vicksburg District, began the reforestation of 3600 hectares of agricultural land located in Yazoo County, MS. The Lake George Wildlife/Wetland Restoration Project was initiated as mitigation for the Yazoo and Satartia Area Backwater Levee Project completed in 1987. The primary objective was to improve wetland and terrestrial wildlife habitat by planting a suite of mast-producing bottomland hardwood tree species. Reforestation was to be accomplished by using 1-O bareroot seedlings. Except for some ponding, about 2650 hectares of the Lake George site is protected from flooding by an existing levee system. However, 405 hectares are unprotected and subject to backwater flooding from the Big Sunflower and Yazoo Rivers. Early survival of planted seedlings was high on areas that did not flood. However, survival was poor on sites where backwater flooding occurred after planting. Many of these areas had to be replanted, resulting in increased restoration costs and changes in the long-term planting schedule. The study objective was to observe the early survival and growth of seedlings planted on flood-prone sites on different dates and using different stocktypes.

METHODS

Container seedlings, 1-O bareroot seedlings and acorns of Nuttall oak (*Quercus nuttallii*, Palmer) were hand-planted on January 22, February 16, March 18, and June 8, 1993. The seedlings were planted on a Sharkey soil series (very fine, montmorillonitic, nonacid, thermic, Vet-tic Haplaquepts) located at the Lake George site (U.S. Department of Agriculture 1975). The exact study location was chosen because the site was known to experience backwater flooding almost every year. The bareroot seedlings were purchased from a local forest tree nursery. All the bareroot seedlings used in the study were delivered in January and placed in cold storage at 5 °C until planting. The bareroot seedlings were packed in Kraft paper bag bundles of 100 to 250 seedlings. The roots were kept moist by a synthetic mulch.

The container seedlings were grown at facilities located at the U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS. In May 1992, artificially stratified Nuttall oak seeds were sown into 164 cubic centimeter plastic cone containers filled with a 1:1 ratio of sphagnum peat moss and vermiculite. The acorns were purchased from a local seed vendor. Seed stratification was consistent with methods as described by Olson (1974). Container seedling density was 258 per square meter. Seedlings were

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established in the greenhouse; then, for the remainder of the growing season, they were placed in a shadehouse covered with a 50 percent shade cloth. Seedlings were watered daily and fertilized weekly with a complete fertilizer (20-20-20 or 15-45-15). Watering and mineral fertilization were reduced in September. Seedlings remained outside and in the containers until planted.

In fall 1992, Nuttall oak acorns for the direct-seeding treatment were purchased from the same local seed vendor as the container seedlings. The seeds were artificially stratified prior to sowing at the study site.

Experimental Design

The study was conducted as a randomized, complete block, split-plot design with four replications. The whole plots were the planting dates and the subplots were the stocktypes. Each subplot contained 25 planting positions. The seedlings and seed positions were on a 3-meter by 3-meter spacing. Seedlings were planted with a shovel and acorns were sown by hand to a depth of 5 centimeters. Two acorns were sown at each position. First-year survival and height measurements were taken in September, 1993. Analysis of variance was conducted using Statistical Analysis System Procedures (SAS Institute Inc. 1989). Results are discussed as significant at the 5 percent probability level.

RESULTS AND DISCUSSION

The bareroot seedlings were taller and had greater shoot and root mass than the container seedlings (table 1). Morphology recommendations for bareroot seedlings include heights greater than 46 centimeters, minimum root-collar diameters of 10 millimeters, and a well-developed root system (Kennedy 1993). An important distinction between stocktypes may be in their root characteristics. The bareroot seedling roots consisted primarily of a large tap root and a few primary and secondary laterals. The container seedling roots were fibrous, consisting of a tap root and many higher-order lateral roots. Container seedling production typically promotes fibrous root system development and protects these roots until planting (Landis and others 1990). Container hardwood seedlings, which experience lower handling stresses prior to planting, may have a better survival rate than bareroot seedlings on poor sites (White and others 1970). While bareroot production may also promote a fibrous root system, many of these roots can be lost during seedling removal from the nursery bed.

Table 1-Morphological comparison between 1-O bareroot and g-month-old container Nuttall oak seedlings prior to planting

Variable	Bareroot	Container
Height (cm)	56	46
Diameter (mm)	7.0	6.2
Root dry weight (g)	5.7	3.8
Shoot dry weight (g)	6.7	4.9

Soil moisture content (oven-dry basis) was about 40 percent for the January, February, and March plantings. Small portions of the site were ponded with rainwater, and the remainder of the soil on the site appeared to be near saturation. The original experimental design called for plantings to occur in April and May. However, above-average rainfall combined with high Mississippi River stages caused backwater flooding to occur at the study site. The seedlings planted in January, February, and March experienced flooding to a depth of 2 meters from late March to late May. For the June planting, soil moisture content in the root zone was about 28 percent. The soil was dry and cracked at the surface, typical for a montmorillonitic clay. Pettry and Switzer (1996) reported moisture contents in the root zone of forested Sharkey soils of about 51 percent and 41 percent for field capacity (.03 MPa tension) and permanent wilting percentage (1.5 MPa tension), respectively. Perhaps the discrepancies in soil moisture retention can be explained by the higher organic matter content that could be expected in a forest soil.

Survival was highest if the seedlings and seeds were planted in January and February (table 2). Survival was reduced significantly if the planting occurred in March or

Table 2-First-year height and survival of 1-O bareroot, 9-month-old container and direct-seeded Nuttall oak seedlings planted on four different dates on a Sharkey clay soil series, Yazoo County, MS

Treatment	Total height	Height growth	Survival rate
	- - - *Centimeters* - - -		*Percent*
Planting date			
January 1993	31	2	62***
February 1993	33	1	58
March 1993	34	0	45
June 1993	32	-5	36
Stocktypes			
Bareroot	34***	-19**	38***
Container	46	3	84
Seed	15	15	30
Date and stocktype			
Jan-bareroot	35	-12	59
Jan-container	44	4	84
Jan-seed	14	14	44
Feb-bareroot	39	-14	56
Feb-container	46	3	80
Feb-seed	14	14	39
Mar-bareroot	37	-21	32
Mar-container	48	4	75
Mar-seed	16	16	28
Jun-bareroot	22	-31	4
Jun-container	48	3	95
Jun-seed	17	17	9

,* = Significant at the 1 percent and 0.1 percent probability level, respectively.

June. Overall, container seedlings had the best first-year survival, while direct seeding of had the worst. Direct seeding of bottomland oak species can be a low-cost and effective means of reforesting agricultural lands (Wittwer 1991, Bullard and others 1992, Stanturf and Kennedy 1996). However, adequate stocking by direct seeding may not be achieved because of seed predation, flooding, or drought (Johnson and Krinard 1987). Considering a recommended sowing rate of 3,600 seeds per hectare (Bullard and others 1992), stocking by direct seeding for the study site was about 1 ,100 seedlings per hectare after the first year. This is twice the minimum 550 seedlings per hectare usually recommended when planting bareroot seedlings for wildlife objectives. Seedling stocking could have been higher; however, many of our acorns sown prior to the flood were found on the soil surface or exposed in the soil cracks in June. Also, the small direct-seeded seedlings will be exposed to future floods and herbivory, probably further reducing the stocking. For reforestation projects initiated by Federal programs or regulation, adequate seedling survival usually must be guaranteed. The required seedling survival can range from 50 to 90 percent. Consequently, direct seeding, although relatively inexpensive, may be too risky for many bottomland hardwood wetland restoration projects.

Excellent survival can be achieved by planting bareroot seedlings, especially when environmental conditions are optimum (Allen 1990, Miwa 1995). For this study, the reduced survival rate for bareroot seedlings planted in March and June may be partially explained by the reduction in seedling viability during long-term cold storage. The long-term cold storage of hardwood seedlings should be avoided. Because of the height of hardwood seedlings, storage bags usually cannot be completely sealed. Long-term cold storage could result in the drying of the roots. Ideally, only the number of seedlings that can be planted in 1 day should be delivered from the nursery to the site (Kennedy 1993). However, nursery location, the size of the reforestation project, and delivery schedules may necessitate receiving all of the seedlings at one time. For large projects, the inability to plant all of the seedlings in a short time period will increase seedling storage time. In addition, planting delays caused by flooding may further keep the seedlings in cold storage. For the Lake George Project, delivery schedules, nursery location, and flooding kept large numbers of seedlings in cold storage for weeks prior to planting.

Flooding appeared to have less adverse effect on container seedling survival. Container seedling survival was higher than bareroot seedling survival when the planting occurred in January or February. In addition, the high June survival for container seedlings suggests that they can be kept in the containers and successfully established after the flood waters recede. The successful establishment of the June-planted container seedlings was achieved even though the seedlings were growing and evapo-transpirational demand on the site was high.

It was anticipated that the direct-seeded seedlings would be smaller than container or bareroot seedlings. However, the amount of stem dieback observed for the container and bareroot seedlings was disturbing. Bareroot seedlings were shorter after the first year in the field than when planted. Container seedlings were about as tall as when they were planted. Adequate survival is usually more important than rapid height and diameter growth for most bottomland hardwood restoration projects. However, the detrimental effects of complete inundation on seedling survival suggests that rapid height growth after planting is desirable.

CONCLUSIONS

First-year survival was highest when seedlings were planted during the conventional planting season. Container seedlings had the best survival regardless of planting date. Their apparent greater tolerance to flooding and handling stress, combined with better planting-time flexibility, may make container bottomland hardwood seedlings the best choice for the reforestation of sites prone to winter/early spring flooding.

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RELATIONSHIP BETWEEN FLOODING REGIME AND INCREASED HERBIVORY OF NUTTALL OAK

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Abstract-The atypical flooding of bottomland hardwood forests during periods of the year that historically did not experience flooding have been shown to have adverse physiological effects on even the most flood-tolerant species. A reduction in oxygen availability in the soil results in decreases of both photosynthesis and the production of compounds considered necessary for plant defense, which could potentially increase the rate of herbivoty on flood-stressed individuals. This study examined the herbivory rates of tussock moth (*Orgyia leucostigma* J.E. Smith) caterpillars on Nuttall oaks (*Quercus nuttallii* Palmer) in a laboratory. Oaks were subjected to four different watering regimes: permanently flooded, intermittently flooded, flooded 10 centimeters below the soil surface, and well-watered controls. Normal plant growth and functioning were adversely affected by flooding. Photosynthetic rates in flooded plants were significantly reduced as compared to control plants. Control seedlings were significantly taller, possessed larger diameters, and had more leaves than seedlings subjected to flooding. Conversely, herbivory was greatest on permanently flooded Nuttall oak seedlings, indicating that flooded seedlings were more palatable to tussock moth larvae than seedlings that were not flood-stressed. This suggests that flooding, and the associated adverse effects on plant physiological functions, may predispose Nuttall oak trees to foraging arthropods. Factors affecting this predisposition are discussed.

INTRODUCTION

A common misconception relating to herbivorous arthropods inhabiting forested ecosystems is that all leaves are identical as a food source. However, leaf traits such as nutritional quality and secondary compounds considered important in plant defenses can be extremely variable. Variations are known to occur not only among individuals of the same host species (Pelham and others 1988, Senn and others 1992), but among leaves within the same host (Witham 1981, Schultz 1983). This variability results in a heterogenous environment in which populations of herbivores are not readily able to exploit (i.e., defoliate) an entire stand of trees or even an entire tree (Witham 1981 and 1983).

Variability in leaf quality can be related to several factors including the position of leaves in the canopy (e.g., sun versus shade leaf) (Field 1983), nutrient availability (Chapin and others 1987), leaf age (Raupp and Denno 1983, and references therein), or physiological stress (Rhodes 1983). Of these factors, physiological stress is likely to have the most dramatic impact on host variability and insect populations. Environmental stress (e.g., drought, freezing, and salinity) can increase the availability of essential nutritional macromolecules such as amino acids and sugars within plants (Levitt 1972, White 1984), and reduce the ability of plants to produce defensive chemicals (Rhodes 1979 and 1983). This increase in nutrients and decrease in defensive allelochemicals are likely induced by a reduction in photosynthesis in an attempt to reduce the potential of desiccation or accumulation of toxic byproducts in the plant (Kozlowski 1982a and 1982b). Price (1991, and references therein) summarizes this scenario as the plant stress hypothesis, which states that stressed plants exhibit a reduction in protein synthesis resulting in an increase in amino acids, and a decrease in the synthesis of defensive chemicals, which results in plants becoming more susceptible to herbivory (fig. 1). Furthermore, as susceptibility increases, herbivore populations are able to reach epidemic proportions after consecutive years of favorable conditions (e.g., leaf quality) for herbivores (Martinat 1987, Mattson and Haack 1987a and 1987b).

Although there have been numerous studies examining the relationship between physiological stress and herbivores (e.g., White 1976, 1984; Mattson and Haack 1987b), few studies have examined how flooding affects herbivores. Flooding does negatively affect the physiological functioning and growth of trees by causing root dysfunction (Kozlowski 1984, Pezeshki 1994), decreased photosynthetic rates (Pezeshki 1994), and decreased production of secondary compounds (Rhodes 1983). Overall variability in leaf traits may also be less pronounced

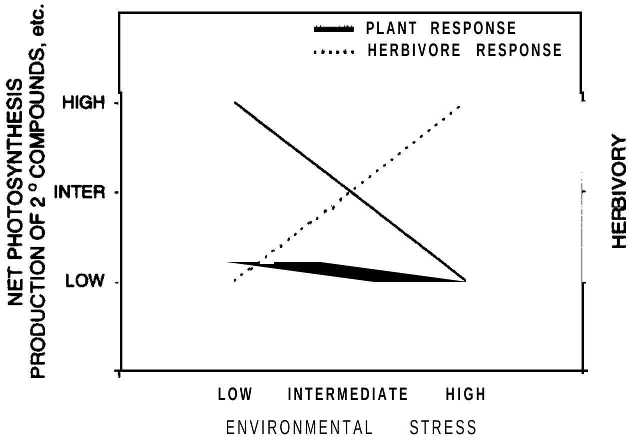

Figure 1-A generalized response of plants and herbivores to physiological stress (but see Bazzaz and others 1987).

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in flood-stressed plants, but little is known of how this and other flood-induced characteristics may influence increases or decreases in herbivory. There is little evidence of herbivory impacts in flooded forests, even in areas where flooding is quite common, such as in the lower Mississippi Alluvial Valley. Many of the bottomland hardwood forests found within this region are inundated for long periods of time due to natural flooding and human-induced changes in the landscape, resulting in the flooding of these systems during periods of the year when flooding was not historically common. These sometimes irregular and extended periods of flooding during the growing season may cause abnormal physiological stress on trees. However, population outbreaks of insect defoliators are historically quite rare in bottomland hardwood forests. The first recorded outbreak of forest tent caterpillars (*Malacosoma disstria* Hübner) in the Mississippi Delta occurred in 1989 (Leininger and Solomon 1995). This outbreak occurred in areas in and around the Delta Experimental Forest and the Delta National Forest. However, these areas are outside the levees, and although they are flooded during the fall and winter, they tend not to be flooded during the growing season; flood stress was not likely a factor in this outbreak. Very few other outbreaks have been documented in this region, although McCasland (1997) found an increase in the number of caterpillars in a year when flooding occurred versus the previous year when no flooding occurred. Thus the question arises, is flooding physiologically stressful enough to evoke a negative response from host species and are herbivores able to take advantage of flood-stressed individuals? The objective of this study was to evaluate the foraging response of a generalist herbivore species to various regimes of flooding of Nuttall oak (*Quercus nuttallii* Palmer), a tree species frequently found on poorly drained soils. Flooding regimes were designed to mimic the natural ranges of conditions experienced by this tree species within a bottomland hardwood forest.

METHODS

Forty-eight 2-year-old Nuttall oak seedlings germinated in a nursery were randomly assigned to one of four treatments: (1) control, well-watered but not flooded; (2) permanently flooded to 1 centimeter above soil surface; (3) intermittently flooded, 2 weeks of flooding followed by 2 weeks of drained, nonflooded conditions; and (4) partially flooded to 10 centimeters below the soil surface. Twelve seedlings were randomly assigned to each treatment and placed in a completely randomized block design. Plants were housed in a well-ventilated greenhouse.

Forty-four third instar white-marked tussock moth (*Orgyia leucostigma* J.E. Smith), (Lepidoptera: Lymantriidae) larvae ware collected from oaks found in bottomland hardwood forests located in the Meeman Shelby Wildlife Management Area, and the Edward J. Meeman Biological Station, Shelby County, TN. Tussuck moths are quite common throughout most of North America and are known to feed on many species of trees, including oak (Van't Hof and Martin 1989).

To assess the status of plant physiological functioning under various flooding regimes, net photosynthetic rates were measured using a portable gas exchange system (Model CIRAS12, PP System Inc., England). Net photosynthesis was measured on 12 sample leaves, one randomly selected leaf per each plant per treatment, prior to conducting herbivore studies. Herbivory experiments were conducted in a laboratory during the evening hours (2200-0200). One caterpillar was placed into a closed Container with one randomly selected leaf from each of the four treatments. Leaves were placed randomly within one Of four quadrants and a water dish was also placed within the container to maintain a constant moist environment. The area (square centimeters) of leaves were measured with a leaf area analysis system before and after the experiment. Herbivory was measured as the percentage of each leaf eaten by the caterpillar during the 4-hour experiment. Chemical analysis of leaf material was not conducted in this experiment. Therefore it was not possible to determine the presence and/or quantity of secondary compounds and nutrients, which play a major role in plant-herbivore interactions. However, the height, diameter, and final number of leaves produced at the end of the experiment were used as a measure of overall plant vigor, which is likely related to the quality of leaves as a food source for herbivores. One-Way Analysis of Variance (ANOVA) (SAS Institute 1989) was used to determine whether the net photosynthetic rates and the percentage of leaf area consumed differed among the four treatments. Tukey's Studentized Range Test was used to determine which treatments were significantly different from one another when there were overall significant differences among the treatments. The final heights, diameters, and number of leaves were strongly correlated with the initial heights and diameters of the seedlings (height $r = 0.7700$, $P = 0.0001$; diameter $r = 0.8416$, $P = 0.0001$; leaves $r = 0.4494$, $P = 0.0014$). Therefore, Analysis of Covariance was used, with the initial height as a covariate, to determine differences in heights and leaf numbers among treatments. Initial diameter was used as a covariate to examine differences in the mean final diameters among treatments.

RESULTS

Gas exchange measurements showed that net photosynthetic rates were reduced significantly ($F = 16.15$ $p < 0.0001$) in response to all three flooding regimes as compared to control plants (fig. 2). The amount of leaf area consumed differed significantly among the four treatments ($F = 4.23$; $P < 0.0001$). Herbivory was related to the amount and duration of flooding. Leaves from flooded plants were consumed significantly more than control leaves, and although not statistically Significant, leaves from intermittently flooded trees were consumed more than leaves from trees subjected to partial flooding (fig. 2). Seedling heights, diameters, and the final number Of leaves per seedlings were significantly different among treatments with control seedlings being taller ($F = 3.87$, $P = 0.0156$), possessing larger diameters ($F = 7.12$, $P = 0.0005$), and having more leaves ($F = 2.88$, $P = 0.0469$) than both permanently and intermittently flooded seedlings (fig. 3).

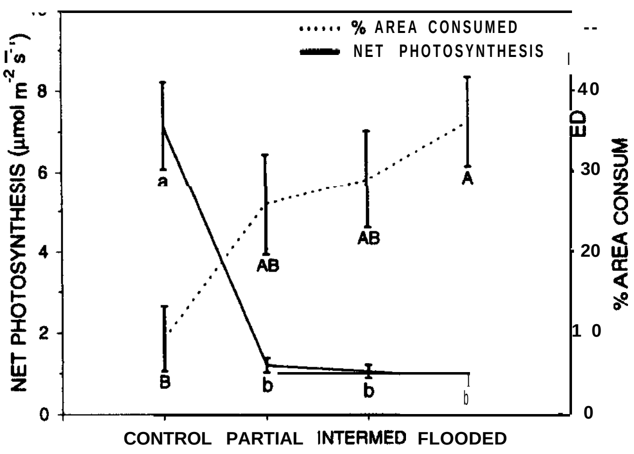

Figure 2-Net photosynthetic responses in Nuttall oak seedlings and percentage of leaf area consumed by tussock moths under various flooding regimes. Treatments with different letters are significantly different.

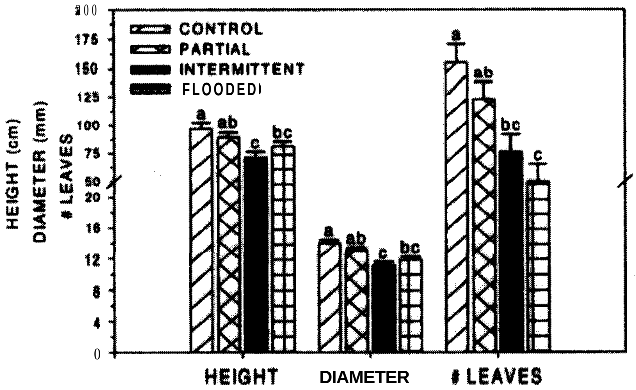

Figure 3-The mean final height, diameter, and number of leaves of seedlings subjected to each flooding treatment. Bars with different letters represent treatments that are significantly different.

DISCUSSION

The present study demonstrates that herbivory rates are affected by flooding in Nuttall oak seedlings. Leaves from seedlings that were flooded the entire length of the study were consumed most often, followed by leaves from trees flooded intermittently. It is apparent that these caterpillars chose flooded leaves above all other treatments. Although these leaves were not analyzed for nitrogen content or the presence of secondary compounds, treatments that were flooded exhibited decreased photosynthetic rates (fig. 2), low final heights, smaller diameters, and fewer leaves than nonflooded seedlings (fig. 3), thus further substantiating that these seedlings were stressed. Reduced photosynthesis is a common response to flooding for a majority of woody species studied (Kozlowski 1984). Such responses have been reported for flood-sensitive and flood-tolerant woody species (Pezeshki 1994, and references cited therein). Net photosynthetic rates were reduced in response to flooding, which suggests important implications for plant physiological functioning. It is possible that reduced net photosynthesis may have resulted in reduced production of secondary metabolites (Rhodes 1983, Estiarte and others 1994), which have been implicated in plant-herbivore defense mechanisms. For instance, phenolic compounds are critical in plant-herbivore interactions (Estiarte and others 1994). Many compounds that have been implicated in herbivore defense are metabolically costly to produce and may either be produced at a lower concentration or not at all under stressful conditions such as flooding when plants switch to anaerobic metabolism.

The significant differences between permanently flooded and control treated individuals in the amount of leaf area consumed and the net photosynthetic rate suggest that forests occurring in permanently flooded areas would have the highest potential impacts from herbivory. There is some evidence for this: for example, forest tent caterpillars in southern Alabama and Louisiana are known to reach epidemic populations in flooded tupelo (*Nyssa aquatica* L.) stands (Ciesla and Drake 1969). However, most bottomland hardwood forests are only temporarily flooded during the growing season. In addition, Nuttall oak does not typically occur in permanently flooded swamps (Filer 1990). There were no significant differences between the control and two intermediate flooding treatments in the leaf area consumed, which suggests that transitory flooding may not affect the relationship between flooding and herbivory. However, when the percentage of leaf area consumed is plotted against the net photosynthetic rate (fig. 2), it is obvious that leaves from any flooding regime were strongly selected over control leaves.

These results suggest that individuals that are exposed to irregular and moderate to prolonged flooding during the growing season may be adversely affected, not only because of the resulting reduction of carbon assimilation (Pezeshki 1994), but also due to a diminished capability to produce secondary metabolites for plant defense. Thus flooding can conceivably cause not only symptoms associated with root hypoxia, but also detrimental effects from defoliation. This reduction in defense and increase in herbivory could cause an increase in insect fecundity within the system, in addition to an increase in tree mortality from diseases linked to insect defoliation (Wargo 1977).

If this is the case, this phenomenon would be readily observable within bottomland hardwood forests found within the levee system of the lower Mississippi River. However, incidences of episodic outbreaks, or even local to moderate defoliation, have rarely been recorded. The question then arises, if a tree species that is readily found on poorly drained soils (e.g., at least moderately adapted to flooded conditions) exhibits the potential for an increase in herbivory related to flood stress, why are there so few documented occurrences? The likely explanation is that this study was conducted with 2-year-old seedlings. It is likely that even trees that are only a few years older (e.g., saplings) may exhibit temporary symptoms of flood stress, but once the roots begin to receive oxygen, the saplings are capable of quickly producing necessary defensive chemicals and, more importantly, converting important nutrients into substances less utilizable to herbivores. This situation is also more likely for older trees that have even more energy stored and are able to recover from the negative effects of flooding faster than seedlings and saplings. Therefore, it is likely that there is only a very narrow window of opportunity for arthropod populations to take advantage of flood stressed trees before they are able to return to preflooded conditions.

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INTRASPECIFIC VARIATION IN THE ROOT ELONGATION OF BALDCYPRESS SUBJECTED TO SALINE FLOODING

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SUMMARY

Many wetland forests in the coastal zone of southeastern Louisiana have been heavily stressed or destroyed by saltwater intrusion. Canal dredging, levee construction, coastal subsidence, and eustatic sea level rise all facilitate the intrusion of seawater into coastal swamp forests, resulting in widespread mortality of glycophytic wetland species. Although salinities in many of these areas are lower and the prospect for future amelioration projects are increasing, acute exposure to saline floodwaters from frontal passage or hurricanes will continue to cause mortality among both mature baldcypress (*Taxodium distichum* (L.) Rich.) and rejuvenating seedlings as long as avenues for saltwater intrusion remain. Researchers have recently focused on the identification of genotypes exhibiting greater tolerance to saline environments. The purpose of this study was to investigate intraspecific variation between progeny of five half-sib family collections of baldcypress from three freshwater and two brackish-water seed sources. Mini-rhizotrons were used to monitor root elongation for a period of 99 days while seedlings were subjected to three salinity levels under nonaerated, flooded conditions. Salinity produced significant species-level effects across all families, with root elongation decreasing with increasing salinity level. Family-level variation was significant as well, with relationships among families varying with treatment. In general, root elongation in families from brackish-water seed sources across all salinity treatments was greater than elongation for families from freshwater sources. Heights and diameters of the same seedlings were monitored for the first 62 days of salinity treatments. Species-level effects were significant for both parameters, but family-level effects were significant only for diameter. Intraspecific variation in root growth may prove to be a useful screening criterion for salt tolerance in baldcypress, since genotypes with greater potential for root development under saline conditions may experience better early survival and growth under saline field conditions.

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EFFECTS OF SEASONAL PRESCRIBED FIRES ON DENSITY OF HARDWOOD ADVANCED REGENERATION IN OAK-DOMINATED SHELTERWOOD STANDS

Patrick H. Brose and David H. Van Lear[1]

Abstract-Effects of seasonal prescribed fire on density of hardwood regeneration were investigated. Three mature mixed-oak (Quercus *spp.*) stands on productive sites were cut using a shelterwood technique, each forming a block of spring burn, summer burn, winter burn, and control treatments. Advance regeneration was inventoried from permanent plots before and after burning. Fires top-killed nearly all hardwood regeneration, forcing the rootstocks to sprout. All fire treatments significantly reduced red maple (*Acer rubrum*) and yellow- poplar (*Liriodendron tulipifera*) densities, primary competitors of oak, for at least 2 years, while oak density was unaffected. Hickory *(Carya spp)* responded to fire similarly to oak. The competitive position of oaks in the advance regeneration pool was enhanced by all fire treatments, spring burning providing the most benefit.

INTRODUCTION

For the past several decades, resource managers have struggled to regenerate oak stands on productive upland sites (Lorimer 1993). This problem has been the subject of numerous conferences and scientific publications. The shelterwood system is often recommended as a technique to promote oak regeneration when it is lacking on productive sites (Sander and others 1983) but often fails because conditions conducive to oak regeneration development stimulate intense competition from less-desirable species (Loftis 1983, Sander 1979, Schuler and Miller 1995).

Supplemental treatments are sometimes prescribed before the initial shelterwood cut, to reduce or eliminate the anticipated competition problem. Loftis (1990) and Lorimer and others (1994) clearly demonstrated the value of competition control with herbicides but this approach is expensive: $70 per acre or more. Barnes and Van Lear (in press) tested understory prescribed burning to accomplish the same task as herbicides and found favorable results but needed multiple burns over several years to obtain similar results.

Hannah (1987) suggested prescribed fire may be an appropriate follow-up treatment to shelterwood harvesting. In 1993, the Virginia Department of Game and Inland Fisheries (VDGIF) tried this approach in a pilot study and found summer burning greatly reduced densities of less-desirable hardwoods, i.e., red maple, sweetgum, and yellow-poplar, more than densities of oak and hickory (Keyser and others 1996).

In this study, we expanded upon VDGIF's pilot study by examining effects of prescribed fire in different seasons on density of advance regeneration of common hardwood species in 2- and 4-year-old shelterwood stands. We hypothesized that prescribed burning of shelterwood stands would reduce densities of red maple and yellow-poplar more than oak, thereby improving oak's competitive position in the advance regeneration pool.

METHODS

Study Area

This study was conducted at the Horsepen Wildlife Management Area in the Piedmont of central Virginia. This area consists of broad, gently-rolling hills with Cecil sandy loam soils (Typic Hapludult). Climate is warm continental with 50 inches of annual precipitation distributed evenly throughout the year and an average growing season of 190 days (Reber 1988). The area is presently owned and managed by VDGIF.

Three mature hardwood stands, cut to shelterwoods 2 to 4 years earlier, were selected in 1994 for the study. According to VDGIF records, the stands had similar site characteristics and species composition before the initial harvest. Average site index 50 for oak was 75 feet and basal area was 110 square feet per acre.

Common overstory trees were, in order of decreasing abundance, white oak (Quercus *alba*), yellow-poplar, northern red oak (Q. *rubra),* black oak (Q. *velutina*), scarlet oak (Q. *coccinea),* pignut hickory *(Carya glabra*), mockernut hickory (*Carya tomentosa*), and chestnut oak *(Q. prinus*). Their ages ranged from 90 to 110 years. Common midstory hardwoods included, in order of decreasing abundance, red maple, blackgum (*Nyssa sylvatica*), flowering dogwood (*Cornus florida*), American beech (*Fagus grandifolia*), and ironwood (*Carpinus caroliniana*).

Harvesting removed poor quality oaks and low value species leaving 50 percent canopy opening. Two stands were harvested in summer 1990 and the third in winter 1992. Slash was left in place. Volumes removed averaged 6 mbf per acre and residual basal areas averaged 41 square feet per acre.

Study Design and Sampling

A randomized complete block design was used to analyze season-of-burn effects on density of advance regeneration. Each stand was divided into four 4- to 10-

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acre treatment areas (winter burn spring burn, summer burn, and an unburned control). Fifteen circular, 212 Square feet plots were systematically located in each treatment area. Advance regeneration stems between 1.0 and 10.0 feet tall were tallied in each plot in fall of 1994 and 1996. Stems were recorded as hickory (mockernut and pignut), mixed oak (black, chestnut, northern red, scarlet, and white), red maple, and yellow-poplar. Multiple Stems arising from the same rootstock were counted as one stem.

Prescribed Fires

The prescribed fires were conducted on February 25 and 27 (winter burn), April 26 (spring burn), and August 24 (summer burn), 1995 by VDGIF personnel in accordance with department policy and state law. Weather conditions varied among seasons but were considered typical. All prescribed fires were ignited by hand with drip torches in a strip-head fire pattern commencing at the downwind side of the treatment. Ignition strips were initially spaced 10- to 15-feet apart and this spacing gradually widened to 50 feet once existing firelines were strengthened, Spring fires produced the most intense fire behavior with flame lengths and rates of spread averaging 3.5 feet and 5.0 feet per minute, respectively. Winter and summer fires behaved similarly to spring fires when weather conditions permitted, but increases in relative humidity and decreases in wind reduced fire behavior to 1- to 2-feet flame lengths and I- to 3-feet per minute rates of spread. Overall, prescribed burns were easily executed and behaved typically of fires in oak forests.

Statistical Analysis

Differences in species densities within treatments were detected using analysis of variance with Duncan's multiple range test (alpha = 0.05) (SAS 1993). Changes in species' densities after treatments were similarly tested. Treatments were compared through covariance analysis of declines in species densities with preburn densities as a covariate (SAS 1993). Data were rank-transformed to correct unequal variances and nonnormality.

RESULTS AND DISCUSSION

Treatment Effects on Species

No block effect was found among stands allowing data to be pooled to decrease variance and simplify reporting. Before burning, yellow-poplar dominated all treatments, averaging over 2,900 stems per acre (table 1). Red maple was the second most abundant species, 1,607 Stems Per acre, with hickory and mixed oak being least common (843 stems per acre).

Relative differences among species did not change in the control treatments during the 2 years of the study (table 1). Yellow-poplar continued as the most abundant species (2,249 stems per acre), followed by red maple (1,789 stems per acre). Hickory and mixed oak were least common, averaging 622 stems per acre.

Table 1—Mean densities (stems per acre ± 1 st. error) of hardwood regeneration before and 2 years after seasonal prescribed fires in oak-dominated shelterwood stands; densities followed by different letters are different within that treatment (alpha = 0.05)

Treatment and species	Preburn	Postburn
Control		
Hickory	760±85c	666±95c
Mixed oak	639±66c	578±103c
Red maple	1809±283b	1786±204b
Yellow-poplar	2256±529a	2249±450a
Winter burn		
Hickory	733±100c	805±140b
Mixed oak	717±75b	1197±68a[a]
Red maple	1539±124b	1138±126a[b]
Yellow-poplar	2960±497a	1302±190a[b]
Spring burn		
Hickory	918±97c	846±88b
Mixed oak	962±107c	1363±209a[a]
Red maple	1807±168b	994±168b[b]
Yellow-poplar	2389±324a	849±179b[b]
Summer burn		
Hickory	783±87c	562±93b[b]
Mixed oak	1230±220b	1166±153a
Red maple	1273±196b	684±104b[b]
Yellow-poplar	4031±657a	1103±243a[b]

[a] Indicates an increase from preburn density (alpha = 0.05).
[b] Indicates a decrease from preburn density (alpha = 0.05).

Winter fires reduced yellow-poplar density from 2,960 to 1,302 stems per acre, a 56 percent loss (table 1). Red maple decreased to a lesser degree, from 1,539 to 1,138 stems per acre (26 percent reduction). Oak density increased by 480 stems per acre and hickory density was unchanged. Two years after winter fires, mixed oak, red maple, and yellow-poplar had equivalent densities with hickory being less numerous.

Spring burning decreased yellow-poplar density by 65 percent, from 2,389 to 849 stems per acre (table 1). Red maple density was reduced from 1,807 to 994 stems per acre (45 percent loss). Oak density increased by 400 stems per acre and hickory density was unchanged. Two years after spring fires, mixed oak outnumbered all other species.

Summer burning reduced densities for all species except oak (table 1). Yellow-poplar declined from 4,031 to 1,103 stems per acre (73 percent loss) while red maple was reduced 46 percent from 1,273 to 684 stems per acre. Hickory decreased by 220 stems per acre (28 percent). Oak density was unchanged. Two years after summer fires, oak and yellow-poplar had equivalent densities, outnumbering hickory and red maple.

Oak and hickory regeneration are apparently more capable of sprouting following fire than red maple and yellow-poplar reproduction of comparable stem size. This may result from seed caching by wildlife and differences in germination strategy, i.e., hypogeal versus epigeal. Sound acorns are routinely buried in the forest floor by birds and small mammals (Galford and others 1988) while red maple and yellow-poplar seeds remain at or near the surface (Beck 1990, Walters and Yawney 1990). Acorns have hypogeal germination (Rogers 1990, Sander 1990), causing the root collar to be below the soil surface (protected from fire), while red maple and yellow-poplar seeds have epigeal germination, placing the root collar at or near soil surface (exposed to fire). Dormant buds at the root collar are essential for sprouting following top-kill so oak and hickory rootstocks were better protected than those of red maple and yellow-poplar. Examined roots of dead red maple and yellow-poplar revealed shallow roots which may have been damaged by the downward heat pulse. It was also observed that new oak sprouts came from below groundline while new red maple and yellow-poplar sprouts originated at or above groundline.

Differences in growth strategies between oak and its competitors also probably contribute to fire selecting against red maple and yellow-poplar. Oaks have a conservative growth strategy of emphasizing root development in lieu of rapid shoot elongation while many competitors take the opposite approach (Kelty 1988, Kolb and others 1990). Because spring burning occurred when leaves were 50 to 75 percent expanded, root reserves of all species were low. However, despite leaf expansion, the larger roots of oaks apparently still contained more carbohydrates with which to sprout than those of red maple and yellow-poplar. These energy reserves helped prevent declines in oak density while competitors lacking such reserves had large losses.

The increase in oak density from 1994 to 1996 was due to previously uncounted small stems sprouting and vigorously growing into the sampling strata (1 .O to 10.0 feet). No mass germination of yellow-poplar occurred despite its abundance in the overstory prior to harvest. Apparently, its soil seed bank was exhausted in the initial germination and removal of mature yellow-poplars prevented additional seed storage during the years between harvest and prescribed burning.

Comparison of Treatments

After adjusting for preburn differences in species density, growing-season fires (spring and summer) were more lethal to most species than winter fires (table 2). Yellow-poplar density declined 1,700 stems per acre in spring and summer fires, significantly more than winter fire (1,134 stems per acre). Also, yellow-poplar was more sensitive than oak to any seasonal fire. Spring and summer fires decreased red maple density about 587 stems per acre, nearly three times more than winter burning (219 stems per acre). Red maple differed from oak only in spring and summer fire treatments. Hickory was reduced more by summer burning (688 stems per acre) than by spring or winter burning (264 stems per acre each) with summer fire being more lethal to hickory than to oak. Likewise, oak was more affected by summer burning, a reduction of 455 stems per acre, than by winter or spring fires (217 stems per acre loss). All fires caused greater mortality than not burning for all species.

The clear difference in hardwood competition control between winter burning and both growing-season fires is due to regeneration being physiologically active during the spring and summer (Hodgkins 1958) and is well documented in southern pine ecosystems (Langdon 1981, Waldrop and others 1987).

Spring fires provide the greatest improvement in the competitive position of oak in the advance regeneration pool because it maximizes reduction of red maple and yellow-poplar with minimal loss of oak. Opportunities for spring burning are common due to high insolation levels, warm temperatures, southerly winds, and low humidities. Drawbacks to spring burning are increased probability of fire escape and overstory tree damage/mortality due to burning during the natural fire season of Eastern North America.

Table 2-Adjusted declines in densities (stems per acre) of hardwood regeneration following seasonal prescribed fires in oak-dominated shelterwood stands; densities followed by different letters are different for that species (alpha = 0.05)

Treatment	Hickory	Mixed oak	Red maple	Yellow-poplar
Control	35c	32c	33c	26c
Winter burn	260b	215b	219b	1134b[a]
Spring burn	268b	219b	577a[a]	1688a[a]
Summer burn	688a[a]	455a	597a[a]	1713a[a]

[a] Indicates that adjusted density decline of species is greater than that of oak for the same treatment (alpha = 0.05).

Summer fires are comparable to spring burning with less risk Of fire escape. The reduced shade in shelterwoods and increased fuel load from the initial cut makes burning them possible when surrounding uncut areas are not highly flammable. However, winds must be moderately high (5 to 10 miles per hour) and fine fuels dry (10 to 15 percent) to counter the presence of partial shade. Another drawback to Summer burning is increased oak mortality relative to other seasons.

Winter burning enhances the competitive position of oak in the advance regeneration pool but not as successfully as growing-season fires. Numerous winter fires are needed to accomplish the competition control possible with a few growing-season burns (Barnes and Van Lear 1997, Langdon 1981, Waldrop and others 1987).

CONCLUSIONS

This study supports our hypothesis that prescribed fire enhances the competitive position of oak in the advance regeneration pool. Prescribed burning of these shelterwood stands was definitely a step in the right direction. Whether this reduction in competition density is enough to produce oak-dominated stands on these productive sites in the future is unknown. Long-term monitoring of these stands is a must as red maple and yellow-poplar are still common and vigorously growing. Additional prescribed fires may be needed, depending on development of the regeneration during the establishment phase. Regardless of whether single or multiple fires are needed to ensure eventual oak domination, this shelterwood-burn prescription is a promising approach to regenerating oak stands on productive sites.

The density reduction of yellow-poplar and red maple has important implications for resource managers. Most importantly, this approach provides managers a simple and environmentally sound way to regenerate oaks on good sites. In addition, residual overstory trees can be harvested to create an evenaged early-successional habitat or retained for a second rotation to make a two-storied stand. If retained, some may die, becoming snags for wildlife while they stand and later, downed woody debris. Reapplication of growing-season fire at frequent intervals (annual or biennial) would eventually lead to an oak-dominated savanna (Thor and Nichols 1973), benefitting numerous plant and wildlife species. In short, this approach favors oak advance regeneration on productive sites, a critical first step in regenerating oak stands (Sander 1971, Sander 1972), and may be appropriate for a wide array of natural resource interests.

More research of the fire-oak relationship is warranted to answer questions arising from this study. Results of this method from other physiographic regions and forest types of North America would be valuable. What are the implications of this approach to understory plants and wildlife species'? Will the short-term benefits shown in this study ensure long-term success? There is a place for prescribed fire in hardwood management. However, guidelines still need to be developed for managers attempting to maintain oaks on productive sites.

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USE OF PRESCRIBED FIRE TO PROMOTE OAK REGENERATION

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Abstract-A 25-acre, 61 -year-old planted slash pine (*Pinus elliottii* Engelm.) stand with yellow-poplar (*Liriodendron tulipifera* L.) and other hardwood volunteers on highly erosive, former agricultural land in the Coastal Plain of West Tennessee was burned three times at 3-year intervals from 1986 to 1992 primarily for enhancement of wildlife habitat, fuel reduction, and control of competing vegetation. A secondary effect of the burning regime was the unplanned development of advance oak (*Quercus* spp.) reproduction from 3 feet to 5 feet in height. Because of the fortuitous amount of oak advance reproduction and the relative absence of other residual species, the entire stand was harvested to release the oak. One-half of the stand was burned again in March 1995 to suppress current year (1994) natural seed from the pine and poplar before the complete harvest in the summer of 1995. Seventy-five permanent plots were established to survey regeneration before and after the harvest. This study presents comparisons of first-year data on amount, form, and composition of regeneration between the recently burned and unburned areas with respect to advance oak reproduction. The burning regime has maintained oak as advance reproduction and limited the amount of yellow-poplar.

INTRODUCTION

Although oaks make up the majority of the overstory across the Eastern United States, silviculturists continue to have difficulty in securing adequate oak regeneration on the better sites. A recent symposium (Loftis and McGee 1993) addressed the problems and opportunities associated with oak regeneration. Success in promoting oak regeneration requires (1) large seedlings capable of fast growth, whether that be from advance regeneration (Loftis 1990) or the planting of physiologically superior seedlings (Pope 1993); and (2) control of competing vegetation.

Fire also appears to have been an important factor promoting oak regeneration and dominance in pre- and postsettlement forests (Abrams 1992, Crow 1988). Fire encourages oaks by reducing competition from fire-intolerant species as well as enhancing oak regeneration through its tenacious ability to root sprout repeatedly following top-kill in frequent fire regimes (Van Lear and Watt 1993). Several authors have suggested that the suppression of fire in recent years has limited oak regeneration (Abrams 1992, Lorimer 1993, Van Lear and Waldrop 1989). Although research has not yet identified a regime for the use of fire in promoting oak regeneration, a series of burns rather than a single burn during the preharvest period will likely be required to favor oak regeneration (McGee 1979, Merritt and Pope 1991).

In Tennessee, many oak forests are regenerating after harvest to yellow-poplar, especially on the better sites. To have oak forests on the better sites, oak regeneration and growth should be promoted, while yellow-poplar should be controlled. A regime of prescribed burning may be part of the answer.

This study capitalizes on a planted bottomland pine stand with a yellow-poplar component that was burned at 3-year intervals for the last 9 years. The prescribed burning regime probably influenced the fortuitous amount of oak regeneration and the scarcity of other species in the understory. However, yellow-poplar was still a concern because, even germinating from seed, poplar generally outgrows oak seedlings (O'Hara 1986). Poplar seed accumulating since the previous burn remains viable in the duff for many years (Clark and Boyce 1964). Fifty percent of the stand was burned again before harvest to control yellow-poplar seed and seedlings. The objective of the study was to compare oak regeneration and its competitiveness with yellow-poplar on recently burned and unburned areas 1 year after the harvest.

STUDYAREA

The study was conducted on a 25-acre stand planted with slash pine at Chickasaw State Forest (CSF) in Chester County, TN, located approximately 20 miles south of Jackson in southwestern Tennessee and managed by the Tennessee Division of Forestry. Soils are Typic Fragiudults (Savannah series), formed in loamy Coastal Plain deposits, severely eroded, moderately drained, slowly permeable, and occasionally flooded with a perched seasonal water table above the fragipan. The study area is on a convex slope (2 to 5 percent) of a terrace near a second-order stream that flows to the Hatchie River. Annual precipitation averages 50 inches, usually evenly distributed in all seasons. Average site index (base age 50) for loblolly pine (*P. taeda* L.) ranges from 80 to 90 feet (Ditzler and others 1994).

The CSF was part of the federal Resettlement Administration purchase of land during the mid-1930's. The study area was a severely eroded, abandoned agricultural field with numerous gullies and ditches. Slash pine was planted to control the erosion. Since that time, the study area remained relatively undisturbed until a 3-year interval of prescribed burning was initiated during the winter of 19851986. NO other cultural treatments or thinnings had occurred. In March 1995, the stand was 61 years old with over 17,000 board feet per acre. Stand basal area averaged 135 square feet per acre. Slash pine composed 66 percent of the stems 8 inches and greater in diameter, and 79 percent of the volume (table 1). Other overstoty tree species that naturally

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Table l-Number of trees and volume by species present on the study area at Chickasaw State Forest before the harvest cut in 1996

Species	Trees		Volume[a]	
	No.	%	Board ft	%
Slash pine	1,069	66	376	79
Shortleaf pine	97	6	26	5
Yellow-poplar	185	11	36	8
Sweetgum	171	10	24	5
Red oak	38	2	7	1
Miscellaneous[b]	61	4	6	1
Total	1,621		475	

[a] International 1/4 inch Rule.
[b] Miscellaneous includes white oak, post oak (*Q. stellata* Wangenh.), hickories (*Carya* spp.) red maple, black cherry (*Prunus serotina* Ehrh.), and blackgum (*Nyssa sylvatica* Marsh.).

invaded the study area were yellow-poplar, shortleaf pine (*P. echinata* Mill.), sweetgum (*Liquidambar styraciflua* L.), red maple (*Acer rubrum* L.), various red oaks (*Q. rubra* L., *Q. phellos* L., Q. *falcata* var. *pagodaefolia* Ell., *Q. shumardii* Buckl.) and white oak (Q. *alba* L.).

In 1994, the stand was being considered for a timber sale. At that time, CSF managers noticed an inordinate amount of advance oak regeneration that was taller than 3 feet and a scarcity of other advance regeneration, particularly yellow-poplar. Since this area probably was a bottomland hardwood stand before cultivation, the opportunity was present for a conversion from planted pine to bottomland hardwoods.

METHODS

The chronology of management activities (burns, regeneration surveys, and timber harvest) in this stand is shown in table 2. Seventy-five permanent plots were established over the 25-acre area on a 120 by 120 foot grid. Regeneration was surveyed before and after the harvest cut by species and height classes (less than 1 foot, 1 to 3 feet, and greater than 3 feet). Plot size was 0.02 acre. In the two treatments (burned and unburned in 1995), 43 plots on 14 acres provided the sample of the burn treatment and 32 plots on 11 acres provided information on the unburned treatment. Data are presented for the regeneration present in 1994, before the 1995 burn and harvest, and in the fall of 1996, one growing season after the harvest.

RESULTS

Initial Survey in October 1994

Three growing seasons after the 1992 prescribed burn and before the timber harvest, the stand contained an average of almost 5,800 woody stems per acre (advance reproduction) that were less than 2 inches in diameter and less than 8 feet tall (table 3). Oaks composed nearly 26 percent of the total stems, most being over 1 foot in height.

Table 2-Chronology of events on the study site at Chickasaw State Forest

Event	Time of occurrence
Prescribed fire (all winter/spring burns)	1986, 1989, 1992
Regeneration survey	Oct. 1994
Prescribed fire (50 percent of area)	Mar. 1995
Timber harvest	Aug. 1995
Remaining residuals >2 inches slashed	Winter 1995-l 996
Regeneration survey (2 treatments)	Oct. 1996

Table 3-Regeneration survey of the study area at Chickasaw State Forest 1 year before the harvest cut and one year after the harvest cut

Treatment	Regeneration survey Oct. 1994		Regeneration survey Oct. 1996	
	#/acre	%	#/acre	%
Burned (n=43)				
Oaks	1,714	28.8	1,690	17.8
Yellow-poplar	557	9.4	482	5.1
Sweetgum/red maple	1,299	21.9	2,529	26.7
Miscellaneous'	2,372	39.9	4,787	50.4
Total	5,942		9,488	
Unburned (n=32)				
Oaks	1,263	22.7	1,326	12.5
Yellow-poplar	601	10.8	881	8.3
Sweetgum/red maple	1,170	21 .o	2,956	27.8
Miscellaneous[a]	2,527	45.4	5,452	51.4
Total	5,561		10,615	

[a] Miscellaneous includes pines, blackgum, black cherry, dogwood (*Cornus florida* L.), river birch (*Betula nigra* L.), sourwood (*Oxydendrum arboreum* (L.) DC.), elms (*Ulmus* spp.), sassafras (*Sassafras albidum* (Nutt.) Nees), sumacs (*Rhus* spp.), alder (*Alnus* spp.) and several other species as minor components.

Yellow-poplar was a minor component of the understory (10 percent), while the miscellaneous species category, consisting primarily of pines, dogwood, elms, and sumacs, had over 40 percent or the majority of the stems. Sweetgum and red maple had fewer stems than the oaks at 21 percent.

Effects of Burn Treatment

Reproduction in the burn treatment measured 1 growing season after the harvest cut, yielded over 9,400 stems per acre (table 3). While numerous oaks were present, the percentage of oaks in the treatment (17.8 percent) was less than that in the initial stand before the harvest and 1995 burn (28.8 percent). The number of sweetgum/red maples and miscellaneous species doubled. Yellow-poplar seedlings decreased initially from 9.4 percent to 5.1 percent in the burn treatment even though the number of seedlings remained similar. The yellow-poplar stems found in the burn treatment were almost exclusively from stump sprouts of harvested stems.

Effects of Unburned Treatment

The total number of stems in the unburned treatment essentially doubled over the study period (table 3). Oaks maintained their numbers and decreased drastically as a percentage of total stems (22.7 to 12.5 percent). Yellow-poplar increased slightly, primarily from stump sprouts after the harvest and from seedlings that remained from the initial survey. Sweetgum/red maple and miscellaneous species both more than doubled their number.

Burned versus Unburned Treatments

The number of oak stems, regardless of treatment, remained similar to the 1994 survey (table 3). Yellow-poplar decreased with burning and increased with the unburned treatment. Regeneration stem counts for sweetgum/red maple and the miscellaneous category doubled over the study period. Most stems in the 1996 survey were 1 to 3 feet tall regardless of species and treatment.

DISCUSSION

First-year results indicate that the burn treatment has maintained the oak advance regeneration component and slightly reduced it for yellow-poplars. Oaks persist following burning due to their ability to resprout repeatedly after top-kill from suppressed buds at or below the ground level. This vigorous resprouting precludes the establishment of most other competing species (Clatterbuck 1990). The prescribed burning regime before the harvest favors the advanced reproduction and establishment of oaks, giving them an ecological advantage over other species (Van Lear and Waldrop 1989).

One year after harvest, the regeneration count for sweetgum and red maple was essentially the same for the burned and unburned samples. The number Of stems doubled from the initial survey regardless of treatment. Both sweetgum and red maple are light-seeded species that invade recently harvested areas. Sweetgum also has the ability to root sprout from suppressed root buds (Kormanik and Brown 1967), while red maple readily stump-sprouts (Hutnick and Yawney 1961). Sweetgum and red maple colonize disturbed areas quickly from both seed and sprouts and tend to dominate during the early stages of succession. However, within a few years, oaks and yellow-poplar usually stratify above these species relegating them to a subordinate position (Clatterbuck and Hodges 1988, O'Hara 1986, Oliver 1978). Red maple and sweetgum, although present in the stand before the harvest, constituted less than 1 percent of the overstory stems and volume (table 1).

Miscellaneous species are composed primarily of noncommercial timber species that remain in the midcanopy layers. Although numerous, these species are not expected to gain prominence over time. Most will be overtopped by oaks, yellow-poplar, sweetgum, and red maple. Species composition in the miscellaneous category shifted somewhat in the initial survey from dogwood, sourwood, elms, and blackgum to the pioneer species such as black cherry, river birch, sassafras, and sumacs in both treatments after the timber harvest. There was little difference in total number of seedlings in the miscellaneous classification between treatments.

The purpose of the burn treatment before the harvest cut was to eliminate the seeds of yellow-poplar and pine that had accumulated on the forest floor since the prescribed burn in the spring of 1992. The yellow-poplar in the unburned treatment had a 4-year seed bank, while those in the burn treatment had seed fall for 1 year. Fire eliminated most of the "from seed" yellow-poplar seedlings that were in the burn treatment. Most seedlings in the burn treatment were from stump sprouts from the logging and slashing activities. Those in the unburned treatment were both from new seedlings that had accumulated over 4 years and stump sprouts from the harvest cut.

SUMMARY

First-year results indicate that the burning regime of repeated prescribed fire enhanced the regeneration of oaks, especially in developing adequate and vigorous advance reproduction. With burning, the oaks had an advantage in their early development compared to other species. Burning tended to reduce yellow-poplar seedling density, but this was confounded with stump sprouting after the harvest. These results should be evaluated, recognizing the rapid growth of yellow-poplar on these good sites. Follow-up studies are planned using these permanent plots to see if whether oaks will maintain their early advantage or be displaced by yellow-poplar or other species.

ACKNOWLEDGMENT

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Pine and Pine-Hardwood Regeneration

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EFFECTS OF FIRE ON SHORTLEAF AND LOBLOLLY PINE REPRODUCTION AND ITS POTENTIAL USE IN SHORTLEAF/OAK/HICKORY ECOSYSTEM RESTORATION

Roger A. Williams'

Abstract-The shortleaf pine/oak-hickory (*Pinus echinata* Mill, *Quercus* spp., *Carya* spp.) forest, once the dominant forest community across north Louisiana, has slowly disappeared from the landscape, and is being replaced by loblolly pine (*P. taeda* L.), mixed hardwood/loblolly, and loblolly/shortleaf forests. One of the reasons for the demise of this fire-dependent ecosystem has been effective fire suppression programs. A study was established in three stands of the Kisatchie National Forest in north Louisiana, comprising a loblolly/shortleaf pine overstory, that were prescribed burned. A regeneration survey two growing seasons following fire revealed that 52 percent to 86 percent of the post-fire pine regeneration was from sprouts, and that 92 percent to 100 percent of these sprouts were shortleaf pine. Loblolly pine accounted for 55 percent to 100 percent of the new seedling germinants after fire. Sprout size averaged 11.2 inches in total height and 0.116 inches in groundline diameter, compared to 4.8 inches total height and 0.060 inches groundline diameter for post-fire seedling germinants. No significant difference was found in sprout size between shortleaf and loblolly pines. Loblolly pine seedlings produced an average of 1.7 sprouts per seedling compared to 2.1 sprouts for shortleaf. The role of fire in the shortleaf pine/oak-hickory forest ecosystem and its potential use in ecosystem restoration is discussed.

INTRODUCTION

It has been estimated that during the early 1800's the shortleaf pine/oak-hickory (*Pinus echinata* Mill./*Quercus* spp., *Carya* spp.) forest occupied some 4 to 5 million acres in Louisiana west of the Mississippi River (Smith 1992). The most recent (1991) forest inventory by the USDA Forest Service indicated that the shortleaf pine and shortleaf pine-oak forest types (FIA types) now occupy just a little over 300,000 acres in the west gulf coastal plain of Louisiana. It is apparent from these figures alone that this forest type-once dominant in the central and north Louisiana uplands-has suffered dramatic declines in acreage.

This dramatic decline has caused concern among conservation biologists and ecosystem managers alike; but perhaps of greater concern are the changes that have occurred in the structure and composition of the shortleaf pine system. It is likely that any examples of the system that are present today are very dissimilar to the historic conditions. As a result of the regeneration dynamics, the historic disturbance patterns of fire and windstorms, and variability in soil/substrate conditions, the density levels were probably quite variable from dense to open stands. Accordingly, this variability permitted a wide diversity of vertical stratification to exist in these forests across the landscape. Also, the species composition, i.e., the abundance of shortleaf versus the abundance of hardwoods [and loblolly pine (*P. taeda* L.)], varied from stand to stand due to differences in substrate and landscape position (ridge, midslope, lower slope, flats, etc.).

There is no doubt that fire was one of the major influences in defining the structure and composition of shortleaf pine systems. In these historic systems, fires are believed to have burned in a cycle of 5 to 15 years-most likely occurring during the growing season (Williams and Smith 1995). The historic fire disturbance regime has been altered significantly many decades ago by a variety of land management practices. Fire frequency in most cases has been significantly reduced from its original rates. In cases where forests are prescribed burned, the rates may be equal or even greater than the original rates, but are performed during dormant seasons. These alterations of the fire regime, combined with past land clearings, widespread timbering, and commercial reforestation with other species, particularly loblolly pine, have caused dramatic changes in the shortleaf system.

If future objectives for some of these lands that once supported shortleaf systems include the restoration of these systems, a better understanding of their regeneration and stand dynamics will be of critical value, notably the fire disturbance regime. It was the objective of this study to collect some baseline data concerning the response of shortleaf and loblolly pine reproduction to fire, to add to present knowledge about fire-impact dynamics, provide data for comparison, and provide direction for future studies in the use of fire to restore the shortleaf pine/oak-hickory system.

BACKGROUND

To provide background on the role of fire in the shortleaf pine/oak-hickory system and the magnitude of change that has taken place in this forest cover in Louisiana as a result of fire regime alteration, a brief description is offered. The most recent forest cover maps produced by the USDA Forest Service indicate that the shortleaf pine and shortleaf pine-oak forest types presently occupy just a little over 300,000 acres in the west gulf coastal plain of Louisiana. The typical designations of this cover include loblolly-shortleaf pine and oak-pine.

However, the latest forest cover map that actually depicts the occurrence of the shortleaf pine/oak-hickory forests in north Louisiana was produced by Brown (1945) (fig. 1). This map departs from the earliest known cover map

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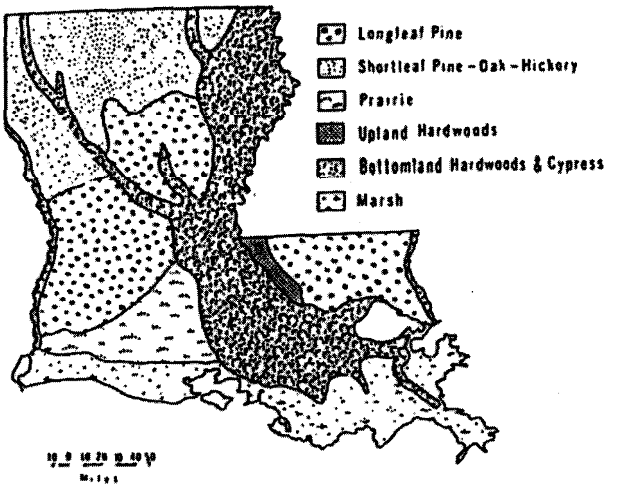

Figure I-A vegetative cover map depicting forest cover types in Louisiana in 1945 (from Brown 1945).

produced of Louisiana in 1881 by Sargent (1884). This and other cover maps prior to 1945 indicate that shortleaf pine was the dominant pine species across north Louisiana. What is noticeably lacking on these early maps is the presence of loblolly pine.

The historical dominance of a shortleaf pine/oak-hickory forest across the uplands of north Louisiana, as documented by Lockett (1874), Hilgard (1873, 1884), and Mohr (1897) was undeniably a result not only of geology and soil conditions, but also of the dramatic influences of fire. It is axiomatic that plant species respond differently to fire; some are fire tolerant while others are fire sensitive, the degree of tolerance or sensitivity varying by species. It is well known that many pines and a number of hardwoods are tolerant of a certain amount of fire. In fact, it seems plausible that many of these species may actually require some level of fire for their perpetuation in particular settings. For example, without fire, fire-sensitive species may eventually come to dominate an upland site by out-competing fire-tolerant but less competitive species.

Shortleaf pine and its natural upland hardwood associates, principally dry-site oaks and hickories, are adapted to and were perpetuated as a forest type by a particular fire regime. It is unclear what that exact regime entailed, but Martin and Smith (1993) have estimated a fire return interval of 5 to 15 years would perpetuate a mixed shortleaf pine/oak-hickory forest type as described in historical accounts. Chapman (1944) stated that shortleaf pine could tolerate fires more frequent than once every 10 years because of its resprouting ability.

The pure shortleaf pine forests and pure hardwood forests reportedly present to some degree in presettlement uplands of north Louisiana (e.g., Lockett 1874, Hilgard 1873, Foster 1912) probably were a result, at least partially, of extremes in fire periodicity for the region, with the former maintained by frequent fire, and the latter by an essential absence of fire and other major disturbances. There is some difficulty, however, in postulating the origin of pure shortleaf forests based strictly on fire influences. While frequent fire (i.e., a fire every 5 years or less) would preclude the establishment and growth of dry-site hardwoods, such as post oak, blackjack oak, southern red oak, and black hickory (*Q. stellata* Wangenh., *Q. marilandica* Muenchh., *Q. falcata* Michx., and *Carya texana* Buckl.), it would do the same to shortleaf, all being roughly equivalent in their tolerance of fire.

It is possible that certain ridgetops of the region possessed particular "extreme" edaphic conditions (possibly very dry, very nutrient-poor, or with a near-surface consolidated and impervious layer, or other factors) that permitted, at least occasionally, the growth of shortleaf to forest-resistant sizes before fire return, but restrained hardwood growth to the extent that it could not attain (even through resprouting) fire-immune size before fire revisited the site. It is also possible that certain circumstances (involving life history characteristics of component species, fire dynamics, etc.) conspired to foster the establishment of an essentially pure shortleaf forest on dry ridgetops, perhaps after severe, forest-leveling windstorms. Regardless, the conspiracy of natural processes that would totally preclude hardwoods from the forest is difficult to specify.

Fires in the presettlement landscape originated from lightning strikes and the actions of aboriginal inhabitants. Lightning fires have been a primary factor in shaping the vegetational communities of the southeast for untold millennia (Komarek 1964), well before the arrival of aboriginal man. Observations of present-day climatic conditions indicate that the great majority of lightning firesin north Louisiana would have occurred between April and September, though also rarely at other times of the year. Spring and summer are characterized by a relatively large number of electrical storms, generated either through active frontal passage in the spring, or through summer heating and convection. Because vegetative litter such as oak leaves, pine needles, and dead grasses resists rapid decay (due to sclerophylly), litter produced in the previous season(s) remains available for fuel throughout the growing season and will readily burn if not too moist.

When compared to the catastrophic fires of the Western United States, presettlement lightning fires in north Louisiana and throughout most of the Southeast (with few exceptions) were relatively frequent but low-intensity surface or ground-level fires. Because of climate, vegetative structure, and fuel characteristics, catastrophic crown fires were essentially nonexistent in the upland pine, pine-hardwood, and hardwood forests of the South.

Prior to settlement by Europeans in north Louisiana, this area was inhabited by tribal American Indians whose main occupations were sedentary hunting, farming, and fishing (Fisk 1938). North Louisiana was inhabited by Caddo Indians before the earliest permanent settlements by immigrants to the Louisiana Territory in 1803 (Soil

Conservation Service 1989). Delcourt (1976) describes the Writings of early authors who indicated that the cultivation Practice of slash-and-burn was common in upland areas of the Southeast by Indians. In fact, Delcourt quotes Dunbar (1804) in his writings that while traveling up the Cuachita River in Louisiana, a smokey appearance in the atmosphere was noted, and attributed the "smokey or misty appearance of the atmosphere which in our Country is common in the months of november and december...to a common practise [sic] of the Indians and Hunters, of firing the woods, planes [sic], or savannahs; the flames often extending themselves some hundreds of miles, before the fire is extinguished..."

The impact native Indians had upon the early forest communities in north Louisiana is not fully known. There is reason to believe that setting fire to the woods was performed; however, the extent and frequency is not known. If it is assumed that the landscape of north Louisiana burned regularly, both by lightning and aboriginal American fires, then the forest communities that existed during the presettlement era and some of the changes in forest communities that have taken place since then can be better understood.

Noticeably absent in presettlement upland forests, when compared to present-day forests, is loblolly pine. Early descriptions of early forest communities in this region display a clear picture of upland forests dominated by shortleaf pine and hardwoods, particularly on the drier sites. Loblolly pine is relegated to the wetter sites and bottoms in many of these descriptions, and often depicted as occurring in sparing groves or scattered throughout the bottomland hardwoods. In fact, many of the early forest-cover-type maps do not include loblolly pine in their type designations. This lack of loblolly pine in presettlement upland forests of north Louisiana relative to its overwhelming dominance today may be partly explained by the fire ecology of the species.

Loblolly pine is typically more sensitive to fire than shortleaf pine, both in seedling and more mature stages (Chapman 1944). However, fires of high intensity can easily kill both species. Fires of lower intensity probably favor shortleaf pine over loblolly pine. In addition, shortleaf pine saplings display better ability than loblolly pine to respond to top kill by producing sprouts. These sprouts exhibit faster initial growth rates over loblolly Pine seedlings that may have established after fire, giving these shortleaf seedlings a competitive advantage Over loblolly seedlings. Fire-free intervals of a few Years allows these shortleaf seedlings to grow more rapidly to more fire-resistant sizes before the loblolly seedlings. Hence, areas where fire has been a major feature of the landscape tends to favor shortleaf pine Over loblolly Pine. Of the southern pines, longleaf and shortleaf pines are best adapted to fire, whereas loblolly and slash Pines are less so. Thus, when fires were a dominant feature across the shortleaf pine region, loblolly pine was generally restricted to those moist or wet sites subjected to infrequent or no fire.

METHODS

Three stands that contained a shortleaf pine/loblolly pine/hardwood mixture that were prescribed burned during the early spring of 1995 were selected for this pine regeneration survey. These stands were located within the Caney Ranger District of the Kisatchie National Forest. They are even-aged, old-field stands approximately 65 years of age that had been placed under typical sawtimber management in the past, including a thinning regime. Within each of these stands, two 0.25r-acre plots were randomly located, from which the overstory measurements were taken. The diameter at breast height and species was recorded for each overstory tree.

The overstory plots were divided into quadrants to help facilitate the locating and measurement of all pine reproduction on the plot. Each quadrant was scanned painstakingly, and each reproductive stem was located, marked, and mapped for future measurement. The groundline diameter and total height of each stem, seedling and sprout, were recorded by species. If the seedling stem that had been killed by the fire and had produced the sprouts was located, it likewise was measured. It was assumed in this study that seedlings were of post-fire origin, and the size of all seedlings found would indicate that this was a correct assumption.

RESULTS

The overstory component of all three stands contained a shortleaf/loblolly pine mix to varying degrees (table 1). The majority of species composition based on basal area was loblolly pine for stands 1 and 2. The third stand was composed mostly of shortleaf pine. Hardwoods were a minor component in the overstory of all three stands,

Table I-Summary of overstory attributes for stands used in this study

Stand	Species	Trees per acre	Average diameter at breast height	Basal area per acre
			- - -Inches-	- - Square ft
1	Loblolly	46	15.3	46.6
	Shot-tleaf	12	12.7	12.2
	Hardwoods[a]	10	8.7	10.1
	Total	68		68.9
2	Loblolly	50	15.4	54.7
	Shortleaf	26	12.1	26.3
	Total	76		81.0
3	Loblolly	14	15.4	14.2
	Shortleaf	42	13.6	46.6
	Hardwoods[b]	10	5.5	16.2
	Total	66		77.0

[a] *Fraxinus americana* L., *Liquidambar styraciflua* L., *Nyssa sylvatica* Marsh.
[b] *Liquidambar styraciflua* L.

especially in stand 2 which had no hardwoods. The total basal area did not vary much, ranging from about 70 to 80 square feet per acre.

Table 2 displays the pine regeneration summary for these sites. Shortleaf pine dominated the regeneration strata in each stand in terms of number of stems per acre, even though the overstory in stands 1 and 2 were dominated by loblolly pine. The reason for the domination by shortleaf is the superior sprouting ability displayed by shortleaf, which accounted for from 52 to 86 percent of all pine regeneration (seedlings and sprouts), and 92 to 100 percent of these sprouts were shortleaf pine. In fact, if it were not for sprout production by shortleaf pine in stand 1, shortleaf would not exist in the regeneration strata of this stand. Loblolly pine sprouts, on the other hand, accounted for 0 to 7 percent of all pine regeneration. In comparing seedlings, loblolly pine produced the largest number of post-fire seedlings, accounting for 55 to 100 percent of the new seedling germinants after fire.

The number of pine seedlings that were top-killed by fire and produced sprouts are displayed in table 3. There were significantly more shortleaf stems producing sprouts on all three sites than loblolly. Shortleaf overall displayed an average ratio of number of sprouts produced per sprouting stem of 2.10 compared to 1.65 for loblolly pine. It is evident that when loblolly seedlings were able to produce sprouts, they were not able to produce as many as shortleaf pine.

The sizes of the sprouts produced by shortleaf and loblolly pine were not significantly different at the $p=0.05$ level, with an average sprout size of 11.2 inches total height and 0.116 inches groundline diameter. Likewise, there was not a significant difference in seedling size at the $p=0.05$ level between the two species, with an average size of 4.8 inches total height and 0.060 inches groundline diameter. However, there was a significant difference in the sizes of sprouts and seedlings. Therefore, shortleaf in this case displayed a distinct advantage over loblolly pine by producing more sprouts per stem and more sprouts per acre; and sprouts have a distinct size advantage over seedlings, making them the dominant source of post-fire regeneration for loblolly pine.

RESTORATION APPLICATIONS

It is evident from this case study survey that under certain conditions, shortleaf pine displays an advantage over

Table 2--Regenerating stems per acre 2 years after fire

Stand	Sprouts: Shortleaf	Sprouts: Loblolly	Seedlings: Shortleaf	Seedlings: Loblolly	Total
1	87	0	0	14	101
2	126	6	12	99	243
3	405	37	37	46	525

Table 3-The number of top-killed seedling stems producing sprouts 2 years after fire

Stand	Shortleaf: No. of stems	Shortleaf: No. of sprouts	Shortleaf: Sprout-to-stem ratio	Loblolly: No. of stems	Loblolly: No. of sprouts	Loblolly: Sprout-to-stem ratio
1	59	87	1.5	0	0	—
2	51	126	2.5	4	6	1.5
3	166	405	2.4	21	37	1.8
Average ratio			2.10			1.65

loblolly pine within a fire disturbance regime. It is not the fact that fire is required to regenerate shortleaf on the site, as it is with other species, but that it is required to maintain it on a site in the presence of other species, notably loblolly pine. Young shortleaf pines grow slower and subsequently take longer to dominate a site than loblolly pine or many of its associated hardwood competitors (Burns and Honkala 1990). It is the sprouting feature of this species-that trees up to age 8 or 10 years (Harlow and others 1991) or diameters of 6 to 8 inches (Burns and Honkala 1990) will sprout if the crown or main stem is killed or badly damaged by fire or cutting-that enables it to be maintained and eventually dominate a site. Loblolly pine seedlings, on the other hand, may sprout from buds in axils of primary needles only up to age 3 years if the tops are killed by fire or cutting (Burns and Honkala 1990).

Hence, a prescribed burn through a stand where the pine regeneration layer is within the 3- to lo-year age range, or diameters at least less than 6 to 8 inches, should discriminate against loblolly pine in favor of shortleaf pine. Prescribed burns of a frequency estimated for the pre-European settlement era of 5 to 15 years should maintain the shortleaf dominance within the regeneration strata.

Even though existence of pure stands of shortleaf pine was documented in the 1800's, most stands contained a mixture of various upland oaks and hickories. Most hardwood species of this mixture will likewise respond to such a fire regime, and develop with the shortleaf pine. Under these circumstances, shortleaf will endure the hardwood competition longer than loblolly pine, and eventually maintain dominance once it overtops its competition (Burns and Honkala 1990). The fast-growing sprouts produced by shortleaf pine will help the species attain a dominant position in the regeneration layer.

On sites where restoring this system is desirous and appropriate, but an adequate seed source is lacking, it may be necessary to plant shortleaf pine seedlings to provide the catalyst for future development. Since the densities of these original forests were quite variable, and the clustering of trees occurred, the planting does not need to be of equal spacing and density. Once the seedlings have been established, then a burning regime as previously described may be employed.

Finally, in any restoration attempts there are three other considerations that must be contemplated and studied. First, most natural fires in the shortleaf pine/oak-hickory system occurred during the growing season. Few studies, if any, have examined the effects of growing season fires upon shortleaf and loblolly pine regeneration. Results reported in this study surveyed the effects following a late-winter prescribed burn. More studies of growing season fires will be necessary to determine if different results are attained.

Second, Native Americans burned the north Louisiana landscape at various intervals, sometimes encompassing extremely large areas. The extent to which this influenced the presence and composition of the shortleaf pine/oak-hickory forest is unknown. However, it is conceivable that the occurrence of some of these forests was a result of this burning.

Third, all that has been addressed here in the context of the restoration of this system has been the forest tree species composition. Whether the methods described here will likewise restore the associated flora and fauna of the shortleaf pine/oak-hickory system is still left to conjecture. However, when these methods are employed, continuous studies will be necessary to document the subsequent changes in flora and fauna, and compare them to what is known about the composition of historic systems.

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OLEORESIN CAPSICUM HAS POTENTIAL AS A RODENT REPELLENT IN DIRECT SEEDING LONGLEAF PINE

James P. Barnett'

Abstract-Direct seeding of southern pines has been a versatile and inexpensive alternative to planting on many reforestation sites across the South. Successful direct seeding has required that seeds be coated with thiram to repel birds, and with endrin to repel rodents. Endrin, which is extremely toxic, is no longer produced in the United States. Therefore, a substitute is needed. Oleoresin capsicum, a natural substance derived from pepper plants, has potential as a repellent. It occurs in an extremely concentrated form, and its repellency is caused by the heat of the capsicum. Preliminary tests have shown that at low rates oleoresin capsicum had little effect on the germination of longleaf pine (*Pinus palustris* Mill.) seeds, and significantly reduced losses from predation.

INTRODUCTION

Direct seeding is an affordable alternative to planting on many sites needing reforestation of the southern pines. It is also an appropriate supplement to natural regeneration where seedfall is inadequate. Techniques were thoroughly researched during the 1950's and 1960's by Derr and Mann (1971) and the 1970's by Campbell (1981a, 1981b). Studies show that success depends on protection of seeds from birds and rodents (Derr and Mann 1971; Campbell 1981 a, 1981 b). The recommended formulation of thiram and endrin protects against all important species of seed-eating birds, and deters small mammals common to most southern pine sites. Many field studies, tests with caged animals, and operational seedings have confirmed the repellent properties of these chemicals (Campbell 1981 c).

Thiram, a fungicide currently marketed as Gustafson 42-S[R2], is safe, effective, and easy to use. Anthraquinone is almost as effective, but is more difficult to apply because it is a powder. It is, however, a good alternative as a bird repellent.

Endrin, an insecticide, is very toxic. Although still registered as a rodent repellent in forestry due to the small quantities used (Barnett and others 1980), endrin is no longer manufactured in the United States because of the lack of demand. Thus, the continued use of direct seeding in southern forestry may depend on finding a satisfactory substitute.

In a series of tests evaluating potential repellents, Barnett (1995) and Campbell (1981c) could not find an effective replacement. Recently, the substance oleoresin capsicum (OC) has shown promise. For example, it is added to the paint used for hulls of ships to deter barnacles. Oleoresin capsicum, a rust- to red-colored liquid obtained from dried cayenne peppers (*Capsicum frutescens* L.), is standardized with olive oil. The chemical in capsicums that can produce a burning sensation in the mouth is capsaicin. Its strength is measured in parts per million (ppm). These ppm are converted into Scoville Units (SV), the industry standard for measuring the heat of peppers (American Spice Trade Association 1960, Hoff man and Lego 1983). One ppm is equivalent to 15 SV. The material used in this study has an SV of 500,000. Although oleoresin capsicum is a natural and nontoxic chemical derived from pepper plants and is used in many foodstuffs to increase their pungency, it is an irritant to the skin or eyes. Protective gloves and eyewear are recommended when handling this product. The repellancy of capsicum is attributed to its heat. This paper describes initial evaluations of oleoresin capsicum as a rodent repellent for direct seeding.

METHODS

Candidate chemicals for direct seeding must meet these criteria: (1) they must be relatively benign to the seeds, and (2) they must repel the target animals. The first tests described, therefore, measure effects of various formulations of capsicum on germination of longleaf pine (*Pinus palustris* Mill.) seeds.

Lab Tests for Germination

Longleaf pine seeds were chosen for the evaluations because they are the most sensitive of the southern pines to such treatments. Germination was tested under standard laboratory conditions for 28 days (Association of Official Seed Analysts 1980). Results were recorded three times weekly during the periods of peak germination. Three replications of 100-seed samples from each treatment replication were tested. The seed treatments used were: an untreated control; thiram- and clay-slurry treatments with and without latex; and lx, 2x, 4x, 8x, and 16x dilutions with capsicum and with thiram- or clay-latex slurry. The lx capsicum treatment (500,000 SV, American Mercantile, P.O. Box 240654, Memphis, TN 38124) was applied at a rate of 1 tablespoon per 25 pounds of seed. The rates of application per pound (454 grams) of seed were: 76 mililiter of thiram, 3 mililiter of latex, 0.6 mililiter of capsium (lx), and 45 grams of kaolin clay in 100 mililiter of water. The latex was added to the mixture to improve binding of the materials to the seeds. The same proportion of materials was used for each treatment. The laboratory tests were conducted in the Alexandria Forestry Center Seed Testing Laboratory.

Field Tests

Longleaf pine seeds, selected from a single lot of Louisiana seed orchard origin, were selected for field evaluations.

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Empty seeds were removed from the lot by pentane flotation (Barnett 1971). Random samples were drawn for treatments. Repellent treatments were applied and the seeds were air-dried overnight.

It is logical to evaluate candidate rodent repellents in caged animal trials before testing in the field. However, the Alexandria Forestry Center no longer has the facilities to conduct such tests. We, therefore, skipped the intermediate step and moved directly to field tests conducted on the Palustris Experimental Forest in central Louisiana.

Five of the seed treatments were evaluated in the field: (1) an untreated control, (2) lx capsicum plus thiram (0.6 milliliter capsicum, 76 milliliter thiram, and 3 milliliter latex per pound of seed), (3) 2x capsicum plus thiram (1.2 milliliter capsicum, 76 milliliter thiram, and 3 milliliter latex), (4) ix capsicum plus kaolin clay (0.6 milliliter capsicum, 45 grams clay in 100 milliliter water, and 3 milliliter latex), and (5) 2x capsicum plus kaolin clay (1.2 milliliter capsicum, 45 grams clay in 100 milliliter water, and 3 milliliter latex). Treatment plots consisted of five 12-inch circular spots arranged around a central stake. Each spot was sown with 100 seeds. Plots were randomly selected for a particular treatment and marked with a flagging pin. Twenty replications, separated by at least 50 feet, were established April 1, 1996, on a previously cleared site. Plots were randomly arranged. Seed losses were determined by counting seeds remaining on the spots at 2- to 3-day intervals. Heavy rains washed the seeds from the spots 12 days after initiation of the test.

Because the plots in this study were small and subject to overwhelming predation, we evaluated them frequently to determine predation patterns for each of the five treatments.

RESULTSANDDISCUSSION

The laboratory germination test results show that capsicum with thiram or clay reduced germination when applied at rates greater than 2x (table 1). However, the lx and 2x rates did not reduce laboratory germination more than the thiram- or clay-latex controls. Thiram alone reduces germination in the laboratory (Campbell 1981 c), but the reduction in these tests was more than expected. Previous studies have shown that thiram has lessimpact on germination in the field (Barnett and others 1980, Campbell 1981 c). The key to success for a repellent is field performance, so field evaluations of capsicum were initiated.

Results from the field evaluations indicate that the seeds were subjected to heavy predation. After 11 days, 78 Percent of the seeds in the control treatment were lost due to predation (table 2). Because rapid losses were anticipated from the small seed spots, seed counts were started 4 days after sowing and continued at 2- to 3-day intervals until heavy rains washed seeds from the spots. Though there were heavy losses in the control and in the clay-capsicum treatments, the thiram-capsicum treatments protected the seeds well through 11 days of the test, with average losses of less than 1 percent. Because this study did not evaluate endrin and capsicum alone, their effectiveness could not be compared. Caged animal and additional field tests will be required to make these comparisons. Losses in the capsicum-clay slurry treatment were less than in the control, but were significant. If these losses were caused by partial predation from birds, treatment with the combination of thiram and capsicum is needed to assure protection.

Table l-Effects of oleoresin capsicum with thiram or clay slurry on the germination of longleaf pine seeds

Variables	None	Treatment combination: Thiram	Treatment combination: Clay slurry
		Percent	
Control	89	—	—
Without latex	—	45	85
With latex	—	46	69
1 x capsicum	—	41	76
2x capsicum	—	47	68
4x capsicum	—	35	59
8x capsicum	—	34	46
16x capsicum	—	23	37

Table 2-Percentages of seeds removed or damaged on each plot 4, 7, 9, and 11 days after seeding on April 1, 1996, by treatment

Treatment	Seed losses at (days): 4	7	9	11
	Percent			
Control	2.2	26.4	58.9	78.5
Thiram + 1xOC	.6	.6	.6	.7
Thiram + 2xOC	.1	.2	.3	.4
Clay + 1xOC	1.1	3.7	22.0	53.6
Clay + 2xOC	.3	3.0	19.3	44.1

The results from this study indicate that oleoresin capsicum has potential as a rodent repellent for southern pine seeds. The lx rate is as effective as the higher 2x rate in these tests.

It is difficult to state with any certainty whether birds or rodents were the primary predators. An examination of remaining seedcoat fragments suggested that both birds and rodents were feeding on the longleaf seeds.

Despite the heavy predation on these small plots, the seed loss figures show that the repellents are effective. However, a larger-scale field evaluation should be conducted to gain additional information on the use of oleoresin capsicum as a rodent repellent for direct seeding. Seeding large acreages with thiram and capsicum treated seeds will be necessary to evaluate the effectiveness of the repellents when exposed to the environment and predators for a longer time period.

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EFFECTS OF STOCK TYPE AND FALL FERTILIZATION ON SURVIVAL OF LONGLEAF PINE SEEDLINGS PLANTED IN LIGNITE MINESPOIL

Mary Anne McGuire and Hans M. Williams'

Abstract-One-year-old longleaf pine (*Pinus palustris* Mill.) seedlings were hand-planted in January 1996 on an east Texas minespoil site. Effects of two seedling stock types and four levels of preplanting fall fertilization on seedling survival were evaluated. Fertilizer treatments consisting of a single application of ammonium nitrate (73 kilograms per hectare N), phosphorus (81 kilograms per hectare P), diammonium phosphate (73 kilograms per hectare N, 81 kilograms per hectare P), or control (no fertilizer) were applied to bare-root and container seedlings in November 1995. Root growth potential, the ability of a seedling to initiate and elongate new roots when placed into a favorable environment, was measured at time of planting. Field survival was surveyed monthly beginning in April 1996. Data were examined using analysis of variance. Container seedlings had significantly higher root growth potential and survival than bare-root. Fertilizer treatment effects, while not significant, tended to decrease both root growth potential and early survival for bare-root seedlings, and to increase root growth potential and decrease survival for container seedlings. Drought conditions during the 1996 growing season probably had a negative effect on survival of both bare-root and container seedlings. Only 2 percent of bare-root and 56 percent of container seedlings survived through the growing season, suggesting that only container stock should be used for reforestation of longleaf on minespoil sites. However, in years with normal precipitation, stock type effects on survival may not be significant and planting bare-root seedlings may be a viable option.

INTRODUCTION

It is estimated that between 1 and 2 million acres of land will eventually be disturbed by surface mining of lignite coal in Texas. Much of this mining will occur in the pineywoods region of east Texas (Hossner and others 1980). The Federal Surface Mine Control and Reclamation Act of 1977 requires restoration of vegetation on these lands for the primary purposes of limiting erosion and controlling flow and quality of water. Establishment of vegetation may be difficult on these sites due to physical properties, chemical toxicities, and nutrient deficiencies of the spoil material.

Reclamation of spoil banks on surface lignite mines in Texas has traditionally been accomplished using pasture grasses, even though many of these sites were forested prior to mining. Pasture grasses are relatively easy to establish, and offer immediate erosion control. However, pastures require long-term maintenance, including weed control and fertilization. On the other hand, establishment of forests is more difficult, but may provide more long-term benefits. Once established, forests require less maintenance than pastures. Forests provide wildlife habitat and recreational and economic opportunities as well as excellent control of erosion and water quality.

Texas Utilities Mining Company (TUMCO) operates several Surface coal mines in east Texas, including the Beckville Mine in Panola County, which supplies fuel for the Martin Lake generating plant. In the early 1980% TUMCO reclamation managers recognized the potential economic and environmental benefits of establishing forests on mined lands, and commenced with a program of intensive tree planting. To date, about 7 million seedlings have been planted on the Beckville Mine, consisting of approximately 85 percent improved loblolly pine (*Pinus taeda* L.) and 15 percent various hardwood species. These seedlings have been planted on both established pastures and recently graded spoil material.

TUMCO is interested in using longleaf pine (*P. palustris* Mill.) in its reclamation program in east Texas because the Beckville Mine site lies within the historical range of longleaf pine (Landers and others 1995). However, establishment of longleaf pine seedlings is more difficult than other southern pines for several reasons. First, bare-root longleaf seedlings are sensitive to handling and do not tolerate long periods of cold storage (Dennington and Farrar 1983, Dougherty and Duryea 1991). When weather delays planting, storage limitations can result in severe seedling mortality. Also, planting depth is critical because longleaf seedlings have no stems. If seedlings are planted too deep, the apical bud is smothered; if planted too shallow, the root collar is exposed and desiccation occurs. Movement of soil onto or away from seedlings after planting can have the same effect as incorrect planting depth. Finally, longleaf seedlings are very intolerant of woody competition (Dennington and Farrar 1983).

Many planting problems may be overcome when using container seedlings. Handling stress and storage are minimized. Container seedlings also perform better than bare-root in droughty conditions, and have an extended planting season. However, container seedlings have disadvantages. Compared to bare-root seedlings, they require more attention while growing, are more expensive to produce, are bulky to handle and transport, and are often smaller (Barnett and others 1989).

Obtaining quality nursery stock is an important factor in planting success. According to Duryea (1985), a high-quality seedling is one that meets defined levels of survival and growth on a given planting site. Late fall nursery

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fertilization has been used to improve the nutrient reserves of seedlings with the intent of improving survival and growth after outplanting. Previous research has shown varying effects of late-season nursery application of fertilizer. Hinesley and Maki (1980) found that fall nursery fertilization increased longleaf seedling dry weight, root collar diameter, and root:shoot ratio over controls. Field survival was not significantly affected, but height growth commenced sooner in fertilized seedlings. Anderson and Gessel (1966) found that late-season nitrogen application in the nursery significantly increased survival and height growth of outplanted Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco]. However, Ursic (1956) found a detrimental effect on field survival when loblolly seedlings were fertilized with nitrogen and potassium in the nursery in January. Shoulders (1959) found that fall nitrogen fertilization improved field survival of longleaf, loblolly, and slash pine (*P. elliotii* Engelm.) from one nursery, while survival of longleaf and loblolly from another nursery was depressed by fertilization.

This study attempts to assess effects of stock type and fall nursery fertilization treatments on survival of longleaf pine seedlings planted at the Beckville Mine.

METHODS

Seedling Treatments

Stock type treatments consisted of bare-root and container seedlings. Bare-root seedlings were commercially grown at the Texas Forest Service nursery located at Alto, TX, using seed obtained from a wild collection in east Texas. Ammonium nitrate was applied to bare-root seedlings weekly from April to August for a total growing-season application of 180 kilograms per hectare of nitrogen. Container seedlings were grown outdoors at the Arthur Temple College of Forestry greenhouse facilities located on the campus of Stephen F. Austin State University in Nacogdoches, TX. Seeds from the same east Texas source were sown in April 1995 in a commercial peat-pinebark-vermiculite growing medium in 144 cubic cm plastic cone containers. Seedlings were fertilized weekly from April to October with a commercial 30-l O-l 0 liquid formula for a total growing-season application of 840 kilograms per hectare of nitrogen.

Four levels of mineral fertilizer treatment were applied to bare-root and container seedlings in November 1995. Treatments consisted of a single application of ammonium nitrate (73 kilograms per hectare N), phosphorus (81 kilograms per hectare P), diammonium phosphate (73 kilograms per hectare N, 81 kilograms per hectare P), or control (no fertilizer). Commercial grade fertilizer was applied to bare-root seedlings using a tractor-drawn agricultural spreader. High-purity ACS grade minerals were applied in liquid form by measured dose to each container seedling.

Design of Experiment

The study was conducted using a randomized block split plot 2 by 4 factorial design with five replications. Stock types were the whole units and fertilizer treatments were the subunits. Data were examined by analysis of variance using Statistical Analysis System procedures (SAS Institute, Inc. 1989). Results are reported as significant at the 5 percent probability level.

Bare-root and container seedlings were hand planted at the Beckville Mine in January 1996. Bare-root seedlings were lifted 1 day before planting and placed in plastic bags. Roots were sprayed with Terrasorb super-absorbent gel, bags were sealed, and seedlings were stored at 3 °C overnight. Container seedlings were watered thoroughly the day before planting. A total of 600 seedlings (15 seedlings per treatment combination per replication) were planted on 3-meters by 3-meters spacing. Field survival counts were made monthly from April to October.

The planting site was located in an area scheduled for machine-planting of loblolly seedlings. Mining operations were completed, the site was graded, and hay mulch was applied for stabilization during the summer of 1995. Winter wheat was sown in September 1995 to further stabilize the site. Seedlings were planted in spoil consisting of mixed overburden material with a silty clay texture and average pH of 6.9. At the time of planting, soil moisture content averaged 30 percent (dry weight basis) and winter wheat was about 10 cm tall.

Root growth potential (RGP) was measured at planting time on a sample of four seedlings per treatment combination per replication, using a hydroponic method modified from Ritchie (1985). RGP is defined as the ability of a seedling to initiate and elongate new roots when placed into an environment favorable for root growth. A seedling with high RGP is expected to have high potential for survival and growth after outplanting (Ritchie 1985). The experiment was conducted in a growth chamber with photoperiod controlled at 16 hours, day temperature controlled at 26 °C and night temperature controlled at 20 “C. After 28 days in the growth chamber, seedlings were removed and root counts conducted. RGP was determined as the number of new roots initiated greater than 1 cm in length.

RESULTS AND DISCUSSION

Root Growth Potential

Stock type had a significant effect on RGP. Mean RGP was 39 for bare-root seedlings and 61 for container seedlings. Of 80 bare-root seedlings tested, 25 initiated no new roots and were dead at the end of the experiment. There was no mortality among container seedlings. We expected container seedlings to have higher RGP than bare-root seedlings. Container seedlings have a fibrous root system consisting of a taproot and many higher order laterals that provide many potential initiation points for new root growth. In comparison, bare-root seedlings have a root system consisting of a large taproot and a few primary and secondary laterals, providing fewer potential initiation points. Also, bare-root seedling root systems are damaged in the lifting process; many fibrous roots are removed and stress may be induced. However, we did not expect mortality among either stock type in the RGP experiment.

Fertilizer treatments did not have a significant effect on RGP (P>0.42). interaction effect between stock type and fertilizer was also not significant (P>0.14), but tendencies were strong, as shown in figure 1. Fertilizer treatments tended to improve RGP for container seedlings and depress RGP for bare-root seedlings. Control (unfertilized) bare-root seedlings had a higher average of RGP (68) than control container seedlings (50), but fertilized bare-root seedlings performed worse than all other treatment combinations. Container seedlings are often subject to nutrient deficiencies because soil-less growing media provide few mineral ions, container volume is small, and frequent irrigation leaches nutrients (Landis 1989). Therefore, fall fertilization was expected to improve container seedling quality and performance. Fertilizer treatments were not expected to be detrimental to bare-root seedlings, and reasons for this effect are not apparent.

Field Survival

Stock type had a significant effect on survival for all monthly counts. RGP results indicated an expected initial mortality of at least 30 percent for bare-root seedlings. No mortality was noticed in a visual inspection in February, but bare-root seedlings appeared stressed and unhealthy. Precipitation in February was less than 25 percent of normal and soil moisture was low. Drought conditions persisted throughout the growing season. Cumulative precipitation and survival count results are depicted in figure 2. In April, 56 percent of bare-root seedlings were dead, while more than 99 percent of container seedlings

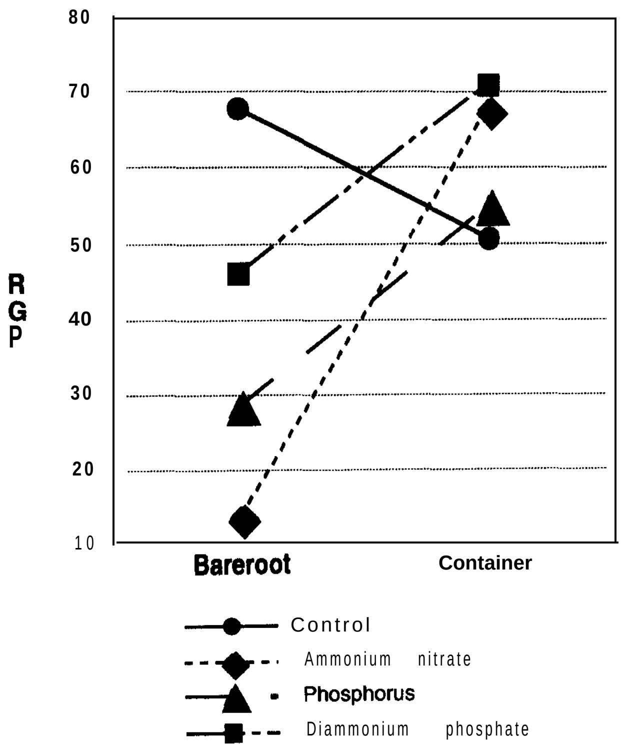

Figure l-Interaction effect of stock type and fertilizer treatments on root growth potential of bare-root and container longleaf pine seedlings.

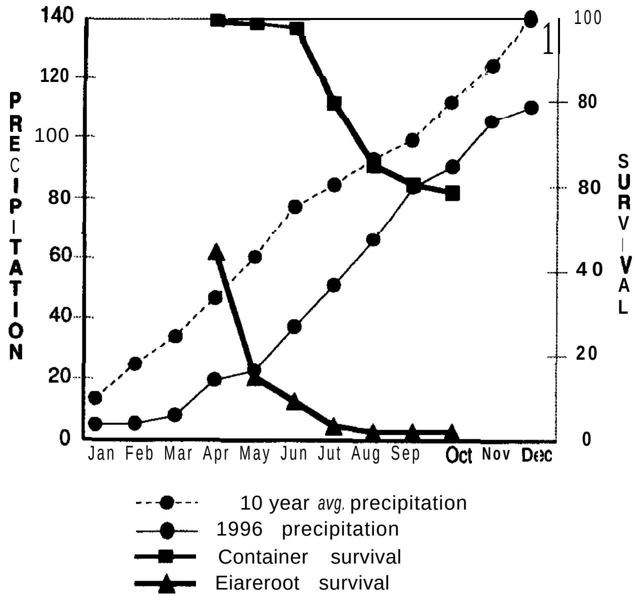

Figure 2-Cumulative 1 O-year average and 1996 precipitation in centimeters, and percent survival of bare-root and container longleaf pine seedlings planted on a lignite minespoil site in Panola County, TX.

remained alive. All living seedlings appeared stressed and competition from winter wheat and hairy vetch was intense. Herbicide was sprayed in a l-meter radius around each living seedling in May to control competition. By June, 91 percent of bare-root seedlings were dead, but container survival was still high at 98 percent. New growth was visible on most living seedlings, but young needles were only 6 to 8 centimeters long. Herbaceous vegetation on the entire site was brown and dry, so effects of herbicide were not obvious. Container survival declined sharply to 75 percent in July, and only 3 percent of bare-root seedlings remained alive. By October, bare-root survival was 2 percent, and container survival had stabilized at 56 percent. Young needles on surviving seedlings had elongated to only 20 to 25 cm.

Container seedlings were expected to survive and perform better than bare-root in this study, but effects of the drought probably intensified this phenomenon. Fibrous root systems of container seedlings have a larger absorptive surface than bare-root root systems and therefore have a greater ability to extract water from the surrounding soil and tolerate drought. However, we believe that both container and bare-root seedlings were negatively affected by the poor soil moisture conditions.

Fertilizer treatments had no significant effect on seedling survival. However, bare-root seedlings fertilized with ammonium nitrate tended to die sooner than those receiving other treatment combinations. Survival of container seedlings also tended to be lower for nitrogen fertilizer treatments for all monthly counts. Perhaps the effects of fertilizer treatments would have been greater if mortality had not been as rapid and severe.

Visual inspection of seedlings in March 1997 indicated no additional over-winter mortality, and new growth was noticeable on most seedlings. Effects of herbicide treatment were obvious; a patch of bare ground surrounded each seedling. Intense winter rainstorms had caused sheet erosion to remove up to 4 centimeters of soil from around the roots of some seedlings. Effects of this soil removal on seedling survival remain to be seen.

CONCLUSIONS

Container seedlings had significantly higher overall RGP and survival than bare-root seedlings. High mortality of bare-root seedlings suggests that only container seedlings should be used for longleaf reforestation on east Texas lignite minespoil sites. However, effects of stock type on survival may not be as noticeable when growing season precipitation is closer to normal. Results of this study indicate that fall fertilization may be detrimental to both RGP and survival of bare-root seedlings, although effects were not statistically significant. Fertilizer effects on container seedlings were also not significant. However, fall fertilization tended to improve RGP of container seedlings; in contrast, survival of container seedlings tended to be depressed by fertilizer treatments. Additional study of the effects of fall fertilization on both stock types is needed before recommendations can be made.

ACKNOWLEDGMENT

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GROWING SEASON EFFECTS ON 5-YEAR GROWTH OF LOBLOLLY PINE NEAR PARKERSBURG, WEST VIRGINIA

David W. McGill and Edmund T. Bridge'

Abstract-A study was established in 1990 to assess the effects of a reduced first growing season due to late planting near Parkersburg, WV. A randomized complete block factorial experiment was used to test the null hypothesis that a reduced first growing season does not significantly influence the long-term development of loblolly pine trees. Seedlings were planted at 2-week intervals from the middle of February until the end of May for five types of seedlings and in each of four blocks. Various seedling types were used in the study to separate the effects of storage method from those of a shortened growing season. Results suggest that following five growing seasons, the effects of a shortened first growing season are still present. This study considered the effects of a shortened growing season for the 1990 planting season only, and the results presented should be interpreted with this in mind.

INTRODUCTION

In the Parkersburg area of Westvaco's Appalachian Region, hardwood stands are converted to loblolly (*Pinus taeda* L.) or pitch x loblolly pine plantations to provide the company with pine fiber for its paper production lines. Most pines are planted in March. However, unfavorable weather or site conditions, and plantation logistics can hamper Planting efforts so seedlings must be stored until conditions are favorable.

Prolonged storage can decrease the effective growing season for newly planted seedlings. Field performance may be negatively affected by this reduction in growing season. In the late 1950's and early 1960's, studies of loblolly pine plantations established in Mississippi showed that cold-stored seedlings had acceptable survival and growth when planted between February and early May (Ursic and others 1966). In plantings made after early May, survival remained satisfactory for plantings made into early June but height growth was reduced.

More recent studies show similar conclusions. In one of these, Hallgren and Tauer (1989) concluded that survival and height growth of shortleaf pine were always less for seedlings stored for 28 days than for unstored seedlings. Furthermore, a decreasing trend in 1 -year total height growth for both stored and unstored seedlings occurred across the early December to mid-April planting dates and points to the negative impact of a shortened growing season.

Hallgren and others (1993) discussed the confounding effects of lifting date, cold storage, and planting date on field performance of shortleaf pine. For example, planting dates will differ for two groups of seedlings lifted on the same date, where one group is planted and one stored. Different planting dates will likely have different field conditions and thus field performance cannot be ascribed to the impact of storage alone.

Bridgen and Nelson (1989) designed and established a study using several storage methods and a single lifting date in an attempt to separate these potentially confounding effects. Working under the notion that seedlings stored in different ways might respond to storage and planting date differently, they proposed that containerized seedlings that are stored outside "should show no growth loss due to time of planting, as they would be able to fully use the normal growing conditions" and thereby maintain a more superior physiological condition. Under this assumption, if the length of the growing season was not important but storage effects were, then these outside-stored seedlings would have equal 5-year performance for seedlings planted at any planting date. Seedlings stored in coolers, on the other hand, should show decreased growth when planted at later and later planting dates because they do not have exposure to the ambient and hypothetically beneficial growing conditions.

Results following 2 years of growth of the loblolly pines were reported by Bridgen (1992). The report ended in the recommendation to monitor and report the study at age 5 since most past studies that examined growing season effects were short term, following growth for only the first year or two after planting. This report documents the impact of a shortened first growing season on the 5-year field performance of loblolly pine.

PROCEDURE

Experimental Design

A randomized complete block factorial experiment was used to analyze the data to test the influence Of a Shortened growing season on the long-term growth of loblolly pine near Parkersburg, WV (Bridgen and Nelson 1989). Seedling type and planting date were the two factors of interest. Seedling type was a combination of production method (nursery or containerized) and storage method (outside under mulch, lighted cooler, and dark cooler); it was treated as a single factor to represent several types of storage systems. The intended purpose of using multiple storage systems was to separate the effects of a Shortened growing season from those of Storage treatment (Bridgen 1992).

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The five seedling types used were:

(1) Nursery-grown, stored in cooler,
(2) Nursery-grown, stored outside (roots in moist sawdust and shoots exposed),
(3) Containerized, stored in cooler,
(4) Containerized, stored in cooler (under 400-watt lights for a 12-hour photoperiod), and
(5) Containerized, stored outside (roots in moist sawdust and shoots exposed).

The initial characteristics of these seedlings are shown in table 1.

The second factor, planting date, was selected to represent the length of growing season; the later a seedling is planted, the shorter is its growing season. Every 2 weeks, from February 14 through May 24, 1990, seedlings of each seedling type were planted in one 25-tree plot in each of four blocks in the Parkersburg area. Nine internal trees on each plot served as measurement trees.

Numerical Analysis

Analysis of variance for a randomized complete block, factorial experiment was performed using the ANOVA procedure in SAS to detect differences between plot-level mean treatment responses (SAS Institute 1988). Quantitative contrasts were written to evaluate trends in response parameters across planting dates. Response parameters of interest included: total height, diameter at breast height (d.b.h.), average tree volume, and survival. Cubic foot volume for the 5-year-old loblolly pines was estimated using volume equations from Owens (1969). Survival values were arcsine transformed prior to analysis. *Ad hoc* contrasts were written to test for differences between groups of seedling types using the SAS GLM procedure with CONTRAST and ESTIMATE statements. Significance levels for all tests were set at $\alpha = 0.05$.

RESULTS AND DISCUSSION

Following 5 years, the resulting range in average tree size went from the smallest: containerized seedlings stored in the dark cooler (0.104 cubic feet) to the largest: nursery-grown seedlings stored in a dark cooler (0.132 cubic feet; table 2). Containerized seedlings stored outside had the lowest survival of 74 percent. Containerized seedlings stored in a lighted cooler had the highest average survival rate of 95 percent over all planting dates.

Averaging over all seedling types, 5-year growth characteristics decreased in the later planting dates (table 3). The seedlings planted on the last few planting dates showed less and less growth on later and later planting dates. Survival ranged from 82 to 92 percent. From this perspective, there were no apparent trends in survival through the planting period. However, planting date was treated as an ordinal variable, which permitted the exploration of potential linear, quadratic, and cubic trends across the range of planting dates.

Analysis of variance for survival showed a significant interaction between seedling type and planting date (table 4). Further, when the variation explained by this interaction

Table l-Average initial size measurements of seedlings planted in spring of 1990 (adapted from Bridgen 1992)

	Containerized			Nursery	
Variable	Dark cooler	Light cooler	Outside	Cooler	Outside
Height (in)	6.65c[a]	6.85abc	7.05a	6.77bc	7.01 ab
DGL (in)	0.11b	0.11b	0.11b	0.18a	0.17a
Number of branches	1.3 b	1.4 b	1.5 b	5.0 a	4.5 a

[a] Mean values followed by a common letter are not significantly different at alpha = 0.05 by Duncan's New Multiple Range Test.

Table 2-Average 5-year growth and survival of loblolly pine trees by seedling type

Seedling type	Height	D.b.h.	Volume per tree	Survival
	Feet	*Inches*	*Cubic feet*	*Percent*
Nursery, dark cooler	12.7	2.11	0.132	93
Nursery, outside	12.5	2.04	0.125	86
Containerized, dark cooler	11.6	1.85	0.104	86
Containerized, light cooler	12.3	2.03	0.126	95
Containerized, outside	11.9	1.91	0.113	74

Table 3-Average 5-year growth and survival of loblolly pine trees by planting date in 1990

Planting date (1990)	Height	D.b.h.	Volume	Survival
	Feet	*Inches*	*Cubic ft*	*Percent*
February 14	12.8	2.10	0.135	82
February 27	12.2	2.02	0.122	84
March 12	12.8	2.13	0.136	92
March 27	12.8	2.17	0.139	87
April 9	12.5	2.04	0.128	92
April 23	12.1	1.94	0.115	87
May 9	11.7	1.86	0.100	83
May 24	10.9	1.66	0.084	87

Table 4—Analysis of variance tables for transformed survival and average tree volume[a]

Source	p-value
Transformed survival:	
Blocks	0.05
Planting date (PD)	0.38
Linear	0.60
Quadratic	0.15
Cubic	0.09
Departure	0.66
Seedling Type (ST)	co.01
PDXST	co.01
PDlinear x ST	co.01
PDquadratic x ST	0.49
PDcubic x ST	0.78
Departure	0.58
Error	
Total	
Average tree volume:	
Blocks	co.01
Planting date (PD)	co.01
Linear	co.01
Quadratic	co.01
Cubic	0.63
Departure	0.64
Seedling Type (ST)	0.05
PD X ST	0.16
PDlinear x ST	0.27
PDquadratic x ST	0.35
PDcubic x ST	0.34
Departure	0.34
Error	
Total	

[a] Diameter and height paralleled the results for average volume. Variation due to planting date is **partioned** into linear, quadratic, cubic and higher order effects. Departure from a cubic model represents the additional sum of squares accounted for by a model fit through the means of each planting date (see Hicks 1984).

term was partitioned into linear, quadratic, cubic, and higher-order effects, the result showed a significant linear interaction. That is, there was evidence that one or more seedling types had linear trends in survival over the planting season.

Figure 1 shows an interaction plot for survival. Containerized seedlings, stored outside, showed a significant increasing trend in survival. High mortality was due to some kind of severe weather conditions. A maintenance log described the seedlings as “appearing frozen at the top.” This climate impact was not noticed until after a couple of planting dates had already passed, then care was taken to use only the more vigorous looking

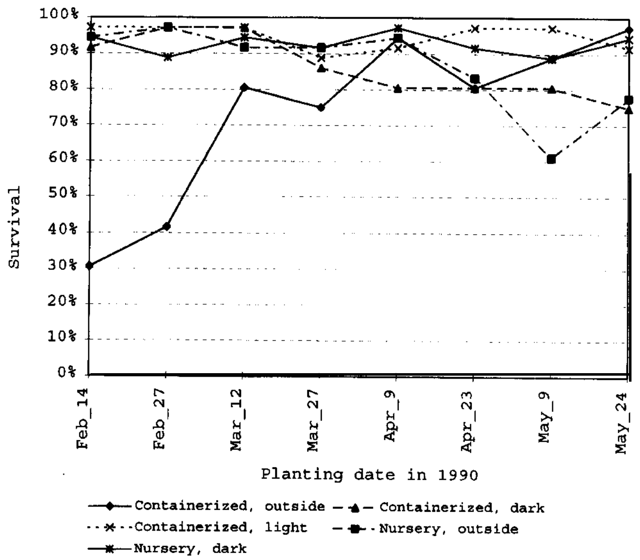

Figure I-Five-year survival by seedling type and planting date. Value for a given planting date x seedling type combination is the average from nine seedlings in each of four blocks.

seedlings for planting at later dates. This change in procedure resulted in a significant increasing trend in survival, where the seedlings of this type had mostly over 80 percent survival for the rest of the planting dates.

There were also two significant decreasing trends in survival. Both containerized seedlings stored in the dark, and nursery-grown seedlings stored outside under mulch showed lower survival for seedlings planted at later planting dates.

For average tree volume, planting date and seedling type explained significant amounts of variation (table 4). Further, orthogonal contrasts pointed to significant quadratic trends in the data. Diameter at breast height, and total height responses paralleled the volume response. The estimated quadratic relationship between planting date and average tree volume is shown in figure 2. The quadratic function has a slight depression in the beginning of the planting season and a significant decreasing trend through the later planting dates.

Seedling type was also significant in explaining variation in 5-year growth in this study. Three important contrasts related to seedling type were performed:
(1) H,: Stored outside = Stored in dark cooler.
(2) H,: Nursery grown (bare-root) = Containerized.
(3) H,: Stored in lighted cooler = Stored in dark cooler.

The first test evaluated whether outside-stored seedlings grew better than the dark cooler-stored seedlings. The results showed no evidence of any interactions or main effects in the comparison. As stated previously, the hypothesized results that would suggest negative storage effects would be no planting date effects for outside-stored seedlings and decreasing 5-year increment for cooler-stored

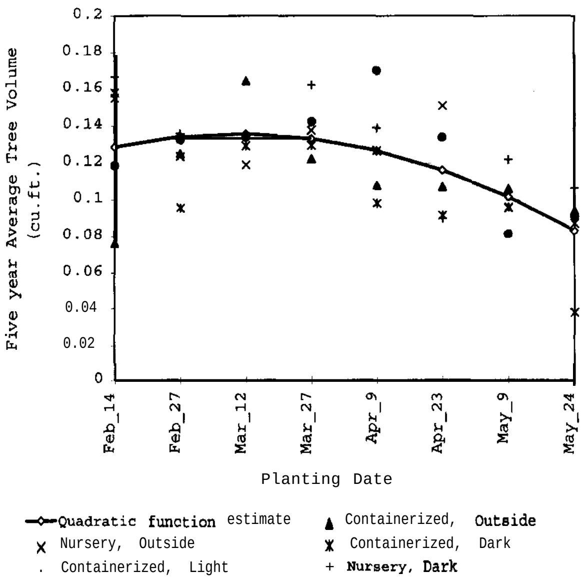

Figure 2—Estimate (line) of quadratic relationship between average tree volume and planting date.

seedlings (leading to a significant seedling type x planting date interaction in the analysis of variance). Thus, the effects of a shortened growing season far overshadow any suggestion that prolonged storage affected these seedlings.

When testing for differences between nursery-grown and containerized seedlings, the nursery-grown seedlings performed slightly better on average than the containerized seedlings. Nursery-grown seedling types were 0.86 feet taller ($p<0.01$), 0.19 inches d.b.h. larger ($p<0.01$), and 0.02 cubic feet greater ($p<0.01$) than containerized seedling types at the end of 5 years.

Containerized seedlings stored in the lighted coolers performed better than containerized seedlings stored in a dark cooler. Containerized seedlings were 0.75 feet taller ($p=0.02$), 0.18 inches d.b.h. larger ($p=0.02$), and 0.02 cubic feet greater ($p=0.03$) than containerized seedlings stored in a dark cooler. This suggests some improvement in the lighted storage conditions over dark storage.

Few studies have investigated the effects of photoperiod during cold storage (Rose 1985). However, in one study, lighted cooler storage of nursery-grown loblolly pine was shown to increase bud activity, accelerate budbreak, and increase first-year height growth (Johnson 1982). Loblolly pine photosynthesizes at temperatures as low as 8 °C. While the cooler temperatures were kept at 4 "C, leaf temperature may have been higher with the high intensity lights. If the lighted-cooler seedlings were actively photosynthesizing, depletion of stored carbohydrate may have been reduced and would have been at higher levels than dark-stored seedlings at the time of planting.[2] This study did not include a lighted, cold storage treatment for nursery-grown seedlings. If containerized seedlings require cold storage, their subsequent field performance may be improved by providing a simulated photo-period. However, prior to implementation, further studies should address this option.

This study assessed the impact of a shortened first growing season on subsequent 5-year tree growth for a single planting season. National Weather Service station data from Parkersburg showed higher than average minimum temperatures through March of 1990, but precipitation was well within the range of 1 O-year observations (except for May having high rainfall). Obviously, each planting season is different with changing patterns of temperature, rainfall, and soil conditions; however, 1990 did not seem to have unusually extreme climatic variation. Still, generalizations of these results should consider these important year-to-year variations in site conditions. Future research investigating plantation establishment would benefit by replicating the study for several years.

CONCLUSIONS

The effects of a shortened first-year growing season in 1990 were evident 5 years following planting. Five-year height, diameter, and volume showed a decreasing trend for plantings made after mid-April. This reduction in 5-year volume shows the importance of early rotation cultural treatment to long-term productivity.

Seedlings stored outside, theoretically having higher physiological activity, did not show consistently greater 5-year height, diameter, or volume growth than seedlings stored in unlighted coolers.

Containerized seedlings stored in lighted coolers in this study had improved 5-year growth over containerized seedlings stored in dark coolers. Lighted coolers may have lowered the depletion rate of these loblolly seedlings, thus improving their physiological condition over those stored in unlighted coolers.

Nursery-grown seedlings produced greater 5-year growth than containerized planting stock. The growth differences may have been due to the initial size, particularly the number of branches and caliper, of the nursery stock at the outset of the study.

The results of this study suggest that loblolly pine plantations in the mid-Ohio Valley near Parkersburg, WV, should be planted by mid-April. Planting before mid-April will avoid the reduced growth associated with a shortened first-year growing season.

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[2] P.M. Dougherty, personal communication.

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POTENTIAL PROBLEMS WHEN PARTIAL CUTTING IN OVERSTOCKED STANDS OF MATURE SHORTLEAF PINES TO ENHANCE NATURAL REGENERATION

Michael D. Cain'

Abstract-A single-tree selection reproduction cut was imposed in a mature, overstocked, natural even-aged stand of shortleaf pines (*Pinus echinata* Mill.) in southeastern Arkansas using basal area-maximum diameter-quotient (BDq) regulation to mold an uneven-aged structure. Hardwood control treatments were applied before and after the reproduction cut to facilitate natural pine regeneration. The effort was hampered by wet summer weather which coincided with the scheduled harvest, a below-average pine seed crop during the winter after harvest, a severe ice storm, and high mortality of residual pines. Recommendations are provided to assist forest managers in circumventing similar problems at the operational level.

INTRODUCTION

When naturally regenerating the southern pines, four reproduction cutting methods are generally recognized. These include the clearcutting method, the seed-tree method, the shelterwood method, and the selection method (Smith 1986). The first three methods result in even-aged stands, whereas the latter technique produces stands with uneven-aged structure. Because of public concerns about the ecological consequences of even-aged management, plans are underway to increase the acreage of uneven-aged stands on some national forests in the Southeastern United States (USDA FS 1990). Uneven-aged management may also serve private nonindustrial forest landowners as a low-investment silvicultural technique (Williston 1978). In the selection system, some trees are harvested regularly as individuals or in groups, with total volume cut at any one time being roughly equal to the growth that occurred since the last harvest (Reynolds and others 1984).

Because loblolly and shortleaf pines (*Pinus taeda* L. and *P. echinata* Mill.) are shade intolerant, certain guiding principles must be followed to secure adequate natural regeneration from these two species in uneven-aged silviculture. These principles involve maintenance of appropriate stocking, regulation of stand structure, and control of competing vegetation (Baker and others 1996). The purpose of this paper is to examine the problems that were encountered in a silvicultural study during conversion of a mature, overstocked, natural even-aged shortleaf pine stand to uneven-aged structure, and to offer suggestions for circumventing such problems. Results were part of a broader investigation to monitor the efficacy of hardwood control treatments for improving pine establishment from seed.

METHODS

Study Area

The study was located within a 36-acre compartment on the Crossett Experimental Forest in southeastern Arkansas. Bude silt loam (Glossaquic Fragiudalf) occurs on 75 percent of the area, and Providence silt loam (Typic Fragiudalf) occupies the other 25 percent (USDA 1979). Both soils have a site index of 85 to 90 feet at 50 years for shortleaf pine. Although the terrain is essentially flat, wetness can limit equipment use during tree harvesting because the soils have a fragipan at a depth of 18 to 24 inches that restricts internal drainage. At the time of study installation, pine and hardwood basal area averaged about 100 square feet per acre and 50 square feet per acre, respectively. There had been no harvests or hardwood oontrol in over 20 years, and the pines averaged more than 50 years old.

Field Methods

The compartment was subdivided into six blocks containing 6 acres each. Three blocks were randomly assigned a preharvest prescribed winter burn, and three blocks were not burned. Within each burned and unburned block, four hardwood control treatments were randomly assigned along with an untreated check. Hardwood control treatments included chain-saw felling or herbicide injection, both before and after a single-tree selection harvest (Cain 1995). Hardwood control plots were 104.4 feet by 104.4 feet (0.25 acre) with 66-feet by 66-feet (0.1 acre) interior measurement subplots. Within each interior subplot, ten 1 -milacre sample quadrants were systematically established and monumented for assessing ground coverage from herbaceous vegetation (forbs, grasses, semiwoody plants, and vines) and submerchantable-sized hardwoods (including shrubs). One year after hardwood control, ground cover was ocularly estimated to the nearest 10 percent by vertical projection of foliar cover to the ground.

The objective of the single-tree selection harvest was to mold the residual stand so that the diameter distribution resembled a reversed-J or uneven-aged structure. Merchantable-sized (>3.5 inches d.b.h.) shortleaf pines were tagged for retention on each plot according to the basal area-maximum diameter-quotient (BDq) technique (Farrar 1984). The BDq technique involves the following guidelines, in order of importance: (1) a specific basal area should be left in residual trees after harvest; (2) all trees larger than a maximum diameter should be removed

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unless some are needed to achieve the target basal area; and (3) the residual diameter distribution should approach a balanced uneven-aged structure, characterized by a constant ratio (q) between the number of trees in succeeding diameter classes. Guidelines for applying the BDq in this study were a basal area of 60 square feet per acre in pines >3.5 inches d.b.h., a maximum d.b.h. of 22 inches, and a q of 1.22 for l-inch d.b.h. classes. Although Pine basal area was prescribed at 60 square feet per acre within each 0.25acre plot, an additional 6 square feet per acre (10 percent) was retained to account for postharvest mortality.

Merchantable-sized pines, reserved as crop trees, were measured to an accuracy of 0.1 inch before harvest and at 1 and 3 years after harvest. In June 1992, about 35 square feet per acre of pine basal area was removed from each plot during the single-tree selection harvest. Throughout the 36-acre compartment, the logging contractor harvested an average of 5,300 fbm per acre (Doyle scale) in pine saw logs.

During the three winters following harvest, shortleaf pine seedcrops were monitored on the area. One seed trap (Cain and Shelton 1993) was placed at the northeast corner of each hardwood control plot and these were visited monthly between October 1 and March 1 for seed collection. A less-intensive assessment was made of the preharvest shortleaf pine seedcrop by monitoring seed catch in five systematically spaced seed traps during the winter before harvest. Collected pine seeds were cut open to determine the number of potentially viable seeds per acre (PVSA). Because of a below-average shortleaf pine seedcrop during the first winter after harvest, study plots were direct seeded with repellent-treated shortleaf seeds at the rate of 0.5 pound per acre during February 1993. The germinative capacity of these seeds was 92 percent according to a 30-day indoor germination test on moist sand.

Data Analysis

Data were analyzed by analyses of variance for a split-plot design. The main effects were prescribed burning versus no burning, with each burning treatment replicated three times completely at random in the 36-acre compartment. Subeffects were four hardwood control treatments and an untreated check. Analyses of variance were used to compare (1) pine seedcrops among years, (2) ocular estimates of ground coverage from competing vegetation, and (3) development of merchantable-sized pines among hardwood control treatments. Ground coverage and crop pine survival were compared following arcsine, square-root proportion transformation of percentage values. Since there were no statistically significant effects ($P>0.05$) from the burn treatments and no burn by hardwood-control interaction in analyses of variance, only means from hardwood control treatments are presented here. A linear regression was fitted for mortality of crop pines relative to d.b.h. All analyses were carried out at the $\alpha=0.05$ probability level (P).

RESULTS AND DISCUSSION

Shottleaf Pine Seedcrops

The potential size of a seedcrop is probably the most important criterion for ensuring the success or failure of any natural reproduction cutting method for loblolly and shortleaf pines (Cain 1991). According to Liming (1945), 1 pound of viable seeds per acre (about 50,000 PVSA) is required for successful natural regeneration of shortleaf pines. In the present study, shortleaf pines produced over 800,000 PVSA during the winter before harvest. The first seedcrop after harvest-the most critical for regeneration purposes-was below average at about 45,000 PVSA, which necessitated direct seeding of study plots. That number was greatly exceeded ($P<0.01$, Mean Square Error=9.347E09) during the second winter (about 1,500,000 PVSA) and third winter (over 500,000 PVSA) after harvest.

Trousdell (1954) proposed that seedbeds in Virginia would remain receptive for loblolly pine establishment 3 years after site disturbance. However, just one growing season after hardwood control in the present study, ground coverage averaged 26 percent from submerchantable-sized hardwoods and 85 percent from herbaceous vegetation (table 1), with no differences (130.05) among hardwood control treatments. This degree of competition diminished seedbed receptivity so greatly that no additional shortleaf pine seedlings could become established even when pine seedcrops were more than adequate during the next two winters after hardwood control.

Table I-Ground cover from submerchantable-sized hardwoods and herbaceous vegetation one growing season after hardwood control

Hardwood control treatment	Ground cover[a]: Submerchantable hardwoods	Ground cover[a]: Herbaceous vegetation
	---------- Percent ------- ---	
Untreated check	22	79
Herbicide injection before harvest	23	91
Herbicide injection after harvest	30	85
Chain-saw felling before harvest	31	85
Chain-saw felling after harvest	25	84
Mean square error	0.0115	0.0233
P>F[b]	0.44	0.16

[a] Submerchantable hardwoods are woody, nonpine rootstocks less than 3.6 inches d.b.h., including woody shrubs. Herbaceous vegetation includes forbs, grasses, semi-woody Plants, and vines.
[b] The probability of obtaining a larger F-ratio under the null hypothesis.

Merchantable Pine Basal Area

Optimum stocking of loblolly and shortleaf pines for maximum growth of both merchantable trees and pine regeneration is between 45 and 75 square feet of basal area per acre (Baker and others 1996). Therefore, basal area in residual pines of merchantable size was specified as 60 square feet per acre, with an extra 10 percent allowance for mortality at the time of initial harvest. Three years after the initial single-tree selection harvest, merchantable pine basal area averaged only 48 square feet per acre, with no differences (A0.05) among treatment means (table 2) for reasons described below.

The initial harvest was conducted within a 4-week window in June 1992, so that hardwood control treatments could be applied while the trees were actively growing, both before and after harvest. Consequently, completion of harvest during this window was specified in the logging contract, regardless of the weather. Removal of cut trees was accomplished with articulated rubber-tired skidders. By happenstance, June 1992 had above-average rainfall (10 inches) when compared to the previous 65-year mean (4 inches) for that month. These wet conditions resulted in undesirable rutting of the soil and, no doubt, pine root damage from skidders, across the entire 36-acre compartment. Slick soil conditions contributed to poor traction, so the skidders often slid into some residual pines, scraping away patches of bark and exposing the tree's cambium. Even when inclement weather is not a consideration during a logging operation, some damage to residual trees should be expected when using a single-tree selection harvest in an initial basal area reduction cut to bring an even-aged stand to uneven-aged structure. For example, Kluender and Stokes (1994) reported that the use of rubber-tired skidders resulted in unspecified damage to 17 percent of residual trees during an initial single-tree selection harvest that removed 29 percent of merchantable-sized pines on a 52-acre tract in northwest Arkansas.

By spring 1993, there was an infestation of bark beetles (*Dendroctonus* spp. and *Ips* spp.) in residual pines. This infestation was attributed to the weakened condition of the trees as a result of thinning shock (Oliver and Larson **1990),** root damage from wet-weather logging (Moehring and Rawls **1970),** cambium exposure, or a combination of these factors. Subsequently, a salvage contract was written to remove these infested trees in an effort to control the insect activity. During the salvage in June 1993, 15,660 fbm (Doyle scale) were removed from the 36-acre compartment (440 fbm per acre in trees 10 to 25 inches d.b.h.).

In February 1994, an ice storm of historic significance (Halverson and Guldin 1995) resulted in collapse of some crop pines and limb breakage on others. This disturbance further exacerbated the bark beetle infestation. During summer 1994, another salvage contractor removed 29,560 fbm (Doyle scale) of dead and dying pines from the compartment (820 fbm per acre in trees 5 to 24 inches d.b.h.). Basal area loss in merchantable pines, that occurred after the June 1992 harvest and before an October 1995 inventory, averaged 18 square feet per acre, with no statistically significant differences (P=0.80) among hardwood control treatments (table 2). The change in basal area from one inventory to the next included both increases from growth and decreases from mortality. On good sites (site index >85 feet at 50 years for shortleaf pine), basal

Table 2-Status of crop pines 3 years after the initial harvest

Hardwood control treatment	Basal area: Residual trees	Basal area: 3-year loss	3-year survival	Annual d.b.h. growth
	------ Ft^2/acre ------		*Percent*	*Inches*
Untreated check	53.6	12.8	70	0.069
Herbicide injection before harvest	50.8	16.7	64	0.086
Herbicide injection after harvest	45.8	18.7	63	0.076
Chain-saw felling before harvest	42.7	22.8	56	0.072
Chain-saw felling after harvest	45.1	19.5	58	0.061
Mean square error	203.8	196.0	0.067	0.00046
P>F[a]	0.68	0.80	0.71	0.41

[a] The probability of obtaining a larger F-ratio under the null hypothesis.

area growth in a well-regulated uneven-aged pine stand should average 3 square feet per acre per year (Baker and others 1996). Therefore, the projected loss in merchantable Pine basal area in this study averaged about 27 square feet per acre between autumn 1992 and autumn 1995.

Chapman (1941) proposed that, in the absence of early thinning in pine stands, crowns of loblolly pines are often reduced to less than 40 percent of total height. According to Chapman, subsequent selection thinning of previously unthinned stands that are older than 50 years often results in heavy mortality of released trees. To test Chapman's hypothesis in the present study, total height and height to live crown were measured during February 1996 on 10 shortleaf pines that appeared healthy, and on 10 shortleaf pines with sparsely foliated crowns and an unhealthy appearance. The sample pines ranged from 12 to 22 inches d.b.h. Live-crown ratio averaged 37.4 percent for the healthy pines and 35.9 percent for the unhealthy pines. Although these data suggest that a low live-crown ratio was probably not responsible for the most recent decline of residual shortleaf crop pines in the present investigation, no crown data are available from pines that died or were salvaged before 1996.

In mid-January 1996, a visual inspection was made of 30 shortleaf pines in various stages of decline to determine whether annosus root rot [*Heterobasidion* annosum (Fr.) Bref., formerly *Fomes* annosus (Fr.) Karst.] might be causing pine mortality. This time of year was chosen because indicator conks are most common from December through March (USDA FS 1989). Litter was removed from around the base of these dead and dying pines, but there was no visual evidence of butt-rot conks. Moreover, finer textured soils, such as occur on the Crossett Experimental Forest, are classified as low hazard for annosus root rot. A more definitive assessment of root disease would require laboratory examination of pathogen cultures.

Bormann (1966) theorized that intraspecies root grafting can permit trees of low vigor to survive by using a food gradient from dominant trees. He noted that this energy transfer is probably important to the survival of low-vigor trees and may account for the observation that weak trees often die after removal of larger members of a stand. Because shortleaf pines dominate the present study area, their root systems may have naturally grafted through time. If so, heavy thinning in 1992 reduced the root-to-shoot ratio of residual pines to the point that the aboveground mass could no longer be sustained by a smaller root system. The greatest crop pine mortality occurred in the smallest d.b.h. classes (fig. 1) where pines were least thrifty due to years of suppression in the undisturbed stand. Similar trends were reported by Chaiken (1941) after partial cutting in a mature loblolly pine stand.

In autumn 1995, survival of crop pines on study plots averaged 62 percent, with no differences (60.71) among hardwood control treatments (table 2), Suggesting uniform mortality across the compartment. Annual d.b.h. growth of these surviving pines averaged only 0.073 inch per year,

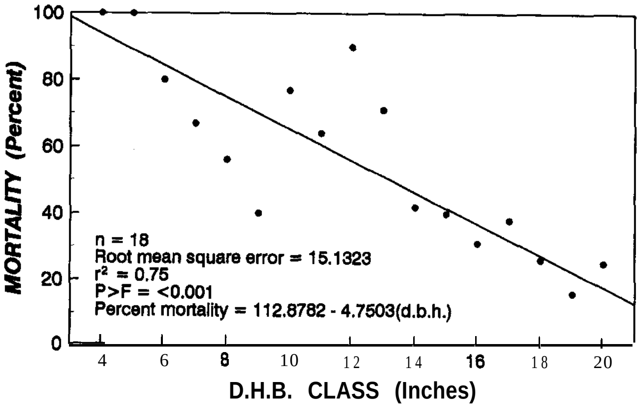

Figure I-Mortality (percent of reserved pines) as related to d.b.h. during 3 years following partial cutting.

also with no differences (P=0.41) among hardwood control plot means (table 2). Yet, on this site, healthy pines with well-developed crowns and room to grow should average 0.3 inch of d.b.h. growth per year (Reynolds and others 1984).

SUMMARY AND RECOMMENDATIONS

Site treatments to ameliorate seedbed conditions for natural pine regeneration are most advantageous when applied just before a better-than-average seed year (Cain 1991). Had the hardwood control treatments and single-tree selection harvest been conducted 1 year previous-to or 1 year later-than what actually occurred in this investigation, good rather than marginal shortleaf pine seed crops would have been disseminated onto the study area. This is important because 1 year after hardwood control, receptive seedbed conditions disappeared on this good site due to invasion by herbaceous and woody nonpine vegetation.

Basal area of merchantable-sized pines was reduced to 66 square feet per acre in a single harvest that removed over 5,000 fbm per acre (Doyle scale). Basal-area reduction was accomplished in one operation so that the efficacy of hardwood control treatments could be assessed when applied before and after a single harvest within the same growing season. Operationally, however, and to avoid excessive mortality of residual pines from thinning shock, pine basal area should be reduced to an acceptable level for uneven-aged management by employing two harvests whenever initial stocking exceeds 90 square feet per acre (Baker and others 1996). The first cut should reduce basal area to about 80 square feet per acre, and 3 to 5 years later, a second cut should reduce basal area to 60 square feet per acre. Because pines were not thrifty in the smaller d.b.h. classes, retention of dominant and codominant pines as crop trees would have been more judicious in this investigation than trying to mold an uneven-aged structure by using BDq guidelines in the initial harvest.

To facilitate the application of hardwood control treatments during a single growing season, before and after harvest, June was chosen as the month of harvest. Based on 65 years of precipitation records, June is normally a dry month in southeastern Arkansas. However, June of 1992 was exceptionally wet, with precipitation that was 6 inches above normal. Use of articulated rubber-tired skidders to remove the high volume of cut pines during these wet conditions resulted in undesirable rutting of the soil and probably caused root damage to residual pines. Because of poor traction on these wet soils, skidders often slid into residual pines, resulting in bark removal near the butt section and exposure of the cambium to insect attack. Operationally, the harvest would have been postponed as soon as the soil could not support the logging equipment.

Because of reduced vigor in residual pines following the single-tree selection harvest, bark beetles infested the area and caused considerable mortality. A salvage cut in June 1993 removed an average of 440 fbm per acre (Doyle scale) in dead and dying pines to stop the infestations. However, a severe ice storm in February 1994 caused breakage of limbs on some remaining pines and complete collapse of other pines. This damage further weakened the residual pines and the bark beetle infestation continued. A second salvage cut was made in the summer of 1994, removing 820 fbm per acre of dead and dying trees to again slow the beetle activity.

The message from this 3-year investigation is quite clear. For a natural reproduction cutting method to be successful, forest managers must pay close attention to site, stand, and weather conditions and plan for unusual events. Lack of attention to detail may result in undesirable consequences that are not consistent with short-term management objectives.

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EFFECTS OF OPENING SIZE ON PINE AND HARDWOOD REGENERATION 3 YEARS AFTER GROUP SELECTION CUTTING IN SOUTHERN ARKANSAS

Michael G. Shelton'

Abstract-Openings of three sizes (0.25, 0.625, and 1 .0 acres) were created in a pine-hardwood stand dominated by loblolly pine (*Pinus taeda* L.), shortleaf pine (*P. echinata* Mill.), and sweetgum (*Liquidambar styraciflua* L.). A randomized complete block design was used with three replicates, and about 16 percent of the total stand area was in openings. Pines in the residual stand were thinned to a merchantable basal area of 75 square feet per acre, but hardwoods, which averaged 30 square feet per acre, were not thinned. Monitoring included: (1) regeneration and competing vegetation before harvesting and after the first and third growing seasons, (2) seedbed conditions after harvesting, and (3) pine seed production through the third year. The 0.25-acre openings had more undisturbed litter and mineral soil but less logging debris than larger openings. The pine seed supply near the center of the 0.25-acre openings was nearly twice that of the 1 .O-acre openings. Seedling densities did not significantly differ among openings after 3 years and averaged 3,833 and 920 seedlings per acre for pines and oaks, respectively. Although pine regeneration was significantly shorter in the 0.25-acre openings than in larger openings, more time will be needed to determine the optimum opening size.

INTRODUCTION

Group selection is an uneven-aged reproduction cutting method that is reputed to favor the more shade-intolerant species by creating larger openings than single-tree selection. However, less is known about group selection than about any of the other natural reproduction cutting methods (Murphy and others 1993). The goal of group selection is to Create or maintain an uneven-aged stand by making a number of small openings during each cutting cycle, in addition to thinning the residual stand as needed. The regeneration effort is focused within the distinctive openings. If group selection is applied over several cutting cycles, a fragmented stand composed of small even-aged groups should result, but this has yet to be tested over a long time period in the Southern United States. The larger openings provided with group selection do not appear to be needed for pine regeneration when traditional stocking guidelines for single-tree selection are followed (Baker and others 1996). However, group selection seems to have merit when a significant hardwood component is desired because the larger openings provide the higher light intensities needed by the shade-intolerant pines and the intermediate-tolerant oaks.

The environmental requirements for regeneration of targeted species are critical to setting suitable opening Sizes. Experience suggests that large openings will favor the establishment and development of the more shade-intolerant species, but large openings are also felt to have poor visual qualities by some forest users. Thus, the optimum opening size would be the smallest one that provides a favorable environment for regenerating targeted species. In 1992, a study was installed in southern Arkansas to provide information on applying the group selection system in pine-hardwood stands; results through the first 3 years are presented in this paper.

METHODS

Study Site

The study was installed in a 34-acre, second growth pine-hardwood stand located in the Crossett Experimental Forest in Ashley County, AR. Soils in the study area are mapped as the Bude series (Glossaquic Fragiudalfs). This soil occurs on broad upland flats and has a silty loam surface horizon and a clayey subsurface. Site index is 85 to 90 feet for loblolly pine (*Pinus taeda* L.) at 50 years.

Before harvesting, merchantable basal areas averaged 84 square feet per acre for loblolly and shortleaf (*P. echinata* Mill.) pines [trees with a diameter at breast height (d.b.h.) of 4.6 inches and larger] and 30 square feet per acre in hardwoods (trees with d.b.h. of 5.6 inches and larger). The hardwoods were mostly in midcanopy positions. Sweetgum (*Liquidambar styraciflua* L.) was the dominant hardwood, accounting for 64 percent of the merchantable hardwood basal area; mixed oaks (*Quercus* spp.) accounted for 29 percent. In addition, 17 square feet per acre in basal area was present in submerchantable hardwoods (trees from 0.6 to 5.5 inches d.b.h.). The most common submerchantable species was flowering dogwood (*Cornus florida* L.) (44 percent of the submerchantable basal area), followed by sweetgum (30 percent), blackgum (*Nyssa sylvatica* Marsh.) (12 percent), and mixed oaks (6 percent). There were no submerchantable pines. The stand was prescribed burned in February 1992, which was during the dormant season before harvest.

Study Design and Treatment Implementation

Treatments were circular openings with areas of 0.25, 0.625, and 1 .OO acres. These openings had diameters that were about 1 .1, 1.8, and 2.2 times the height of the dominant trees in the surrounding stand (about 105 feet). Each opening size was replicated three times in a randomized, complete block design. Adjacent openings were separated by at least 100 feet, and about 16 percent

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of the total stand area was in openings. Because stand conditions were uniform, openings were located systematically within the 34-acre stand. Boundaries were established for each opening, and all merchantable pines and hardwoods occurring within the area were marked for harvest. The stand between the openings was marked to leave 75 square feet per acre of pine basal area; marking was for an improvement cut focusing on the pine sawtimber. No hardwoods were marked outside the openings.

Harvesting was conducted during November and December 1992. The only restriction imposed on loggers was that no trees from one opening could be skidded through another opening; this prevented greater traffic from occurring in the openings near landings. The loggers removed the pine sawtimber first and then the pine and hardwood pulpwood. Pine sawtimber was skidded in 34-foot lengths using rubber-tired skidders. Pulpwood was cut in 5-foot lengths and hauled to landings by forwarders. The timber volume removed within openings averaged 3,416 cubic feet per acre, of which 10 percent was pine pulpwood, 23 percent hardwood pulpwood, and 67 percent pine sawtimber. The thinning in the residual stand averaged a total of 377 cubic feet per acre, of which 15 percent was pine pulpwood and 85 percent was pine sawtimber.

Removal of the submerchantable hardwoods within openings was delayed until October 1993 (after the first growing season) because few residual stems existed after harvesting. All submerchantable hardwoods with d.b.h. ≥ 1 inch were stem-injected with Tordon® 101 R.

Measurements

Within each opening, permanent points were systematically located to monitor regeneration and seedbed conditions. There were 9, 13, and 17 points in each of the 0.25, 0.625-, and 1 .O-acre openings, respectively. The sample points were located so that each represented an equal area, which prevented any bias caused by bordering trees. One point was located at the opening center. The remaining points were located along eight radii, beginning at 0 degrees and repeated at 45-degree intervals.

Seedbed conditions were evaluated immediately after the completion of harvesting at 12 locations along a 24-foot line transect with the midpoint positioned at each permanent point. The seedbed at each location was classified as undisturbed litter, disturbed litter, exposed mineral soil, logging debris, or natural features (mainly coarse woody debris not associated with logging).

Regeneration inventories were conducted at the permanent points during September 1992 (before harvest), October 1993 (after the first growing season), and September 1995 (after the third growing season). Woody plants in the seedling size class (10.5 inches in d.b.h.) were counted by species or species group in a circular milacre plot (3.72 feet in radius) centered around each permanent point. Seedlings were recorded by the following size classes: 10.5, 0.6 to 2.5, and 2.6 to 4.5 feet in height, and ≥4.6 feet in height but ≤0.5 inch in d.b.h. Seedlings with multiple stems were tallied as one rootstock. Stems of woody plants in the sapling size class (0.6 to 3.5 inches in d.b.h.) were counted by l-inch d.b.h. classes and by species or species group in a O.Ol-acre plot (11.78 feet in radius) around each permanent point. Coverage of understory vegetation was ocularly estimated within each milacre plot to the nearest 10 percent for grasses, forbs, vines, shrubs, hardwoods, pines, and total vegetation.

During the 1995 inventory, the two tallest pines and the two tallest nonpine woody plants within each milacre plot (if present) were measured for groundline diameter (to 0.04 inch) and height (to 0.1 foot). These stems were also classified as being free to grow or overtopped by understory vegetation, and the species group of overtopping vegetation was recorded.

Pine seed production was monitored from October 1993 through February 1995 in three 0.9-square foot seed traps (Cain and Shelton 1993) per opening: traps were located 20 feet from the opening center in a triangular pattern. Seeds were collected during the middle and end of each October-to-February period. Seed viability was determined by splitting seeds and inspecting the contents (Bonner 1974). Seeds with full, firm, undamaged, and healthy tissue were judged to be potentially viable and were recorded as sound seeds.

Data Analysis

Mean values were calculated for the regeneration plots for each opening. Milacre plots were considered stocked by pine or hardwood regeneration if at least one seedling represented the species or species group. To facilitate presentation of regeneration results, species were grouped by genus for the pines and oaks. Other woody vegetation was grouped by potential stature and form as follows: (1) other canopy trees, principally ashes *(Fraxinus* spp.), blackgum, sweetgum, and hickory *(Carya* spp.); (2) midcanopy trees, principally dogwood, red maple (*Acer rubrum* L.), black cherry (*Prunus serofina* Ehrh.) and winged elm (*Ulmus alata* Michx.); and (3) shrubs, principally American beautyberry (*Callicarpa americana* L.), sumac (*Rhus* spp.), and huckleberries *(Vaccinium* spp.).

Analysis of variance for a randomized, complete block design was used to test for treatment differences, which were isolated by using the Ryan-Einot-Gabriel-Welsch Multiple Range Test at the 0.05 probability level (*P*). This procedure, which is one of the most powerful step-down, multiple-range tests available, controls the experiment-wise error rate (SAS Institute 1989). Changes in regeneration and understory coverage through time were analyzed as a split-plot in time (Steel and Torrie 1980).

RESULTSANDDISCUSSION

Seedbed Conditions

The harvesting operation modified the existing seedbed conditions by disturbing litter, exposing mineral soil, and creating logging debris. The 0.25acre openings had significantly less logging debris and significantly more exposed mineral soil than the larger openings (table 1). Undisturbed litter in the 0.25-acre opening was nearly twice that in the larger openings, although this difference was not significant. The lower percentage of exposed mineral soil in the 0.625 and 1 .O-acre openings probably reflected the covering of mineral soil by logging debris. The lower percentage of logging debris in the 0.25-acre openings appeared to be related to the small opening diameter (118 feet) and the great height of the dominant and codominant pines (over 100 feet)-the crowns of cut trees tended to fall outside the opening's boundary.

Pine Seed Supply

The seed supply was not monitored during the fall and winter of 1992-93 because the stand was being harvested. However, nearby stands that were similar to the one in this study produced about 80,000 sound seeds per acre, which was a below-average seed crop (Cain and Shelton 1996).

The 0.25-acre openings consistently had about twice as many seeds dispersed near their center as the 1 .O-acre openings, but differences were significant only during 1994-95 and for sound and total seeds (table 2). This dispersal pattern reflected the distance from the seed traps to the bordering trees-39 feet in 0.25acre openings, 73 feet in 0.625-acre openings, and 98 feet in 1 .O-acre openings. Pomeroy (1949) described a similar dispersal pattern for pine seeds into clearcut strips. A bumper seed crop was produced during 1993-94 when more than 1 ,OOO,OOO sound seeds per acre were dispersed into the 0.25-acre openings. This was followed by an above-average seed crop the next year, when about 250,000 sound seeds per acre occurred in the 0.25-acre openings. The dispersal of seeds within the 1 .O-acre openings should not adversely affect regeneration when seed crops are average or better, but may limit regeneration during marginal years.

Table 1—Seedbed conditions after the initial harvest implementing group selection in a pine-hardwood stand in southern Arkansas

Condition	Opening area (acres) 0.25	0.625	1.0	Mean square error	*P*
	Percent of area				
Undisturbed litter	21	10	10	33.5	0.12
Disturbed litter	32	30	28	49.2	0.78
Mineral soil	16a	8b	6b	12.1	0.05
Logging debris	27b	49a	50a	27.7	0.01
Natural feature[b]	4	3	6	5.9	0.46

[a] Row means followed by different letters are significantly different (P=0.05) by the Ryan-Einot-Gabriel-Welsch Multiple Range Test.
[b] Mainly coarse woody debris not associated with logging.

Table 2—Dispersal of pine seeds near the opening center after the initial harvest implementing group selection in a pine-hardwood stand in southern Arkansas

Seed condition and year	Opening area (acres) 0.25	0.625	1.0	Mean square error	*P*
	1,000 per area				
Sound					
1993-94	1,300	820	560	154,000	0.19
1994-95	260a	90b	140b	3,090	0.04
Unsound					
1993-94	620	470	320	33,700	0.25
1994-95	250	170	150	2,120	0.12
Total					
1993-94	1,920	1,290	880	315,000	0.20
1994-95	510a	260b	290b	1,650	<0.01

[a] Row means followed by different letters are significantly different (P=0.05) by the Ryan-Einot-Gabriel-Welsch Multiple Range Test.

Regeneration Density and Stocking

An average of 1,387 pine seedlings per acre occurred before harvesting, and milacre stocking averaged 43 percent (table 3). Most of these seedlings were less than 0.5 feet tall and developed from the 1991-92 seed crop. The presence of pine seedlings before harvesting demonstrates that pine regeneration can periodically become established even beneath a closed canopy, but these seedlings will gradually die because of shading

Table 3-Density and stocking of pine seedlings before and after the initial harvest implementing group selection in a pine-hardwood stand in southern Arkansas

Property and growing season	Opening area (acres) 0.25	0.625	1.0	Mean square error	*P*
	Stems per acre				
Density					
Preharvest	960	1,800	1,400	1.02E6	0.60
First	960	2,400	1,900	4.37E5	0.12
Third	4,100	3,900	3,500	2.69E6	0.89
	Percent				
Milacre stocking					
Preharvest	29	62	39	4.19E2	0.25
First	45	64	63	1.72E2	0.25
Third	52	72	61	4.75E2	0.57

(cam and Shelton 1995). Some of the existing Seedlings were destroyed during logging, but others survived. In addition, this base was supplemented by seedlings developing from the 1993-94 seed crop, resulting in an average of 1,750 seedlings per acre and 57 percent milacre stocking after the first growing season. Seedling density in the 0.25-acre openings averaged considerably lower than that in the larger openings, but differences were not significant. By the third growing season, however, the pine regeneration was very similar in all openings, averaging 3,833 seedlings per acre and 62 percent milacre stocking. These levels of regeneration are considered adequate by uneven-aged guidelines (Baker and others 1996). There were no pines in the sapling size class during any inventory.

Density of nonpine woody stems in the seedling size class was not significantly affected by opening size either before or after harvesting (table 4). Mean densities ranged from about 4,000 to about 10,000 rootstocks per acre and are typical of similar sites and stand conditions (Cain 1994, Cain and Shelton 1995).

Density of nonpine woody rootstocks in the sapling size class was very uniform before harvesting, ranging from 500 to 600 stems per acre (table 4). Many of these saplings were killed or damaged during logging, which reduced density to about 200 stems per acre in the 0.25-acre openings and to about 100 stems per acre in the larger openings. This difference was significant and reflected the greater logging disturbance in the larger openings, where high timber volumes were removed and where skidder maneuvering and traffic were less restricted by bordering trees than in the 0.25-acre openings. The saplings existing after the first growing season were stem-injected with herbicide shortly after they were inventoried. Thus, the saplings present after the third growing season (200 to 300 stems per acre) represented outgrowth from the seedling size class.

The species groups making up the nonpine seedlings and saplings are shown in table 5. Most of the seedlings were midcanopy species (33 percent) and shrubs (38 percent). However, there were also 920 rootstocks per acre for the oaks after the third growing season and 600 rootstocks per acre for the other canopy species group. Thus, there appears to be ample regeneration of desirable species to achieve the mixed pine-hardwood regeneration goal for the stand. The changes in seedling density through time reflected: (1) mortality of existing seedlings, chiefly from logging disturbance and self thinning; (2) sprouting of cut or damaged stems; (3) outgrowth of seedlings to the sapling size class; and (4) new seedlings developing from seed.

Table 4-Seedling and sapling density for all nonpine woody species before and after the initial harvest implementing group selection in a pine-hardwood stand in southern Arkansas

Size class and growing season	Opening area (acres)[a] 0.25	0.625	1.0	Mean square error	*P*
	- - -Rootstocks per acre - - -				
Seedlings					
Preharvest	4,150	9,540	8,660	8.28E6	0.16
First	9,970	8,640	9,340	4.02E6	0.72
Third	7,170	6,310	6,970	2.41 E5	0.24
	- - - - Stems per acre - - -				
Saplings					
Preharvest	600	515	512	2.80E5	0.78
First[b]	211a	98b	95b	9.19E2	0.02
Third	300	220	200	2.87E3	0.15

[a] Row means followed by different letters are significantly different (P=0.05) by the Ryan-Einot-Gabriel-Welsch Multiple Range Test.
[b] These saplings were stem-injected with herbicide shortly after the inventory.

Table 5-Seedling and sapling density for hardwood and shrub species groups before and after the initial harvest implementing group selection in a pine-hardwood stand in southern Arkansas

Size class and species group	Growing season[a] Preharvest	First	Third	Mean square error	*P*
	- - -Rootstocks per acre - - -				
Seedlings					
Oaks	750	600	920	1.62E2	0.40
Other canopy species	730	620	600	4.43E4	0.40
Midcanopy species	3,300a	2,200b	2,400b	6.88E5	0.05
Shrubs	2,800b	5,900a	2,900b	3.37E6	0.01
Total	7,450	9,320	6,820	4.18E6	0.06
	- - - - Stems per acre - - -				
Saplings					
Oaks	39	10	20	1.07E3	0.20
Other canopy species	93b	29c	180a	9.83E2	0.01
Midcanopy species	400a	92b	25b	8.82E3	<0.01
Shrubs	10	3	12	1.66E2	0.31
Total	542a	135c	237b	1.01E4	<0.01

[a] Row means followed by different letters are significantly different (P=0.05) by the Ryan-Einot-Gabriel-Welsch Multiple Range Test.

The saplings present before harvest were mostly midcanopy species, which accounted for 74 percent of the total (table 5). After the third growing season, however, 77 percent of the saplings were in the other canopy species group (mostly sweetgum), which reflects the rapid growth of sprouts and advance regeneration in this species group.

Regeneration Size

After the third growing season, dominant pine regeneration was considerably smaller than that of any other species group, by 2 to 10 times for groundline diameter and 4 to 10 times for height (table 6). Opening size significantly affected only the height of the pines, which were about twice as tall in the 1 .0-acre openings as in the 0.25acre openings. This difference reflects both the younger age of the pine seedlings in the 0.25acre openings and probably the greater suppression by bordering trees. An average of 33 percent of the dominant pines were free to grow. Vines were the most frequent type of overtopping vegetation, accounting for 51 percent of the total. Dominant regeneration in the other canopy species group averaged 8.1 feet tall after the third growing season and was followed by shrubs (5.4 feet), oaks (5.0 feet), and midcanopy species (4.7 feet).

Table 6-Size of the dominant regeneration occurring three growing seasons after the initial harvest implementing group selection in a pine-hardwood stand in southern Arkansas

Property and species group	Opening area (acres) 0.25	0.625	1.0	Mean square error	*P*
		Inches			
Groundline diameter					
Pines	0.12	0.17	0.21	0.001	0.07
Oaks	0.29	0.50	0.48	0.037	0.41
Other canopy species	1.17	0.61	0.71	0.091	0.22
Midcanopy species	0.31	0.47	0.46	0.009	0.17
Shrubs	0.36	0.40	0.43	0.011	0.72
		Feet			
Height					
Pines	l.lb	1.6ab	2.0a	0.08	0.05
Oaks	3.8	5.7	5.5	8.04	0.68
Other canopy species	10.6	6.0	7.7	6.98	0.33
Midcanopy species	3.7	4.9	5.4	0.60	0.14
Shrubs	5.4	5.9	5.0	1.05	0.57

[a] Row means followed by different letters are significantly different (P=0.05) by the Ryan-Einot-Gabriel-Welsch Multiple Range Test.

The results of this study differ from those obtained by Perry and Waldrop (1995), who reported that pines planted in small openings had overtopped competing hardwoods after 2 years. These conflicting results can be attributed to differences in site quality (loblolly pine site index was 85 to 90 feet at 50 years in this study and 70 feet at 50 years in Perry and Waldrop's study) and to differences in seedling origin (natural regeneration in this study compared to planted, genetically improved seedlings in Perry and Waldrop's study).

Vegetative Coverage

Horizontal coverage by understory vegetation changed dramatically through time but was not significantly affected by opening size during any of the inventories. Therefore, only changes through time are shown in table 7. Grasses and forbs displayed the greatest increase in coverage during the first growing season, when their coverage essentially doubled over preharvest levels. In contrast, vines and all woody groups increased dramatically only after the first growing season. Vines, shrubs, and hardwoods essentially doubled in coverage between the first and third growing seasons, while coverage of the pines increased from 0.0 to 0.7 percent. This developmental pattern shows that most of the early competition to the desired regeneration in this stand was from grasses and vines. Although the pines appear to be overwhelmed by the nonpine vegetation at this stage of development, experience has usually shown that an acceptable pine component will eventually develop under these stand conditions.

CONCLUSIONS

This study showed that opening size affects the level of logging disturbance within openings (the 0.25-acre openings had less disturbance than larger openings) and

Table 7-Horizontal coverage of understory vegetation before and after the initial harvest implementing group selection in a pine-hardwood stand in southern Arkansas

Vegetative group	Growing season)[a] Preharvest	First	Third	Mean square error	*P*
		Percent of area			
Grasses	15.1 b	33.3a	35.9a	29.8	co.01
Forbs	6.7b	14.3a	5.0b	40.2	0.02
Vines	21.7b	22.2b	48.1a	73.0	co.01
Shrubs	6.2b	9.0b	17.7a	4.0	co.01
Hardwoods	9.7b	8.7b	21.4a	28.4	co.01
Pines	O.Ob	0.0b	0.7a	0.1	C0.01
Total vegetation[b]	47.3c	75.9b	90.9a	156.4	co.01

[a] Row means followed by different letters are significantly different (P=0.05) by the Ryan-Einot-Gabriel-Welsch Multiple Range Test.
[b] Total vegetation is less than the sum of the species groups because of overlapping.

the dispersal of pine seeds (the 0.25-acre openings had more pine seeds dispersed to their interior than larger openings). Since increases in both disturbance and seed supply tend to favor the establishment of pine regeneration, their opposing relationship with opening size essentially cancels out so that opening size has little net effect on the density and stocking of pine regeneration. However, opening size significantly affected the height growth of pine seedlings (seedlings were shorter in the 0.25-acre openings than in larger openings), and this may ultimately affect the success of regeneration. Early results suggest that ample regeneration of desirable hardwood species exists after harvesting to achieve the mixed pine-hardwood regeneration goal within openings. More time will be needed to make specific recommendations for the optimum opening size for natural regeneration of pine-hardwood stands using group selection.

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NATURAL REGENERATION IN CANOPY GAPS IN PINE, PINE-HARDWOOD, AND HARDWOOD FOREST STANDS IN THE UPPER COASTAL PLAIN

Polly-Anne Rantis and James E. Johnson'

Abstract-Canopy gaps are a common feature in temperate forests, and stem from a variety of natural and man-caused disturbances. A study was conducted in three forest cover types in the upper Coastal Plain of Virginia to assess the abundance and composition of natural regeneration found in small gaps. Across all three cover types, the number of seedlings of intolerant species was greater than the number of seedlings of tolerant species in gaps as compared to nongap areas. For example, in the pine cover type, intolerant seedlings in the gaps numbered 39,271 per hectares, whereas intolerant seedlings in the nongap areas numbered 8,125 per hectares. Loblolly pine (*Pinus* taeda L.) was the dominant species in the gaps in both the pine and pine-hardwood cover types. White oak (Quercus *alba* L.) was the dominant regeneration species in the canopy gaps of the hardwood cover type. Although intolerant seedlings were abundant in the canopy gaps, they are not expected to persist, since the gaps were small and canopy cover (overstory and understory combined) averaged over 90 percent.

INTRODUCTION

Small-scale disturbances, such as single tree deaths, are an integral part of the forest regeneration cycle (Whitmore 1989, Pickett and White 1985, Runkle 1985). In natural forests, small disturbances have an important function influencing species regeneration. In many natural forest types, like parks and preserves, small canopy openings, or gaps, are the primary recruitment areas where future forest canopy individuals develop (Cho and Boerner 1991, McClure and Lee 1993, Oliver and Larson 1990, Pickett and White 1985, Runkle 1981). Currently, these forests are undergoing successional change in the absence of fire (Cooper 1989). These forests may exhibit any number of features, including southern pine beetle (*Dendroctonus frontalis* Zimm.) patches, dense understories, invasive exotic species, heavy browsing, and, recently, recurrent droughts linked to increased mortality (Clinton and others 1993).

Canopy gaps may be characterized by many variables, such as frequency, size, and severity, all of which have impacts on the amount and type of regeneration (Pickett and White 1985). Generally, southeastern forests experience frequent small-to-medium natural disturbances resulting from recurring tornados and hurricanes.

Many studies have investigated forest regeneration in canopy openings in the temperate forests of the Northeastern United States and the Southern Appalachian Mountains. Few studies examine natural regeneration in single tree openings in southeastern forests. In addition, small disturbance studies seldom explore all the variables influencing regeneration, including light and soil conditions associated with the disturbance. The objectives of this study were to quantify seedling abundance and species composition in small canopy gaps and adjacent forested areas (nongaps) of pine, pine-hardwood, and hardwood forest cover types.

METHODS

Study Area

The study was conducted in the forests of the Petersburg National Battlefield (PNB) in Petersburg, VA, which is in the upper Coastal Plain physiographic province (Frye 1986). The underlying rock in the Petersburg area is a combination of Petersburg granite, which is mostly feldspar and quartz, and the late Pliocene Bacons Castle formation (Frye 1986). Developing from a combination of marine sediments and residual parent materials, the dominant soil series represented are the Emporia and Slagle in the Ultisol soil order, which are well-drained, sandy loams with a clay loam subsurface.

The PNB is one of many commemorative Civil War battlefields administered by the National Park Service, U.S. Department of the Interior. Historical use of the park land before the Civil War was half forest and half agriculture, with tobacco and cotton as principal crops (Wallace 1983). Currently the forests are in the late consolidated and subclimax successional sere, with loblolly pine (*Pinus taeda* L.), several oak species (Quercus spp.), sweetgum (*Liquidambar styraciflua* L.), and tulip poplar (*Liriodendron tulipifera* L.) as the dominant canopy species.

Within the PNB, forests were classified into the three following cover types:

Pine: Species composition consists of >75 percent pine basal area, including loblolly pine, Virginia pine (*P. virginiana* Miller), and shortleaf pine (*P. echinata* Miller).

Pine-hardwood: Species composition consists Of 25 to 50 percent pine basal area, with the remaining composed of any mixture of oak, hickory (*Carya* spp.), tulip poplar, sweetgum, or red maple (*Acer rubrum* L.).

Hardwood: Species composition consists of 775 percent oak basal area, with the remaining composed Of any

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mixture of pines, hickory, tulip poplar, sweetgum, or red maple.

For this study, four stands were randomly selected from each of the three cover types. Each stand was traversed to locate gaps, which were canopy openings where the stocking level was below 60 percent (Roach and Gingrich 1968, USDA 1986). In each stand, three paired plots (gap and adjacent nongap) were randomly established, for a total of 36 paired observations in the study.

Gap Measurements

To determine the size of each gap, the length and width of the gap were measured from the base of the surrounding border trees, consistent with the "expanded gap" definition used by Runkle (1981, 1982). Gap area was estimated using the formula for either a circle or an ellipse, depending upon gap shape (Runkle 1985). Gap age was approximated through examination of growth rings of two dominant trees bordering each gap and two dominant saplings within each gap.

Site and Vegetation Sampling

Site and vegetation sampling were conducted within each gap and its adjacent forest. In the center of each gap a fixed, circular, 0.04-hectare plot was established where canopy cover was determined at each plot center using a spherical densiometer (Lemon 1956). The same size plot was randomly established at least 25 meters inside the adjacent undisturbed forest, creating the gap and nongap pair. Woody stems over 5 meters tall were classified as part of the canopy and measured by species, diameter at breast height (d.b.h.), and crown class on each plot. Within each overstory plot, a circular 0.004-hectare subplot was located at about the plot center. In two random quadrants of the subplot, four l-square meter plots were used to tally the seedlings (<1 .37 meters tall) by species.

Data Analysis

Seedling importance value was calculated as the mean of relative density and frequency. Differences in vegetation variables between gap and nongap areas were determined using the paired-t test for sample means at the 0.05 alpha level.

RESULTS AND DISCUSSION

Gap Measurements

Gap size and age help explain the presence and abundance of regeneration within gaps (Clinton and others 1994). At PNB, the mean sizes of the canopy openings in each cover type were similar, ranging from 281 square meters in the pine-hardwood cover type to 317 square meters in the hardwood cover type (table 1).

Gap ages were estimated from interpretation of growth rings of border trees and saplings growing within the gaps. Three gap age classes were developed: young (<5 years), intermediate (6 to 9 years), and old (>10 years). The majority (58 percent) of the gaps were in the intermediate age class (table 2).

Table l-Mean size (square meters) of gaps in pine, pine-hardwood, and hardwood forest cover types at Petersburg National Battlefield, VA

Cover type	Number	Area	Seedling density	Range
		-Square meters		
Pine	12	308	110	93-474
Pine-hardwood	12	281	115	138-665
Hardwood	12	317	122	152-597
Total	36	—	—	—

Table 2-Distribution and mean size (square meters) of gaps by age class in pine, pine-hardwood, and hardwood forest cover types at Petersburg National Battlefield, VA

	Young		Intermediate		Old	
Cover type	No.	Area	No.	Area	No.	Area
			-Square meters			
Pine	2	298	9	319	1	303
Pine-hardwood	1	292	7	313	4	320
Hardwood	0	—	5	299	7	335
Total	3		-21		-12	—

Canopy Cover

The gaps in each forest cover type consistently had significantly less cover than their associated nongap counterparts (table 3). In general, the canopy cover was high in the gaps, none less than 90 percent. This is a result of most of the gaps being older, with lateral branches invading the gaps.

Vegetation Characteristics

Overstory composition-The pine cover type had the most diverse overstory, with 19 different species totaling 45 square meters of basal area per hectare and 310 trees per hectare (table 4). Loblolly pine, with 127 trees per hectare and 36 square meters per hectare basal area, clearly was the dominant species (table 4). Sweetgum was the most important species in the pine-hardwood cover type; however, loblolly pine composed 54 percent of the basal area and was also a major species. In the hardwood cover type, white oak (*Quercus alba* L.) and blackgum (*Nyssa sylvatica* Marsh.) composed over half of the total density, with a combined importance value of 46 percent (table 4). Blackgum was present as many small stems, compared to white oak which appeared as fewer and larger trees.

Table 3—Canopy cover (percent) for gap and nongap areas in pine, pine-hardwood, and hardwood forest cover types at Petersburg National Battlefield, VA (means within a row followed by a different letter are significantly different at the 0.10 level)

	Gap			Nongap		
Cover type	Mean	Seedling density	Range	Mean	Seedling density	Range
	Percent					
Pine	91a	5	78-97	98b	2	93-99
Pine-hardwood	95a	2	89-98	99b	1	98-l 00
Hardwood	92a	10	61-99	98b	1	96-100

Table 4-Overstory density, basal area, and importance values of gap and nongap areas in the pine, pine-hardwood, and hardwood cover types in the Petersburg National Battlefield, VA

Species	Mean	Standard deviation	Basal area	Importance value
	No./ha		*----m²/ha----*	*---Percent---*
Pine				
Loblolly pine	127	57	36	31
Tulip poplar	56	105	2	13
Sweetgum	29	44	3	11
Red maple	23	48	<1	9
Misc.	71	—	3	36
Total	310	—	45	100
Pine-hardwood				
Sweetgum	77	54	4	22
Loblolly pine	52	43	18	19
Blackgum	31	66	<1	9
Red maple	29	52	<1	10
Misc.	92	—	11	40
Total	281	—	34	100
Hardwood				
White oak	60	57	20	24
Blackgum	50	70	1	22
Sweetgum	27	42	<1	13
Willow oak	21	46	10	9
Misc.	54	—	12	32
Total	212	—	43	100

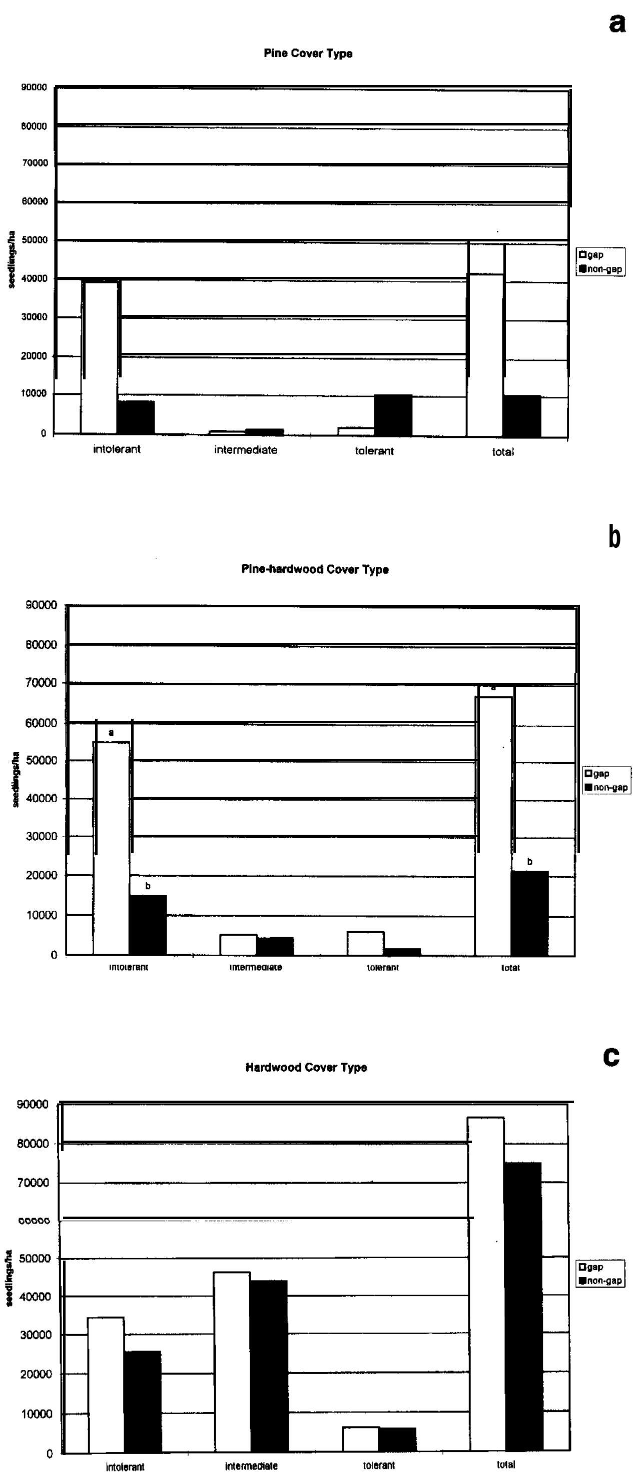

Figure l-Seedling density for (A) pine, (B) pine-hardwood, and (C) hardwood cover types in total and for shade tolerance classes in gap and nongap areas in Petersburg National Battlefield, VA.

Regeneration composition-Total seedling density, which was composed primarily of shade-intolerant seedlings in the gaps of the pine cover type, was greater than in the nongap areas, although not significant (p = 0.15) (fig. 1). Loblolly pine, sweetgum, and tulip poplar were the most important species in the gaps as well as in the nongap areas (fig. 2). The miscellaneous group of 10 species contained over half of the importance value in the nongap areas, and includes the shade-tolerant species, which were more dense in the nongap areas than in the gaps. Gap size was large enough to allow for

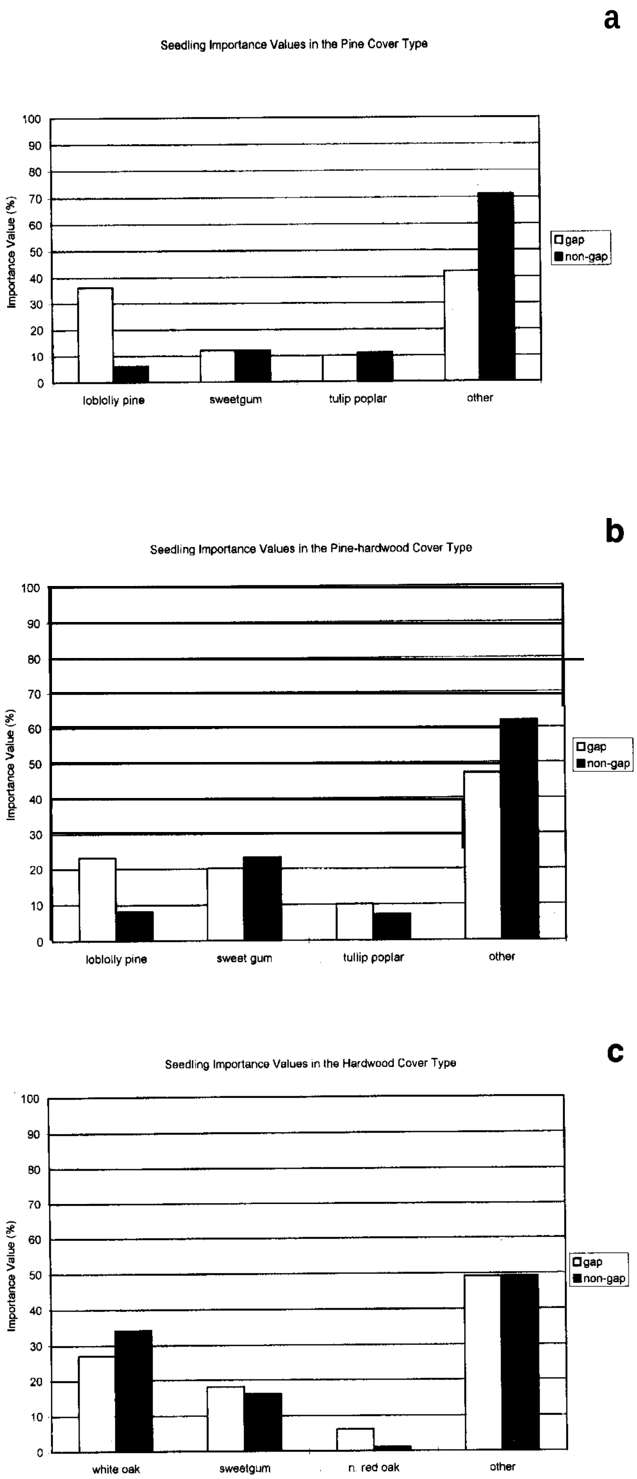

Figure 2—Seedling importance values by species for (A) pine, (B) pine-hardwood, and (C) hardwood cover types in gap and nongap areas in Petersburg National Battlefield, VA.

ample pine regeneration. However, it is not expected that many of the seedlings will survive into a canopy position because of crown closure, unless another disturbance occurs.

The gaps in the pine-hardwood cover type had a significantly greater number of shade-intolerant seedlings, mostly made up of loblolly pine, with an importance value of 23 percent, compared to the nongap areas (p = 0.01) (figs. 1 and 2). In fact, the gaps had greater seedling density in all of the shade-tolerant groups, and total seedling density was significantly greater than in the nongap areas (p = 0.01). Such a significant difference is interesting, given that mean gap size was the smallest and percent canopy density was the highest in the pine-hardwood cover type compared to the other cover types (tables 1, 2, and 3). Shade-intolerant species were also the three most important species in both gap and nongap areas. The miscellaneous group contained 14 species in the gaps, and 15 species in the nongap areas.

The hardwood cover type had prolific and diverse regeneration within the gaps, represented by 19 different species. Total seedling density was the highest in this cover type, approaching 87,000 seedlings per hectare (fig. 1). Generally, the regeneration within both areas was similar. There was no discrimination between gap and nongap densities. White oak was the most important species in both the gap and nongap areas, followed by sweetgum. The similarity in composition and density of the gap and nongap areas in this cover type is a function of the older age of the gaps, allowing equilibrium site conditions to develop (table 2).

CONCLUSIONS

Small canopy gaps create an environment for large influxes of natural regeneration to develop. Most of these seedlings will die as the gaps close and resources are recaptured, and there will be a small group of saplings remaining. Gradually, the individual sapling that outcompetes the others will develop into the canopy position.

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Impacts of Harvesting and Site Preparation

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SEDIMENT SOURCES TO THE CHATTOOGA RIVER

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Abstract-Sedimentation is a major water quality issue in Southern Appalachian streams, but sources of sediment in large watersheds have seldom been fully documented. The objectives of this study were (1) to identify and locate sources of sediment in the Chattooga River watershed, (2) to learn which subbasins within the watershed are primary contributors of sediment, and (3) to determine coverage and composition of fine sediments in pools of the river. We found that the Wild and Scenic River corridor was well vegetated in mature forests and contributed relatively little new sediment to the main stem of the river. Fine sediments dominated the substrate of pools in the river. Certain tributaries were major contributors of suspended and bed-load sediment. The majority (80 percent) of sediment sources were associated with graveled and unsurfaced roads. Timber harvests, pastures with unfenced riparian zones, developments, and recreation were important contributors of sediment at specific sites. If current sources of sediment are ameliorated, the river can recover from land-use abuses that have accelerated sedimentation over the past century.

INTRODUCTION

As one of the few remaining free-flowing rivers in the Southeast, the Chattooga is famous for its boating, fishing, wildlife, scenery, and aesthetic value. In 1974 Congress designated the Chattooga as one of America's Wild and Scenic Rivers, under the Wild and Scenic Rivers Act of 1968.

With the exception of Stekoa Creek, which has a sewage treatment plant, few point-source discharges into the Chattooga River exist. The principal threats to water quality in the watershed are from non-point sources. However, no comprehensive study has identified and located these sources of sediment in the Chattooga River watershed Or quantified their relative contribution to sedimentation of the river.

Objectives of this study were to (1) identify and locate present sources of sediment to the Chattooga River, (2) learn which subbasins within the watershed are primary contributors of sediment, and (3) determine coverage and composition of fine sediments in pools of the river.

Study Area

The Chattooga River originates along the slopes of the Southern Appalachian Mountains in southwestern North Carolina and subsequently forms the scenic state boundary between Georgia and South Carolina. Its 180,000-acre watershed is underlain by crystalline bedrock composed primarily of gneisses, mica-schists, quartzes, and granites (Meyers and others 1986). Soils and the underlying saprolite are heavy in micaceous schist, a material that erodes easily once the vegetative cover and forest floor have been removed.

Forestation

Dry ridges and south slopes in the watershed are dominated by Virginia pine *(Pinus virginiana)*, shortleaf pine (*P. echinata*), chestnut oak (Quercus *prinus*), and scarlet oak (Q. *coccinea).* Moist, cool, north slopes and coves Often support white pine (*P. strobus*), eastern hemlock (*Tsuga canadensis*), yellow-poplar (*Liriodendron tulipifera*), and mixed mesophytic hardwood overstories with thick understories of rhododendron *(Rhododendron* sp.) and mountain laurel (*Kalmia latifolia*). Somewhat drier slopes Support oak-pine mixtures as the dominant forest association (Meyers and others 1986).

The majority of the watershed is forested, with 68 percent of the subbasin held in national forests. In recent decades, residential development in the privately owned segments of the watershed has increased, leading to additional impacts on water quality. Public lands used for dispersed and developed recreation also have numerous signs of heavy use with resultant impacts on resource conditions. Agricultural activities include growing corn, apples, and cabbage, accompanied by poultry and livestock husbandry.

METHODS

Road Survey

Sediment sources that could be observed from unpaved roads were identified in a road survey. Approximately 92 percent of the open, public, unpaved roads in the watershed were inventoried by locating and describing obvious sedimentation problems on data sheets. Private roads were often not accessible. Sources of sediment that could be observed from paved roads were also noted, but traffic hazards prevented their detailed description.

Sediment sources were classified into one of six categories: (1) roads, (2) timber harvest, (3) agriculture (both crop farming and animal husbandry), (4) residential development, (5) recreational trails and facilities, and (6) any other type of soil-disturbing activity. The majority of sediment sources in the timber harvest category were associated with short (<1 mile) logging roads and skid trails.

The severity of each sediment source was subjectively ranked. Ranking was intended only to provide a scale of relative differences in impacts of different sediment sources. Locations of severe sources of sediment identified during the road survey were digitized into a GIS database and their locations mapped.

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Total Suspended Solids

Thirteen subbasins within the Chattooga River watershed, ranging in size from 906 to 24,460 acres, were selected for sampling the total suspended solids (TSS). These subbasins made up about 60 percent of the entire Chattooga watershed and contained a wide variety of road densities, land-use histories, and ownership patterns.

Depth-integrated water samples were collected twice monthly, usually during baseflow conditions, from each study subbasin from November 1993 through early April 1994. A vertical series of single-stage samplers was used to collect stormflow samples when erosion and sediment transport were most likely to occur. The highest sampler was positioned just above the level of bank-full flow. This sedimentation monitoring program was based on a similar monitoring program of TSS that has been successfully used on over 40 sites in the Southern Appalachians by Duke Power Company (Braatz 1994). Concentrations of suspended solids are expressed in parts per million (ppm) rather than milligrams per liter, since we use English units in this paper.

Fine Sediments in the Substrate

Coverage of pool bottoms by fine-sediment deposits, i.e., deposits dominated by sand and finer materials, was estimated using low-altitude videography. Video footage was shot from a helicopter on March 14, 1994 with an Ikegami HL55 Betacam. Average helicopter height above the river varied from 150 to 200 feet depending on conditions. About 58 percent of the Beta videotape could be analyzed for substrate coverage by fine sediments. Glare from sunlight, helicopter angle, and other factors prevented analysis of the remainder.

Within reaches of the river, the percentage of pool area in fine sediment deposits was visually estimated using representative frames from the Beta tape and an on-screen grid. An average flight speed was calculated and used to convert numbers of frames (30 per see) to linear stream lengths.

Four locations were ground-truthed to confirm that videotape estimates of the area covered by fine sediment deposits were reliable. Grab samples of the substrate material were also taken from shallow pools at these locations to determine the particle-size distribution of material classified as fine sediment in the visual estimates (Van Lear and others 1995).

RESULTS

Road Survey

The road survey of 205 miles of open, unpaved roads in the Chattooga Watershed documented 1 ,106 observable sources of sedimentation, an average of 5.68 sediment sources per mile. The impact of some land uses causing sedimentation may have been underestimated because only sediment sources visible from surveyed roads were included in the survey. However, an aerial reconnaissance of much of the watershed by helicopter prior to leaf development in March 1994 did not identify any significant sediment sources that would have been missed by the road survey.

The greatest frequency of sediment sources (80 percent) in the watershed was associated with gravel and unsurfaced roads (fig. 1). Among the commonly noted causes of sedimentation from roads were: (1) poor location and design; (2) rutting, gullying, and sheet erosion of road surfaces; (3) road bank slumping; (4) erosion of roadside ditches; (5) stream and drainage crossings; (6) poor placement of ditch turnouts or outlets; and (7) improperly located or functioning culverts. Approximate locations of major sediment sources were digitized into a GIS data base so that landowners and managers could find and correct these sources.

About 9 percent of the sediment sources observed during the road survey were attributed to timber harvesting operations. The great majority of these sources were associated with short (generally less than 1 mile) logging access roads that connected to the multipurpose roads, rather than to the cutting of timber.

Agriculture accounted for 4.5 percent of the identified sediment sources from the road survey. Most observed agricultural impacts were associated with grazing in the riparian zones of small to intermediate perennial streams. About 3 percent of the noted sediment sources were related to residential development. These sources were generally new house sites and the driveways leading to these sites. Recreational impacts accounted for only a small percentage (2.6 percent) of the observed sources of sediment. However, many roads remain open for public access and recreational use. Sediment sources falling in the “other’ category ranged from landfills to beaver impacts.

Total Suspended Solids

Stekoa and Big Creeks had by far the highest levels of stormflow TSS of any of the 13 study streams, with both storm event maximums and storm event means averaging over 2000 ppm and single extreme samples of 21 ,018 and 16,462 ppm (table 1). Estimates suggest that 80 percent of the total Chattooga River sediment load can be associated with these two streams. Whetstone had the third highest level of stormflow TSS.

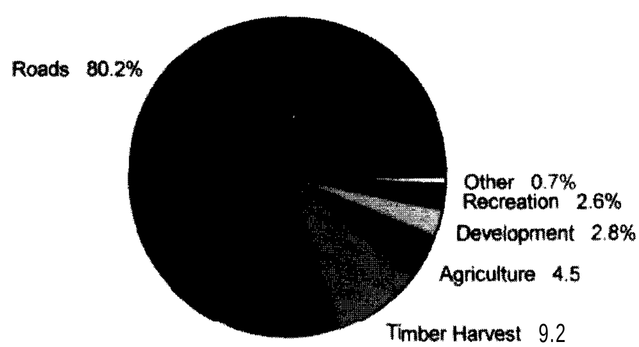

Figure l-Distribution of sediment sources observable from a survey of public, unpaved roads in the Chattooga River watershed.

Table l-Relative ranking of 13 subbasins within the Chattooga River watershed based on average storm event maxima for total suspended sediment (TSS)

Subbasin	Ranking	Avg. of storm event max. TSS[1]	Storm flow mean TSS	Max. TSS	Base flow mean TSS
		---------- Ppm	----------	----------	----------
Stekoa	1	3057 (8)	2501 (18)	21018	13 (10)
Big	2	2197 (9)	2255 (19)	16462	10 (10)
Whetstone	3	619 (6)	734 (8)	1523	16 (10)
Warwoman	4	167 (9)	128 (20)	359	10 (10)
King	5	151 (5)	151 (5)	489	23 (9)
Reed	6	150 (7)	118 (12)	476	10 (9)
East Fork	7	144 (7)	94 (15)	503	16 (9)
Long	8	112 (9)	99 (15)	274	11 (10)
Bull Pen	9	93 (6)	71 (23)	142	11 (7)
Harden	10	84 (5)	93 (7)	300	10 (9)
Holcomb	11	66 (9)	39 (30)	182	13 (9)
S. Fowler	12	65 (6)	57 (10)	132	9 (8)
Overflow	13	64 (9)	51 (21)	138	7 (10)

[1] Mean with number of samples in parenthesis.

There was no TSS sampling station on the West Fork of the Chattooga, although its three major tributaries (Big, Overflow, and Holcomb) were sampled. During high-intensity storms, steep-gradient sections of overflow Creek Road, just above the bridge on Forest Service Road 86, flushes heavy sediment loads at numerous locations into the West Fork. This section is downstream of the TSS sampler on Holcomb Creek. Warwoman, King, Reed, East Fork, and Long Creeks had average TSS storm event maximums that ranged between 167 and 110 ppm. Streams with the lowest stormflow TSS levels included Bullpen, Harden, Holcomb, S. Fowler, and Overflow Creeks (above the confluence with Clear Creek).

Stormflow TSS levels of subbasins in the Chattooga Watershed varied widely in their concentration of suspended sediment. However, baseflow TSS conditions were similar across all study subbasins, with averages ranging from 7 to 23 ppm.

Fine Sediments

The river was extremely clear at normal flow when the low-altitude helicopter videography was conducted. Fine sediments could clearly be detected in the two upper sections on the videotape (table 2). Fine sediments covered about 63 percent of pool substrate in Section I. The percentage of the pool substrate covered by fine sediments increased in Section II (Russell Bridge to Dick Creek) to 85 percent due to sediment inputs from tributaries and decreased gradient.

Because of greater pool depth, water turbulence, glare, and helicopter angle in the steeper Section III, fine sediment coverage could not be estimated with confidence.

Table 2-Coverage of pool substrates of the Chattooga River by fine sediments, as estimated from analysis of aerial videotape

Section[1]	Gradient	No. of pools sampled	Ave. coverage of pool substrate by fine sediment
	Feet/mile		*---Percent---*
I	44	22	63
II	15	23	85

[1] I = Bull Pen Bridge to Russell Bridge; II = Russell Bridge to Dick Creek.

The stream channel in Section III is tightly constrained by geology. Stekoa Creek, the major contributor of sediment and other pollutants to the river, enters midway through this section.

DISCUSSION

Road Survey

Open graveled and unpaved roads were the major source of sediment surveyed in the Chattooga River watershed. Many of these roads evolved from old wagon trails near the turn of the century and frequently occur on flatter terrain, which often is along stream courses. From a water quality standpoint, roads adjacent to streams are in the worst possible location.

Many of the unpaved, open roads surveyed were within national forests, including about 68 percent of the watershed. Multi-purpose unpaved roads with the greatest frequency of sediment sources were generally those with heavy vehicular traffic. Heavy vehicle use, especially during wet weather, causes rutting of road surfaces which increases the need for maintenance. Road maintenance operations are major causes of sedimentation of streams in the Chattooga River watershed, especially where vegetative buffer strips are inadequate to filter loosened sediments. Roads adjacent to streams are especially prone to deliver sediments to the stream.

Unpaved, graveled roads, because of their location, extent, heavy use, and frequent maintenance, are the major source of sediment in the Chattooga River watershed. The frequency with which roads crossed drainages (culvert density) has been positively correlated with the amount of fine substrate and embeddedness in Wyoming trout streams (Eaglin and Hubert 1993). Similar findings have been noted by Durniak and Ruddell (1990) in north Georgia and Swift (1984) in western North Carolina.

Unpaved roads with a high frequency of travel should be surfaced with a coarse gravel foundation for stability prior to adding a finer surfacing material. Aggregates with a high proportion of fine material should be avoided. Placement of large gravel in roadside ditches would reduce the need for maintenance and protect this very sensitive portion of the road. Strict adherence to Best Management Practices guidelines and appropriate use of inexpensive water control features (Tew and others 1985, Swift 1987) would minimize sedimentation problems associated with unpaved roads.

A relatively small proportion (9 percent) of total observed sediment sources was attributed to timber harvesting. Most of these sources were associated with short spur roads accessing the harvest site. Cutting of timber per se rarely causes erosion; rather, the cause is generally the transportation system required to remove the harvested trees (Douglass 1974, Kochenderfer and Aubertin 1975, Hewlett 1979). If timber removal is the primary use, roads should be surfaced with aggregate dominated by large rock (particles 3 to 4 inches in size). These temporary-use roads should normally be closed or maintained for high-clearance vehicles following harvest.

Gated Forest Service roads whose surfaces had been graveled and vegetated were no longer a significant source of sediment to adjacent streams. These roads are open to foot traffic but closed to vehicles, except in cases of extreme need. They become excellent linear wildlife strips and are aesthetically attractive. Periodic mowing keeps them accessible for forest management emergencies or other needs.

Closing those unpaved, graveled roads that are not heavily used or necessarily kept open would reduce impacts on water quality. Closed roads remain as valuable assets used by hunters, fishermen, hikers, and others with minimal impact on streams of the area. Although some unpaved, graveled roads, because of design, location, or other factors, do not contribute significant sedimentation to streams, many do. Often these roads or sections of them are the major source of sediment to a particular stream. A significant reduction in the density of open graveled and unsurfaced roads would probably have a greater influence on water quality in the Chattooga River watershed than any other single recommendation.

Paved roads also contribute sediment to streams in the Chattooga River watershed, especially during and following their construction/reconstruction and right-of-way maintenance phases. Deeply entrenched ditches along many paved roads are evidence that they have been chronic sediment producers for decades. Federal and state highway agencies should consider the benefits of stable vegetation as an effective cover to prevent erosion and minimize maintenance costs. Routine pulling of road ditches during maintenance is often unnecessary and disruptive to bank stability and water quality.

Stream bank fencing is a simple and effective way for farmers to improve water quality, maintain soil productivity, and protect their livestock from waterborne bacteria. Soil and water conservation districts, State environmental, water, forestry, and agricultural agencies are good contacts for discussing cost-share opportunities available to private landowners to protect streams and improve water quality. Work on national forest roads is conducted through various road construction, reconstruction, and maintenance funds. Timber harvest activities also contribute to road costs.

Sedimentation from development is likely to escalate in the future. Strict enforcement of Section 404 of the Federal Clean Water Act and a State and 12 local sediment control laws would reduce development-related sedimentation in the Chattooga River watershed. Best Management Practices, when properly applied, are effective measures in protecting water quality.

The relative contribution of recreational sources of sediment (2.6 percent) is misleading. Recreationists of all pursuits, including rafters, anglers, hunters, hikers, campers, and scenic drivers, account for most of the traffic on the road network. Roads would require less maintenance and contribute far less sediment if they were not heavily used by recreationists.

Sedimentation

Fine sediments exert detrimental effects on benthic macroinvertebrates by altering and degrading critical habitats (Reiser and White 1988, Wesche and others 1989). Excessive fine sediments cover and fill interstices of gravel and cobble substrates, transforming the stream bottom to a habitat composed of small unstable particles which can be utilized by only a relatively few species. Species characteristic of stony-bottomed riffles may disappear, as will many species whose food supply is covered by sediment (Bjornn and others 1977, Minshall 1984, Wallace and others 1992).

An increase in fine sediments within stream substrates generally has a negative impact on salmonids. Fine sediments prevent oxygen from reaching eggs, trap fry in the substrate, and retard the removal of toxic compounds from reads (Waters 1995). In addition to adverse effects on reproduction, excessive fine sediments can be detrimental to the habitat and survival of adult trout (Chapman 1988, Young and others 1991, Waters 1995). Both suspended and settled fine sediments adversely affect trout and other fish species (Young and others 1991, Waters 1995). Although high water temperatures, low fertility, and lack of coarse woody debris limit production of trout streams in the Southern Appalachians (Habera and Strange 1993), it is also reasonable to assume that excessive fine sediments adversely affect trout production in the Chattooga River.

High suspended-sediment levels were documented in certain tributaries of the Chattooga River. Aerial videography showed that tributaries also contribute heavy bed-loads of fine sediments to the river. Until sedimentation problems of tributaries are corrected, it will be impossible to reduce impacts of sedimentation on the aquatic community within the main river. Concentration of restoration efforts in Big Creek and Stekoa Creek, the major contributors of sediment, appears to be the proper approach to improve water quality in the Chattooga River. However, contributions from lesser tributaries should not be dismissed.

The single-stage samplers used in this study to sample TSS were effective and inexpensive, yet simple to install and use. They could be used in streamwatch programs by volunteer organizations to monitor water quality, although users should be aware of the limitations of the technique. The low levels of baseflow TSS from all 13 tributaries emphasize the importance of sampling representative storm events to obtain a realistic comparison of suspended sediment transport by different streams (Braatz 1994).

Because of the geology of the watershed, much Of this stored sediment is undoubtedly a natural feature of the river. It is equally certain that man's activities have contributed large quantities of sediment to the river. Because of the huge quantities of sediment stored in the channel and its embeddedness in the substrate, it may take decades or even centuries for the river bottom to approach full recovery, assuming that anthropogenic sources of sediment are minimized. Nevertheless, now is the time to initiate a major watershed effort to control sedimentation and allow the river and its tributaries to begin progressing toward their full biological and aesthetic potential.

CONCLUSIONS

This study utilized various methods, including a road survey, water quality sampling, helicopter videography, and substrate sampling, to evaluate sedimentation in the Chattooga River watershed. Major conclusions are:

- Unpaved multipurpose roads were associated with about 80 percent of the sediment sources observed from roads in the Chattooga River watershed. Other sources of sediment, although perhaps locally important, were relatively minor.
- Heavy recreational use of these unpaved gravel roads contributes to their sedimentation potential through heavy trafficking and by increasing the need for maintenance.
- Suspended sediment levels were highest in subbasins heavily impacted by roads, pastures with unfenced riparian zones, and development.
- Land-uses in drainages of major tributaries that expose, compact, or trample mineral soil are the major causes of high stormflow levels of suspended sediment in the Chattooga River. The Wild and Scenic corridor of the main stem of the river contributes relatively little new sediment.
- A long history of land use within the Chattooga River watershed has significantly contributed to excessive sedimentation of the river. A major effort by all landowners, both public and private, and users, to reduce and reclaim sources of sedimentation, could quickly initiate a recovery of the watershed and lead to continuing enhancement of resource values associated with the river and its tributaries.

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GROWTH AND DEVELOPMENT OF WATER TUPELO (*NYSSA AQUATUCA*) - BALDCYPRESS (*TAXODIUM DISTICHUM*) FOLLOWING HELICOPTER AND SKIDDER HARVESTING: IO-YEAR RESULTS

W.M. Aust, S.H. Schoenholtz, M. Miwa, and T.C. Fristoe'

Abstract-Ground-based timber harvesting operations in forested wetlands have the potential to cause soil disturbances. Similar soil disturbances on upland sites have been linked to reduced site productivity, but the effects of such disturbances on the long-term site productivity of bottomland hardwoods is not well documented. In 1986, a long-term research project was established to compare the effects of helicopter and skidder timber harvesting on the regeneration, growth, and development of naturally regenerated water tupelo (Nyssa *aquatica*) - baldcypress (*Taxodium distichum*) stands. At stand age 10 years, both treatment areas have well-stocked, vigorously growing stands composed of coppice-regenerated water tupelo, Carolina ash (*Fraxinus caroliniana*), baldcypress, and seed-origin black willow (*Salix nigra*). Although both areas are well stocked, the skidder treatment favored the growth of water tupelo, while the helicopter treatment had densities and growth rates for Carolina ash. Apparently, the initial effects of the skidder traffic puddled soils, causing more reduced soil conditions that removed less flood-tolerant species, leaving the very flood-tolerant water tupelo. Stand growth parameters suggest that both treatments will produce stands that will be similar to the previous stands in terms of species and volume. Recovery in this area was speeded by annual inputs of nutrient-rich sediment and the shrink-swell nature of the soil.

INTRODUCTION

Forested wetlands, such as bottomland hardwoods, have unique landscape positions and ecological processes that allow them to provide numerous benefits to society. Examples of societal values include storm water storage, provision of habitat, improvement of water quality, and production of timber (Walbridge 1993). Although timber harvests have occurred in these areas for over 200 years, the effects of harvesting on subsequent wetland ecosystem processes have been evaluated only over the past decade (Lockaby and others 1997). The objectives of this research project are to evaluate the effects of helicopter and rubber-tired skidder timber harvests on subsequent stand growth and development after 10 growing seasons.

METHODS

Study Site

The study site is located along the Tensaw River within the Mobile-Tensaw River Delta in Baldwin County, AL. Prior to treatment installation, the stand had a two-aged overstory as the result of previous float and pull-boat harvesting operations that occurred in the mid-1800's and early 1900's, respectively (Aust 1989, Mader 1990). The majority of the stand was composed of 70-year-old water tupelo (Nyssa *aquatica*) and baldcypress (*Taxodium distichum*), while a few older residual trees were present. The overstory was composed of approximately 85 percent water tupelo, 10 percent baldcypress, and 5 percent Carolina ash (*Fraxinus caroliniana*). The site had a site index (50 years) of 85 feet for water tupelo and produced approximately 80 cords per acre of merchantable timber. The site floods annually; average annual flood peaks exceed 3 feet in depth (U.S. Army Corps of Engineers 19851996). Levy is the dominant soil series (fine, mixed, acid, thermic Typic Hydraquents) (USDA Natural Resources Conservation Service 1997).

Treatments

Pretreatment site characterization was conducted during the spring, summer, and fall of 1986 to ensure that the stands were homogeneous in terms of hydrology, soils, and vegetation (Aust 1989, Mader 1990). During late fall 1986, three disturbance treatments were installed in a three 3 by 3 Latin squares design. The Latin square statistical design was used so that gradients parallel to and perpendicular to the river could be examined. Each of the three disturbance treatments had nine replications within this design.

Each of the 27 treatment plots measured approximately 3 chains by 3 chains, containing slightly less than 1 acre. The entire treatment area (27 treatment plots) received chainsaw felling and helicopter removal of all merchantable stems and nonmerchantable stems greater than 2 inches in diameter at breast height (d.b.h.). This level of treatment comprised the helicopter treatment and nine of the treatment plots remained in this state.

After helicopter timber removal was completed, the skidder treatment was installed on nine additional plots. These plots received trafficking with a Franklin 105 cable skidder equipped with 34-inch-wide rubber-tires. The skidder simulated harvesting operations by trafficking across the skidder treatment plots until approximately half of each skidder plot was rutted to an average depth of 1 foot. Local procurement foresters stated that the results were very similar to normal skidding on such sites.

The remaining nine plots were treated with glyphosate herbicide during the first two growing seasons following

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harvest. This herbicide treatment controlled vegetative regrowth (glyphosate treatment), so that the effects of the lack of vegetation on early restoration processes could be evaluated as reported in Aust and Lea (1991).

Although not included within the experimental design because of helicopter logistics, a reference area was left downstream from the disturbance treatments. This area has the same hydroperiod, soil, and vegetation as the disturbance area did before treatments were installed.

The glyphosate treatment area is currently a scrub-shrub wetland dominated by herbaceous vegetation. While this is an interesting successional state, it is not an operationally feasible, nor desirable, forest. The older reference area has similar species composition as within the helicopter and skidder treatments, but the difference in age makes comparison difficult. Therefore, within this paper, only the helicopter and skidder treatments will be considered., Additional details concerning the original study site conditions; treatment installation; 1 -year, 2-year, 7-year, and 8-year measurements and results are available (Aust 1989, Aust and Lea 1991, 1992, Aust and others 1991, 1997, Mader 1990, Mader and others 1989, Szabo and others 1994, Zaebst 1997).

Ten-Year Data Collection and Analyses

Circular measurement subplots (1/30 acre) were established in each of the nine replications of the skidder and helicopter treatment plots. For each overstory stem (d.b.h. > 1.49 inches) in the subplot, the following attributes were measured: species, azimuth from plot center, d.b.h., total height, crown class, tree vigor, and number of stems per stump. After field work was completed, total biomass for each species was determined using biomass equations developed on these sites by Mader (1990) and Zaebst (1997). Standard analyses of variance were conducted for the three 3 by 3 Latin squares (Steel and Torrie 1980). If significant treatment differences were detected by the analysis of variance (alpha < 0.05), then treatments were separated with a Fishers protected LSD test.

RESULTSANDDISCUSSION

Sources of Regeneration

Regeneration levels following the clearcutting with helicopter and skidder treatments were very successful, primarily due to abundant coppice regeneration. Over 90 percent of the water tupelo, Carolina ash, and baldcypress remaining after 10 growing seasons were of stump origin. Black willow was the only seed-origin species still present in the overstory after ten growing seasons. The previous stand was also dominated by coppice origin, with two and three stems per stump being common and evident even after 70 years. The average numbers of stems per stump that were in an overstory position at age 1 O-years are presented in table 1.

The success of the coppice regeneration was not a foregone conclusion. Kennedy (1982) had cautioned that coppice of water tupelo was erratic and unreliable. Larsen (1980) reported that baldcypress sprouting is of minor importance, and Ewel (1996) found that only 17 percent of pondcypress sprouted after harvests. The success of the water tupelo coppice was probably enhanced by several factors. During the harvesting operation, sawyers felled the trees in standing water and cut relatively high stumps. These higher stumps increased the initial number of stems per sprout, but the higher stumps have not led to undue windthrow at 10 years. Another important factor explaining the success of the coppice is the annual inputs of sediment (Aust and others 1991, 1997). These inputs have facilitated coppice growth by ensuring adequate nutrition and by physically reducing the height of the stumps above the soil surface, actually masking the higher stumps.

Table l-Helicopter and skidder treatment effects on average number of sprouts per stump for species remaining in the overstory after 10 growing seasons

Common name (Genus species)	Helicopter	Skidder
	---Sprouts	per stump---
Black willow (*Salix nigra*)	1.0[a]	1.0[a]
Water tupelo (Nyssa *aquatica*)	4.2	4.7
Carolina ash (*Fraxinus caroliniana*)	3.4	2.6
Baldcypress (*Taxodium distichum*)	2.2	2.2
Red maple (*Acer rubrum*)	1.4	1.2
Water elm (*Planara aquatica*)	3.9	3.5

[a] Black willow regenerated from seed only.

Species Growth and Yield

Four species composed over 97 percent of the overstory density: black willow, water tupelo, Carolina ash, and baldcypress, with two species, red maple and water-elm, being less common associates (table 2). This species mix is relatively common for water tupelo-baldcypress stands in

Table 2-Helicopter and skidder treatment effects on the density of overstory species after 10 growing seasons (different letters represent significant treatment effects on the density of a species at alpha levels of 0.05)

Common name *(Genus species)*	Helicopter	Skidder
	----Stems	per acre----
Black willow (*Salix nigra*)	436 a	506 b
Water tupelo (*Nyssa aquatica*)	476 a	506 b
Carolina ash (*Fraxinus caroliniana*)	683 b	447 a
Baldcypress (*Taxodium distichum*)	60	80
Red maple (*Acer rubrum*)	16	40
Water elm (*Planara aquatica*)	27	7
Total	1698	1826

deep alluvial swamps (Larsen 1980). Black willow was the only overstory species present in the 1 O-year-old stand that had not been present prior to harvest. Black willow is a very intolerant, pioneer species that commonly seeds into disturbed bottomlands (Meadows and Stanturf 1997), but the species is relatively short-lived and will eventually be replaced by longer-lived, or less intolerant species (Krinard 1980). There were no significant differences in regeneration of black willow between the helicopter and skidder harvested areas after 10 years, although the skidder treatment had favored willow regeneration during the first two growing seasons (Mader 1990, Mader and others 1989).

The helicopter and skidder treatment areas did have significantly different densities of water tupelo and Carolina ash (table 2). The skidder treatment had 57 percent more water tupelo stems per acre, while the helicopter treatment had 53 percent more Carolina ash stems per acre. These differences are explained by the treatment effects on soil and hydrologic properties at 1 and 2 years (Aust 1989, Mader 1990).

The skidder treatment plots had average trafficked areas of 52 percent and the ruts averaged over 1 foot in depth (Aust 1989). The soils of the skidder treatment had been trafficked during saturated soil conditions and the soil had literally flowed from the ruts, a disturbance referred to as puddling. This destroyed soil macropore space and reduced saturated hydraulic conductivity values (table 3), causing soil water movement to be restricted. Soil oxygen values and soil redox potentials were also lower within the skidded treatment areas (Aust 1989, Aust and Lea 1992). Although not statistically significant, the water tables within the skidded plots tended to be closer to the soil surface than in the helicopter plots. This trend continued as late as 8 years after harvest (Aust and others 1997, Szabo and others 1994). The wetter and more reduced conditions within the skidder treatment favored the growth of the more flood-tolerant water tupelo (Larsen 1980) by reducing competition from other species, while the less reduced conditions within the helicopter treatment allowed the Carolina ash to regenerate more successfully.

Growth characteristics of the water tupelo and Carolina ash were also affected by the helicopter and skidder treatments. Average diameter, total height, basal area, and total biomass of water tupelo were significantly increased within the skidder treatments. Conversely, average diameter, height, basal area, and biomass of Carolina ash were favored by the helicopter treatment (tables 4, 5, 6, 7). These results were similar to those observed at age 7 years (Aust and others 1997, Zaebst 1997); however, the percentage of difference between the species was less at 10 years, indicating that treatment differences for these two species will be minimized further over time. This conclusion assumes that the belowground carbon allocation within the helicopter and skidder treatment areas are similar, which may not be correct. Powell and Day (1991) found that a higher percentage of belowground net primary productivity was allocated to water tupelo that were grown under drier soil conditions. Sediment deposition has probably helped to mitigate the differences between the helicopter and skidder treatment results (table 8).

Table 3-Average saturated hydraulic conductivity, soil oxygen percentage, and redox potential (pH 6.0) in the helicopter and skidder treatments for the first two growing seasons (1987, 1988) (different letters represent significant treatment effects at alpha levels of 0.05)

Treatment	Average saturated hydraulic conductivity	Average soil oxygen	Average redox potential (at pH 6.0)
	Inches/hour	*Percent*	*mV*
Helicopter	*3.3* b	*2.2* b	*220* b
Skidder	2.9 a	1.4 a	125a

Table 4-Helicopter and skidder treatment effects on the average diameter at breast height of overstory species after 10 growing seasons (different letters represent significant treatment effects on the density of a species at alpha levels of 0.05)

Common name *(Genus species)*	Helicopter	Skidder
	-----Inches-----	
Black willow (*Salix nigra)*	*3.5*	*3.7*
Water tupelo (*Nyssa aquatica*)	2.9 a	*3.3* b
Carolina ash *(Fraxinus caroliniana*)	1.9 b	1.5 a
Baldcypress (*Taxodium distichum)*	*2.0*	1.9
Red maple (*Acer rubrum*)	*2.0*	*2.0*
Water elm (*Planara aquatica*)	1.7	1.8

Table 5—Helicopter and skidder treatment effects on average total height of overstory species after 10 growing seasons (different letters represent significant treatment effects on the density of a species at alpha levels of 0.05)

Common name *(Genus species)*	Helicopter	Skidder
	------Feet------	
Black willow (*Salix nigra)*	*34.8*	*35.1*
Water tupelo (*Nyssa aquatica*)	27.9 a	*30.2*
Carolina ash *(Fraxinus caroliniana*)	*26.0* b	*21.2* a
Baldcypress (*Taxodium distichum)*	14.7	14.0
Red maple (*Acer rubrum*)	*27.9*	21.3
Water elm (*Planara aquatica*)	21.3	16.7

Table 6-Helicopter and skidder treatment effects on the basal area of overstory species after 10 growing seasons (different letters represent significant treatment effects on the density of a species at alpha levels of 0.05).

Common name (Genus *species*)	Helicopter	Skidder
	---Square feet per acre---	
Black willow (*Salix nigra*)	29.1 a	37.8 b
Water tupelo (Nyssa *aquatica*)	21.8 a	44.3 b
Carolina ash (*Fraxinus caroliniana*)	13.5 b	5.5 a
Baldcypress (*Taxodium distichum*)	1.3	1.6
Red maple (*Acer rubrum*)	0.3	0.9
Water elm (*Planara aquatica*)	0.4	0.1
Total	66.4 a	90.2 b

Table 7-Helicopter and skidder treatment effects on the woody biomass in overstory species after 10 growing seasons (different letters represent significant treatment effects on the density of a species at alpha levels of 0.05).

Common name (*Genus species*)	Helicopter	Skidder
	-----Tons per acre-----	
Black willow (*Salix nigra)*	13.27	16.41
Water tupelo (*Nyssa aquatica*)	11.85 a	18.09 b
Carolina ash (*Fraxinus caroliniana*)	2.08 b	1.17 a
Baldcypress (*Taxodium distichum*)	1.69	2.17
Red maple (*Acer rubrum*)	0.19	0.43
Water elm (*Planara aquatica*)	0.28	0.06
Total	29.36 a	38.33 b

Table 8-Average and total accumulated sediment in the helicopter and skidder treatments after 10 growing seasons (different letters represent significant treatment effects at alpha levels of 0.05)

Treatment	Average annual sedimentation	Total sedimentation for 10 years
	Inches/year	*Inches*
Helicopter	0.41	4.1
Skidder	0.32	3.2

CONCLUSIONS

Regeneration at stand age 10 years was good in both the helicopter and skidder treatments. With the exception of black willow, coppice regeneration dominated the overstory canopy within both treatments. The only significant seed-regenerated species, black willow, is a shade-intolerant, pioneer species. Due to its naturally short life expectancy, black willow is expected to experience heavy mortality within the next 20 to 40 years. At that time, the species composition in the helicopter and skidder treatments will be similar to the preharvest stand. Both treatments will have an overstory dominated by water tupelo, with baldcypress and Carolina ash being less important overstory associates.

At stand age 10, the skidding treatment favored the growth of water tupelo at the expense of Carolina ash. We hypothesize that this treatment effect was caused by the initial effects of the skidding treatment on site hydrology. The skidder traffic rutted and puddled the soils, initially reducing soil water movement and aeration as compared to the soils in the helicopter treatment. The more reduced conditions in the skidder treatment favored the very flood-tolerant water tupelo at the expense of the slightly less flood tolerant Carolina ash. We hypothesize that, over time, the treatment differences between the growth of water tupelo and Carolina ash will lessen. As canopy stratification increases, the naturally slower growing Carolina ash will fall into the midstory canopy within both treatments.

At present, the skidder treatment unexpectedly produced more total aboveground biomass (table 7) than did the less soil disturbing helicopter treatment. There are several plausible explanations for this phenomena. Perhaps the increase in microtopography within the skidded treatment area increased the proportion of aerated soils that roots can exploit, an effect similar to mechanical site preparation for pine on wet sites. Perhaps the reduced conditions in the skidder treatment favored aboveground biomass production at the expense of belowground biomass production, as found by Powell and Day (1991). Also, the reduced soil conditions within the skidder treatment area have favored the water tupelo and intraspecific patterns of competition, while the helicopter treatments have favored a pattern of interspecific competition. Additionally, the sedimentation patterns and clay mineralogy of the site make these site more difficult to damage with traffic as compared to non-alluvial, 1 :1 clay-dominated sites. The annual sediment deposition in both treatments enhances soil nutritional levels and fills in ruts. The shrink-swell clays also allowed the rutted soils to recover saturated hydraulic conductivity rapidly. Hopefully, we will establish the exact processes that facilitated the rapid recovery in future studies, but the differences between the helicopter and skidder treatment areas will probably lessen as the rotation proceeds.

Overall, the stand composition, growth rates, and biomass accumulation in the helicopter and skidder treatment sites indicate that recovery is progressing rapidly. If expected patterns of stand development occur, the future stands will have species and volumes similar to the previous stands.

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INTERACTION AMONG MACHINE TRAFFIC, SOIL PHYSICAL PROPERTIES AND LOBLOLLY PINE ROOT PROLIFERATION IN A PIEDMONT SOIL

Emily A. Carter and Timothy P. McDonald'

Abstract-The impact of forwarder traffic on soil physical properties was evaluated on a Gwinnett sandy loam, a commonly found soil of the Piedmont. Soil strength and saturated hydraulic conductivity were significantly altered by forwarder traffic, but reductions in air-filled porosity also occurred. Bulk density did not increase significantly in trafficked treatments. The greatest impacts to soil physical properties occurred in the surface layer. Loblolly pine root proliferation increased in both trafficked and untrafficked treatments but differed in the soil depth at which this occurred. Further investigations are necessary to understand the response of roots to machine traffic.

INTRODUCTION

The impact of forest machinery on harvested sites traditionally has been gauged by changes in soil physical properties including bulk density, soil strength, macroporosity, saturated hydraulic conductivity, and water infiltration (Gent and Ballard 1984, Greacen and Sands 1980, Lenhard 1986, Reisinger and others 1988, Wronski 1984). Soil physical properties are negatively impacted during trafficking; the results can persist for many years and limit tree productivity (Greacen and Sands 1980, Tuttle and others 1988). Low productivity of selected pine species is correlated with impaired root growth and development in compacted soils. Compaction restricts the volume of soil that can be exploited for available moisture and nutrients (Mitchell and others 1982, Sands and Bowen 1978, Tuttle and others 1988). The relationship among machinery, root systems, and soil physical properties has been extensively investigated in agricultural systems and linked to numerical values of soil physical properties that are considered to be root limiting (Unger and Kaspar 1994). An understanding of this relationship for tree species is limited, and future productivity would be aided by an understanding of soil physical changes and their role in root growth.

The objective of the study was an evaluation of the impact of forwarder traffic on selected soil physical properties of a Piedmont soil, and determination of a response by loblolly pine roots to forwarder traffic.

METHODS

The study was established in June 1996 on experimental sites managed by the School of Forestry, Auburn University, and cultivated for agricultural use prior to its conversion to a loblolly pine (*Pinus taeda*) stand. The study site supported a 15-year-old loblolly pine stand with an average diameter at breast height (d.b.h.) of 21 centimeters in a 2.7- by 1.8-meter spacing. The soil series within the study site was identified as a Gwinnett sandy loam, a member of the clayey, kaolinitic, thermic family of Typic Rhodudults. The experimental design consisted of a randomized complete block with two treatments: untrafficked (UNT) and trafficked by a loaded forwarder (TR), and replicated twice. Each replication encompassed an area approximately 3,700 square meters, subdivided into two treatment areas each approximately 1,350 square meters in size and separated by a buffer strip measuring approximately 9 by 45 meters. Each treatment plot contained approximately 12 rows of loblolly pines with 15 trees per row.

Pretreatment site preparation was necessary to permit movement of the forwarder through the stand. This consisted of hand-felling every other row of trees, limbing and topping of trees on site, winching boles to the edge of each treatment block, and removal from treatment areas. Similar pretreatment site preparation was applied to the UNT treatment areas to ensure uniform site conditions for consistency in comparisons. Trafficked treatments consisted of 10 passes of a loaded Franklin 710 forwarder weighing approximately 13 tons and driven at a rate of 3 miles per hour after removal of slash from traffic lanes.

Soil sampling was conducted in three phases: (1) bulk soil sample collection in June 1996 after pretreatment site preparation; (2) collection of soil core after pretreatment and again after installation of traffic treatments in June 1996 in one replication to assess impact of traffic; and (3) collection of soil cores in fall 1996 from each treatment in both replications to compare soil physical properties of UNT and TR treatments. Bulk soil samples were collected at 12 locations in each block with a hand-held auger, in increments of 15 centimeters to a depth of 90 centimeters. The samples were then air-dried, ground, and passed through a 2 millimeter sieve for soil chemical and physical analyses. Sixteen soil cores, 5 centimeters in diameter and 5 centimeters in length, were collected from the soil surface layer (0 to 10 centimeters) at random locations along traffic lanes in one replication of TR prior to and at the conclusion of traffic treatments. Soil cores of similar dimension were collected along traffic lanes at regular intervals (approximately 10 meters) in UNT and TR in each replication to compare treatments; the number of cores collected was dependent on the type of soil physical analysis and the number of soil depths.

Bulk soil samples were analyzed for particle size by the hydrometer method according to Klute (1986). Soil cores

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collected from pre- and post-traffic treatments were analyzed for bulk density, gravimetric water content; saturated hydraulic conductivity; soil moisture retention characteristics at potentials of -l/l 0, -1/3, -1, and -5 bar; and porosity (total and microporosity) according to Klute (1986). Air-filled porosity was measured in each core according to Carter (1990). A total of 72 soil cores was collected from the UNT and TR treatment areas of each replication from three locations per track (or row) at three depths: 0 to 10, 10 to 20, and 20 to 30 centimeters. The cores were analyzed for bulk density and gravimetric water content according to methods previously cited. Additional cores were collected in each row at one location in each treatment, at two depths (0 to 10 and 10 to 20 centimeters) for a total of 20 soil cores per replication. These were analyzed for saturated hydraulic conductivity, soil moisture retention characteristics, and air-filled porosity.

Soil strength was determined with a Rimik CP 20 cone penetrometer with a base cone diameter of 113 square millimeters, manually inserted to a depth of 300 millimeters, and recorded in 25 millimeter increments. Soil strength is expressed indirectly as cone index (Cl), or the force required divided by the cross-sectional area of the base of the cone and measured in units of pressure (megapascals). Soil strength is reported for fall 1996 only.

Root samples were collected prior to installation of traffic treatments in June 1996 and in traffic lanes in fall 1996. Root samples were collected in June 1996 by manually driving polyvinyl chloride (PVC) cores, 7.6 centimeters in diameter and 60 centimeters in length, in 12 random locations in each block. The PVC cores were removed, subdivided into 10 centimeter increments, and roots and soil separated in a Gillison Root Washer. Root length (centimeters) was estimated utilizing a Comair Root Length Scanner and root length densities were calculated by dividing total root length (centimeters) by soil core volume (cubic centimeters). Root length densities were estimated for trafficked and untrafficked sites in one block in Fall 1996 through the collection of five soil cores, 5 centimeters in diameter and 30 centimeters in length, as a transect across one traffic lane (outside track, in track, and between tracks) in three locations along the length of one traffic lane; a total of 15 cores per treatment was collected. Preparation of root samples and root length density calculations were performed as previously described.

Statistical analyses were performed utilizing the Statistical Analysis System (SAS) (SAS 1988). Data collected for soil physical properties were analyzed in an analysis of variance (ANOVA), and means were analyzed by paired t tests. Comparisons of soil physical data from pre- and post-traffic sites was performed by paired t tests.

RESULTSANDDISCUSSION

Soil Physical Characterization

Soil texture and bulk density of the study site are typical for soils of the Piedmont physiographic region (tables 1 and 2). Particle size analysis indicated the presence of subsoil layers with a high percentage of clay. This is indicative of the presence of an argillic horizon (B2t), a defining characteristic of the Ultisol soil order of which the Gwinnett soil series is a member. Bulk density values of 1.3 megagrams per cubic meter of the surface soil layer were higher than expected for forest soils of the Piedmont. The high soil porosity, both total and air-filled, high hydraulic conductivity, and low percentage of gravimetric water content at field capacity (-1/10 bar) is a consequence of the sandy nature of the surface soil layer and the positive influence of undisturbed tree growth (table 1 and fig. 1).

Soil physical characteristics determined for soil samples of the study site are similar to properties reported for a Gwinnett sandy loam (SCS 1981). The Gwinnett soil series is a highly weathered, Piedmont soil of low moisture capacity in surface horizons underlain by a B2t, or argillic, subsoil horizon. Bulk density reported for an undisturbed Piedmont forest soil was 1 .16 megagrams per cubic meter

Table l-Impact of forwarder traffic on selected soil physical properties of a Gwinnett sandy loam soil

	Physical Property					
				Porosity		
Soil status	Bulk density	Moisture content	Saturated hydraulic conductivity[a]	Air-filled	Microporosity	Total
	Mg/m^{-3}	Percent	Cm/hr^{1}	Percent		
Pretraff ic	1.30	21.4	2.43	32.5	20.3	52.7
Posttraff ic	1.56	19.7	0.177	22.7	18.4	41.2

[a] Means of soil physical parameters were significantly different at the P = 0.05 level.

Table 2-Particle size analysis of a Gwinnett sandy loam soil

Depth	Sand	Silt	Clay	Classification
----Cm----	-------Percent-------			
O-10	72	6	23	Sandy clay loam
IO-20	47	18	35	Sandy clay
20-35	30	28	43	Clay
35-45	30	25	43	Clay

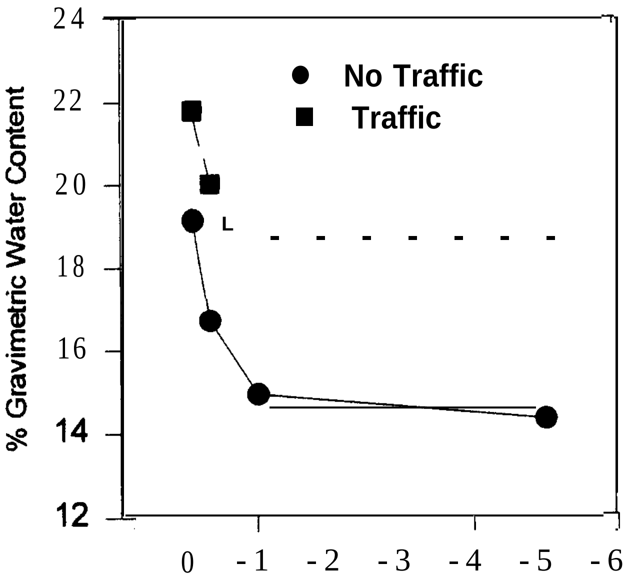

Figure I-Soil moisture retention characteristics of the surface layer of a Gwinnett sandy loam subjected to no traffic (UNT) and traffic (TR).

(Gent and Ballard 1984). In spite of elevated bulk density values, saturated hydraulic conductivity of 2.34 centimeters per hour and macroporosity in the vicinity of 33 percent are typical of forest soils that remain undisturbed for extended periods of time (Reisinger and others 1988).

Impact of Forwarder Traffic

Bulk density, soil moisture retention, hydraulic conductivity, and porosity of the soil surface layer responded negatively to forwarder traffic (table 1 and fig. 1). Soil compaction as a result of forwarder traffic increased in the study site as indicated by increased bulk density and decreased air-filled porosity. Total porosity was reduced at the expense of the large, air-filled pores in the surface layers after trafficking, which converted soil macropores to micropores. This change in pore size reduced the ability of the soil to transmit water and increased the soil moisture retention rate at each soil moisture potential. An indication of the alteration of pore size from trafficking is the shift in moisture retention characteristics in TR compared to UNT (fig. 1).

The changes in soil physical properties reported in this study are typical of the impact of machine traffic on bulk density, macroporosity, and saturated hydraulic conductivity of forest soils (Incerti and others 1987, Lenhard 1986, Wronski 1984). Bulk density increased to 1.56 megagrams per cubic meter in the surface layer of TR, matching bulk density values reported for heavily trafficked (in skid trails) sandy loam soils in North Carolina (Gent and others 1984). Air-filled porosity decreased from 33 to 23 percent in traffic lanes but the post-traffic air-filled porosity of 22 percent exceeds the minimum air filled percentage of 10, which is considered to be the lower limit for proper oxygen diffusion (Incerti and others 1987). Saturated hydraulic conductivity reductions from 2.34 to 0.177 centimeters per hour were typical of sandy loam (or finer) soils subject to compaction (Akram and Kemper 1979).

Subsoil Response to Forwarder Traffic

Soil response to forwarder traffic was detectable in subsurface (greater than 10 centimeters) as well as surface (0 to 10 centimeters) layers (table 3 and fig. 2). Bulk density was lower in UNT compared to TF? at comparable depths, and may indicate a response, however slight, to forwarder traffic. An ANOVA determined that neither the treatment, the depth, nor their interaction was significant for bulk density. Cone index (Cl) values were consistently and significantly higher in TR than in UNT at all sampled depths ($P > 0.001$). Although significant differences were detected at every depth, the impacts associated with trafficking may be limited to the upper 15 centimeters where the greatest differences occurred. A 10 percent difference in air-filled porosity and a tenfold reduction in saturated hydraulic conductivity were detected between TR and UNT in the surface layer, and little difference was discerned in the

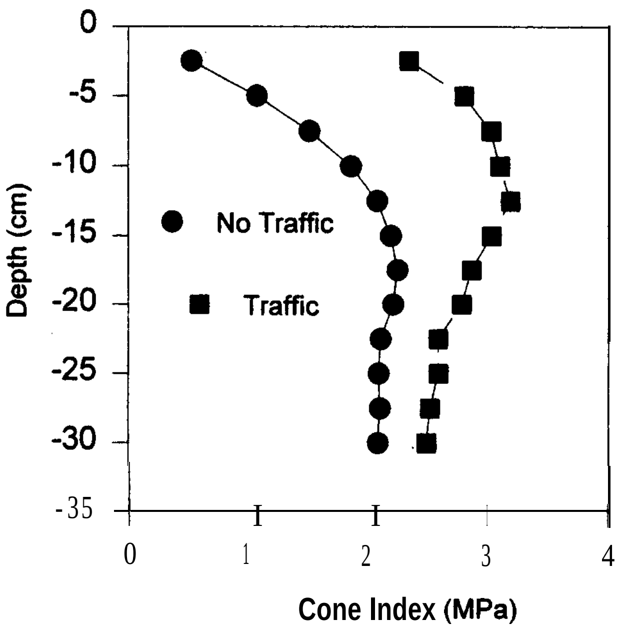

Figure 2-Cone index (MPa) measurements of a Gwinnett sandy loam subjected to no traffic (UNT) and traffic (TR). All depths are significantly different between treatments ($P > 0.001$).

Table 3-Comparison of soil physical properties at selected depths of a Gwinnett sandy loam subjected to two levels of trafficking

Treatment	Bulk density	Gravimetric water content	Air-filled porosity	Saturated conductivity
	Mg/m^{-3}	---------------Percent	----------------	Cm/hr^{1}
Traffic				
o- 10	1.57	21 .o	27.7	0.27
10-20	1.70	15.2	21.1	0.186
20 - 30	1.77	17.4	ND	ND
No Traffic				
o- 10	1.51	22.1	37.3	3.12
10-20	1.69	16.5	18.7	0.078
20 - 30	1.66	18.9	ND	ND

ND = no samples analyzed.

subsoil layer. Treatment alone did not significantly affect air-filled porosity but was significantly lower in subsoil layers than in surface layers. Saturated hydraulic conductivity of TR slightly exceeded UNT in the 10 to 20 Centimeter layer and is potentially explained by the higher porosity of this layer. Treatment, depth, and their interaction were significant sources of variation for saturated hydraulic conductivity. Saturated hydraulic conductivity in surface layers was significantly higher than in subsoil layers for both treatments, and conductivity was reduced significantly in the surface layer in trafficked soils.

Natural differences in soil physical properties between surface and subsurface layers may be present in highly weathered soils and potentially explained in terms of soil texture. Bulk density and soil strength increases with depth, under undisturbed conditions (UNT), occurred simultaneously with clay content increases and sand fraction decreases. Bulk density and soil strength are known to vary under the influence of particle size distributions in a soil layer (Carter 1990, Tuttle and others 1988). The presence of clay and very fine sand correlated well with higher bulk density and soil strength values in undisturbed profiles in North Carolina (Vepraskas 1988).

Machine traffic exacerbates natural conditions by packing soil particles closer together regardless of texture, and increasing bulk density and soil strength at the expense Of porosity (Greacen and Sands 1980). The impact of such activities is often limited to the near-surface soil environment, although changes in soil properties can be induced below 40 centimeters by increasing loads (Burger and others 1985, Greacen and Sands 1980). Soil strength data may corroborate this observation as the extent of impact from machine traffic was greatest in the upper 15 centimeters. Significant differences in CI between treatments at every depth may reflect the influence Of varying moisture conditions at the time of measurement. Cone index was determined in one replication under low moisture conditions rather than field capacity, which is necessary to minimize the influence of related soil factors on penetration resistance (O'Sullivan and others 1987). This may have overestimated soil strength when CI values were averaged for each treatment.

Loblolly Pine Root Proliferation

Root length proliferation within the soil profile was highest in the surface layer and tapered with depth. Root length densities were less than 4 centimeters per cubic centimeter at each depth interval, with a high standard deviation (table 4). The high standard deviations indicate a high degree of variability for root densities, which is typical of this type of data. Root proliferation increased in trafficked treatments (UNT vs. TR) from the pretraffic levels and appeared to be influenced by forwarder traffic. However, significant increase in root biomass in UNT also occurred. Regardless of the reason for these differences, total root biomass accumulation in the sampled profile in UNT and TR were similar, but distribution differences were evident. The

Table 4-Root length densities and standard deviations of a 15-year-old loblolly pine stand under pretraffic and trafficked conditions in a Gwinnett sandy loam

	Root length density		
		Posttraffic	
Depth	Pretraffic	Traffic	No traffic
Cm	----------------	Cm/cm^{-3}	----------------------
o- 10	3.72 (1.58)	17.87 (9.46)	6.39 (0.66)
10-20	1.99 (1.52)	3.57 (2.13)	20.07 (21.46)
20 - 30	1.72 (0.76)	2.50 (1.54)	1.92 (0.09)

majority of root mass accumulation in UNT occurred in the intermediate depth of 10 to 20 centimeters as opposed to TR, which experienced root proliferation in the surface layer.

Root length distribution under undisturbed conditions (pretreatment) was similar to root distributions reported for *Pinus elliottii* Engelm. and *P. radiata* (Davis and others 1983, Escamilla and others 1991). The natural decline in root length density with depth may reflect subsoil conditions that limited root growth and proliferation. The limited number of studies on the influence of soil physical properties on pine root growth have found root growth to be limited at bulk densities of 1.4 and 1.6 megagrams per cubic meter in a sandy clay loam and sandy soil, respectively, and at cone index values in excess of 3.0 MPa (Sands and Bowen 1978, Sands and others 1979, Tuttle and others 1988). Root response after trafficking may be the result of soil physical properties that changed in surface layers. This may have induced a large degree of proliferation due to its inability to penetrate below 10 centimeters. A similar situation had the potential to occur in UNT as naturally occurring limits were encountered at the 20 centimeter depth. The impact of traffic on root proliferation requires more indepth evaluation.

CONCLUSION

Forwarder traffic had a negative impact on the soil physical properties of a Gwinnett sandy loam. Significant changes occurred in soil strength and saturated hydraulic conductivity as a result of forwarder traffic. The impacts were greatest in the surface layer and, to a lesser degree, in subsoil layers. Root distribution within undisturbed profiles was relatively uniform but forwarder traffic appeared to induce root proliferation. The change in soil properties was consistent with other studies but root performance in trafficked plots did not agree with results reported by others.

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LOW COST FOREST OPERATION SYSTEMS FOR MIXED SPECIES MANAGEMENT

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Abstract-This is a summary paper about the development of forest operation systems for regenerating mixed pine and hardwood stands that reduce costs and environmental impacts by working more in concert with natural successional trends. The environmental impacts focus on protecting site productivity, primarily through reducing the impacts of forest operations on post-harvest soil movement. The cost savings result from not spending resources on trying to eradicate the hardwood component that develops naturally over time on these kinds of sites. The primary operations involve clearcutting the merchantable stand, felling the residual trees, implementing post-harvest site preparation burns, and planting pine seedlings at wide spacings among the hardwood regrowth. Timing of the residual felling affects fuel structure and subsequent intensity and uniformity of the post-harvest fire. A key step in protecting against excessive soil movement is to not consume the forest floor with the fire. As forest floor is reduced, soil movement increases. Timing of the residual felling also affects post-harvest fire behavior, early vegetative development of the hardwood regeneration, and small mammal population dynamics. We have results from a preliminary investigation into the interrelations that forest operations have with landform and edaphic properties of site. It links vegetative response to land units defined and delimited by an ecological classification system. This classification system uses landform and edaphic variables to predict the range of seral plant-community development to expect on a particular parcel of land. Preliminary results from a case study show how ecological units can respond differently when treated similarly.

INTRODUCTION

Seventy-five percent of the forest land base in the Piedmont region of the Southern United States is controlled by nonindustrial private forest (NIPF) landowners. The NIPF land base is large, but individual holdings are on the average small, which means that the number of landowners is large. The landholders own land for many different reasons, so it stands to reason that they have widely varying land-use objectives. A major disincentive for these landowners to practice good forest management is low unit value for stumpage due to an overabundance of low-quality timber and the risks associated with the long-term nature of forestry investments. The consequence Of these disincentives is a harvest-only management approach that removes marketable trees and leaves behind low-quality residual trees. The larger, low-quality residual trees disproportionately capture the site because of their size advantage relative to the regeneration that results from the harvest activities. This produces a negatively reinforcing cycle of increasingly poor-quality trees, and further erosion of the incentive for investing in higher future timber yields.

Industrial assistance programs for NIPF landowners, and government supported cost-share incentives have helped put some of these lands into productive pine plantations, but this effort is small relative to the magnitude of the problem. Furthermore, the objectives of pine plantation management are often too narrow for NIPF landowners, and the public incentive dollars used to create the plantations are becoming increasingly difficult to justify as tax dollar expenditures. Pine plantation establishment procedures are designed to reduce or temporarily eliminate the hardwood component that develops naturally in Piedmont stands, but these kinds of activities extract a high cost in terms of energy used and productivity lost through soil disturbance and nutrient loss from the site. The end result of these constraints is that a high percentage of the 21 million-acre NIPF land base is being stocked with timber Of low quality and/or lower than optimal density.

The guiding hypothesis for our overall research program has been that low-quality, mixed-species stands like those developing naturally on much of the NIPF land base can be cost-effectively managed for improved timber production as mixed southern yellow pine and hardwood stands. Naturally regenerated, largely low-quality, mixtures of pines and hardwoods are presently found on about one quarter (or about 7.1 million acres) of the total Piedmont commercial forest. This research has focused on how understanding the disturbance patterns and post-disturbance species composition responses that produce these pine-hardwood stands can be used to develop forest operation systems that work with nature. The result is operations that produce good-quality, well-stocked, pine-hardwood mixtures at less investment cost, with less impact to the site, and which meet a wider range of land management objectives than does the proven pine plantation system.

This paper does not report the results from a single study, with the usual detailed descriptions of the experimental design, methods, and results. Rather, it summarizes most of the literature that the USDA Forest Service and other research institutions have reported about pine-hardwood regeneration dynamics in the Piedmont physiographic region, and the implications these biological responses have On forest operation systems. The first group of studies deals with quantifying the effects of several forest operation scenarios on pine-hardwood regeneration dynamics and site productivity. We conclude by examining what a case study has to suggest about the potential role of ecological land classification on forest operation prescriptions, Or

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specifically: how ecological units can be used to relate vegetative response to forest operations using spatial measures of landform and soil attributes.

FOREST OPERATIONS FOR ESTABLISHING PINE-HARDWOOD MIXTURES

The rapid initial height growth of hardwood coppice relative to pines from seed or planted seedlings has been a source of concern to managers and researchers interested in establishing pine when hardwood competition is not controlled. As a result, initial research emphasis was on cost-effective means of controlling hardwood regeneration long enough to allow the shade-intolerant pines to become established as a component of the overstory canopy. McGee (1986, 1989) reported high survival and rapid growth of planted loblolly pines (*Pinus taeda* L.) after harvesting low-quality hardwood stands by chainsaw to a 4-inch lower diameter limit (with and without herbicide injection of residuals) and by shearing to a l-inch limit. Lloyd and others (1991) showed for the Appalachian foothills region of South Carolina that diameter growth of shortleaf pines (*P. echinata* Mill.) in pine-hardwood mixtures improved after release at age 4, but that release was not necessary to assure survival. In a study by McMinn (1989), naturally regenerated shortleaf, Virginia (*P. virginiana* Mill.), and loblolly pines were largely absent from areas harvested in the growing season and were suppressed in dormant-season commercial clearcuts that left large (relative to regeneration) residual trees.

Much of our research on hardwood control has centered on a set of operations described by Abercrombie and Sims (1986) which proved successful in the Southern Appalachian Mountains (Phillips and Abercrombie 1987). The technique includes a commercial clearcut followed by spring felling of residual hardwood stems (> 2 meters in height) and a summer broadcast burn. Felling and burning are designed to control hardwood sprout growth so pines can be established without eliminating hardwoods. Pines are planted the following winter at a wide spacing (15 by 15 feet or more) to reduce costs and to avoid early canopy closure of the pines over the hardwood, thus insuring that some hardwoods will receive direct light from above, and thus contribute significantly to merchantable stand growth.

Site preparation burning is an attractive operation for pine-hardwood regeneration in the mountains for several reasons. Burning is less expensive than mechanical site preparation and, if done properly, has less environmental impact. By burning in July, as suggested by Abercrombie and Sims (1986), hardwood sprouts are top-killed and new sprouts that emerge after burning have a shortened growing season. These new sprouts remain shorter than sprouts in unburned stands for 4 years or more, allowing pines a better chance to survive (Waldrop 1995). Sprout quality is improved by burning because stump sprouts are replaced by well-anchored basal or root sprouts (Augspurger and others 1989). Site preparation burning proved to be particularly attractive in areas with heavy coverage of mountain laurel (*Kalmia latifolia* L.) that would be too expensive to regenerate using mechanical control (Williams and Waldrop 1995).

Early trials of pine-hardwood regeneration in the Piedmont suggested that site preparation burning might be too risky (Waldrop and others 1989). In this region, forest floor thickness varies by site, but remains substantially thinner than in the mountains (Ball and others 1993). Therefore, the danger of exposing soil to erosion by consuming the forest floor organic layer is much greater in the Piedmont. For example, Van Lear and Kapeluck (1989) reported the loss of over 1.5 inches of topsoil during a g-month period after burning a Piedmont site that had been subjected to an extended dry period prior to the rain event that prompted the burn. Other than the weather conditions prior to the burns, the burning prescription used in that study was identical to one used in a previous study in the Appalachian foothills region in South Carolina (Van Lear and Danielovich 1988) where burning caused no increase in erosion. In this Piedmont experiment, the rainfall events that prompted the burn were insufficient to break the preceding drought, thus allowing the fire to totally consume the forest floor. This, coupled with the thinner organic layer characteristic of the Piedmont, resulted in damaging results.

Several studies are being conducted to learn how to use site preparation burning without causing erosion. Robichaud and Waldrop (1994) burned adjacent mountain sites using burning prescriptions that created conditions of low- and high-severity fire impacts (with regard to soil exposure). Low-severity burns were conducted 6 days after a 4-day rainfall event totaling 1.5 inches. For this burn, the moisture content of the litter layer was 65.2 percent. High-severity burns were conducted 14 days after a rainfall of 1.7 inches and with the moisture content of the litter layer at only 5.9 percent. Sediment loss for one year after burning totaled 2.33 tons per acre from the high-severity burns, but only 0.06 tons per acre from the low-severity burn (Stone and others 1995). Site productivity was reduced by high-severity burning with biomass production being two times greater in the low-severity sites (0.32 vs. 0.68 tons per acre). Even though high-severity burning reduced site quality, pine survival was significantly higher in the high-severity burn areas (77 percent in the high-severity area versus 58 percent in the low-severity). This result was attributed to increased vegetative competition on the low-severity sites.

Fire severity is also related to another operation used to establish pine-hardwood mixtures: the felling of residual hardwood stems. Residual stems are supposed to be felled by chainsaw crews during the spring when new leaves are almost fully developed. Broadcast burns are conducted 4 to 6 weeks after the stems are felled, generally in mid-July to early August. By that time, the fine woody fuels are dried sufficiently to burn intensely. Waldrop (1995) showed how fire behavior and fire severity is controllable by varying the season of the residual-stem felling. By felling during winter, foliage was not present. Therefore, the easily ignited leaf litter was limited to that found on the forest floor, and if burning conditions are as they should be, this material will be relatively moist and will not burn well, thus making it difficult to get the fire to carry between areas of accumulated slash. In spring-felled areas, dry leaves left on the felled residuals carried the fire, producing uniform burns across the entire study area, while winter felling produced a patchy burn pattern. The patchy burns for the winter felling operation may help meet some objectives by increasing early-successional plant and animal species diversity (Evans and others 1991) and contributing to early stand structural diversity by leaving more woody debris. Also, winter felling may reduce erosion by decreasing burn severity and leaving more debris dams; however, this effect has not been studied.

Even though winter felling may reduce erosion, it may not control hardwood competition as well as felling in spring. Phillips and Abercrombie (1987) suggested that spring felling would better control hardwood sprout growth than winter felling because spring felling is conducted when carbohydrate reserves in root systems have been exhausted by the early season growth initiation. Geisinger and others (1989) found that hardwood sprouts in the Piedmont region were shorter in spring-felled areas than in winter-felled areas after one growing season. However, by the end of six growing seasons the winter felling of residual stems, followed by a summer site preparation burn, had produced nearly identical stands to those regenerated by spring felling and summer burning (Waldrop 1997). Growth reductions from spring felling lasted only one growing season and had no apparent effect on stand development. This result suggests that the precise timing of felling as described by Phillips and Abercrombie (1986) is not as critical for the Piedmont ecosystem.

Several studies of regeneration techniques in the Piedmont suggest that little or no site preparation is needed to establish pine-hardwood mixtures on the medium-to-dry sites. Waldrop (1991) and Perry and Waldrop (1993) report on a study that harvested small groups in 0.10- and 0.33-acre openings, in a merchantable-sized hardwood stand, with the long-term goal of creating multi-aged, pine-hardwood stands. They found that edge trees reduced hardwood height growth in the opening more than that of planted loblolly pines. This pattern allowed the pines to overtop hardwoods within 2 years with no site preparation. In another study involving clearcutting the entire stand, Waldrop (1997) found that site preparation burning did not improve the survival or growth of planted loblolly pines. Pines overtopped hardwoods in burned areas by age 4 and in unburned areas by age 6 (fig. 1).

We know that hardwood regeneration is more abundant and faster growing on high productivity sites, so crown closure could occur on these better sites before pines reach the upper canopy. Additional research is needed to identify the kinds of sites where forest operation systems designed to regenerate pine-hardwood mixtures will work. Ecological land classification might have a role to play in improving these kinds of decisions.

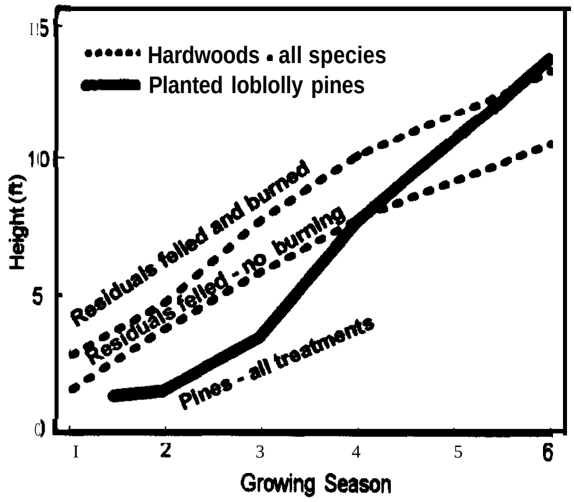

Figure 1-Mean height of natural hardwood regeneration (by site preparation treatment) and planted loblolly pines (all treatments combined) for 6 years after harvest.

USING ECOLOGICAL CLASSIFICATION IN PLANNING FOREST OPERATIONS

Pine-hardwood regeneration research in the Piedmont physiographic region has focused so far on the dryer-than-average sites. These results on dry sites suggest that little more than felling the non-merchantable residuals and planting pine with wide spacing is needed to get a productive pine-hardwood mixture. However, it is well known that hardwood coppice and advanced seedling regeneration will outgrow pine seedlings on the better sites. In the upland forest of the Piedmont region, an important productivity gradient is due to increasing soil moisture availability. Hardwoods are not only more sensitive to site productivity than pines, but they are also more abundant on the better sites. If we had a practical way to model moisture gradients, we might be able to tailor harvesting prescriptions to site conditions. Jones (1991) has developed a promising model of land classification for the Piedmont region that appears to capture a meaningful ecological gradient that has potential for helping tailor forest operation prescriptions.

A lot of soil-site research has tried, with very limited success, to develop predictor equations of site productivity using only a few key variables. Jones' (1991) approach recognizes the inherent difficulty in identifying a few predictor variables that will reliably quantify an ecologically meaningful gradient. In most cases, the gradients to which plants respond are very complex, involving the interplay of numerous variables, many of which we do not even know about. His approach is to let the plants do the integration of variables for us through the patterns of species birth, growth, and death that produce the range of plant communities we find developing on a site over time. Specifically, he investigates the presence and absence of plant species on reference sites, where reference sites are areas that have no signs of major species-eradicating disturbances. Classification methods are used to organize and present the results through the use of the relationship that species presence and absence has with spatially oriented landform, and edaphic variables. The spatial (or map oriented) nature of the landform and edaphic variables are then used to identify and delimit ecologically equivalent land units.

These spatially explicit, vegetation-derived, landform/ edaphic relationships are then used to delimit land units independent of vegetative cover presently on the land. This approach provides a way to sort out and categorize the wide array of seral communities that can occur across an entire region. The hypothesis is that the range of seral community development within ecological classes will be less than the range of seral communities encountered across all site units. This approach has provided an easy-to-use land classification format useful in organizing what experienced foresters learn intuitively from field observations about site and plant community relationships. We see potential for using the ecological classification to predict species compositional dynamics that follow specific forest operations on specific land units.

Although the pine-hardwood regeneration study reported by Waldrop (1997) was not designed to investigate the potential of Jones' model in aiding forest operation prescriptions, it did contain three site unit types (submesic, intermediate, and subxeric) within one treatment area. Guidelines in effect at the time the regeneration study was installed said that pine-hardwood regeneration should be restricted to south-facing slopes. This resulted in all plots in the regeneration study being located on subxeric ecological land classification units. At stand age 6, we installed four additional plots on the intermediate and submesic land units in one of the treatment areas of his study (two plots in each ecological unit), and compared the results with those on the subxeric units in the original study design. The results are presented in tables 1-3.

Table 1 shows that there is a dramatic change in hardwood stocking in terms of numbers of stems (greater than 6 feet tall) per acre between the submesic versus the intermediate and subxeric land units. Although pines (planted and naturally regenerated from seed) are present on all ecological units, table 2 shows pines making up only 15 percent of the total basal area on the submesic land units, compared to 45 and 46 percent, respectively, for intermediate and subxeric units. This is in spite of the fact that the numbers of pines are also much larger on the submesic site unit because of a large number of volunteers

Table l-Hardwood stocking by ecological unit

Unit	Stems	Basal area
	No./acre	*Ft²/acre*
Subxeric	760	6.8
Intermediate	920	5.6
Submesic	2960	16.8

Table 2-Planted pine stocking by ecological unit

Unit	Stems	Basal area	Survival
	No./acre	Percent	
Subxeric	140	46	72
Intermediate	130	45	76
Submesic	100	15	52

Table 3-Heights of dominant hardwoods and pines

Unit	Hardwoods	Pines
	Feet	
Subxeric	12.1	17.0
Intermediate	14.1	17.7
Submesic	16.4	15.4

seeded in from an adjacent pine stand. Most of these volunteer pines will die from being overtopped by the vigorous hardwood regeneration. The planted pine component on the submesic unit appears to have sufficient height to become a viable part of the mature stand; however, these pines are smaller in diameter and height than the corresponding set of planted pines on the intermediate and subxeric land units,

Since the goal is to develop pine-hardwood mixtures, the 6-year, average cumulative height growth of dominant oaks and pines is presented in table 3. "Dominant" means the tallest hardwoods at a density (numbers per acre) equivalent to the pine planting density. The hardwoods display the expected growth patterns of increasing average height to increasing site quality represented by the ecological land units. The lower total height of pine on the submesic area (15.7 feet on the submesic compare to an average of 17.4 feet on the intermediate and subxeric units) is attributed to hardwood competition effects. A further indication of the hardwood competitive effect is that at age 6 on the submesic unit, the tallest hardwoods averaged a foot taller than the pines. Although it cannot be determined from this study, the results raise the question of whether the pines would have survived at all without the summer fire treatment that set back the initial hardwood growth response. These results offer a working hypothesis that this kind of ecological land classification system has potential for tailoring our forest operation prescriptions to the land. Further research is needed to fully test this hypothesis.

CONCLUSIONS

These studies suggest that forest operations designed to develop pine-hardwood mixtures can produce productive timber stands and diverse plant communities at a lower cost and with less degradation to site quality than the intensively site prepared, pine plantation system. Mixed pine-hardwood stands meet a wider array of land management objectives and require less costly (both environmentally and economically) forest operations. The resulting pine-hardwood forest operation systems are well suited to the economic conditions and land management needs of many NIPF landowners.

Ecological classification offers a tool for transferring research results to the particular management application, and a way to tailor forest operations within stands. Although results are preliminary, indications are that without the use of a post-harvest site preparation fire, pine-hardwood management in the Piedmont will not work better on ecological site units than intermediate, that is, the mesic and submesic land units of Jones' model. Although mesic and submesic ecological land units are scarce in the Piedmont relative to the area composed of intermediate and subxeric land units, they nevertheless are productive pine-hardwood sites suitable for sawtimber management, in which case post-harvest fire would likely be needed to get a pine component established.

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CHARACTERIZATION OF DISTURBED FOREST SOILS IN THE LOWER COASTAL PLAIN OF SOUTH CAROLINA

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Abstract-Wet site harvesting operations may cause severe soil disturbances that may reduce long-term site productivity. Voluntary Forestry Best Management Practices (BMPs) have been developed to minimize and ameliorate the disturbances. However, the effects of soil disturbance on long-term productivity and the effects of amelioration techniques on site hydrology are uncertain. The objectives of this study were to characterize disturbed forest soils to understand the mechanisms of the disturbance and the potential effects on site hydrology and site productivity. The study site is located in an intensively managed loblolly pine plantation in the lower coastal plain of South Carolina. Dry and wet weather harvesting treatments were installed in summer 1993 and winter 1994, respectively. Soil profiles were described for recently disturbed, deeply rutted areas and 2-year-old, deeply rutted and churned areas. Intact soil core samples were collected from each morphological section for soil physical and hydraulic characterizations. Soil profile descriptions disclosed significant soil structural changes and increased redoximorphic features caused by deep ruts indicating decreases in hydraulic conductivity. Preliminary results of soil physical and hydraulic properties indicated significant change in the site hydrology. Although recent deep ruts showed directional hydraulic characteristics, the characteristics disappeared 2 years after the disturbances, which suggested that natural soil restructuring processes were taking place.

INTRODUCTION

Long-term forest productivity of intensively managed pine plantations has become a major concern among natural resource managers and environmental conservationists since the 1950's, when harvesting operations became more mechanized. Heavy harvesting equipment may cause severe soil disturbance when forest sites are wet. A number of studies around the world have indicated that forest productivity may decline under certain circumstances (Powers and others 1990). In a review paper by Powers and others (1990), decreased productivity of Norway spruce [*Picea abies* (L.) Karst] in Europe, radiata pine (*Pinus radiata* D. Don) plantations in Australia, and Scots pine (*P. sylvestris* L.) in eastern Germany were caused by organic matter decreases and/or soil compaction which created poor drainage. These soil changes caused nutrient deficiencies and created an imbalance in soil water and air availability.

In the U.S. southeastern coastal plain, pine flatwood productivity declines were also reported. Gholz and Fisher (1983) estimated that a natural long leaf pine (*P. palustris* Mill.) forest produced approximately 450 to 600 cubic meters per hectare, almost twofold the productivity of current slash pine (*P. elliottii* Engelm.) plantations, and concluded that organic matter removal during intensive harvesting and site preparation operations caused productivity decreases on the typical flatwood soils (Typic and Ultic Haplaquods) found in their study sites. Tiarks and Haywood (1996) evaluated the effect of disking and bedding site preparations on the productivity of slash pine plantations in the West Gulf Coastal Plain of Louisiana. They concluded that site preparation in the first rotation depleted nutrients and decreased second-rotation pine height.

Earlier researchers recognized severe disturbance after harvesting and its negative effects on tree growth. Pearson and Marsh (1935) found that soil disturbance by grazing and logging operations on wet clayey-textured soil created adverse conditions for seedling establishment because of reduced water and air permeability. Moehring and Rawls (1970) documented organic matter loss from sites harvested under dry conditions, and organic matter loss and soil compaction, puddling, and smearing on sites harvested under wet conditions. Youngberg (1959) reported that a significant increase in bulk density in the surface 0 to 30 centimeters, and a decrease in organic matter on tractor roads reduced soil aeration and created a nitrogen deficiency. These effects significantly decreased Douglas-fir [*Pseudotsuga menziesii* (Mirb.) Franco] seedling growth. Hatchell and others (1970) found that a significant change after harvesting in soil physical properties in low-lying wet areas reduced loblolly pine (*P. taeda* L.) seedling growth. Scheerer and others (1994) compared loblolly pine seedling response between rutted and undisturbed sites and found higher mortality and lower seedling growth in the rutted sites. They concluded that the results were caused by a higher water table, decreased saturated hydraulic conductivity, and decreased soil drainage due to the soil disturbance.

Although numerous studies have characterized compacted agricultural and forestland soils (Hillel 1982, Pritchett and Fisher 1987, Marshall and others 1996), the morphology and physical characteristics of deeply rutted and churned forest soils are not well documented. Burger and others (1988) found that soil horizons may be severely disturbed in wet skid trails. Aust and others (1995) compared dry and wet weather harvesting effects on soil physical properties in a wet pine flat. They concluded that dry weather harvesting created soil compaction and subsequent soil physical property changes on primary and secondary skidding trails,

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and wet weather harvesting created more severe soil disturbance and complex soil physical property changes which increased water tables.

Severe disturbance can cause drastic soil hydraulic property alteration. Rutted and churned soils have different soil water release patterns than undisturbed soils (Jamison 1963, Gradwell 1966, Huang and others 1996). Jamison (1963) conducted a laboratory experiment of disturbed soil physical properties and found that macroporosity and available water-holding capacity of puddled soils were significantly lower than those of other disturbed soils. Huang and others (1996) reported significant decreases of sorptivity and unsaturated hydraulic conductivity after harvesting operations. These laboratory experiments and field studies indicate that puddled soils contain less available water and lower water infiltration rates, both of which create less desirable conditions for seedling growth. Forest soil disturbances produced by heavy equipment are deeper and more severe than pasture soil disturbances, suggesting that heavier equipment may have a more significant effect on soil physical and hydrological properties and future forest productivity.

Despite the concern among environmental managers and the efforts of many researchers, the soil disturbance effect on site hydrology and future forest productivity is still relatively unknown, and harvesting and amelioration techniques on wet sites have not been rigorously evaluated. Therefore, detailed characterization of disturbed forest soils is critical for understanding mechanisms of disturbance and for predicting potential effects on site hydrology and site productivity. The objectives of this study are to characterize disturbed forest soil morphology and physical properties in order to understand the processes that control site hydrology and productivity.

MATERIALS AND METHODS

This disturbed soil characterization study was conducted as part of a long term soil productivity study located in an intensively managed loblolly pine plantation in the lower coastal plain of South Carolina. The area is a typical wet pine flat. The majority of the soils within the study area were Typic Ochraqualfs. These Alfisols typically have a heavy clay argillic Bt horizon at a depth of 50 to 60 centimeters and an incipient E horizon just above the Bt. Drainage classes of these soils are intermediate to poorly drained, as indicated by “aquic” suborder or subgroup taxonomic classes, and these soils are considered hydric soils (Soil Conservation Service 1991).

The study was established in 1991 and included dry and wet weather harvesting and several mechanical treatments. Details of the study layout and project design are contained in Preston (1996). Dry and wet weather harvesting treatments were installed in summer 1993 and winter 1994, respectively, and site preparation treatments were installed in fall 1995.

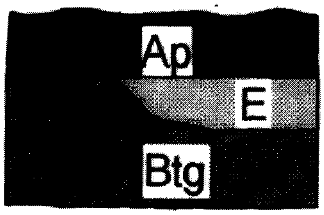
Soil profiles were described at 2-year-old deeply rutted and churned areas within the wet, nonbedded plots of the study site and at recently created deep ruts on similar soils near the study site. Intact soil core samples were collected from each morphological section (horizons) (Blake and Hartge 1986) in horizontal and vertical directions. These intact cores were used for soil physical characterization and directional hydraulic characterization. Soil physical characterization included bulk density (Blake and Hartge 1986) and macro-, micro-, and total porosity (Danielson and Sutherland 1986). Hydraulic characterization included saturated hydraulic conductivity (Klute and Dirksen 1986) and air permeability (Groenevelt and Lemoine 1987). Soil structural stability index, expressed as the ratio between air permeability and water permeability (k_{air}/k_{water}) (Whelan and others 1995), was also measured to evaluate soil structural changes resulting from soil disturbances. Water permeability (k_{water}) was calculated from saturated hydraulic conductivity by an equation developed by Hubbert (1940). Soil strength of each morphological section was measured using a pocket penetrometer (Bradford 1986). These results were compared to typical intact and undisturbed soil profile descriptions (Soil Conservation Service 1982) and soil physical properties reported by Burger (1994).

RESULTS AND DISCUSSION

Soil Profile Description

The soil profile descriptions revealed that significant changes had occurred in surface and subsurface horizons (fig. 1). Typical undisturbed soils contained incipient E horizons and well-developed argillic horizons (Soil Conservation Service 1982). All disturbed soils contained disturbed surface and subsurface horizons above undisturbed subsurface horizon (Bt or Btg), and no E horizon was observed in any disturbed soils (fig. 1). Disturbed surface horizon was designated as Ap or Apl , and surface horizon within the ruts was designated as Ap’. Disturbed subsurface horizons were designated as Ap2 and Ap3 in the fresh, deep ruts, Ap2 and Apg in the 2-year-old deep ruts, and Apg in the e-year-old churn. Disturbed subsurface horizons were characterized by loam to silty clay textures, which were probably caused by physical mixing of surface and subsurface soils. Gray or dark grayish matrix colors were common, due to the inclusion of few-to-many distinctive mottles. Structure was predominantly massive with fragments of weak platy or subangular blocky structure caused by normal and shear stresses from surface disturbances. These characteristics indicated a change in saturated hydraulic conductivity or internal soil water drainage patterns. Burger and others (1988) reported similar soil characteristics caused by the wet weather harvesting operations and found severely disturbed subsurface soil horizons under the disturbed surface horizon.

Distinctive characteristics of the deeply rutted soils are deep skidding ruts and associated disturbed soil structures within the ruts (fig. 1). Fresh deep ruts contained a churned and compressed horizon (Ap’) along the side and bottom of ruts. Many coarse, prominent, mottle patterns, oriented with a weak medium platy structure in the horizon, indicated restricted water movement (low lateral water flow from ruts

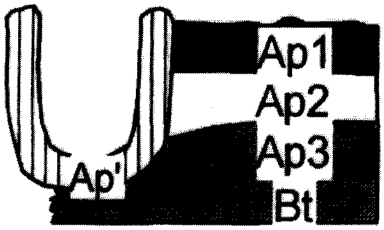


Undisturbed (Soil Conservation Service 1982)

Ap ---- 0 to 13 centimeters; very dark gray (10YR3/1) loam; moderate medium granular structure; friable; many fme, common medium, and common large roots; very strongly acid; clear wavy boundary.

Btgl ---- 13 to 86 centimeters; grayish brown (10YR5/2) clay, common medium distinct brownish yellow (10YR6/6) mottles; moderate medium subangular blocky structure; firm; sticky, plastic; few fme and few medium roots; prominent clay film on faces of peds; few fme flakes of mica; very strongly acid, gradual smooth boundary.

Btg2 - - 86 to 145 centimeters; gray (10YR5/1) clay; common medium distinct olive brown (2.5Y4/4) mottles; moderate medium subangular blocky structure; firm; very sticky; very plastic; few fme roots; thin patchy clay film on face of peds; few fine flakes of mica; medium acid.



Fresh deep ruts

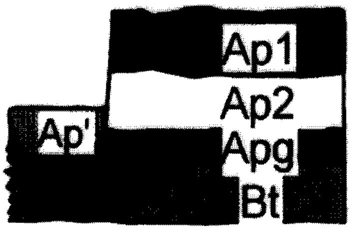
Apl ---- 0 to 25 centimeters; very dark gray (10YR3/1) silt loam; weak fme granular structure; firm; nonsticky; nonplastic; few fine roots; abrupt wavy boundary.

Ap2 ---- 25 to 5 1 centimeters; dark grayish brown (2.5Y4/2) loam, few fme prominent yellowish brown (10YR5/6) and gray (10YR5/1) mottles; massive structure with fragments of weak medium subangular blocky and platy; frm; slightly sticky; slightly plastic; few fine roots; clear wavy boundary.

Ap3 --- 51 to 76 centimeters; light yellowish brown (2.5Y6/4) silty clay loam; common medium distinct reddish yellow (7.5YR6/8) and grayish bmwn (2.5Y5/2) mottles; massive structure with weak medium subangular blocky; friable; slightly sticky; slightly plastic; few fine roots; clear wavy boundary.

Bt ---- 76 to 102 centimeters; light olive brown (2.5Y5/4) silty clay; common medium distinct yellowish red (5YR5/8) and weak red (2.5YR5/2) mottles, moderate tine subangular blocky structure, friable; slightly sticky; slightly plastic; few medium roots; few faint clay film on faces of peds.

Ap' - - olive (5Y5/3) loam, many coarse prominent yellowish brown (10YR5/8) and grayish brown (2.5Y5/2) mottles; weak medium platy structure; slightly plastic; few very fine roots; clear irregular boundary.



2-yr old deep ruts

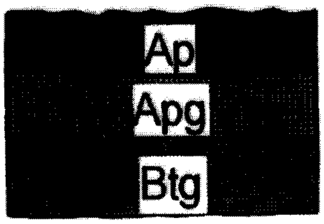
Apl -- 0 to 8 centimeters; very dark grayish brown (10YR3/2) silt loam; weak fine granular structure, friable; nonsticky; nonplastic; common very fme roots; clear smooth boundary.

Ap2 ---- 8 to 33 centimeters; dark grayish brown (2.5Y4/2) fme sandy clay loam; few fine prominent strong brown (7.5YR5/8) and gray (N5/0) mottles; massive structure; slightly sticky; slightly plastic; few very tine roots; gradual wavy boundary.

Apg ---- 33 to 61 centimeters; olive (5Y5/3) silty clay; many coarse prominent (5GY5/1) and yellowish brown (10YR5/8) mottles; massive structure with fragments of weak medium platy; slightly sticky; slightly plastic; few very fme roots; common faint stress surfaces on face of peds; gradual wavy boundary.

Bt ---- 61 to 102 centimeters; olive (5Y5/3) fine sandy clay; many medium prominent yellowish brown (10YR5/6) and gray (N5/0) mottles; moderate coarse subangular blocky structure; firm; sticky; slightly plastic; few fine roots; few faint clay film on faces of peds.

Ap' ---- very dark grayish brown (2.5Y3/2) loam; weak tine granular structure; nonsticky; nonplastic; common very fine roots; clear irregular boundary.



2-yr old chum

Ap ---- 0 to 28 centimeters; very dark gray (5YR3/1) silt loam, moderate medium granular/massive structure; firm; nonsticky; nonplastic; many very fine roots; abrupt wavy boundary.

Apg ---- 28 to 48 centimeters; very dark gray brown (10YR3/1) silty clay loam; many medium prominent dark reddish brown (5YR3/4) and very dark gray (10Y3/1) mottles; massive structure; firm; slightly sticky; plastic; common vary few fine roots; clear wavy boundary.

Btg --- 48 to 89 centimeters; olive (5Y5/3) silty clay; many fme pmminent dark gray (N4/0) and brownish yellow (10YR6/8) mottles; moderate medium subangular blocky structure; fum; sticky; slightly plastic, few tine roots; few faint clay film on face of peds; few medium irregular carbonates concretion.

Figure l-Soil profile descriptions of undisturbed and disturbed soils in the lower coastal plain wet pine flats.

into soil). This reduced water flow probably caused higher water tables and slower drainage in the rutted sites. Two years after the disturbance, this churned horizon was weathered and deposited in the bottom of ruts (Ap') (fig. 1). This deposited horizon had relatively high organic matter and weak fine granular structure. Consequently, a cross section of soil horizons was exposed in the side of the ruts, and lateral water infiltration was less restricted, which may have improved site hydrology.

Soil Physical and Hydraulic Properties

Although harvesting operations caused extensive rutting, the soil physical properties were not altered in the surface horizons to the same extent as in the subsurface horizons. Disturbed surface horizons (Ap and Ap1) generally had lower bulk density and higher porosity, strength, and saturated hydraulic conductivity than disturbed subsurface soils, and those properties were relatively similar to the undisturbed surface soil properties (table 1). Negative soil physical property changes in surface horizons, which had been reported by many studies (Pearson and March 1935, Youngberg 1959, Moehring and Rawls '1970, Hatchell and others 1970, Aust and others 1993, 1995), were probably prevented by mixing various sizes of organic debris during the operation. In 2-year-old, deep ruts, natural weathering processes formed the Ap' in the bottom of the ruts (fig. 1); therefore, the Ap' properties were very close to the undisturbed surface horizon.

Although the disturbed subsurface horizons have intermediate soil textures between Ap and Bt horizons (fig. 1), the physical and hydraulic properties of the disturbed horizons were more similar to the Bt horizon (table 1). Bulk density of the disturbed subsurface horizons ranged between 1.29 to 1.47 megagrams per cubic meter, similar to the bulk density of the Bt horizons which ranged between 1.25 to 1.48 megagrams per cubic meter. These high bulk density may restrict root penetration since a bulk density of 1.4 megagrams per cubic meter commonly limits root growth.

Porosity of the disturbed subsurface horizons was similar to those of Bt horizons. Macro-, micro-, and total porosity of

Table l--Soil physical and hydraulic properties of undisturbed and disturbed soils in a wet pine flat[a]

Horizon	BD[b]	n_{macro}[c]	n_{micro}	n_{total}	σ[d]	K_{sat}[e]	k_{air}[f]	k_{air}/k_{water}
	Mg/m^3	Percent				Kg/cm^2	m/day	$m^2 x 10^{-13}$
Undisturbed"								
Ap	1.18	13.1	39.1	52.2	NA	8.22	NA	NA
E	1.64	14.5	21.2	35.7	NA	0.72	NA	NA
Bt	1.45	6.1	40.5	47.0	NA	0.09	NA	NA
Fresh deep ruts								
Ap1	1.05 a[i]	4.0 a	38.9 a	42.9 a	1.61 a	3.12	1.72 ab	15.6 a
Ap2	1.46 c	1.3 b	31.0 b	32.3 b	1.81 a	0.02	2.19 a	22.7 a
Ap3	1.47 c	0.9 b	31.4 b	32.5 b	2.29 b	0.00	1.46 ab	93.4 b
Bt	1.25 b	2.5 ab	36.2 a	38.7 a	1.56 a	0.05	1.88 ab	63.6 ab
AP'	1.45 c	0.9 b	31.8 b	32.7 b	1.76 a	0.01	0.96 b	27.4 a
2-yr-old deep ruts								
Ap1	1.11 a	5.7 a	43.5 a	49.2 a	0.43 b	2.73	2.48 ab	0.77 a
Ap2	1.47 c	1.6 b	30.3 c	31.9 c	0.99 c	0.00	2.17 ab	94.6 b
Apg	1.29 b	1.3 b	37.6 b	38.9 b	0.82 c	0.00	1.65 bc	86.3 b
Bt	1.48 c	1.1 b	28.1 c	29.2 c	1.53 d	0.00	0.83 c	52.8 ab
AP'	1.09 a	5.1 a	38.4 b	43.5 b	0.14 a	3.57	2.84 a	0.97 a
2-yr-old churn								
Ap	0.62 a	8.5 a	48.7 a	57.2 a	0.26 a	14.2 a	2.65 a	0.06 a
Apg	1.35 b	3.4 b	31.1 b	34.5 b	0.95 b	0.03 b	2.85 a	102.5 b
Btg	1.43 c	1.6 b	30.5 b	32.1 b	1.48 c	0.02 b	1.47 b	21.2 ab

[a] Values are means of six samples.
[b] Bulk density.
[c] Macro, micro, and total porosity.
[d] Soil strength, corresponding gravimetric soil moisture content are Ap ≅ 15% and B and C ≅ 18-26%.
[e] Saturated hydraulic conductivity.
[f] Air permeability.
[g] Soil structure index.
[h] Data are from Burger 1994, and no statistical analysis is available.
Means followed by the same letter within a column and soil profile are not significantly different according to Fisher's LSD at a 0.05 probability level.

disturbed subsurface horizons ranged 0.9 to 3.6 percent, 30.3 to 37.6 percent, and 31.9 to 38.9 percent, respectively (table 1). These results were clearly lower than those of surface horizons but similar to those of undisturbed subsurface horizons. The lower macro- and micro-porosity and higher bulk density values of the disturbed horizons suggested that their water holding capacities were decreased significantly.

Saturated hydraulic conductivity was so variable that statistical differences were not discernible among horizons. However, the data trends indicated that the disturbed subsurface horizons had significantly lower saturated hydraulic conductivity than the surface horizons, but they were not significantly different from Bt horizons (table 1). The low saturated hydraulic conductivity of disturbed horizons was caused by the lower macro-porosity and reduced total porosity. Aust and others (1993, 1995) found similar results in lower coastal plain wet pine flats.

Disturbance altered the intrinsic permeability of subsurface horizons. The air permeability of disturbed subsurface horizons was relatively higher than that of associated Bt horizons, and their stability indexes were significantly higher than those of other horizons because of the high ratio between air and water permeability (table 1). Hubbert (1940) showed that permeability was a function of matrix structure, not a function of media. Therefore, as structure becomes more stable, the stability index approaches 1 (Whelan and others 1995). The high stability index of the disturbed horizons indicated weakened soil structure and decrease of internal drainage due to the disturbance, which explained the massive soil structure and gray mottling in the soil profile descriptions (fig. 1).

Soil strength is an integrated measurement of soil properties. Soil strengths of disturbed horizons in the 2-year-old, deep ruts and churn were significantly lower than these of associated Bt horizons, even though the bulk density values of the disturbed horizons were about the same as those of the Bt horizons (table 1). This is explained by physical mixing of the soils, alteration of soil textures, massive soil structures (fig. 1), and higher soil stability indexes of the disturbed horizons.

Directional Hydraulic Properties

Fresh deep ruts had significantly different vertical and horizontal air permeability values among horizons (table 2). Vertical air permeability was higher than horizontal air permeability in the surface horizon (Apl), which indicated that infiltration of surface water was not restricted. However, in the disturbed subsurface horizons (Ap2 and Ap3), vertical air permeability was lower than horizontal air permeability, which indicated a restriction of vertical permeability. These characteristics probably caused a higher water table in the disturbed sites. In the churned horizon inside of the ruts (Ap'), vertical air permeability (parallel to the platy structure) was higher than horizontal air permeability (perpendicular to the platy structure), which indicated low water infiltration from ruts into the soil. This

Table 2-Vertical and horizontal direction air permeability measurements in the fresh deep ruts[a]

Direction	Ap1	Ap2	Ap3	Bt	Ap'
Vertical	2.17[b]	1.97	1.36	2.64	1.55
Horizontal	1.25	2.42	1.57	1.12	0.36

[a] Values are means of three samples.
[b] Overall p-value = 0.022 from ANOVA test.

was probably causing slower drainage in the disturbed site. However, 2-year-old, deep ruts and churned soils did not show directional permeability differences, which indicates that natural soil restructuring processes occurred during the 2 years.

CONCLUSIONS

Preliminary results of soil profile descriptions and soil physical and hydraulic property measurements described disturbed soil characteristics. Although harvesting operations caused extensive rutting, the soil physical properties of the surface horizons were not altered because of incorporation of organic matter. However, disturbed subsurface horizons were affected significantly by the operations. Soil profile descriptions showed that the disturbed subsurface horizons had different horizonations, mixed texture, weakened structure, and increased redoximorphic features. Significant soil physical and hydraulic property changes indicated lower water-holding capacity and available water for plant growth, and slower internal drainage and water sorptivity, which explained the higher water table, slower site drainage pattern, and consequent alteration of site hydrology. The difference between vertical and horizontal air permeability in the fresh deep ruts indicated restricted surface water infiltration and limited lateral perched water flow through the ruts. However, this restricted water movement was improved after 2 years, probably due to natural soil restructuring processes.

This study showed that altered properties of the disturbed subsurface horizons remained 2 years after disturbance. Bedding is a common site preparation technique used in wet pine flats to ameliorate the soil disturbances. Although Gent and others (1983) found that bedding site preparation did not ameliorate disturbed subsurface horizons, a number of other studies showed that bedding improved surface soil conditions and seedling survival in wet sites (Haines and Prichett 1964, Derr and Mann 1977, Pritchett 1979, Sarigumba and Anderson 1979, Shiver and Fortson 1979). Therefore, bedding site preparation is probably the best current solution for disturbed soil amelioration, although long-term effect of disturbed subsurface horizons on site hydrology and future productivity is still unknown.

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AMELIORATION OF COMPACTED AND RUTTED SKID TRAILS ON WET PINE FLATS: FOURTH-YEAR RESULTS

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Abstract-Wet-weather harvesting operations on wet pine fiats can cause soil disturbance that may reduce long-term site productivity. Site preparation and fertilization are often recommended as ameliorative practices for such disturbances, but few studies have actually quantified their effects on restoration. The purposes of this study were to quantify the effects of wet-weather harvest traffic on soil properties and loblolly pine (*Pinus taeda*) growth, and to evaluate the ameliorative effects of site preparation. Study sites were established on wet pine flats of the lower coastal plain within the Francis Marion National Forest (Berkeley County, SC). Eight replications were installed on sites that were salvage logged during wet soil conditions, following Hurricane Hugo. Treatments were arranged in a split-split plot within a completely randomized block design. Treatments were two levels of traffic (nontrafficked, trafficked), four levels of mechanical site preparation (none, disking, bedding, disking with bedding), and two levels of fertilization (none, 300 pounds per acre of 10-10-10 fertilizer). Initially, the trafficking increased soil bulk densities and reduced soil water movement and subsequent growth of loblolly pine. Bedding combined with fertilization restored site productivity to nontrafficked levels within 4 years, but disking or fertilization treatments alone were not effective at ameliorating the traffic effects. The effectiveness of the bedding and fertilization treatments for amelioration of traffic effects was probably related to the relatively small area of disturbed skid trails (<10 percent) found on these sites. Areas having more severe disturbance or higher percentages of disturbance might not be ameliorated as rapidly.

INTRODUCTION

Wet pine flats of the southeastern coastal plain typically have coarser textured surface soil horizons over finer textured argillic horizons (Allen and Campbell 1988). Consequently, vertical soil water movement is often limited by the subsurface horizon, while the almost level topography of the lower coastal plain limits horizontal water movement within the surface horizon. Thus, these wet pine flats often have perched water tables in close proximity to the soil surface. However, wet pine flats are often specifically selected for wet weather harvesting operations because of the slow water movement within the subsurface soils. Following rainfall events, the surface soil horizons moisten within hours, but the argillic horizons moisten very slowly. Therefore, the subsurface soil horizon retains high soil strength, even after rainfall events, which can support heavy harvesting equipment until the horizon eventually moistens. Loggers often refer to such sites as having a “hard bottom” and operations can continue on these sites long after rainfall events have halted operations in other areas. However, these wet weather harvesting operations can result in considerable amounts of soil compaction and rutting, which have been suggested as possible causes of reduced long-term site productivity (Aust and others 1993, Burger and others 1989, Childs and others 1989, Hatchell and others 1970, Lockaby and Vidrine 1984).

Soil aeration and soil nutrition are often limiting factors on wet pine flats (McKee and Hatchell 1987). Harvest operations that rut and compact soils have been shown to reduce soil water movement and soil oxygen levels, and reduce the volume of soil from which nutrients can be extracted (Aust and others 1995). The natural recovery time of wet pine flats from harvest disturbances has been estimated as being 15-20 years (Hatchell and Ralston 1971). Therefore, several researchers have proposed that these mechanical and chemical amendments should be used for amelioration of disturbed forest soils (Foil and Ralston 1967, Gent and others 1983, Hatchell 1981, McKee and Hatchell 1987, Tiarks and Haywood 1996, Wilhite and McKee 1986). The normal technique for the establishment of loblolly pine (*Pinus taeda*) plantations on wet flats usually entails some combination of mechanical site preparation or fertilization (Allen and Campbell 1988). The objectives of our investigation were to determine whether wet weather harvest traffic affected soil, hydrologic, and site productivity parameters and whether such disturbances could be ameliorated by site preparation and fertilization.

METHODS

Study Site

The research was conducted on wet pine flats located within the Francis Marion National Forest in Berkeley County, SC. These lower coastal plain sites were somewhat poorly to poorly drained. The Francis Marion National Forest was heavily damaged by Hurricane Hugo in September 1989, and many salvage operations were conducted during saturated soil conditions in an effort to salvage downed wood and reduce subsequent wildfire fuel loads. In effect, many of these salvage operations were clearcuts because fewer than five live trees per acre remained following the storm. Sites were selected so that within-site soil variation was limited to one soil series. Three soil series were identified across all sites. The very poorly drained to poorly drained Bethera series is a clayey, mixed, thermic, typic Paleaquult. A typical Bethera series profile

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consisted of a loamy surface underlain by a clay-textured argillic horizon. The poorly drained Rains series is a fine-loamy, siliceous, thermic Typic Paleaquults. The Rains series had a sandy loam surface texture and sandy clay loam subsurface texture. Both the Bethera and Rains series are hydric soils. The nonhydric, somewhat poorly drained Lynchburg series was identified on only one site. The Lynchburg series is a fine-loamy siliceous, thermic Aerenic Paleaquult having sandy loam surface textures underlain by sandy clay loams (USDA Soil Conservation Service 1980).

Treatments

All sites were salvage-logged with chainsaw felling and grapple skidders during saturated soil conditions in the late fall and winter of 1989. In winter 1989 and spring 1990, 12 sites were selected. Each site represented one replication. All sites were typical wet-weather harvests, each had obviously compacted and rutted primary skid trails (< 10 percent of the total area) and nontrafficked areas. Eight 20-feet by 80-feet treatment plots were located within each site. Four of these treatment plots were located in the trafficked primary skid trails and four were located in the nontrafficked areas. During 1990, soil physical, soil chemical, and site hydrological evaluations were completed as reported by Tippett (1992) and Aust and others (1995). In September, 1991, each treatment plot in the two disturbance classes (trafficked skid trail or nontrafficked) received one of the following site preparation treatments: none, disking, bedding, or disking with bedding. Each of these site preparation treatment areas were split into two 20-feet by 40-feet fertilization treatment areas; one of these split plots received no fertilization while the other received 300 pounds per acre of 1 O-l O-l 0 fertilizer. Loblolly pine seedlings were hand-planted in February 1992.

Measurements

Postharvest and presite preparation measurements were conducted during the spring, summer, and fall of 1990 in order to characterize the soil physical properties within all trafficked and nontrafficked areas prior to site preparation. Detailed descriptions of these measurements and results are provided by Tippett (1992) and Aust and others (1995).

Following site preparation, soil and hydrologic characterizations were conducted in the 1992 growing season and second-year seedling growth was measured in fall 1993 as described by Scheerer (1994) and Scheerer and others (1995). During the late winter of 1996, fourth-year growth measurements were taken. Total tree heights were measured to the nearest 0.05 meter with a height pole, and diameters were measured to the nearest centimeter with diameter tapes. After 4 years, only eight of the original twelve replications remained; four had been compromised by wildfires. Therefore, all data from presite preparation, 2-years after site preparation, and 4-years after site preparation were re-analyzed with only eight replications. All data were analyzed as a split-split Plot within a completely randomized block design (Steele and Torrie 1980) as presented in table 1. If significant effects were detected (P-value c 0.1), then a Fishers Protected LSD test was used to separate the means.

Table l-Generalized analysis of variance table

Source of variance	Degrees of freedom
Replication	7
Traffic	1
Error a	7
Site preparation	3
Site preparation X traffic	3
Error b	42
Fertilization	1
Fertilization X traffic	1
Fertilization X site preparation	3
Fertilization X traffic X site preparation	3
Error c	56
Total (corrected)	127

RESULTS AND DISCUSSION

Effects of Traffic Prior to Site Preparation

The traffic associated with the primary skid trails caused by wet weather harvesting had several effects on the soil physical and hydrologic properties prior to site preparation (table 2). Within the primary skid trails, soil bulk density values were higher and these increases in soil bulk density resulted in reduced soil macropore space. Macropore space is critical for internal soil drainage and aeration of the soil rooting zone (Greacen and Sands 1980). The reduction of macropore space within the trafficked areas was reflected by reduced saturated hydraulic conductivity values within the skid trails and higher water tables below the skid trails (table 2). Overall, the initial effect of the disturbance was to decrease drainage of these poorly drained soils. These results emphasize the need for some type of amelioration for compacted and rutted sites.

Two-Year Effects of Traffic and Site Preparation

Site preparation effects on soil and vegetative properties were evaluated after the second growing season (tables 3 and 4). Site preparation did not significantly affect soil bulk

Table 2-Traffic effects on soil physical and hydrological properties prior to site preparation (Tippett 1992)

Treatment	Bulk density	Macro-pore space	Saturated hydraulic conductivity	Relative water table
	Mg/M³	*Percent*	*Cm/hour*	*Cm*
Non-trafficked	1.24 b	15.2 b	5.2 a	0.0 a
Trafficked	1.39 a	5.9 a	1.6 b	+18.0 b

Table 3-Traffic and site preparation effects on soil properties 2-years after treatment installation (Scheerer 1994)

Treatment	Bulk density	Macro-pore space	Saturated hydraulic conductivity
	Mg/M³	*Percent*	*Cm/hour*
Non-trafficked			
None	1.22 a	15.1 c	5.0 c
Disking	1.23 a	12.5 b	0.5 a
Bedding	1.25 a	14.3 c	2.9 bc
Disking and bedding	1.25 a	14.6 c	2.2 b
Trafficked			
None	1.33 b	2.6 a	1.0 a
Disking	1.38 b	2.7 a	0.5 a
Bedding	1.29 b	13.3 bc	1.4 ab
Disking and bedding	1.34 b	9.9 b	0.5 a

Table 4-Traffic and site preparation effects on loblolly pine growth 2 years after treatment installation (treatment values include fertilized and nonfertilized treatment data; Scheerer 1994)

Treatment	Total height	Diameter at breast height[a]
	----m----	——Cm——
Nontrafficked		
None	0.6 bc	0.9 b
Disking	0.5 b	0.9 b
Bedding	0.8 c	1.7 d
Disking and bedding	0.9 c	1.8 d
Trafficked		
None	0.2 a	0.4 a
Disking	0.3 a	0.8 b
Bedding	0.6 bc	1.2 c
Disking and bedding	0.5 b	1.1 c

[a] Includes trees that were too short to have d.b.h. values. Diameter recorded as 0 centimeter for those trees.

density values, but the harvest traffic effects on bulk density were still evident. Overall, trafficked areas had soil bulk density values that were approximately 0.1 megagrams per cubic meter higher than those found in the nontrafficked treatments. The macropore space percentages and saturated hydraulic conductivity values followed the same general trends of bulk density; site preparation did little to restore either of these two soil physical properties (table 3). In fact, the site preparation treatments actually decreased hydraulic conductivity compared to the nontrafficked treatment that received no site preparation. The negative effect of site preparation on saturated hydraulic conductivity was most pronounced on the disking and disking with bedding treatments. The negative effects were less severe on the bedding treatments. Apparently, the disking and disking with bedding treatments reduced soil water movement by interrupting the natural channels of flow, such as old root channels and earthworm burrows.

After 2 growing seasons, the bedding and bedding with disking treatments were effective in partially restoring the diameter and height growth of loblolly pine grown in skid trails (table 4). However, the disking treatment had either no effect or a slightly negative effect on tree growth. Apparently, the interruption of soil water movement within the disked areas was sufficient to negatively affect loblolly pine seedling growth.

Fourth-Year Effect of Traffic and Site Preparation

Four years after the site preparation treatments had been installed, the effects of wet-weather harvest traffic on the growth and survival of loblolly pine were almost totally mitigated by the bedding and bedding with disking treatments (table 5). Growth differences between the nontrafficked and trafficked areas were no longer significant, although the absolute growth values were always greater in the nontrafficked areas. These data appear to indicate that bedding or bedding with disking are effective ameliorative practices for repair of primary skid trails on wet pine flats, at least with respect to the 4-year growth of loblolly pine. However, it is important to recall that these primary skid trails were relatively small and covered less than 10 percent of the total area of each harvested site.

Fertilization enhanced the effects of all site preparation treatments (table 6), but fertilization alone did not mitigate the effects of wet weather trafficking. However, fertilization combined with bedding or bedding with fertilization provided the best overall ameliorative treatment, at least in terms of loblolly pine growth.

CONCLUSIONS

Wet-weather harvesting operations initially increased soil bulk density and decreased soil drainage of skid trails compared to the nontrafficked areas. After 2 growing seasons, the nonsite-prepared skid trails had lower survival percentages and smaller loblolly pines. The disking treatment was totally ineffective for amelioration of soil physical properties for the growth of loblolly pine for several reasons. Disking caused additional consolidation and compaction of the soils, flattened the small amount of existing microrelief, and probably caused further elimination of natural soil drainage channels.

After 2 growing seasons, neither the bedding nor the disking and bedding treatment had totally ameliorated the reduction of pine productivity, but both treatments clearly resulted in a partial amelioration. After 4 growing seasons, bedding or disking with bedding treatments had comparable growth rates in both the trafficked and

Table 5—Traffic and site preparation effects on loblolly pine growth 4 years after treatment installation (p-values < 0.05) (treatment values include fertilized and nonfertilized data)

Treatment	Total height	Diameter at breast height[a]	Survival
	Meters	*Centimeters*	**Percent**
Nontrafficked			
None	**1.6 a**	1.6 a	64 a
Disking	1.5 a	1.2 a	68 a
Bedding	2.7 b	3.4 b	85 b
Disking and bedding	2.5 b	3.1 b	84 b
Trafficked			
None	1.4 a	0.9 a	66 a
Disking	1.5 a	1.1 a	71 a
Bedding	2.5 b	3.0 b	87 b
Disking and bedding	2.3 b	2.7 b	82 b

[a] Includes trees that were too short to have d.b.h. values. Diameter recorded as 0 centimeter for those trees.

Table 6-Traffic, site preparation, and fertilization effects on loblolly pine height, diameter at breast height, and survival at age 4 years

Treatment	Total height	Diameter at breast height[a]	Survival
	---*m*---	--------*Cm*--------	*Percent*
Nontrafficked			
None			
Without fertilizer	1.5 a	1.4 a	59 a
With fertilizer	1.9 ab	1.8 a	69 a
Disking			
Without fertilizer	1.2 a	0.8 a	67 a
With fertilizer	1.7 ab	**1.6 a**	69 a
Bedding			
Without fertilizer	2.3 b	2.7 b	85 b
With fertilizer	3.0 b	4.1 b	86 b
Disking and bedding			
Without fertilizer	2.3 b	2.8 b	83 b
With fertilizer	2.6 b	3.3 b	87 b
Trafficked			
None			
Without fertilizer	1.3 a	0.9 a	65 a
With fertilizer	1.5 a	1.0 a	67 a
Disking			
Without fertilizer	1.4 a	0.8 a	68 a
With fertilizer	1.6 ab	1.4 a	77 a
Bedding			
Without fertilizer	2.1 ab	2.5 b	87 b
With fertilizer	2.8 b	3.8 b	88 b
Disking and bedding			
Without fertilizer	1.9 ab	2.0 b	76 b
With fertilizer	2.5 b	3.3 b	84 b

nontrafficked areas. These results indicate that some type of bedding treatment should be considered for similar sites that have been compacted or rutted by wet-weather harvesting. Site preparation of this nature is usually done on industrial lands, but small, private landowners could also benefit. It is important to note that the disking with bedding treatment is more expensive than bedding alone, while it offers no advantages over bedding alone.

The bedding treatment favored the growth of loblolly pine by creating microsites and partially restoring soil water movement, perhaps due to the incorporation of organic matter. Fertilization had a positive effect on loblolly pine growth and survival within all combinations of harvest traffic and site preparation. However, fertilization alone was not totally effective in restoring the productivity of trafficked areas as has sometimes been suggested. The fertilization was most effective in enhancing loblolly pine growth when it was combined with the bedding treatment.

Overall, the bedding and fertilization treatment appeared to ameliorate the effects of wet-weather harvesting within 4 growing seasons. However, it should be noted that these sites had relatively low overall levels of site trafficking (< 10 percent). We speculate that the trees growing within the skid trails have probably developed root systems that were able to exploit adjacent nontrafficked soils. Sites having higher levels of disturbance would probably have slower recovery rates because the roots would not be able to grow out of rutted and compacted areas as quickly.

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LOBLOLLY PINE PLANTATION SOIL NITROGEN AND PHOSPHORUS RESPONSE TO CLEARCUT HARVESTING AND SITE PREPARATION TECHNIQUES

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Abstract-Exchangeable nitrogen and extractable phosphorus concentrations were determined monthly over a 59-month period for two South Carolina lower coastal plain soils supporting young loblolly pine (*Pinus taeda* L.) plantations. Both plantations were clearcut harvested (at ages 17 and 20 years) and replicated blocks of five site preparation techniques were installed in each stand after soil sampling had begun. No consistent seasonal pattern or abnormal increases in soil nitrogen or phosphorus were detected following either harvest or site preparation. This lack of response was attributed to the small amount of mineralizable residual biomass left after harvest. Because little mobile nitrogen and phosphorus were released, the harvest and site preparation operations retained these nutrients onsite, which both maintained site productivity and minimized offsite effects.

INTRODUCTION

The response of loblolly pine (*Pinus taeda* L.) to nitrogen and phosphorus fertilization, especially on coastal plain soils, is well researched (Allen 1985, 1987, Wells and Allen 1985). Phosphorus is generally applied at planting while nitrogen, with or without phosphorus, is applied to established stands (McKee and Wilhite 1986, Wells and Allen 1985). There is concern that forest fertilization may be a nonpoint source of nutrients which degrades downstream water quality (Amatya and others 1996, Hughes 1996). Therefore it is desirable to retain as much nitrogen and phosphorus onsite as possible to minimize both the need for fertilization and any downstream impacts.

Loblolly pine ecosystems conserve nutrients onsite by several nutrient cycling mechanisms that are disrupted by harvesting and site preparation (Jorgensen and Wells 1986). The purpose of this research was to test the hypothesis that there will be a measurable release of nitrogen and phosphorus following clearcut harvesting and site preparation by several operational techniques. The approach was to periodically sample the upper soil horizon of two loblolly pine plantations prior to harvest and for several years after stand establishment. The preharvest data provide a baseline control and the postsite preparation data indicate the timing and pattern of any nutrient release.

METHODS

The study design was replicated, randomized, complete blocks established in two South Carolina coastal plain loblolly pine plantations. The Snow Mill plantation was established in 1969 on a poorly drained Bladen loam soil by shearing, raking, and bedding with phosphorus fertilization at planting. Likewise, the Greeleyville plantation was established in 1967 on a somewhat poorly drained Lynchberg sandy loam by shearing, raking, and bedding with phosphorus fertilization at planting. Treatment plots (61 meters by 61 meters with a l&meter buffer) were installed in a grid pattern in each stand prior to harvest. Plots in each stand were grouped into three blocks by tree height, and site preparation treatments were randomly assigned to plots within blocks. Site preparation treatments included shearing, raking, and bedding (intensive); bedding only (rebed); disking only; burning only; and herbicide spraying of residual trees (chemical). An unharvested control area was retained in each stand. After site preparation, each treatment plot was split and one-half was assigned a release treatment that maintained 75 percent bare ground for the first growing season after planting. The Snow Mill stand was harvested in June 1986 and was site-prepared a year later in July 1987. The Greeleyville stand was harvested in July 1987 and immediately site-prepared in August. Both stands were hand-planted in December 1987 with 1-0, improved, coastal, loblolly pine, seedlings.

This study focused on a subset of site preparation and release treatments rather than sampling all combinations. Three plots in each stand receiving treatments were sampled as summarized in table 1.

A composite soil sample was obtained from each plot by mixing approximately seven 2-centimeter by 15-centimeter soil cores extracted with an Oakfield tube sampler. Samples were taken from the 0- to 15-centimeters depth and 15- to 30-centimeters depth of the new or old beds. The Snow Mill stand was sampled 61 times from February 1986 until October 1992, mostly on a monthly basis.

Table l-Site preparation and competition release treatments sampled in two study stands

Site preparation	Release treatment	Stands sampled
Intensive	Unreleased	Both
Intensive	Released	Greeleyville (two plots)
Rebed	Unreleased	Both
Chemical	Unreleased	Both
Chemical	Released	Both
Control		Both

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Likewise, Greeleyville sampling began in April 1987 and continued until October 1992, which included 45 sampling periods. Sampling was completed in 1 day and the samples were stored for less than 10 days prior to analysis. Samples taken prior to April 1988 were stored in an unheated basement until analysis. Samples taken between April 1988 and April 1991 were frozen until analysis, and subsequent samples were immediately air-dried. Nitrate and ammonium nitrogen were extracted with 2M KCl, and phosphorus was extracted with the double acid solution. Concentrations were determined colorimetrically. All concentrations were reported in parts per million and data for the two depths were averaged. The sum of nitrate and ammonium nitrogen was considered as available nitrogen. Data analysis was simply plotting phosphorus and nitrogen data against time to detect unusually large releases.

A special set of samples from three plots in the Snow Mill stand was stored by the three methods to determine whether the different storage methods affected nutrient concentrations. Storage method did not affect the nitrogen concentrations of samples from treatment plots, but the ammonium concentrations of samples from control plots were elevated by basement storage. Immediate air-drying elevated the phosphorus concentrations of all samples.

Another factor that might confound data interpretation was rainfall timing. If so, the soil nitrogen content would decrease with increasing amounts of rainfall and will be less with the same amount of rainfall if it occurred just prior to sampling as opposed to occurring 20 to 30 days prior to sampling. To test this, the soil nitrogen and rainfall data were examined for 15 months for the Snow Mill stand and for 13 months for the Greeleyville stand. The highest correlation between soil nitrogen and amount of rainfall in the prior 5 days, 10 days, 15 days, and 30 days had a correlation coefficient of +0.50, indicating a very weak relation.

RESULTS

Control Plots

Because these plots were neither harvested nor site-prepared, data from these plots reflect natural seasonal patterns and the effects of a change in soil sample storage method. Although the test of storage method discussed above indicated that basement storage of samples from control plots elevated nitrogen concentrations, this is not seen in the monthly data from Snow Mill (fig. 1) or Greeleyville. Both stands exhibited a fluctuating soil nitrogen concentration with no seasonal pattern. There was an unexplained increase in the samples from Greeleyville

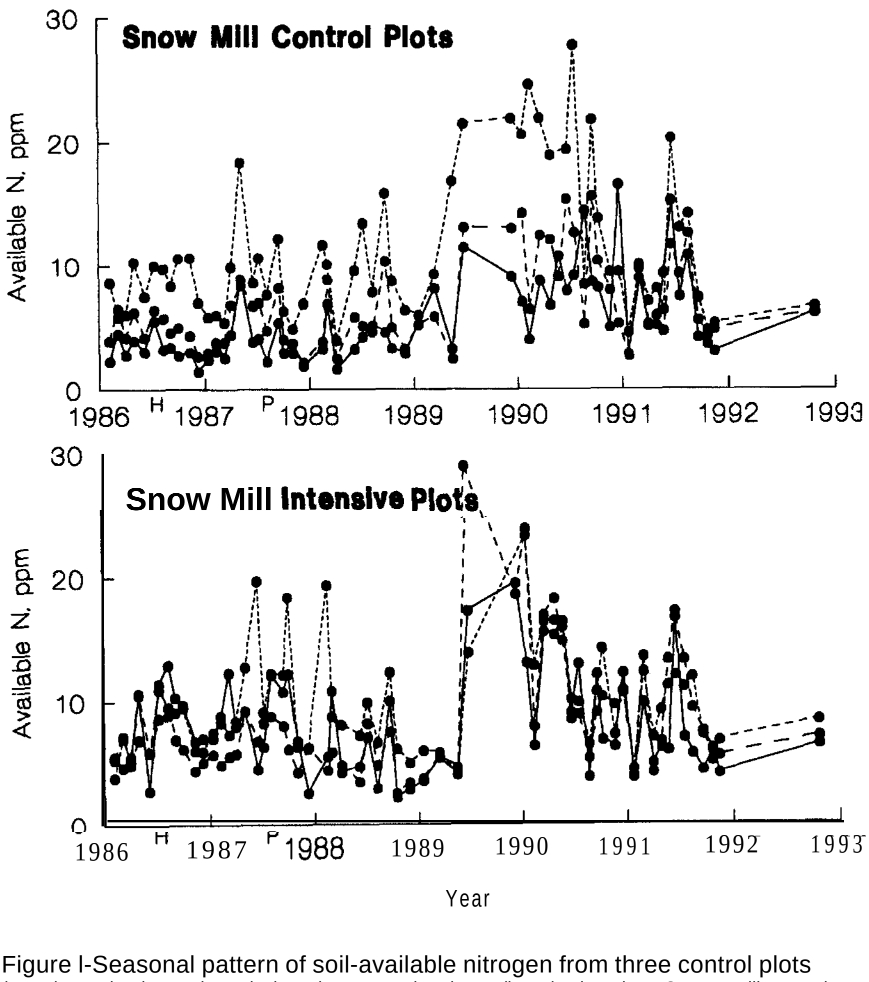

Figure l-Seasonal pattern of soil-available nitrogen from three control plots (upper) and three intensively site-prepared plots (lower) in the Snow Mill stand. "H" indicates the time of harvest and "P" indicates the time of site preparation.

from June 1989 until June 1990. Likewise the phosphorus data from both stands did not reflect the change in storage methods or any seasonal patterns.

Intensive Site Preparation

Any nitrogen or phosphorus release due to disrupting nutrient cycling mechanisms should be seen in data from plots that were harvested, sheared, raked, and bedded prior to planting. The Snow Mill nitrogen data (fig. 1) indicated a release after both harvest and site preparation and a return to preharvest levels within 3 to 4 months. Greelyville nitrogen data also indicated a release, but this release was delayed for 3 months after site preparation and nitrogen concentrations returned to preharvest levels within 12 months. The Snow Mill phosphorus data did not show a response to harvest or site preparation. The Greeleyville phosphorus data did indicate a release after site preparation, but similar releases occurred many months after disturbance.

Rebed-Only Site Preparation

These plots received far less disturbance than did the intensively site-prepared plots, thus any releases should also be less. The nitrogen data for rebed-only plots were quite similar to the nitrogen data for intensively prepared plots. Snow Mill plots showed an immediate release after both harvest and site preparation with a 3-month recovery. Greelyville rebed-only plots also indicated a release, but it was delayed and recovery was longer, about 12 months. There was no response to disturbance and no discernable seasonal patterns in the phosphorus data from the two stands.

Chemical Site Preparation

Plots receiving the chemical site preparation treatment were the least disturbed because the litter layer and soil were not disturbed by rebedding. In Snow Mill, the response of soil nitrogen was similar to that of the rebed plots, except there was no release after site preparation. In Greeleyville, the response was quite similar to that of the rebed-only plots. Also like the rebed-only plots, the phosphorus data showed no response to harvest, site preparation, or season.

DISCUSSION

These data do not show a major pulse of nitrogen or phosphorus being released in response to harvesting and/or site preparation as was seen in the well-known Hubbard Brook experiment (Bormann and Likens 1970). There are many possible reasons for this including different site, different forest cover, and less destructive treatments. However, the clearcut harvest followed by intensive site preparation was a relatively destructive treatment, yet a release was not detected. I speculate that the lack of release is related to the paucity of material left onsite after harvest that could mineralize and release nutrients.

The preharvest stands were relatively pure loblolly pine plantations, with very few hardwood stems among the pines. After clearcutting, the tracts were clean, open areas. Little biomass was added to the litter layer from harvest because the trees were delimbed at the deck. The only source of mineralizable nitrogen and phosphorus onsite after harvest was the original forest floor, and this was burned after harvest, which may have released nitrogen and phosphorus to the atmosphere as well as to the soil.

Why weren't nutrients released after the residual biomass was incorporated in the soil by the bedding part of site preparation? Again, little organic matter was left onsite to mineralize, and what nutrients were released were probably quickly fixed by the dense grass and sedge cover that developed after site preparation. By the time the grass cover began to die out and release nutrients, the pine seedlings probably had sufficient root biomass to take up these nutrients.

This study clearly shows that loblolly pine plantation re-establishment by clearcut harvesting and intensive site preparation does not release a pulse of nitrogen or phosphorus on the sites studied. The ecosystem and management system used were very nutrient-retentive, providing both onsite and offsite benefits.

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RESPONSE OF SOIL BULK DENSITY AND MINERAL NITROGEN TO HARVESTING AND CULTURAL TREATMENTS

Minyi Zhou, Mason C. Carter, and Thomas J. Dean'

Abstract-The interactive effects of harvest intensity, site preparation, and fertilization on soil compaction and nitrogen mineralization were examined in a loblolly pine (*Pinus taeda* L.) stand growing on a sandy, well-drained soil in eastern Texas. The experimental design was 2 by 2 by 2 factorial, consisting of two harvesting treatments (mechanical whole-treeand hand-fell boles only removed), two site preparation treatments (bedded and unbedded), and two fertilization treatments (fertilized and unfertilized). Soil bulk density was measured before and after harvesting and site preparation. Ion exchange resin bags located at the bottom of soil columns were used to monitor nitrogen mineralization rates in the upper 15 centimeters of soil during the first two growing seasons following harvesting. The mechanical treatment had no effect on soil bulk density at 0 to 5 and 10 to 15 centimeter depths but significantly increased it at 20 to 25 centimeters. Bedding reduced soil bulk density at 10 to 1.5 and 20 to 25 centimeter depths. The mechanical treatment removed 16 percent more biomass and 127 percent more nitrogen than the hand-fell treatment, but had no affect on nitrogen-mineralization rates. Bedding significantly increased both total mineral nitrogen and nitrate formation during the first growing season but had no effect during the second year. The increase in mineral nitrogen due to the bedded preparation was equal to the increase in mineral nitrogen following application of 250 kilograms per hectare of diammonium phosphate. The results suggest that logging slash and other surface biomass has little influence on nitrogen-mineralization for the first two years after harvesting unless there is considerable soil disturbance and/or incorporation of the surface organic matter.

INTRODUCTION

Declining productivity with successive rotations has been reported for *Pinus radiata* in south Australia (Keeves 1 966), *Pinus patula* in Swaziland, Africa (Evans 1978), *Pinus radiata* in New Zealand (Whyte 1973), and *Pinus taeda and P. elliottii* in Louisiana, USA (Haywood 1994) raising concerns over the sustainability of current intensive management practices (Powers 1990, Powers and others 1996). In 1989, the USDA Forest Service initiated a series of nationwide studies of long-term soil productivity (LTSP) on the National Forest System (Powers 1990). To complement and extend the LTSP program to industrial forests, a cooperative effort among forest industries, universities, and the U.S. Department of Agriculture was begun in 1993 (Powers and others 1996). This cooperative effort, known as MPEQ for "Monitoring Productivity and Environmental Quality in Southern Pine Plantations," has research installations in four locations in the Southern United States. This is one of the first in a series of reports from this cooperative effort.

Harvesting promotes nutrient losses from forest ecosystems through biomass removal (Kimmins 1977, Tew and others 1986) and increased nutrient mineralization in the soil (Likens and others 1970). Whole-tree harvesting and short rotations accentuate such losses (Switzer and others 1978, Stevens and others 1995). Nitrogen is especially susceptible to losses during harvesting and regeneration (Vitousek and Melillo 1979). Since nitrogen is one of the most limiting factors in many forest ecosystems (Keeney 1980), nitrogen (N) availability is considered an index of soil fertility and soil productivity (Powers 1980). Tew and others (1986) reported that complete-tree harvesting of a 22-year-old loblolly pine (*Pinus taeda* L.) plantation on a Piedmont site in North Carolina removed twice as much N as stem-only harvesting, while Vitousek and Matson (1985) found that harvesting and site preparation increased soil nitrate formation significantly.

Soil compaction caused by harvesting equipment (Guo and Karr 1988, Guo and others 1990) may reduce future forest productivity (Powers and others 1996) unless this compaction is mitigated. Site preparation by bedding improves soil internal drainage increasing survival and/or growth of pine seedlings on poorly drained and moderately well-drained soils (Ducan and Terry 1983, Tiarks 1983, Gent and others 1986, Mckee and Wilhite 1986). On drier sites, bedding can cause moisture stress by channeling water away from seedling root zones (Broeman and others 1983). Mounding and concentrating the surface horizon by bedding could mitigate compaction resulting from harvesting traffic, but the soil disturbance incurred by bedding could also increase nutrient mineralization.

The objectives of the study reported here were to determine the effects of standard operational practices on soil compaction and N availability on a sandy, well-drained soil in the gulf coastal plain of eastern Texas.

MATERIALS AND METHODS

The study site is located in Tyler County, TX, on the property of Temple Inland Forest Products Company. The soil belongs to the Besner series, a coarse-loamy, siliceous, thermic Typic Glossudalf. At time of harvest in August 1994, the site was occupied by a stand of loblolly pine direct-seeded in 1968 and thinned in corridors at age 15 years. There have been at least three harvests of loblolly pines on this site and no history of cultivation. Other characteristics of the stand and soil are shown in table 1.

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Table I-Characteristics of the loblolly pine plantation at the time of harvesting

Characteristics	Block A	Block B	Block C
Age	26	26	26
Site index (meters, 25 years)	17.1	17.4	17.5
Stand density (stems per hectare)	1962	1625	1805
Basal area (square meters per hectare)			
Pine	29.6	25.1	29.4
Hardwood	2.7	2.3	2.5
Volume[a] (cubic meters per hectare)			
Pine	246.5	221.2	255.8
Hardwood	21.0	21.2	18.9
Overstory biomass[a] (tons per hectare)			
Pine	115.1	101.7	120.7
Hardwood	11.2	11.8	10.1
Understory biomass (tons per hectare)	5.3	12.1	14.0
Litter biomass (tons per hectare)	24.3	17.7	17.5
Soil carbon: 0 to 15 centimeters (pct)	1.075	1.058	1.422
Soil nitrogen: 0 to 15 centimeters (pct)	0.038	0.030	0.045
Soil CEC: 0 to 15 cm (meq per gallon)	0.725	0.688	0.638
Soil pH: 0 to 15 centimeters	4.9	5.0	4.8

[a] Volume and biomass equations for pine from Baldwin (1987), for hardwood from Clark and others (1985).

Prior to harvesting, three experimental blocks were established. Each block was divided into eight 42- by 28-meter (0.12 hectare) plots. On each plot, height and diameter at breast high (d.b.h.) were recorded for all trees > 5 centimeters d.b.h. Four 1- by 2-meter subplots were established in each main plot. All vegetation < 5 centimeters d.b.h. was clipped, weighed, and subsampled for moisture determination and elemental analysis. The litter was also weighed, subsampled, and returned to the laboratory for analysis. Three dominant and codominant pines were felled on each plot for stem analysis. Starting at groundline, a disc was removed every 0.5 meters for 10 meters and every 1 meter from 10 meters to the tip. From the 0-, 5-, and 1 O-meter discs, a 22.5-degree wedge was removed. Wood and bark were separated, dried, ground, and cornposited for elemental analysis.

Soil samples for elemental analysis were collected from four locations on each plot at depths of 0 to 10 centimeters, 10 to 20 centimeters, and 20 to 30 centimeters. Soil bulk density was determined in June 1994, 1 month before harvesting, and in May 1995, 9 months after harvesting. Volumetric samples were taken at four locations on each plot at depths of 0 to 5 centimeters; 10 to 15 centimeters; 20 to 25 centimeters. The volumetric samples were dried at 105°C to a constant weight.

Harvesting was conducted July 25 through August 5, 1994. The mechanical whole-tree treatment (MWT) employed a 600 series Hydro-Ax feller-buncher with a rotary cutter and three rubber tire skidders. All merchantable pine (and most unmerchantable pine and hardwoods) were felled, bunched, and skidded to the loading deck where they were delimbed and topped. On the hand-felled boles only (HFB) plots, merchantable pine were felled with chainsaws, delimbed, and topped in place. Merchantable boles were lifted from the plots by a loader positioned outside the plot.

On September 20, 1994, the entire harvested area was treated aerially with a mixture of imazapyr and triclopyr (0.5 plus 2.0 kilograms per hectare). Bedding was performed on October 17 and 18, 1994, with a Savannah stump-jump plow on a D-7 tractor. The site was planted with improved 1-O loblolly pine seedlings in February 1996. On May 6, 1996, DAP was broadcast by hand.

Nitrogen mineralization was monitored in soil columns enclosed in an uncovered, polyvinyl chloride tube with a package of mixed-bed ion exchange resin (IER) at the bottom (Binkley and Matson 1983, Hart and Binkley 1985). Binkley (1984) suggested this technique was most appropriate for field estimation of both N-mineralization and transport. We further confirmed that no further transformation or removal of NH_4^+ or NO_3^- occurred once adsorbed by the IER.

The 5- by 30-centimeter tubes, beveled on the lower rim, were driven into the soil approximately 15 centimeters and carefully removed. Approximately 1 .O centimeter of soil was removed from the bottom of the tube and replaced with a bag of resin. The tube was then returned to the hole. IER bags contained 8 grams of Fisher No. R276-500 plus a perforated plastic disc about 5.1 centimeters in diameter. Both disc and resin were wrapped in nylon mesh. Bags were assembled and stored frozen until transported to the field in a cooler. Four tubes were placed in each plot. The incubations were conducted May 15, 1995 to November 9, 1995 and May 17, 1996 to November 12, 1996. Resin bags were replaced approximately every 8 weeks during these periods. To determine ambient levels of mineral N, soil samples were collected with a push-tube adjacent to the incubation tubes at the beginning and end of each incubation period.

Mineral N was determined by the same methods for both soil and resin. Ten grams of soil (or 8.0 grams of resin) were placed in 80 mililiters two nitrogen potassium chloride (a 20-gram sample of soil was dried at 105°C for moisture determination). Extractions were shaken at approximately 275 revolutions per minute for an hour, allowed to settle for an hour, filtered, and stored at 4°C until analyzed. Ammonium and nitrate N were determined with Alltech's Ammonia Analyzer system. Net N mineralization was determined by subtracting initial (May) soil mineral-N (NH,+ + NO,) from the sum of final (Nov) soil mineral-N plus mineral-N captured by IER bags.

Since fertilizer was not applied until May 6, 1996, the statistical model for the 1995 N-mineralization data was an unbalanced 2 by 2 factorial. Soil bulk density after harvesting and site preparation was subjected to analysis of covariance with bulk density before harvesting as the covariate. Unless indicated otherwise, all significant difference refers to $\alpha=0.05$.

RESULTS

MWT harvesting did not alter soil bulk density at 0 to 5 centimeters or 10 to 15 centimeters but significantly ($p<0.005$) increased it at 20-25 cm depth (table 2). Bedding did not change soil bulk density in the first 5 centimeters from the surface but reduced it 10 to 15 centimeters ($p<0.001$) and 20 to 25 centimeters ($p<0.001$) soil depths (table 2). However, the crests of the beds were 15 to 30 centimeters above the original soil surface datum. Thus, the stratum at 20 to 25 centimeters from the crest of the beds is not comparable to the stratum sampled at that depth on the unbedded plots. In the near term, bedding appears to have increased the volume of low density soil available for root growth, but a zone of soil compacted during harvesting may still remain.

Assuming all aboveground components of merchantable pine (d.b.h. > 15 centimeters) were removed from the MWT plots while only boles of merchantable pine were removed from the HFB plots, MWT harvesting removed 16 percent more biomass and 127 percent more N than was removed by HFB harvesting (table 3). To verify this assumption, three MWT and three HFB plots were selected and residue biomass determined on the same 1- by 2-meter subplots used in the original biomass sampling. Actual residue differed from estimated residue by less than 5 percent although the coefficient of variations among subplots was quite high.

However, the large differences in nitrogen-rich residue remaining on the HFB plots did not result in a detectable difference in mineral N in the soil during the first two growing seasons following harvest (tables 4 and 5). Conversely, bedded soils were approximately 30 percent higher in mineral N than unbedded soils (table 4). And more mineral N was captured in the resin bags from bedded soil during the May/July monitoring period of the

Table 2-Mean soil bulk density by depth in May 1995 after harvesting in August 1994 and bedding in October 1994 (adjusted by covariance bulk density determined before harvesting)

Harvest method	Not bedded	Bedded	Mean[a]
Soil depth: 0 to 5 centimeters			
Hand fell, boles only	1.11	1.21	1.16a
Mechanical whole tree	1.26	1.19	1.22a
Mean[a]	1.18a	1.20a	
Soil depth: 10 to 15 centimeters			
Hand fell, boles only	1.31	1.17	1.24a
Mechanical whole tree	1.39	1.13	1.26a
Mean[a]	1.35a	1.15b	
Soil depth: 20 to 25 centimeters			
Hand fell, boles only	1.38	1.28	1.33b
Mechanical whole tree	1.49	1.31	1.40a
Mean[a]	1.44a	1.30b	

[a] Means in the same column or row within depths followed by different letters are significantly different ($p<0.05$).

Table 3—Estimated[a] biomass and nitrogen (N) removal by mechanical whole tree (MWT) and hand-fell, boles only (HFB) harvesting based on removal of all pine with d.b.h. > 15 centimeters

Factor measured	MWT	HFB	Difference
			Percent
Total aboveground biomass (tons per hectare)	148	160	-08
Biomass removal (tons per hectare)	92	78	+16
Total aboveground N (kilograms per hectare)	402	462	-13
Nitrogen removal (kilograms per hectare)	134	59	+127

[a] Volume and biomass equations for pine from Baldwin (1987), for hardwood from Clark and others (1985).

Table 4-Ambient mineral N content of upper 15 centimeters of soil in May 1995 after harvesting in August 1994 and bedding in October 1994

	Site preparation		
Harvest method	Not bedded	Bedded	Mean[a]
	-------*Kilograms per hectare*-------		
Hand-fell, boles only	59.8	79.2	69.7a
Mechanical whole tree	65.1	81.1	73.1a
Mean[a]	62.5b	80.2a	

[a] Means within the same column or row followed by different letters are significantly different ($p<0.05$).

first growing season. But after the middle of the first growing season, differences due to bedding were not detected after the July 1995 sampling (table 5).

Application of diammonium phosphate resulted in an increase of 8 to 10 kilograms per hectare mineral N moving through the soil profiles in the sampling tubes, and the increase was consistent across both harvesting and site preparation treatments (table 5). But even with the addition of mineral N fertilizer, the amount of soil mineral N during the second growing season appeared to be below that of the first.

DISCUSSION

Increased soil bulk density at 20 to 25 centimeter depth following mechanical harvesting but not at 0 to 5 or 10 to 15 centimeters was observed on the MPEQ site in north Louisiana as well as in the present study.[2] The relatively high organic matter content of the upper soil strata may offer sufficient resilience to prevent compaction near the surface. Bedding, which produces a ridge of unconsolidated soil and surface organic matter, may mitigate any loss of readily exploitable soil volume caused by compaction at 20 to 25 centimeters. But bedding does not necessarily eliminate this pan or zone of compacted soil below the surface horizons. Since soil compaction may last a decade or more (Wells and Morris 1983, Miller and others 1996), a compacted zone below 20 centimeters may reduce root penetration and productivity later in the rotation.

On the basis of earlier reports (Well and Jorgensen 1978, Vitousek and Matson 1985), we expected the N-rich residues left by HFB harvesting to result in higher net soil N mineralization than MWT. Our data did not support this hypothesis. In the studies of Vitousek and Matson (1985), harvesting was followed by further disturbance of the surface soil by burning, discing, or both. When we disturbed the soil by bedding, we observed increased N mineralization but again no difference between harvesting systems was apparent.

Recently, Wilson (1994) reported a series of studies of N mineralization on the LTSP study plots in eastern North Carolina. Two years after harvesting, he could find no difference in N mineralization rate between organic removal levels ranging from a level comparable to our HFB to a complete removal of all surface organic matter to the mineral soil. Soil compaction, however, significantly reduced N mineralization.

While the amount on N contained in the branches and tops of harvested pine is considerable (table 3), over five times as much is present in the 0 to 15 centimeter layer of mineral soil (table 1). The large amounts of N mineralized during the first growing season (1995) most likely derived from root mortality and other below-ground sources. Differences in surface residue or mechanical traffic between the two harvesting systems did not influence the process. Severing the overstory forest results in a vigorous but rather brief period of N mineralization. Bedding incorporates fresh

[2] Personal communication. K. Farrish. 1996. College of Forestry, S.F. Austin State University, Nacogdoches, TX 75962.

Table 5-Total mineral (NH_4^+ + NO_3^-) captured by ion exchange resin (IER) bags during the first two growing seasons after harvesting and site preparation of a loblolly pine plantation in eastern Texas

Main treatment[a]	Monitoring Period			
	May/ July 95	July/ Sep 95	May/ July 96	July/ Sep 96
	----Kilograms per hectare----			
Hand-fell, boles only				
No added N	51.6	18.1	16.9	15.4
Added N	—	—	28.5	21.0
Mechanical whole tree				
No added N	52.1	21.0	19.2	13.0
Added N	—	—	24.4	17.3
Not bedded				
No added N	45.1[a]	17.4	17.8	13.2
Added N	—	—	26.7	25.0
Bedded				
No added N	58.4[a]	21.7	18.4	15.3
Added N	—	—	26.2	23.6
Not fertilized	n.a.	n.a.	18.1[a]	14.2[a]
Fertilized	n.a.	n.a.	26.4[a]	24.3[a]

[a] The main effect of bedding was significant ($P<0.05$) for the May/July 95 monitoring period and the main effect of fertilizer was significant ($P<0.05$) for both monitoring periods in 1996. No other main effects or interactions were found to be significant at $P<0.05$.

carbon sources from the surface, increases aeration, severs and macerates root systems to a depth of 10 to 20 centimeters and increases the magnitude but not the duration of the mineralization process.

Continued monitoring to determine the long-term role of surface biomass in maintaining soil organic matter and nutrient richness is a major objective of both LTSP and MPEQ research.

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SOIL STRENGTH, VOLUMETRIC WATER CONTENT, AND SOIL ROUGHNESS CHARACTERISTICS OF A BEDDED WET PINE FLAT

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Abstract-Harvest operations conducted under high soil moisture conditions often result in highly disturbed areas. Strategies adopted to avoid a high degree of site disturbance from harvesting can include harvesting under low moisture conditions or utilization of site preparation techniques. However, in this study we found that harvesting under low moisture conditions increased soil strength. Bedding is able to reduce soil strength and lower volumetric water content in both harvest conditions. Bedding increases surface roughness in harvested sites and elevates local topography. Low moisture conditions resulted in a higher degree of surface roughness resulting in greater bed height. No differences were detected in first-year loblolly pine survival for harvested or bedded treatments, but long-term assessments are necessary to truly investigate the relationship between bed characteristics and loblolly growth.

INTRODUCTION

Forest harvest operations conducted on wet pine flats result in surface soil disturbances that have been classified as compacted, rutted, and puddled (Burger and others 1989). The type and degree of disturbance varies with soil moisture content and a greater susceptibility to disturbance occurs as soil moisture content increases (Aust and others 1993, Burger and others 1989, Burger and others 1995). Soil physical properties that are altered in disturbed sites include bulk density, soil strength, hydraulic conductivity, porosity, and soil moisture content (Aust and others 1993, Aust and others 1995). The net result of these impacts is lowered site productivity.

Site productivity can be enhanced on wet pine flats through site preparation prior to planting, especially by bedding. Bedding reduces soil moisture content, improves soil aeration, lessens impacts to soil physical properties, and provides roughness on the soil surface (Gent and others 1983, Pritchett 1978, Terry and Campbell 1981). Improvements in the productivity of loblolly (*Pinus taeda*) and slash (*P. elliottii* Engelm.) pine have occurred in bedded wet pine flats, especially on poorly and very poorly drained soils (Cain 1978, Gent and others 1986, Wilhite and Jones 1981). However, information is not available on soil physical properties of bedded sites, the influence of site conditions on bed characteristics, and/or the relationship between soil physical properties of beds and pine productivity.

The objective of this study was to evaluate bedded surfaces of a wet pine flat for soil roughness, soil strength, volumetric water content, and loblolly pine survival to determine whether differences due to harvesting conditions (moisture levels of wet and dry) and site preparation (bedding and mole plowing/bedding) exist, and the impact on first-year survival of loblolly pine.

METHODS

Study Site

The study site was located on the lower coastal plain of South Carolina on an area of low elevations of marine and fluvial deposits. The stand was a 20-year-old loblolly pine stand owned and managed by Westvaco Corporation of Summerville, SC. The understory consisted of red maple (*Acer rubrum*), water oak *(Quercus nigra),* willow oak (Q. *phellos*), cherrybark oak (Q. *falcata* var. *pagodifolia*), sweetgum (*Liquidamber styraciflua*), and palmetto (*Sabal sp.*). Soils within the study site were members of the Alfisol, Mollisol, and Ultisol orders.

Treatments

The experimental design consisted of a randomized complete block assessing the impact of harvesting under two moisture levels (high moisture vs. low moisture) and two methods of site preparation (bedding and mole plowing/bedding) on soil strength, soil roughness, and volumetric water content, replicated three times. Treatment combinations consisted of wet harvesting and no site preparation (flat planting) (WFP), wet harvesting and bedding (WB), wet harvesting and mole plowing/bedding (WMB), dry harvesting and no site preparation (flat planting) (DFP), and dry harvesting and bedding (DB) as well as an undisturbed control (CON) area in all blocks. The entire study area encompassed 57.6 hectares subdivided into three blocks, each approximately 19.2 hectares in size and further subdivided into six treatment plots of 3.2 hectares. Volumetric water contents of 30 and 12 percent corresponded to soil moisture content at the time of wet harvesting and dry harvesting, respectively. Site preparation was conducted at an average soil moisture content of approximately 45 percent.

Soil Measurements

The site was assessed after harvest operations for the occurrence of site disturbances and classified according to preselected disturbance classes: compressed soil, ruts less

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than 0.2 meters, ruts greater than 0.2 meters, and churned soils. Site preparation activities were initiated and completed in fall 1995 and hand-planting of seedlings completed in January 1996. Five disturbance classes were mapped in wet harvested sites and two disturbance classes were mapped in dry harvested sites. The percentage of disturbance in each harvest treatment was calculated by summing the mean percentages of each disturbance class; this consisted of four disturbance classes in wet harvested treatments and one in dry harvested treatments.

Soil roughness estimates were made by placing a chain approximately 6.1 meters in length over the exposed soil surface and fitting the chain to the contours of the soil surface fully extending each link and measuring the distance between the origin and its endpoint (Saleh, 1991). A ratio of fitted length to horizontal length was calculated and termed the roughness coefficient, RC. A logging chain was chosen for the estimation of RC rather than a roller chain due to distances between beds and site conditions. Soil strength was determined with a Rimik CP20 recording cone penetrometer with a base cone diameter of 113.0 square millimeters, manually inserted to a depth of 0.50 meters and recorded in 0.025 meter increments in accordance with ASAE standards (ASAE 1992). The required force divided by the cross sectional area of the base of the cone gives cone index (Cl) in units of pressure (Megapascals). Volumetric water content was determined by Time Domain Reflectometry (TDR) at soil depths of 0.0 to 0.15, 0.0 to 0.30, and 0.0 to 0.45 meters, using standard rod lengths corresponding to previous depth increments, and volumetric water content estimated for the depth increments of 0.0 to 0.15, 0.15 to 0.30, and 0.30 to 0.45 meters according to Topp and others (1982). Statistical analyses were conducted with the Statistical Analysis System.

RESULTS AND DISCUSSION

Site Disturbances

A higher percentage of site disturbance occurred during harvest operations under high moisture conditions (WFP) compared to low moisture conditions (DFP) (table 1). Site disturbances often exceeded 75 percent in WFP compared to less than 10 percent in DFP. Other studies have found greater levels of disturbance under high moisture conditions and attributed disturbance to lowered soil strength that resulted in compaction, rutting, and puddling upon trafficking (Burger and others 1995).

Soil Response to Harvesting

Soil strength, or cone index (Cl), generally increased at all depths in response to harvesting in comparison to its undisturbed state (CON) (table 2). Soil moisture status influenced the degree of change in soil strength as Cl values were consistently higher in DFP compared to WFP at comparable depths (table 2). Differences in soil strength in this study due to moisture status were similar to results reported by Murosky and Hassan (1991) for soil surface layers of a wet pine flat in Louisiana. The results of this study and others underscores the influence of soil moisture status at the time of harvesting on resulting impacts associated with harvesting.

Volumetric water contents (VWC) of 0.40 centimeters per cubic centimeter and higher were noted for each depth in each treatment (table 2). Elevated VWC may have resulted from the impact of harvest traffic on soil physical structure by increasing bulk density and reducing pore space which simultaneously increased VWC and lowered soil strength (Burger and others 1989). Since there is an inverse relationship between Cl and VWC, the elevated VWC may have masked more significant differences in Cl between treatments.

Effect of Bedding Treatment

Site preparation of wet pine flats primarily consists of bedding, but some benefit may be derived by mole plowing in conjunction with bedding. Mole plowing is employed in sites of high clay content and water saturation to reduce the depth of the water table (Robinson and others 1987). Site preparation of wet harvested treatments reduced Cl and VWC from initial harvested (WFP) and undisturbed (CON) site conditions (table 2). Little difference was detected for Cl and VWC between site preparation methods on wet harvested sites. Mole plowing reduced VWC at all depths but Cl remained similar to WB at all depths.

Table l-Percent disturbance of each treatment block after harvest prior to the application of site preparation treatments

	Percent disturbance	
Condition/treatment	Undisturbed	Disturbed
High moisture	9.2	90.8
Low moisture	96.2	3.8
Wet harvesting and mole plowing/bedding	20.5	79.5
Wet harvest/bedding	15.7	84.3
Bedding alone	89.8	10.2

Table 2-Cone index and volumetric water content of selected soil depths (0 to 15, 15 to 30, and 30 to 5 centimeters) in a wet pine flat after harvest and site Preparation, South Carolina

Treatment	Depth	Cone index	Volumetric water content
	cm	*MPa*	*cm/cm³*
CON	0.15	0.518	0.360
	0.30	1.134	0.356
	0.45	1.157	0.436
WFP	0.15	0.625	0.473
	0.30	1.030	0.399
	0.45	1.350	0.453
DFP	0.15	0.912	0.439
	0.30	1.182	0.403
	0.45	1.376	0.422
WMB	0.15	0.351	0.325
	0.30	0.627	0.346
	0.45	1.164	0.337
WB	0.15	0.358	0.334
	0.30	0.659	0.359
	0.45	1.143	0.450
DB	0.15	0.377	0.273
	0.30	0.556	0.392
	0.45	0.920	0.424

Site preparation in dry harvested treatments was limited to bedding alone (DB). Reductions in Cl and VWC in response to bedding were noted from initial site (DFP) and undisturbed (CON) conditions (table 2).

Relative differences in soil strength between preharvest and postharvest conditions were greater for dry harvested sites than for wet harvested sites. Soil strength in DB was approximately 2 times lower than WMB or WB after bedding of the original harvest surface (table 2). One consistent result observed in all bedded treatments was a greater change in intermediate soil layers from the initial harvest conditions to bedded conditions.

Volumetric water content was reduced by bedding of each treatment, with the highest reductions in VWC in surface soil layers. Volumetric water content also decreased in subsoil layers with greater reductions in the subsoil of wet harvested treatments, especially where mole plowing was implemented.

From this study the benefits of bedding are evidenced from the reductions in soil strength and volumetric water content. Bedding enhances survival and growth of pines on harvested sites and is applied extensively in poorly drained sites of the coastal plain (Allen and others 1990). Its utility may be limited in sandy soils but significant improvements may occur in soils with significant clay content (Allen and others 1990, Haines and others 1975). At the present time, the benefit of bedding exists in the early stages of pine growth but more long-term investigations are necessary to fully assess the relationship between bed quality and pine productivity.

Soil Roughness

Soil roughness coefficients (RC) may range from 0 to I where 1 is indicative of a flat, or undisturbed, soil surface. Soil roughness coefficients were higher in harvested sites (WFP and DFP) as a result of less surface disturbance (table 3). The formation of beds on harvested sites elevated the soil surface and increased surface relief, which resulted in lower RC values. Roughness coefficients were significantly higher in bedded treatments compared to flat planted treatments, as expected. A comparison of bedded treatments indicated RC was significantly lower ($P = 0.10$) in DB compared to WB and WMB. Soil roughness would then be expected to be greater in dry harvested sites.

Bedding increases surface roughness by elevating the soil surface to a specific height above the harvested surface. Bedding of dry harvested treatments increased surface roughness, indicating the importance of moisture condition at the time of bedding. Soil moisture status was a significant factor in increasing soil roughness on agricultural soils and was maintained for extended periods when roughness was created under low moisture conditions (Allmaras and others 1967, Lehrsch and others 1987). Pine productivity was enhanced in a sandy soil in Florida as a result of higher beds (Outcalt 1984), which further underscores the importance of proper bedding. Future pine productivity on these sites may benefit from bedding under low moisture conditions.

Loblolly Pine Survival

An examination of first year survival of loblolly pine did not indicate any direct benefits from bedding of harvested sites (table 4). Future assessments of tree growth and survival will be necessary to identify specific characteristics that determine pine productivity.

Table 3-Mean roughness coefficients of a Wet pine flat subjected to harvest disturbance under two moisture conditions and two methods of site preparation, South Carolina

Condition/treatment	Roughness coefficient	
High moisture condition	0.824 b[a]	
Low moisture condition	0.851 b	
Wet harvesting and mole plowing/bedding	0.769 a	a[b]
Wet harvesting/bedding	0.770 a	a
Bedding alone	0.748 a	b

[a] Means with the same letter in each column are not significantly different from each other at the P = 0.05 level.
[b] Means with the same letter in each column are not significantly different from each other at the P = 0.10 level.

Table 4-First-year loblolly pine survival in a wet pine flat in response to harvesting under two moisture conditions and two methods of site preparation, South Carolina (data provided by W.M. Aust)

Condition/treatment	Survival rate
	Percent
High moisture condition	*87.6* [a]
Low moisture condition	*86.3*
Wet harvesting and mole plowing/bedding	*86.8*
Wet harvesting/bedding	83.9
Bedding alone	81.8

[a] Mean comparison among percent survival (log transformation) were not significantly different from each other at the $P = 0.05$ level.

CONCLUSIONS

Soil moisture status affected the occurrence of site disturbances on a wet pine flat with higher soil moisture contributing to a higher degree of soil disturbance. Soil strength and volumetric water content increased in response to harvest traffic under both low and high moisture conditions compared to undisturbed conditions. Higher soil strength was associated with harvest traffic under low moisture conditions. Bedding reduced soil strength and volumetric water content under high and low moisture conditions. However, the greater reductions in CI occurred in dry harvested treatments, while the highest volumetric water content reductions occurred in wet harvested treatments. Bedding increased surface roughness in both treatments but significantly more roughness was associated with low moisture conditions.

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Pine Nutrition Management

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THE EFFECT OF FERTILIZATION ON LUMBER QUALITY IN PLANTATION LOBLOLLY PINE

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Abstract-The effect of fertilization on lumber grade yield was investigated for six trees selected from a loblolly pine (*Pinus taeda* L.) plantation at the Hill Farm Research Station in Homer, LA. The plantation was originally planted on an 8-foot by 8-foot spacing (680 trees per acre). The stand was thinned from 550 to 100 trees per acre (TPA) 20 years after planting; from 100 to 50 TPA 25 years after planting; and from 50 to 25 TPA 30 years after planting. From age 20 until harvesting at age 30, part of the stand was used for cattle grazing and was fertilized annually with a nitrogen:phosphorous:potassium ratio of 100:35:18 pounds per acre, while part was not fertilized. At age 30, six trees were selected, three from the fertilized portion of the stand and three from the nonfertilized portion. Because the lower boles of all trees were free of branches by age 25, 5 years after fertilization began, it was hypothesized that the fertilized trees would not only have larger diameter growth, but more clear wood, which equates to high-quality lumber grades. Individual tree basal area growth of fertilized trees exceeded that of nonfertilized trees by 40 percent at age 30. All sample trees were sawn into high-quality lumber using a Wood-Mizer$_{TM}$ horizontal bandsaw. Both l-inch and P-inch lumber were produced. Nonfertilized (control) trees yielded 63 percent of their volume as lumber. The fertilized trees produced 62 percent of their volume as lumber. Fertilization resulted in a 13-percent increase in high-quality, high-value lumber in the finish grade and a 40-percent increase in high-quality, high-value lumber in the shop grade. Based on cubic foot volume scale, the butt logs consistently gave lower lumber yields than the top logs, which is explained in part by the larger taper of the butt logs.

INTRODUCTION

Under most conditions, thinning and fertilization have increased growth in southern pines. Forest fertilization, in fact, has become a valuable silvicultural tool in our efforts to improve forest productivity. Allen (1987) reported that more than 1.2 million acres of loblolly pine were operationally fertilized by 1987. This acreage increased to 1.5 million by the end of 1988 (NCSFNC 1989). Allen (1987) also indicated that older stands usually respond better to nitrogen or nitrogen plus phosphorus than to phosphorus alone. According to Megraw (1985), fertilization, particularly with nitrogen, increases growth rate in loblolly pine, but in older trees can reduce breast height specific gravity by 5 to 10 percent for several years after treatment. Williams and Farrish (1995) determined that diameter increment increased an average of 24.5 percent over the control treatment during the 2 years following fertilization in 25- and 30-year-old loblolly pine plantations. The volume increment from the fertilizer treatment on a per-tree and per-acre basis showed a similar percentage increase during the same period. Jokela and Stearns-Smith (1993) found fertilization of 14- to 17-year-old loblolly and slash pines (*Pinus elliottii* Engelm. *var elliottii*) still showing cumulative responses for basal area and stand volume growth greater than the controls 8 years after initial treatment.

Growth increase, in terms of additional wood volume, is unquestionably important, but fully as significant is the quality of wood produced by fertilized trees. Quality may be measured in terms of wood properties such as specific gravity, strength, stiffness, rate of growth, etc., or in terms of the quantity and location of defects. Permissible defects for southern pine lumber are specified in grading rules published by the various grading associations. When the tree is converted to lumber, characteristics such as knot size and location, slope of grain, rate of growth, and density, are limiting factors in arriving at a specified grade and reflect the inherent quality of the resource. Since these factors can be influenced by silvicultural practices, forest managers can significantly impact sawn lumber grade yields.

This paper reports the results of a preliminary study to investigate the effects of thinning and fertilization on clear lumber yields from an older loblolly pine plantation.

METHODS

The study was carried out in an established plantation located at the Hill Farm Research Station, Homer, LA. The plantation was originally planted with 1 -year-old loblolly pine seedlings on an 8-foot by 8-foot spacing (680 TPA). The entire plantation was thinned from 550 to 100 TPA 20 years after planting; from 100 to 50 TPA 25 years after planting; and from 50 to 25 TPA 30 years after planting. From age 20 until harvesting at age 30, a portion of the plantation was used for cattle grazing and was fertilized annually with a nitrogen:phosphorus:potassium ratio of 100:35:18 pounds per acre, while the remainder was neither fertilized nor grazed. Table 1 shows the mean tree data (d.b.h., height, and basal area) for the plantation at age 20, 25, and at age 30 prior to harvest. At age 30, six trees were selected for harvest, three from the fertilized portion of the stand and three from the nonfertilized portion. The terrain sloped from a hilltop downward toward a pond; hence, to better represent the plantation, one tree from each treatment came from the hilltop, one from midway down the slope, and one from the bottom of the slope. An effort was made to locate sample trees with similar breast height diameters (table 1). After felling, each tree was bucked to produce a single 20.5-foot-long log. These six logs were transported to Wade Correction Center in Homer, LA, for processing into

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Table I-Mean sample tree data 20, 25, and 30 years after planting

Plantation age	D.b.h.	Height	Basal area
	In.	*Ft*	*Ff*
Fertilized			
20	10.6	59	0.613
25	13.5	70	0.994
30	15.8	72	1.362
Control			
20	11.0	62	0.660
25	13.2	71	0.950
30	14.8	74	1.195

lumber. Each log was inspected for straightness and defects. This information was used to buck each log into two separate, shorter logs, thus yielding six logs from the fertilized treatment and six from the control treatment. Ideally, two 1 O-foot logs plus trim allowance resulted; however, the location of defects and crooks in two of the six original 20.5-foot logs resulted in an 8-foot and 12-foot log from each. Each of these shorter logs was assigned four grading faces and graded based upon the clearness and straightness of each face. All logs were sawn using a Wood-Mizer$_{TM}$ portable horizontal bandsaw by opening the higher grade face first. Both 1 -inch and 2- inch lumber were produced. The lumber was graded green, fresh from the saw, using the Southern Pine Inspection Bureau grading rules for shop grade and finish grade lumber (SPIB 1994). Finish grade lumber is used where appearance and finishing qualities are critical and is assigned the grades of B&B, C, C&Btr, and D. Shop grade lumber is produced or selected primarily for industrial uses or remanufacturing purposes and is assigned grades No.1 and No.2.

RESULTSANDDISCUSSION

The lower boles of all trees were free of branches by age 25, 5 years after fertilization began; hence, it was hypothesized that the fertilized trees would not only have larger diameter growth, but more clear wood, which equates to high-quality lumber grades. Results indicate that individual tree basal area growth of fertilized trees exceeded that of nonfertilized trees by 40 percent at age 30 (table 1). Nonfertilized (control) trees yielded 63 percent of their volume as lumber. The fertilized trees produced 62 percent of their volume as lumber. Hence, total lumber yield as a percentage of log volume did not differ significantly among treatments; however, lumber grade (quality) was high for both treatments. Table 2 shows the finish grade lumber yields by treatment. It is evident that the fertilizer treatment produced a larger percentage of

Table 2-Finish grade lumber yields by treatment and position within the tree

Position in tree	No. of logs	Top DIB	Doyle scale	Grade yield B&B	C	D	Sheathing	Total	Overrun
		In.	*fbm*						
Fertilized:									
Board foot volume									
Tree	6	12.9	316	210	28	88	201	528	67
Butt	3	13.5	201	146	28	37	120	331	65
Top	3	12.2	116	64	0	51	81	197	70
Percent of total volume									
Tree	6	12.9	316	40	5	17	38	100	67
Butt	3	13.5	201	44	8	11	36	100	65
Top	3	12.2	116	33	0	26	41	100	70
Control:									
Board foot volume									
Tree	6	12.9	*297*	160	32	110	198	500	68
Butt	3	13.2	166	92	14	54	95	254	54
Top	3	12.5	131	68	18	56	103	246	87
Percent of total volume									
Tree	6	12.9	*297*	32	6	22	40	100	68
Butt	3	13.2	166	36	5	21	37	100	54
Top	3	12.5	131	28	7	23	42	100	87

Table 3—Shop grade lumber yields by treatment and position within the tree

Position in tree	No. of logs	Top DIB	Doyle scale	Grade yield No. 1	No. 2	Sheathing	Total	Overrun
		In.	*fbm*					
Fertilized:								
Board foot volume								
Tree	6	12.9	316	298	96	134	528	67
Butt	3	13.5	201	186	47	98	331	65
Top	3	12.2	116	100	61	36	197	70
Percent of total volume								
Tree	6	12.9	316	56	18	25	100	67
Butt	3	13.5	201	56	14	30	100	65
Top	3	12.2	116	51	31	18	100	70
Control:								
Board foot volume								
Tree	6	12.9	297	267	127	106	500	68
Butt	3	13.2	166	141	64	49	254	54
Top	3	12.5	131	126	63	57	246	87
Percent of total volume								
Tree	6	12.9	297	53	26	21	100	68
Butt	3	13.2	166	55	25	19	100	54
Top	3	12.5	131	51	26	23	100	87

high-quality lumber (B&B) than did the control treatment, whether comparing butt logs, top logs, or combining them to obtain an average value for the tree. If the comparison is made with C&Btr (all lumber of grade C and above), the yield for the fertilizer treatment exceeds that of the control for butt logs and the combined tree value, but the control treatment is slightly better in the upper log. This reversal is partly explained by the presence of two 8-foot-long logs in the upper log category, both of which came from the fertilizer treatment. The 8-foot length limits the ability to obtain the higher lumber grades since the minimum allowable lengths are: B&B-8 feet, C-6 feet, and D—4 feet. Hence, what would be a B&B grade in a IO-foot log becomes a C grade in the 8-foot log.

Table 3 shows the shop grade lumber yields by treatment. There is little difference in the yield of No.1 grade between the fertilizer and control treatment.

Table 4 displays the percentage of clear lumber by treatment and grade. The fertilizer and control treatment did differ slightly in the percentage of clear shop grade lumber produced: 11 percent and 8 percent, respectively. This 3-percent difference equates to a 40-percent increase in high-quality, high-value lumber. Finish grade lumber did not differ greatly in the percentage of clear lumber produced by the two treatments: 9 percent for fertilized versus 8 percent for the control. However, this 1 -percent difference does equate to a 13-percent increase in high-quality, high-value lumber. This disparity is due in part to the more strenuous grading requirements of the finish grade.

Table 4-Percentage of clear lumber by treatment and grade

Grade	Treatment Fertilized	Control
	Percent	
Finish	9	8
Shop	11	8

Based on cubic foot volume scale, the butt logs consistently gave lower lumber yields than the top logs, which is explained in part by the larger taper of the butt logs.

CONCLUSIONS

Based on this study, the following conclusions can be drawn:

1. Individual tree basal area growth of fertilized trees exceeded that of control (nonfertilized) trees by 40 percent.

2. The percentage of clear lumber produced was slightly greater for the fertilized treatment (9 to 11 percent) than for the control treatment (8 percent).

3. Fertilization produced a 40-percent increase in high-quality, high-value lumber for the shop grade and a 13-percent increase for the finish grade.

4. Based on cubic foot volume scale, the butt logs consistently gave lower lumber yields than the top logs, which is explained in part by the larger taper of the butt logs.

5. Fertilization in conjunction with thinning did increase both volume yield and yield of clear lumber.

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NITRATE DISTRIBUTION IN SOIL MOISTURE AND GROUNDWATER WITH INTENSIVE PLANTATION MANAGEMENT ON ABANDONED AGRICULTURAL LAND

Thomas M. Williams'

Abstract-Loblolly pine (*Pinus taeda* L.) and sweet gum (*Liquidambar styraciflua* L.) were grown with irrigation, continuous fertilization, and insect pest control on a l-year-old abandoned peanut (*Arachis hypogaea* L.) field. Wells and tension lysimeters were used to measure nitrate in soil moisture and groundwater on three replicate transects for 2 years. Each replication had five treatments: maximum plantation management, complete vegetation control, optimal irrigation, optimal fertilization, and insect pest control; minimum plantation management, complete vegetation control; old field, no activity; forest edge, 50-year-old longleaf pine forest; lake edge, pine-to-hardwood transition. Groundwater nitrate concentration beneath the minimum treatment [8.1 milligrams per liter (mg/)] was significantly higher than the maximum treatment and the old field (5.84 and 5.05 mg/l, respectively). All three treatments frequently exceeded the 10 mg/l drinking water standard. The forest and lake edge were both significantly lower at 0.30 and 0.32 mg/l respectively. Averaged over all depths, soil moisture nitrate concentrations in the two plantation treatments were significantly higher (11.4 and 11.5 mg/l) than the old field (5.4 mg/l), which was significantly higher than the forest edge (0.24 mg/l).

INTRODUCTION

Abandoned agricultural land is being actively examined for highly intensive forest management in the Southeastern United States. In addition to DOE and USDA interest in bioenergy production, forest industry is also examining intensive management for fiber production. Industry is experiencing an increased demand for fiber on company lands coupled with increasing limitations on forest land use. Concerns for wetlands protection, biodiversity, and forest practice certification will tend to limit the extent of commercial forest land dedicated to intensive management. Several companies are investigating use of highly intensive management on abandoned agricultural lands as a source of increased fiber production.

It is usually assumed that intensive forestry on agricultural land will produce few environmental concerns, since the proposed management is no more intense than current agricultural practice. Although nitrate leaching can be a problem in agriculture (Leslie and Barnett 1991), it is seldom a problem in normal southern forest management (Riekerk and others 1989). Plant uptake and heterotrophic bacteria are believed to compete more effectively than nitrifiers for available NH_4^+ in forest soils (Vitousek and others 1982). However, there is some evidence that nitrifiers can also be effective competitors, at least in grassland systems (Davidson and others 1990). Johnson and Todd (1988) found that quarterly nitrogen (N) fertilization resulted in greater nitrate loss than a single annual application, Johnson(1992) states nitrifying bacteria may be more effective competitors on better sites and that frequent fertilization might also increase their importance on "N poor' sites, more common on forest land. Use of herbicides for vegetation control seldom results in leaching of herbicide (Neary 1983), but herbicide application to forest land may result in increased nitrate leaching (Neary and others 1986). Finally, growth rates, and thereby N uptake, of most agricultural crops greatly exceed tree growth rates early in a forest rotation. It appears that application of intensive forest management to abandoned agricultural land might increase nitrate leaching early in plantation management.

Site Description

This paper outlines nitrate leaching results for the first 2 years of intensive plantation management on an abandoned peanut field on the lower coastal plain of southwest Georgia. The study was done at International Paper's Silver Lake Experimental Forest near Bainbridge, GA, on a former peanut field near the shore of Silver Lake. Silver Lake is a small stream valley that flooded subsequent to creation of Lake Seminole by a dam on the nearby Flint River. Soils of the site are Lakeland (Typic Quartzipsamments) and Eunola (Aquic Hapludult). In the old field, soils are excessively well-drained fine sand to loamy sand.

The plantation management experiment is laid out as three replicates of a randomized block, 2x4 factorial experiment. Factors are species (loblolly and sweetgum) and management intensity (control, irrigation, irrigation + fertilizer, and irrigation + fertilizer + pest control). Since all the blocks had herbaceous competition control and genetically improved seedlings, the controls were still rather intensive cultural treatments.

METHODS

The nitrate study addressed two main environmental concerns: (1) Do the cultural treatments result in leaching of nitrate? (2) Was there groundwater transport of nitrate to the adjacent Silver Lake? Both these questions were examined using multilevel soil moisture and groundwater sampling of three transects, one from each replicate. Each transect consisted of five plots: minimum treatment (control defined above), maximum treatment, old field outside of the treatment plots, within a 50-year-old pine stand surrounding the field, and at the edge of the lake. In each replicate, the five plots were aligned perpendicular to the land slope from the field to the lake edge (fig. 1).

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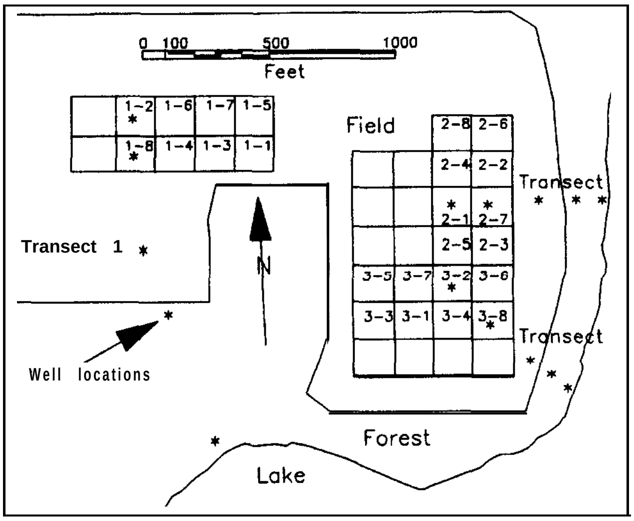

Figure l-Map of study'area. Plot numbers (l-l) represent replication-treatment. Odd treatment numbers are loblolly plots, even are sweetgum. Minimum treatment = 1&2, Irrigation = 3&4, Irrigation+Fertilizer = 5&6, Maximum = 7&8.

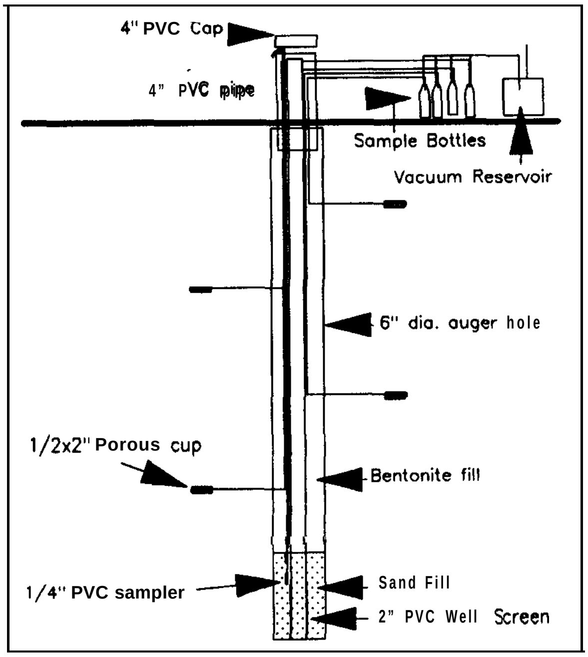

Figure 2-Schematic of water sampling devices placed at each well location.

In April 1995, a 15-centimeter (cm) diameter hole was augured below the water table and a 5-cm PVC well screen was placed 60 to 120 cm below the water table at each sample location. All plots, except the lake edge, had water tables at approximately 6 meters (m) depth and auger holes were 7 to 7.5 m deep. Soil samples were taken in 15-cm intervals throughout the depth of each installation. Soil colors were consistent with the water tables discovered in April. No soil, and few mottles, showed low chroma indicative of poor soil aeration. In addition to the well screen, small screened samplers (5 cm by 6 millimeters (mm) diameter) were also installed near the water table in several wells. The purpose of these was to collect small volume samples without disturbance associated with bailing of the well screen. Horizontal drilling was used to place four (2.5 cm by 10 cm long) tension lysimeters in undisturbed soil approximately 30 cm from the central shaft. Tension lysimeters were connected to sample bottles in a box on the soil surface, and all sample bottles were connected to a central vacuum manifold (fig. 2).

Trees were planted in February 1995 and cultural treatments were begun in April 1995. Sampling of soil moisture and groundwater was begun in May 1995 and samples were collected twice each month until December 1996.

Tension lysimeters were maintained at tensions between 0.5 and 0.7 bar continuously throughout the period. At each sampling, water was poured from the lysimeter sample bottles into 60-milliliters (ml) polyethylene bottles, all 5-cm wells were pumped until clear and a 60-ml sample was collected, and a 60-ml sample was collected from any of the small screened samplers that were below the water table. All samples were placed in coolers and returned to the Baruch Institute Lab in Georgetown, SC, and nitrate determinations were made within 24 hours. Nitrate analyses were done using cadmium reduction technique on a Technicon autoanalyser (Greenberg and others 1992).

Water tables were measured in each 5-cm well prior to each sampling. A local datum was established on a dock in Silver Lake and given an arbitrary elevation of 30.5 m (100 foot). Elevation of each well top was surveyed from the local datum by closed traverse. Lake level was measured by a tape at each sampling. Water levels in the wells were measured with two connector wires and a heavy weight. The wire was connected to a simple amplifier circuit that sounded a speaker when water completed the circuit. The wire, marked at 30-cm intervals, was lowered into the well until the speaker sounded. The distance was then measured with a tape to the nearest marker. All well depths were converted to elevation relative to the temporary datum.

RESULTS

Nitrate Concentrations in Soil Moisture

The tension lysimeters were connected to the vacuum system constantly such that water was withdrawn from the soil whenever soil moisture potential was below 0.5 bar. All percolating water was collected during the 2-week period between samplings. However, the use of tension of 0.5 to 0.7 bar also included some water that was not free to percolate.

Nitrate concentrations in the individual lysimeters were highly variable over the 2 years of sampling with ranges over four orders of magnitude (0.01 to >100 mg/l) and coefficients of variation of over 100 percent. Average values (fig. 3) showed considerable variation among depths, replications, and treatments. There were no significant differences between depths but significant differences in treatments, replications, and all two-way interactions.

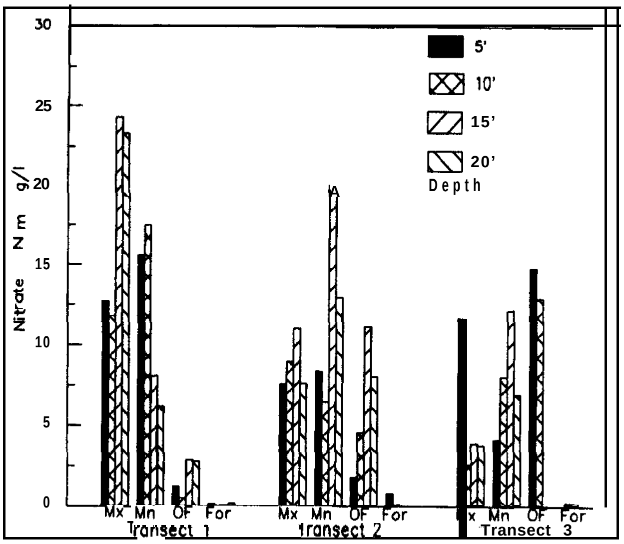

Figure 3-Soil moisture nitrate-nitrogen concentrations averaged by depth, transect, and treatment. MX-Maximum, Mn- Minimum, OF-Old Field, For-Forest.

There is a clear separation between treatments in the field compared to those in the natural forest. Comparison of treatments, averaged over all depths and reps, indicates soil moisture nitrate concentrations are significantly higher on both the plantation treatments than on the other three treatments (fig. 4). The old field vegetation is also significantly higher than the two natural forest treatments. There is little difference in the ranking whether the first year's or both years' data are included in the analysis.

Nitrate Concentrations in Groundwater

Groundwater nitrate concentrations were similar to soil moisture in relatively high variability, individual well coefficients of variation over 100 percent, and mean values. Groundwater nitrate, however, is evaluated in relation to drinking water standards. Compliance with drinking water standards requires the range of measured concentrations be below 10 mg/l. The only well on the abandoned field that complied with the standard was the maximum treatment plot on transect 2 (fig. 5).

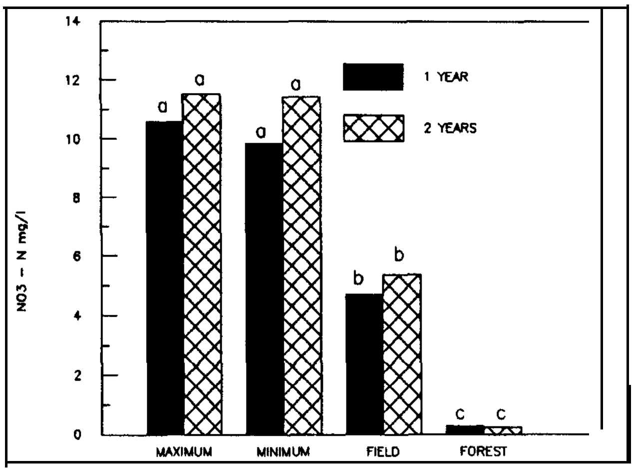

Figure 4-Average soil moisture nitrate-nitrogen concentrations over all depths and transects for 1995 and both years combined. Bars with the same letter within a year are not significantly different at 95 percent confidence level.

The pattern of groundwater nitrate concentrations by treatment was nearly identical to that of soil moisture. The only difference was the maximum treatment was not significantly different from the field treatment for groundwater. In 1995 the minimum and maximum plots were similar and not significantly different. With both years combined, the nitrate concentration below the minimum treatment was significantly higher than the maximum (fig. 6).

The second objective was also to determine the potential of nitrate movement into Silver Lake by groundwater flow. Nitrate concentrations were clearly higher below the

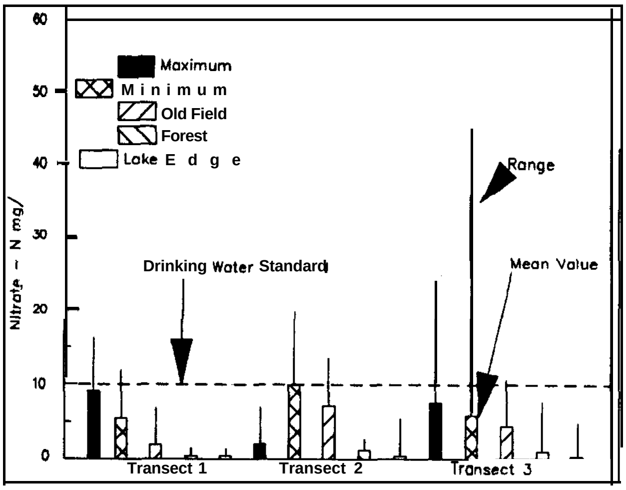

Figure 5—Groundwater nitrate-nitrogen concentration means and ranges compared to drinking water standards.

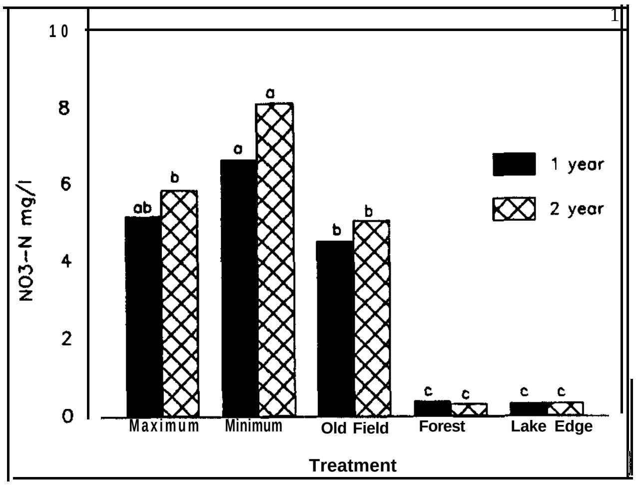

Figure 6-Groundwater nitrate-nitrogen concentrations for 1995 and both years combined. Bars with the same letter within a year are not significantly different at 95 percent confidence level.

abandoned peanut field. However, contamination of the lake requires groundwater flow toward the lake. In no case was there potential for flow from the field to the lake. The water table in the forest near the lake edge was consistently higher than any of the wells in the field (fig. 7).

DISCUSSION

In this study, nitrate concentrations in soil moisture and groundwater were significantly elevated in an abandoned peanut field for at least 2 years after agriculture ceased. Groundwater nitrate concentrations beneath all plots on the abandoned field violated drinking water standards with the minimum plantation management having the highest concentrations. Intensive plantation management increased the nitrate concentration in soil moisture above that found in the abandoned field with no treatment. There was no difference between the minimum and the maximum treatments in soil moisture nitrate.

The most important factor in nitrate concentrations was the presence of an abandoned peanut field. Values under the field were more than an order of magnitude larger than in the old forest or lake edge. Groundwater nitrate often exceeded drinking water standards in nearly every well beneath the field and never exceeded the standards outside of the field. Nitrogen fixation is active in peanuts, even in the dark and after aboveground parts are removed (Siddique and Bal 1991). Lynd and Ansman (1991) found decomposing nodules of sirato (*Macroptilium atropurpureum* DC.) stimulated rapid nitrification. Peanut residue also increased the rate of nitrogen mineralization (Smith and Sharpley 1990) in contrast to nonleguminous residue that caused immobilization of soil nitrogen. It seems quite likely that nitrification was enhanced throughout the abandoned peanut field, resulting in high nitrate concentrations in both soil moisture and groundwater.

Nitrate concentrations were also significantly higher beneath the plantation treatments than the old field.

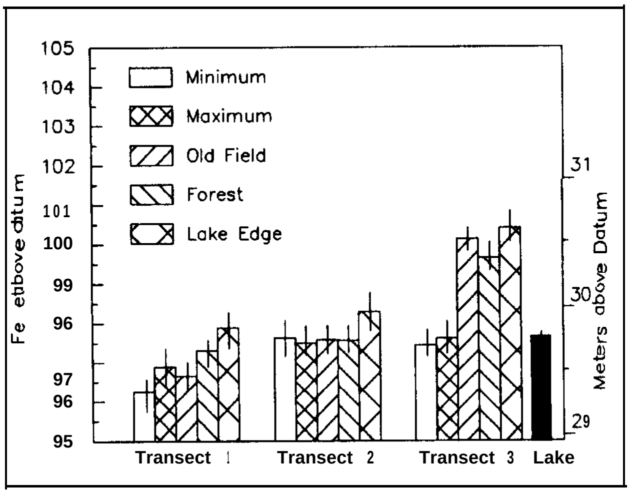

Figure 7-Average water table elevations and 95 percent confidence limits, relative to an assumed datum (30.5 meters).

Plantation establishment seems to have increased nitrate concentrations, although there was little difference between the minimum and maximum treatments. Nitrification has been found associated with vegetation control using herbicides (Likens and others 1969, Neary and others 1986, Munson and others 1993). These studies suggest that elimination of competing vegetation may result in increased nitrate leaching. All plantation treatments in this study included nearly complete elimination of competing vegetation.

In this study, intensive plantation management on an abandoned peanut field showed nitrate concentrations in soil moisture and groundwater at undesirable levels. It suggests caution in application of intensive plantation culture on abandoned agricultural land. It is not possible to determine causes or predict results from a single study, especially one established on the site of a crop that exhibits vigorous nitrogen fixation. However, agricultural land does have conditions more favorable to nitrification (better drainage, higher pH) than forested lands.

ACKNOWLEDGMENT

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EFFECTS OF SOIL COMPACTION AND ORGANIC MATTER REMOVAL ON MORPHOLOGY OF SECONDARY ROOTS OF LOBLOLLY PINE

Charles H. Walkinshaw and Allan E. Tiarks[1]

Abstract-Root studies are being used to monitor possible changes in growth of loblolly pines on a long-term soil productivity study site. Here, we report the results of a preliminary look at roots in the sixth growing season. Roots were collected from loblolly pines grown in soil that was first subjected to three levels of compaction (none, moderate, severe) and three levels of organic matter removal (stem only, total tree, and total aboveground biomass). Roots were fixed, sectioned, and stained for examination by light microscope. The proportion of roots with bark formation decreased from 70 percent in uncompacted soil to 43 percent in severely compacted soil. Depletion of starch grains was significantly less in samples from uncompacted soil than in compacted soil.

INTRODUCTION

Management practices that change soil properties may affect growth and health of secondary roots and eventually the long-term productivity of the site. The USDA Forest Service's long-term soil productivity (LTSP) study, which has recently been installed at several sites in the United States and Canada (Tiarks and others 1993) is designed to measure such changes over a rotation. its primary purpose is to monitor changes in productivity and soil processes. Three levels of soil compaction, three levels of organic matter removal, and two levels of vegetation control were applied (Powers and others 1990). Ultimately, interpretation of the relationship between these treatments and productivity will require the linking of changes in soil properties to soil processes, including root growth and health.

Anatomical study of roots is particularly useful for assessing root health (Walkinshaw 1995). Soil compaction affects root health and subsequent crop production in annual crops (Allmaras and others 1988, Feldman 1984). Compacted soils have fewer and smaller pores, and such conditions damage roots and alter their morphology. Loblolly pine roots less than about 5 millimeter (mm) in diameter appear to be particularly vulnerable to soil compaction (Copeland 1952). Shedding of dead cortex reduces root diameter and eliminates large numbers of root hairs in loblolly and other conifers (Kozlowski and Scholtes 1948, Leshem 1974). Many injuries develop after the period of root extension during secondary root development (Coutts 1987).

The objectives of the present study were to evaluate the usefulness of root morphology variables as indicators of root health, and to measure the effects of soil compaction and organic residue removal on anatomy of secondary roots.

METHODS

The root samples used were collected at the LTSP site located in Rapides Parish, LA, (Tiarks and others 1991) at the beginning and end of the sixth growing season. A 40-year-old loblolly pine stand on the site was harvested in 1989. The compaction treatments (none, moderate, and severe) and organic matter treatments (stem only, total tree, and total aboveground biomass) were applied soon after harvest. The plots were planted with containerized seedlings from 10 open-pollinated loblolly pine families in February 1990. Soil bulk densities were measured with a core sampler at planting and at stand age 5. Tree volumes were calculated on the basis of pine heights and diameter at breast height (d.b.h.) measured at age 6 (Schmitt and Bower 1970).

Roots were sampled twice in the sixth growing season. In the first sampling (March 24, 1995) roots from 10 trees were collected in the plots representing the extremes of the treatments (OM_0C_0 and OM_2C_2). In the second sampling (October 10, 1995) we sampled roots of five pines per treatment. There were 9 different treatments, and an average of 14 roots per tree was collected at each sampling. The March sampling yielded 264 root specimens and the October sampling 753. Root samples were from pines randomly selected from among the families. To ensure that nonpine roots were not included in the samples, we collected only in subplots that had received herbicide treatment.

Roots were collected in a 25-centimeter (cm) by 25-cm area located about 1 meter (m) from the stem of a pine. All soil and roots between a depth of 2 cm and a depth of 20 cm were collected and the roots gently shaken to remove excess soil. The center 2 to 4 cm of each root was excised and placed into formalin-acetic acid-alcohol (FAA) fixative for 14 days (Sass 1951). Fixed root specimens were re-cut to 1 to 3 mm, dehydrated in alcohol series, embedded in paraffin, and cut into 7 micrometers (m) to 10 m transverse sections. Sections were stained by hematoxylin-eosin, Papanicolaou's schedule, or the acid-schiff procedure (Haas 1980). Three to nine stained sections were prepared from each root, but only the first usable section from each root was read. Observations on root sections were at 100 to 500 diameters with a photomicroscope. Halogen and polarized light sources and neutral density filters were used

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to differentiate tannin and cellulose:lignin complexes. The percentage of roots meeting the criteria for a variable was calculated by tree. If the cambium appeared dead and tannin accumulation was excessive, the root was considered to be dead and not used in further analysis. No dead roots were found in the March sampling and only four roots were dead in the October sampling.

Variables for Histological Observations

Based on past observations of root samples from Louisiana (2,619 roots), Mississippi (623 roots), and North Carolina (1,221 roots), 10 variables were selected for further testing. They were:

Variable	Description
Cortex shedding	Cortical cells are dead and remain attached or are released into the soil. The shed is invaded by many soil microbes.
Periderm formation	The first stage in replacement of shed cortex. Cortical cells are coated with a protective layer of tannin and cellulose:lignin complex.
Bark formation	Intact layer of bark cells identical to those found in the stem encompasses the root. Protects the root from injuries and microbial invasion.
Starch	Degradation of starch grains in the cells is degradation 50 percent in the cells. Starch test in cortical and ray cells is negative.
Tannin	Accumulation of tannin-containing ceils in accumulation the cortex, rays, and inner xylem. Number of cells with accumulations range from less than 10 to over 100.
Mycorrhizal	Status of short roots that are shed during status the early stage of cortical-cell death. New lateral roots often develop at the sites where mycorrhizal roots have shed.
Lateral root	Formation of roots that arise from the xylem formation and phloem and remain permanent rather than being shed like root hairs and mycorrhizae.
Pathogenic	Infection of living cambial or fiber cells, infection in contrast to invasion of the dead cortex in the shed. Root appears to die from this invasion.
Section	Tissue tearing that occurs during sectioning tearing and makes it difficult to examine specimens for periderm formation, starch degradation, and formation of lateral roots.
Number of	Number of starch-containing plastids per cell starch grains when the cell is viewed at a single focal per cell length at 100 to 500 diameters.

Data Analysis

Treatments were not replicated, but the plots were sufficiently large and uniform so that within-plot sampling could be considered replication in this preliminary test of root variables. Thus, trees within plots were used as replications. Analysis of variance was used to separate the means of the two treatments sampled in March. For the October sampling, analysis of variance for a factorial design was used to test the significance of the main effects (compaction and organic matter level) and of their interaction.

Results and Discussion

March sampling-Four of the 10 variables measured on samples collected March 24, 1995, were significantly affected by the two soil treatments (table 1). The combination of soil compaction and removal of aboveground organic matter delayed cortex shedding, periderm formation, and starch degradation. The proportion of roots with complete bark was 70 percent in the severely treated plot and only 43 percent in the low-impact

Table l-Measurements of root samples collected March 24, 1995 by soil treatments

	Compaction-OM treatment		
Root variable	None-stem removal only	Severe-total aboveground	Probability of> F value
	Percentage of roots		
Cortex shedding	52	31	0.012
Periderm formation	53	28	0.002
Bark formation	43	70	0.001
Starch degradation	29	6	0.001
Tannin accumulation	12	12	0.830
Mycorrhizal status	9	8	0.851
Lateral root formation	6	5	0.809
Section tearing	28	18	0.166
Pathogenic infection	0	0	1.000
	Grains per cell		
Starch formation	10.9	10.7	0.848

treatment. The other variables were not significantly affected by the soil treatments.

October sampling-Of the 10 variables measured in the fall sampling, only 4 were significantly affected by the treatments (table 2). Cortex shedding, periderm formation, section tearing, and number of starch grains per cell were affected by soil compaction, while only periderm formation and number of starch grains per cell were significantly affected by removal of organic matter. None of the interaction terms was significant.

Removal of limbs and foliage during the harvest decreased the proportion of roots with periderm formation from 35 to 24 percent (table 3). Removal of the forest floor had no further effect on the percentage of roots with periderm formation. Removal of organic matter had a mixed effect on the number of starch grains per root cell, with the greatest number of starch grains per cell occurring in samples from the intermediate treatment. Although this effect was statistically significant, a biological explanation is not readily apparent.

As compaction increased, the percentage of roots with periderm formation decreased (table 3), with the greatest effect occurring as compaction was increased from 1.40 to 1.46 grams per cubic centimeter. The number of starch grains per root cell increased as the level of compaction increased. The change in number of starch grains per cell was proportional to the change in bulk density. The percentage of roots with cortex shedding decreased as

Table 2-Probability of differences occurring by chance for root variables in samples collected October 10, 1995

Root variable	Compaction	Organic matter treatment	Interaction
	Probability		
Cortex shedding	0.017	0.164	0.060
Periderm formation	0.016	0.045	0.171
Bark formation	0.084	0.126	0.299
Starch degradation	1.00[a]	1 .00	1 .00
Tannin accumulation	0.362	0.466	0.132
Mycorrhizal status	0.357	0.145	0.300
Lateral root formation	0.556	0.128	0.168
Section tearing	0.030	0.577	0.978
Pathogenic infection	0.289	0.537	0.586
Starch grains	0.001	0.025	0.089

[a] Only four roots showed signs of starch degradation.

Table 3-Means (percentage) of roots with periderm forming and number of starch grains per root cell, by soil treatment, for sample collected October 10, 1995

Compaction	Organic matter removed: Stem only	Total tree	Total above ground	Mean
	Pct. of roots with periderm forming			
None (1.40a)	45	27	33	65
Moderate (1.46)	28	27	31	27
Severe (1.49)	33	20	9	21
Mean	35	24	25	
	Number of starch grains per cell			
None (1.40)	5.0	6.7	6.1	5.9
Moderate (1.46)	7.0	6.9	6.4	6.7
Severe (1.49)	6.8	7.5	7.1	7.1
Mean	6.3	7.0	6.5	

a = bulk density (grams per cubic centimeter) at age 5.

bulk density increased from 1.40 to 1.46 grams per cubic centimeter but was not affected by a further increase in compaction (table 4). The percentage of sections that were torn decreased as the compaction level decreased. Percentage of torn sections could be an artifact of the sampling or related to the physical strength of the roots. Further evaluation of this variable will be necessary if the meaning of the difference is to be understood.

The compaction and organic-matter removal treatments affected pine height and volume growth by age 6 (table 5). In general, the plot means for volume declined with increased compaction. The same was true for percentage of roots with cortex shedding and periderm formation. When the height and volume of single trees were regressed against root variables for the same trees, no significant relationships were apparent. However, the sampling method does not guarantee that a root sample is from the correct tree.

Table 4-Effect of soil compaction on percentage of roots with cortex shedding and torn sections

Compaction	Bulk density	Cortex shedding	Torn section
	Grams/cm^{-3}	*Percentage*	
None	1.40	52	20
Moderate	1.46	38	18
Severe	1.49	38	10

Table 5—Effect of compaction and organic matter removal on growth of loblolly pine at age 6

Organic matter removal	Compaction treatment	Soil bulk density	Height	Volume
		G/cm-3	m	D	m3/tree
Stem only	None	1.40	5.6	15.8
	Moderate	1.46	5.9	18.3
	Severe	1.49	4.8	9.5
Total tree	None	1.40	4.7	9.2
	Moderate	1.46	5.0	11.0
	Severe	1.49	4.9	11.0
Total aboveground	None	1.40	4.9	9.6
	Moderate	1.46	5.1	10.9
	Severe	1.49	4.4	7.8

Tannin accumulation, pathogenic infection, mycorrhizal status, and formation of lateral roots were unaffected by the soil treatments. These variables have shown promise as indicators of root health in older stands. In this 6-year-old stand, the roots were all generally healthy. Root morphological characteristics that were affected by the compaction, such as periderm formation and number of starch grains per cell, are probably more indicative of tree vigor than of the health of root systems.

CONCLUSIONS

A variety of histological measurements used in the two root samplings significantly separated effects of soil treatments. The variables we measured were easy to tabulate and had relatively low coefficients of variation. Overall, the root health of the trees growing in all soil treatments appeared the same. Cortex shedding and periderm formation, which may be predictors of pine growth, were the only two variables statistically affected by the soil treatments in both sampling periods. Degradation of starch and formation of bark were significantly different by treatment only in the March sampling, while number of starch grains per cell differed by treatment in the October sampling. Soil compaction had a more consistent effect on root morphology than did organic matter removal.

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EFFECT OF A BIOSOLIDS APPLICATION ON PLANTATION LOBLOLLY PINE TREE GROWTH

E. David Dickens and Ansel E. Miller[1]

Abstract-The long-term growth response of a loblolly pine (*Pinus taeda*, L.) plantation to a one-time biosolids application was investigated. The study area was located in the upper Atlantic Coastal Plain on the Savannah River Site in Aiken County, SC. Permanent measurement plots were installed in an a-year-old loblolly pine stand using a randomized complete block design. Three replications of three treatments (control=0, low=400, and high=800 kilograms TKN per hectare) were assigned on two soil series, Fuquay and Wagram. Biosolids were applied one time in September 1981 at canopy closure. Tree measurements were made at plantation ages 8, 9, 11, 17, and 20 years. Mean diameter, volume per tree, and volume per hectare differences between the control and biosolids plot trees were insignificant until age 11, three growing seasons after biosolids application. Significant mean height differences between the control and biosolids plots did not occur until age 17, nine growing seasons after biosolids application. Merchantable volumes per hectare of the biosolids plot trees were 20 and 30 percent greater than the control's nine growing seasons after biosolids application on the Wagram and Fuquay soils, respectively. Overall, a single biosolids application at canopy closure greatly improved long-term growth of plantation loblolly pine on these soils.

INTRODUCTION

The increased emphasis of the U.S. Congress and the EPA to promote the beneficial land use of biosolids coincides with an interest in increasing forest productivity. Forest soils of the Southeast are generally marginal in fertility. The use of both inorganic commercial fertilizer and biosolids in forest stands has been effective in increasing crop tree growth (Wells and others 1985, McKee and others 1986, NCSFNC 1994). Loblolly pine (*Pinus taeda*, L.) will generally respond to nitrogen and phosphorus inorganic fertilization on better-drained upper coastal plain and Piedmont soils (Hynynen and others 1995). Information is lacking concerning the long-term growth response of loblolly pine to biosolids application (McKee and others 1986). A forest land application of biosolids study was initiated in 1981 on the Savannah River Site to discern the magnitude and duration of growth benefits of loblolly pine due to biosolids application. The differences between control and biosolids plot tree growth parameters through 12 growing seasons after biosolids application will be addressed in this paper.

METHODOLOGY

The study area is located in the upper Atlantic Coastal Plain of Aiken County, SC. Two soil series are present in the study area: the Fuquay soil series (loamy, siliceous, thermic Arenic Plinthic Paleudult) and the Wagram soil series (loamy, siliceous, thermic Arenic Paleudult). The study area was machine planted with nursery-run loblolly pine seedlings at a 1.8- by 3.05-meter spacing in early 1974. Site index for loblolly pine (base age=50 years) is 26.0 meters for the Fuquay and 24.5 meters for the Wagram soil series. The site had previously supported an immature pine stand that was harvested before 1974. The planting had 60 percent survival at age 8 prior to biosolids application. Approximately 55 percent of the trees had fusiform rust (*Cronartium quercum* f. sp. *fusiforme*) cankers on the stems before treatment. Canopy closure was nearly complete at treatment time.

The experimental design employed was randomized complete block with three replications (blocks) per treatment and soil series. Each plot measured 46 by 46 meters. Internal permanent measurement plots were established within each gross plot and were approximately 0.07 hectare in size. Permanent measurement plot trees were assigned a number and tagged with aluminum nails and tags. The loblolly pine stands had about completed their eighth growing season when the liquid biosolids were applied one time in September 1981 by pressure spray guns from tankers. Treatments were as follows: (a) control (no biosolids applied), (b) low liquid @ 400 kilograms TKN per hectare, and (c) high liquid @ 800 kilograms TKN per hectare. The liquid biosolids were anaerobically processed and mainly of domestic origin (80 percent) with an initial pH of 7.3, a carbon:nitrogen ratio of 3:1 and 7.2 percent TKN (dry basis, table 1). Diameter at breast height (d.b.h.) (1.37 meters above groundline), and total height (tht) measurements were taken on all living tagged trees in December 1981 (age 8), March 1983 (age 9), March 1985 (age 11), December 1990 (age 17), and February 1994 (age 20). Total tree volumes were estimated using a stem volume equation (total volume in cubic feet = $0.0014793 * d.b.h.^{1.821} * tht^{1.1629}$) developed for site-prepared loblolly pine in the upper coastal plain of Alabama, Georgia, and South Carolina (Bailey and others 1985). These cubic foot volume values were then converted to cubic meter values (cubic meters = cubic feet/35.31). The perimeter of each of the 18 permanent measurement plots was measured and a plot factor for each plot was used to convert from average volume per tree and number of trees to volume per hectare. Diameter at breast height, total height, volume per tree, and volume per hectare averages were tested by year, using analysis of variance and least squares differences at the 5 percent alpha level. Annual

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Table I-Mean concentrations and application levels for liquid biosolids applied to an 8-year-old loblolly pine plantation on the Savannah River Site in Aiken County, SC (Wells and others 1986)

Component	Concentration	Application level low	Application level high
	----Percent---	---- kg/ha[a] ----	
Biosolids	2.48[a]	5,555	11,110
Ash	46.02	2,556	5,113
Carbon	23.20	1,300	2,600
	---- mg/kg[a] ----		
Kjeldahl-N	72,374	400	800
NH_4-N	30,361	169	338
NO_3-N	149	0.82	1.64
P	16,209	90	180
K	2,661	15	30
Ca	14,556	81	162
Mg	2,460	14	28
Cu	318	1.8	3.6
Mn	137	0.76	1.52
Zn	1,330	7.4	14.8
Cd	44	0.24	0.48
Ni	44	0.24	0.48

[a] d.b.= dry basis.

incremental growth between measurement years was also determined to discern if and when control and biosolids plot tree growth was converging.

RESULTS

Topsoil (0 to 15 centimeters) and forest floor nutrient and trace metal rates and distributions 1, 4, and 12 growing seasons after biosolids application are reported elsewhere (Dickens and White 1996). The results (concentrations and kilograms per hectare) were reported across the two soil series as there were no significant soil series (Fuquay versus Wagram) differences. The biosolids-treated plots (low and high levels averaged), when compared to the control at age 20 (12 growing seasons after biosolids application), had 20 percent more surface soil organic matter, 10 percent more total nitrogen, 150 percent more plant-available phosphorus (Bray-P), 45 percent more extractable calcium, and 40 percent more extractable magnesium.

Nitrate-N concentrations were determined from soil solutions collected quarterly from suction lysimeters installed in all plots to a l-meter depth. The peak soil solution nitrate-N concentration in the low-level plots was 4.8 milligrams per liter, occurring 6 and 12 months after biosolids application and returned to background levels (c 1 .O milligrams per liter) within 2 years (Wells and others 1986). The high biosolids level plots' nitrate-N peak concentration (at 1 meter in soil solution) was 21 milligrams per liter, occurring 15 months after application, and returned to background levels 24 months after application. Two groundwater wells, one upgradient and one downgradient of the study area, were also installed to a depth of 13 meters. These wells were monitored quarterly for 6 years. Results of all analyses indicate no groundwater degradation as a consequence of the biosolids treatments (Lower 1985, unpublished data). The mean nitrate-N concentration for the upgradient well was 0.70 milligrams per liter and for the downgradient well was 1.8 milligrams per liter. The maximum nitrate-N values were below the 10 milligrams per liter maximum contaminant level.

There were no significant tree diameter (@ 1.37 meters above groundline) differences among the three treatment levels at stand age 9 years, one full growing season after biosolids application (fig. 1 -A). Loblolly pine mean diameters grown on the biosolids plots were significantly

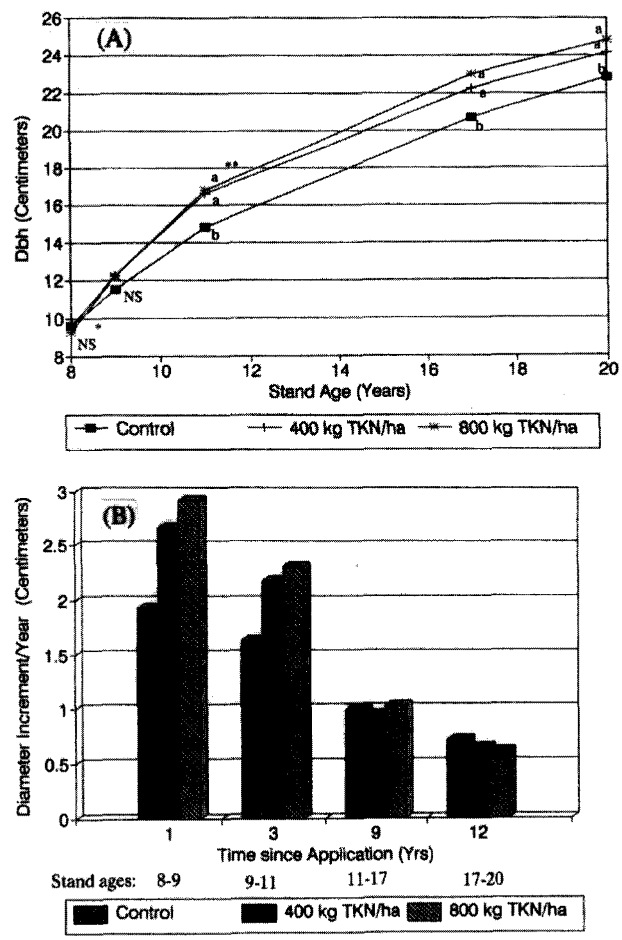

Figure l-Mean diameter (d.b.h.) at stand age (A) and (B) annual incremental growth between stand ages in a loblolly pine plantation after biosolids application on the Savannah River Site in Aiken County, SC.

*NS = Not significant using LSD at the 5 percent alpha level.
**Within same year, means followed by the same letter are significantly different.

greater, by 1.81 and 2.01 centimeters, than on the control plots at age **11,** three growing seasons after biosolids application. The maximum diameter difference between the two different biosolids rates and the control occurred at different times. The maximum diameter difference between the low biosolids level and control plot trees (1.81 centimeters) occurred at age 11, three growing seasons after biosolids application. The maximum difference between the high biosolids and control plot trees (2.27 centimeters) occurred at age 17, nine growing seasons after biosolids application. The biosolids plot mean tree diameter at age 17 years (22.6 centimeters) was approximately equal to the mean control plot average tree diameter (22.8 centimeters) at age 20 years, thus reducing the potential rotation age by 3 years with a single biosolids application. Tree diameter annual increment (diameter growth between sampling dates) differences between the biosolids plot trees and the control plot trees were greatest between ages 8 and 9 (38 percent and 51 percent greater; fig. 1 -B). The control plot trees' diameter annual increment exceeded the low biosolids increment for the period between ages 11 and 17, and the high biosolids tree diameter increment between ages 17 and 20. The mean diameter for the control plot trees (22.86 centimeters) was still significantly less than both biosolids levels tree mean diameters (24.14 and 24.83 centimeters for the low and high levels, respectively) by age 20, 12 growing seasons after the one-time biosolids application.

Initially (ages 8 and 9 years) the mean total heights of high biosolids plot-grown loblolly pine trees were significantly less than the control's (fig. 2-A). Three growing seasons after biosolids application (age 11) there were no significant height differences between the three treatment means. The low and high biosolids plot trees' total height means were significantly greater than the control's at age 17 (an average of 0.70 meters taller) and age 20 (0.38 meters greater). Loblolly pine height growth annual increment was greater for biosolids plot-grown trees than the control's for the sampling periods between stand ages 9 to 11 and 11 to 17 years. The height growth annual increment for the control plot trees was greater than the biosolids plot trees between ages 17 and 20 (fig. 2-B).

There were no significant mean-total-volume-per-tree (cubic meters per tree) differences between the three treatment levels at the first two sampling dates (ages 8 and 9 years, fig. 3-A). The biosolids plot-volume-per-tree means were significantly greater (21 and 27 percent greater) than the control's at age 11, 3 growing seasons after biosolids application. Mean volume-per-tree values for the biosolids plot-grown trees continued to be significantly greater than the control's at ages 17 and 20. The percent difference between the biosolids plot volume-per-tree and the control's was decreasing after 1985 (age 11) to 18 and 26 percent at age 17 and 11 and 19 percent at age 20 (control versus the low and high biosolids, respectively). Total volume-per-tree annual increment between measurement years increased for all three treatment levels from age 8 through age 11 years. The low and high biosolids plot volume-per-tree annual increment was greater than the control's between ages 8 and 9, 9 and 11, and 11 to 17 (fig.

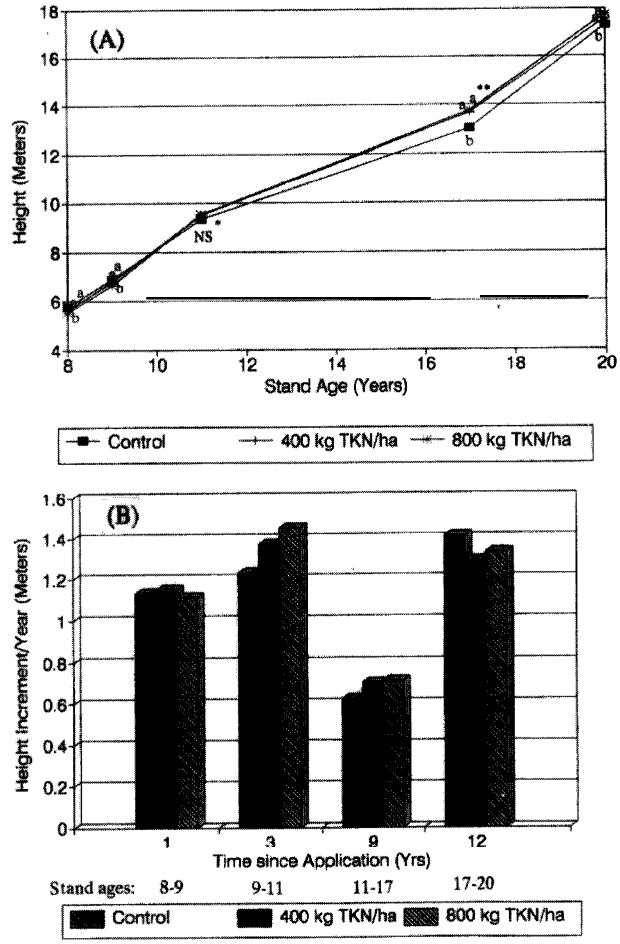

Figure 2-Mean height at stand age (A) and (B) annual incremental growth between stand ages in a loblolly pine plantation after biosolids application on the Savannah River Site in Aiken County, SC.

*NS = Not significant using LSD at the 5 percent alpha level.
**Within same year, means followed by the same letter are significantly different.

3-B). Maximum volume-per-tree annual increment differences between the biosolids and control plot trees appears to have occurred between ages 9 and 11.

Mean total volume-per-hectare values (cubic meters per hectare) were not significantly different for the three treatment levels at ages 8 and 9 years (fig. 4-A). The biosolids plots' tree volume-per-hectare means were significantly greater than the control's at ages 11, 17, and 20. The greatest total volume percent difference between the low level and control was 22 percent occurring at age 17 years, and 26 percent between the high level and control occurring at age 11 years. Tree losses to a beetle spot infestation between 1985 and 1990 in one of the high-level plots reduced the number of trees, reducing high-level mean-volume-per-hectare at age 17. The total volume-per-hectare annual increments for all treatment levels increased between stand ages 8 to 9 and 9 to 11 years. The biosolids plot volume-per-hectare annual increment

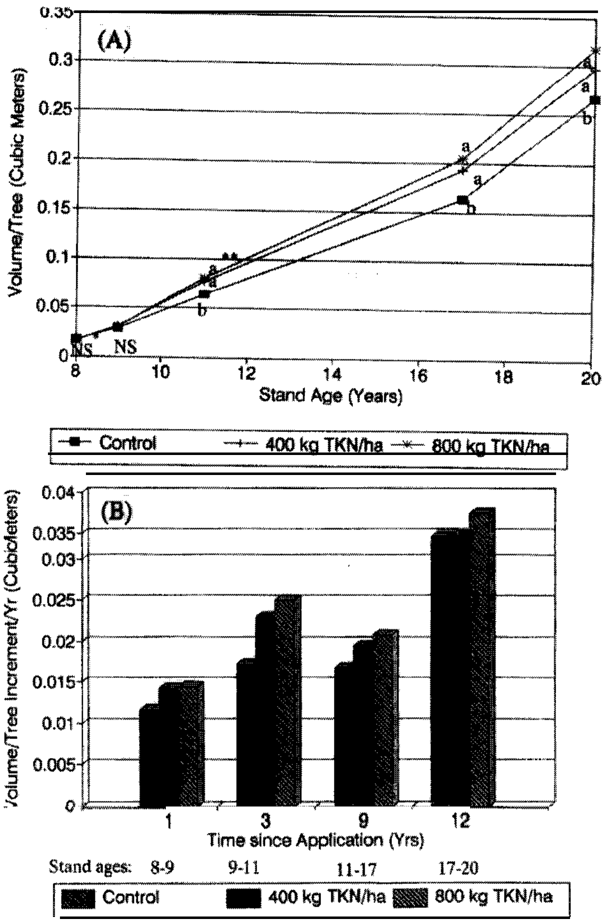

Figure 3-Mean volume per tree at stand age (A) and (B) annual incremental growth between stand ages in a loblolly pine plantation after biosolids application on the Savannah River Site in Aiken County, SC.

*NS = Not significant using LSD at the 5 percent alpha level.
**Within same year, means followed by the same letter are significantly different.

was greater than the control's between 8 and 9, 9 and 11, and 11 to 17 (fig. 4-B). The maximum volume-per-hectare annual increment differences between the biosolids plot and control plot trees appears to have occurred between ages 9 and 11.

DISCUSSION AND CONCLUSIONS

The one-time application of biosolids in an 8-year-old loblolly pine stand proved beneficial by increasing loblolly pine tree growth (over non-biosolids plot tree growth). Loblolly pine growth response to the biosolids appears to be somewhat similar to that of inorganic fertilizer. Hynynen and others (1995) found loblolly pine growth response to inorganic fertilizer peaked 4 years after one-time application at levels of 110, 220, and 330 kilograms of nitrogen per hectare (with 28 to 56 kilograms phosphorus per hectare). The maximum growth differences between the three levels and control were 14, 24, and 34 percent occurring 4 to 6 years after fertilization. Biosolids plot

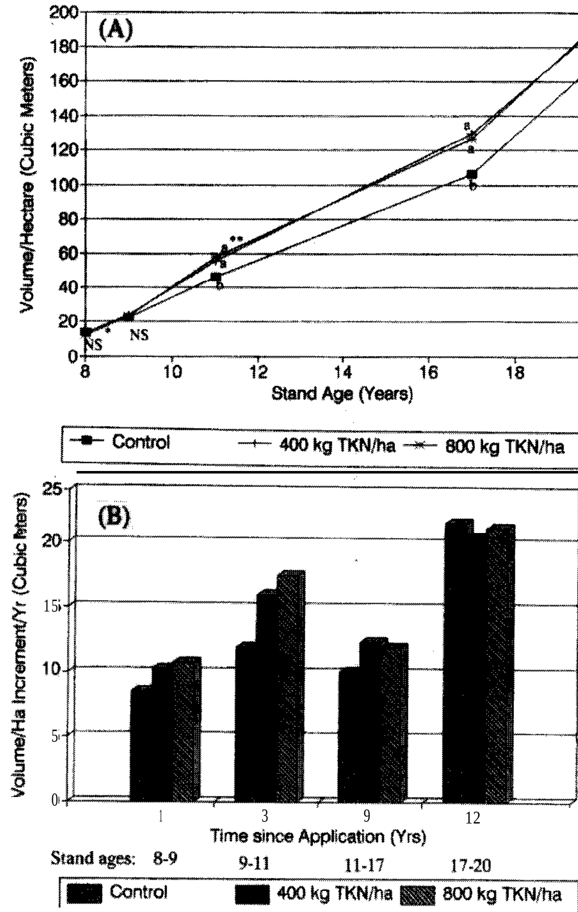

Figure 4—Mean volume per hectare at stand age (A) and (B) annual incremental growth between stand ages in a loblolly pine plantation after biosolids application on the Savannah River Site in Aiken County, SC.

*NS = Not significant using LSD at the 5 percent alpha level.
**Within same year, means followed by the same letter are significantly different.

volumes per hectare were 21 to 26 percent greater than the control's at age 11 years, three growing seasons after biosolids application and 19 to 22 percent greater than the control's at age 17 years, nine growing seasons after biosolids application.

Total volume per tree (fig. 3-B) and volume per hectare (fig. 4-B) annual increment between ages 11 and 17 were less than those between ages 9 and 11 years. If maximizing wood yield is a primary objective, a thinning, with or without a second biosolids application, may be feasible between these years. Palmer drought index numbers (Palmer 1965, unpublished data 1997) between stand ages 11 and 17 (February 1985 to December 1990) indicated more prolonged and severe growing season droughts for the Savannah River area than the measurement period before 1985 or after 1990. Extended growing season droughts between stand ages 11 and 17 (1985 to 1990) may explain the reduction in annual height, volume per tree, and volume per hectare growth. Increasing available soil moisture, sunlight, and nutrients to the more dominant residual trees, by thinning, may increase the annual volume growth.

Merchantable volume (to a 7.5 centimeter top inside bark) per hectare in the low biosolids plots was 20 percent greater than the control on the Wagram soil and 30 percent greater than the control on the Fuquay soil nine growing seasons after biosolids application on the Savannah River (Dickens 1993). The averaged merchantable wood increase due to biosolids application after nine growing seasons (age 8 to age 17 years) accounts for a $500 per hectare return increase (at $35 per cord).

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PELLETIZED CHICKEN LITTER AS A NUTRIENT SOURCE FOR PINE ESTABLISHMENT IN THE GEORGIA COASTAL PLAIN

Parshall B. Bush, William C. Merka, and Lawrence A. Morris[1]

Abstract-A series of three loblolly pine (*Pinus taeda* L.) regeneration plots were established in the Georgia coastal plain to evaluate chicken litter as a potential phosphorus source for pine regeneration. Treatments consisted of (1) standard fertilization with diammonium phosphate, (2) broadcast of litter at 1 ton per acre, (3) control, (4) 0.5 pounds per tree at planting, (5) 1 .0 pounds per tree at planting, and (6) 3.3 pounds per tree at planting.

Chicken litter broadcast at a rate of 1 ton per acre produced greatest pine growth response. Early pine mortality was observed on one wet site. A greenhouse study of the value of poultry manure stabilized with a high carbon:nitrogen ratio primary sludge from a Kraft paper mill shows that mixtures have potential as slow-release nutrient sources. Fresh mixtures of the two materials retain some adverse properties that lead to poor seedling survival in soils amended with fresh poultry manure.

Litter application cost Of approximately $9.25 per ton compares favorably with the estimated $29 per acre for diammonium phosphate.

INTRODUCTION

Georgia's forest and poultry industries are two of the largest industries in the State, contributing an estimated $26 billion to the annual economy and directly employing 175,000 workers (Georgia Forestry Commission 1995, Mauldin and others 1993). Favorable soil and climatic conditions and the availability of rural expanses in the State have fostered the development and success of these two industries. The annual production of approximately one billion birds generates 1.5 million tons of litter. The recent expansion of the poultry industry into south Georgia has generated concern over waste and nutrient management on sandy coastal plain soils.

The potential use of poultry litter as a fertilizer source is limited by: (1) low nutrient density, (2) low bulk density, and (3) nonuniformity. Because of its low nutrient/bulk density, cost of transportation of this material is high. Previous work at The University of Georgia[2] has determined that a blend of fine fraction/middle fraction litter material produces a better pellet and requires much less energy than pellets made from the raw (whole) litter. By separating the litter fractions prior to pelleting, the mill was also able to (1) decrease the material flow through a hammermill process, reducing energy costs and reducing maintenance on the hammermill itself, and (2) produce a uniform product with a nutrient (N, P_2O_5, K_2O) analysis of 4.6, 3.9, and 2.9 percent, respectively.

Since phosphorus (P) is often a limiting nutrient in coastal plain forested pine stand establishment, it is of interest to attempt to utilize chicken litter as a P source during stand establishment. In addition to supplying the P requirement, the litter would also supply some other essential elements for pine growth. Previous attempts at broadcast application of chicken litter at stand establishment have resulted in aggravated weed problems. Since intensive pine silviculture prescriptions include weed control, a study was established in the coastal plain to evaluate graded levels of chicken litter as a nutrient source.

Use of pelleted chicken litter as a fertilizer source for pine establishment could produce (1) a new market for a waste product (chicken litter), (2) a balanced fertilizer source, (3) a minimal impact on soil micro/macro organisms and on the environment, (4) savings in fertilizer costs to the forest industry, and (5) new jobs and/or increased profits for the rural poultry and timber producers.

The use of poultry litter as the P source at stand establishment in this region was evaluated. The project compares the growth rate of pine seedlings fertilized with poultry litter at four different rates to seedlings fertilized with commercial fertilizers presently used in intensive pine silviculture. Test plots were established in the coastal plain counties of Bulloch, McIntosh, and Tattnall.

The addition of mixtures of pulp mill sludge and poultry litter was evaluated for use as fertilizer for stand establishment. Primary sludge from pulp and paper production largely consists of organic fiber with varying amounts of inorganic fillers. Its high carbon (C) and low N content can result in N deficiencies when used in land application programs. An alternative to direct application of primary sludge is to produce a nutritionally balanced and more easily handled product by combining these sludges with animal wastes having higher N contents, such as poultry litter. For instance, primary sludge with a C:N ratio of 100:1 can be combined with poultry litter with C:N ratios of 5:1 to produce a slow-release fertilizer with initial C:N ratios of 25:1. Ash generated from combustion of wood wastes can also be combined in the mixture for odor reduction and as a means of improving overall nutritional value.

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As part of an ongoing School of Forest Resources study on mill residue utilization, noncomposted mixtures of primary mill sludge and poultry litter were evaluated in a greenhouse study. Growth was measured following application and compared with growth on experimental plots amended with sludge and commercial fertilizer. Foliage samples were collected to assess nutritional benefits of applications.

PROJECT PURPOSE AND OBJECTIVES

The major objectives of this study were to:

1. Determine whether pelleted poultry litter can be used as a fertilizer source for pine seedling establishment in the Georgia coastal plain.

2. Compare graded levels of poultry litter pellet applications (0, 0.5, 1 .O, and 3.3 pounds per seedling) to current stand fertilization practices.

3. Evaluate mixtures of poultry litter and primary sludge from a pulp and paper mill for its uses as fertilizer in newly established loblolly pine (*Pinus taeda* L.) plantations.

4. Prepare an economic assessment of the use of poultry litter in terms of the cost savings to the forest industry.

Field Study (Objectives 1 and 2)

Two field studies were established in 1995 on Union Camp sites in McIntosh and Tattnall Counties, GA. The experimental design for each consisted of six treatments and three replications. An additional study was established (two soil types x six treatments x two replications) in 1996 in Bulloch County. Tree spacing at these sites was 6 by 12 feet (approximately 600 trees per acre). Plots consisted of 7 trees in each of 7 adjacent rows (49 trees per plot).

Treatments consisted of the following:

1. No litter or chemical fertilizer applied (control).

2. Litter applied at 0.5 pounds per seedling (9 pounds P_2O_5 per acre).

3. Litter applied at 1 .0 pounds per seedling (18 pounds P_2O_5 per acre).

4. Litter applied at 3.3 pounds per seedling (60 pounds P_2O_5 per acre).

5. Litter broadcast at 1 ton litter per acre (60 pounds P_2O_5 per acre).

6. Fertilization at the operational rate (125 pounds diammonium phosphate per acre: 18, 46, 0; 58 pounds P_2O_5 per acre).

For the 0.5 and 1 .0 pounds per seedling rate, litter was applied in dibble holes drilled on opposite sides of each seedling, approximately 12 inches from the seedling. For the 3.3 pounds per seedling rate, litter was applied in four dibble holes drilled at right angles from each other, approximately 12 inches from the seedling. Although the fertilizer tag showed an analysis of 4, 3, 2, analysis of the litter indicated a fertilizer equivalent of 4.0, 4.1, 4.0. Tree growth was assessed 12 months after the initial fertilization. Growth was compared among all treatments and results were analyzed by ANOVA at the 0.05 level of significance.

Extensive pine mortality was observed on the poorly drained Bladen soil site, which exhibited survival rates of 97.3 percent with standard fertilization, 95.3 percent with broadcast, 90.9 percent with the control, 86.4 percent with 0.5 pounds per acre, 75.1 percent with 1 pound per acre, and 60.0 percent with 3.3 pounds per acre. Pine survival (all treatments >95 percent) and growth on the well-drained Ludowici, GA, site characterized by Chipley soils was excellent. Pine mortality on the Bladen soils appeared to be more severe in the wetter portions of the site. One might speculate that under the anaerobic conditions encountered on the wet site, ammonia buildup occurred to toxic levels at high litter application rates. Surviving trees on these plots were the largest trees in the study area. Since these sites received extensive weed control, there was no evidence of enhanced weed competition.

Field study results from the Bladen and Ludowici sites (1995) indicate that broadcast application of pelletized chicken litter at a rate of 1 ton per acre produced significantly greater growth (tree height) and root collar diameter than in standard commercial fertilization treatment or the control (tables 1 and 2). Evaluation of the Ludowici site at the end of the second growing season (table 2) showed that treatment-related differences carried through year 2. Unexpectedly, there was no difference in growth between the control and commercial fertilization treatment.

Table l-Evaluation of l-year pine growth on the Bladen, GA, site

Treatment	Observations	Height	Root collar diameter
	Number	*Feet*	*Inches*
Standard fertilization	154	2.94A[a]	0.726
Broadcast (1 ton/ac)	155	3.03A	0.82A
Control	159	2.98A	0.76AB
0.5 lbs/tree at planting	128	3.14A	0.78AB
1 .O lbs/tree at planting	112	2.83A	0.77AB
3.3 lbs/tree at planting	99	2.93A	0.77AB

Site 1: Miller #1 Tract, McIntosh County, near Bladen, GA (N of Brunswick along Warsaw Road near intersection of Warsaw Road and Brookston Road). Soil type: Bladen series soils are very deep, poorly drained, slowly permeable soils that formed in thick beds of acid clayey sediments on fluvial or marine terraces. Slopes range from 0 to 2 percent. Mean annual precipitation is -50 inches and mean annual temperature is -69 °F. Plot design: six treatments, three replications per treatment. Pretreatment soil test results: pH=4.7-5.1; P=6.2-13.9 lbs/ac; K=37-81 lbs/ac; N=0.045-0.070 percent N.

[a] Means in the same column followed by the same letter are not significantly different using the Duncan Multiple Range Test.

Table 2—Evaluation of 1 and 2-year pine growth on the Ludowici, GA, site

Treatment	Observations Yr 1	Observations Yr 2	Height Yr 1	Height Yr 2	Root collar diameter Yr 1	Root collar diameter Yr 2
	----Number		Feet		Inches	
Standard fertilization	162	147	2.47 C[a]	5.24 C	0.82 B	1.68 c
Broadcast (1 ton/ac)	145	141	2.99 A	5.81 A	0.94 A	1.94 A
Control	158	150	2.57 C	5.29 C	0.86 B	1.68 c
0.5 lbs/tree at planting	147	140	3.00 A	5.61 AB	0.91 A	1.80 B
1.0 lbs/tree at planting	139	134	2.88 AB	5.54 B	0.91 A	1.79 B
3.3 lbs/tree at planting	150	147	2.81 B	5.53 B	0.91 A	1.80 B

Site 2: Near Ludowici, GA, Long County (along Magnolia Road just past intersection with Kings Road). Soil type: Chipley series soils are very deep, moderately well-drained to somewhat poorly drained, rapidly permeable soils that formed in thick deposits of sandy marine sediments. They are on uplands in the lower coastal plain. Slopes range from 0 to 2 percent. Plot design: six treatments, three replications per treatment. Pretreatment soil test results: pH=4.8 to 5.1; P=6.2 to 14.1 pounds per acre; K=29.3 to 59 pounds per acre; N=0.030 to 0.041 percent N.

[a] Means in the same column followed by the same letter are not significantly different using the Duncan Multiple Range Test.

Plant tissue analysis did reflect an increase in P from fertilization on the standard fertilization site. Plant tissue analysis pooled from both sites revealed no treatment-related effects in nitrogen, phosphorus, potassium, calcium, magnesium, manganese, iron, boron, or zinc content (data not presented). The significant differences in tissue aluminum values can be attributable to alterations in root zone soil pH or contamination of some tissues by aluminum-containing soil. Commercial fertilization tended to elevate tissue copper levels. This is somewhat surprising in light of anticipated elevated copper levels normally associated with chicken litter.

Pine survival (>95 percent) and growth on the well-drained Ludowici, GA, site characterized by Chipley soils was excellent (table 2). Evaluation of plant tissue analysis from the Ludowici site by itself revealed that chicken litter treatments elevated the foliar phosphorus levels and that this increase was significant in the second-year postplant (table 3). Although all treatments were in the sufficiency range, a linear increase in phosphorus foliage content with increasing chicken litter treatment level was observed. The chicken litter did, therefore, serve as a phosphorus source. In general, the broadcast treatment was as good as the in-hole treatments.

Foliar nitrogen levels did not increase with increased litter level. All foliar nitrogen levels, including the control, were in the sufficiency range. If there was any benefit from the nitrogen, we are not seeing it at the 1 -year evaluation. The foliar potassium levels were all within the sufficiency range and only the 3.3 pounds per tree rate increased the level above the control (table 3).

An additional set of plots was established in 1996 on a site near Oliver, GA, that has wet soils (Albany soil series) and relatively well-drained soils (Blanton soil series). The Oliver site evaluation consisted of six treatments x two soil types x two replications. Survival was good on both soil types (>95 percent). Again the broadcast application of chicken litter at a 1 ton per acre rate produced the greatest growth, followed by 3.3 pounds per tree, 1 pound per tree, control, 0.5 pounds per tree and standard fertilization (table 4). There was significant interaction between the soil type and tree growth, with the greatest growth occurring on the Albany soil. Plant tissue analysis conducted on 1 -year foliar samples showed no significant differences in nitrogen, phosphorus, potassium, magnesium, manganese, iron, aluminum, boron, calcium, or copper. Nutrients were in the sufficiency range.

Response of Greenhouse-Grown Seedlings to the Poultry Manure Addition (Objective 3)

In an earlier study[3], survival of greenhouse-grown loblolly pine seedlings was poor following application of fresh poultry manure. Foliage symptoms were consistent with

[3] Unpublished data. Lawrence A. Morris, Associate Professor, Department of Poultry Science, The University of Georgia, Athens, GA 30602.

Table 3-Plant tissue analyses for Year 1 and Year 2 of pine regeneration/chicken litter study at the Ludowici, GA, site

Treatment[a]	Nitrogen Yr 1	Nitrogen Yr 2	Phosphorus Yr 1	Phosphorus Yr 2	Potassium Yr 1	Potassium Yr 2
	Percent					
Standard	1.66A[b]	1.39A	0.135ABC	0.114 B	0.508AB	0.436A
Broadcast	1.55AB	1.36A	0.136ABC	0.128AB	0.545AB	0.494A
Control	1.43AB	1.37A	0.123 C	0.115AB	0.469 B	0.439A
0.5 lbs	1.45AB	1.35A	0.128 BC	0.121AB	0.515AB	0.463A
1 .O lbs	1.28 B	1.31A	0.140AB	0.113 B	0.517AB	0.484A
3.3 lbs	1.44AB	1.36A	0.145A	0.138A	0.536A	0.482A

[a] Standard=Standard fertilization; Broadcast=Broadcast (1 ton per acre); 0.5=0.5 pounds per tree at planting; 1 .0=1 .O pounds per tree at planting; 3.3=3.3 pounds per tree at planting.
[b] Means in the same column followed by the same letter are not significantly different using the Duncan Multiple Range Test.

Table 4-Evaluation of 1 -year pine growth on the Oliver, GA (near Statesboro) site

Treatment	Observations Albany	Observations Blanton	Height Albany	Height Blanton	Root collar diameter Albany	Root collar diameter Blanton
	Number		*Feet*		*Inches*	
Standard fertilization	122	121	3.08 C[a]	3.08ABC	0.90 BCD	0.90AB
Broadcast (1 ton/ac)	97	101	3.56A	3.1 OABC	0.99 A	0.96A
Control	152	97	3.26 BC	2.96 C	0.86 D	0.87 B
0.5 lbs/tree at planting	94	96	3.09 c	3.24A	0.87 CD	0.93AB
1 .Olbs/tree at planting	95	97	3.36AB	3.23AB	0.93ABC	0.91AB
3.3 lbs/tree at planting	95	92	3.59A	2.98ABC	0.96AB	0.87 B

Site 3: Near Oliver, GA, Bulloch County. Soil types: Albany and Blanton series. The Blanton series consists of deep, moderately well-drained, very strongly acid soils of the coastal plain (slopes 0 to 5 percent). The soils are low in fertility and contain little organic matter. Albany series consists of very deep, somewhat poorly-drained soils that formed in coastal plain deposits of sandy material underlain by loamy sediments (slopes 0 to 6 percent). Permeability is rapid in the thick sandy surface horizon and moderate to moderately slow in the loamy subsoil. Plot design: two soils, six treatments, three replications per treatment. Pooling data for site produced significant treatment, soil, and treatment-by-soil interaction for tree height. Only treatment effects were significant for root collar diameter.
[a] Means in the same column followed by the same letter are not significantly different using the Duncan Multiple Range Test.

ammonium toxicity, suggesting the potential value of reducing initial nitrogen availability in low C:N ratio poultry manure by combining it with high C:N ratio materials prior to use as a soil amendment.

A greenhouse study of the value of poultry manure stabilized with a high C:N ratio primary sludge from a Kraft paper mill was conducted as part of a larger study of the use of paper mill residues as soil amendments. The entire study consisted of 23 organic and inorganic paper mill residues applied at two levels to two soil types in four complete blocks. Four of these treatments were of interest to this study of poultry manure. These are: the unamended control; primary sludge (0.068, 0.09) applied alone; primary sludge combined with poultry manure (4.7, 1.3, 2.2) in a 3.251 ratio to achieve a final C:N ratio of 20:1; and Black Kow® (0.5, 0.49, 0.50), a commercially available organic amendment derived from cow manure and wood bark. Low (71 grams per pot) and high (425 grams per pot) rates of each residue, which corresponded to a field rate of 10 and 60 dry tons per acre, were mixed with surface soil (a horizon material) from two soil series widely used for pine plantations (Leon and Orangeburg). Following residue addition, loblolly pine seedlings from four half-sib families that had been lifted from planting beds and acclimated to the greenhouse for 4 weeks were planted in 350 cubic inches plastic pots (two seedlings per pot). Pots were spatially arranged on greenhouse benches to provide four family blocks split into the two soil types. Amendment type and level were located at randomly selected positions within the soil type main plots. Blocking the experiment in this manner minimized differences associated with position within the greenhouse and limited the possibility of an accident causing loss of several replications of one or more treatments. Family effects were confounded with blocks and no family treatment interaction evaluations were possible.

At the start of the experiment, seedlings averaged 20.9 centimeters in height and soil pH averaged 5.5 and 5.4 for Leon and Orangeburg soils, respectively. Following planting in August 1995, seedlings were grown under well-watered conditions for 5 months without additional fertilizer addition. In January 1996, seedling height and diameter were measured and seedlings harvested and separated into branch and foliage components. Foliage and branches were dried and ground prior to analysis for nitrogen, phosphorus, potassium, calcium, and magnesium concentration.

Seedling size at the end of the 5-month experimental period is provided in table 5. Seedling survival was decreased by the high rate of the poultry manure-primary sludge amendment on both soil types. Large impacts on survival were not observed for the low application rate. For the Leon soil, seedling height and diameter (data not shown) were dramatically increased at the low addition rate of the poultry manure-primary sludge mixture, a response that was not as obvious at the high rate of addition. The few seedlings that survived the high rate of addition of this mix in Orangeburg soils were also larger than seedlings in the control, primary sludge, or Black Kow® treatments.

Foliage nutrient concentrations (table 6) indicate that by the time the experiment was harvested, seedlings in all treatments were deficient in nitrogen. Seedlings in the poultry manure-primary sludge mixture had the highest overall concentrations of nitrogen, phosphorus, potassium, calcium and magnesium in foliage. This indicates that poultry manure-primary sludge mixtures have potential value as a slow-release nutrient source but fresh mixtures of the two materials retain some adverse properties leading to poor seedling survival in soils amended with fresh poultry manure. This survival problem may be reduced or eliminated by allowing poultry manure-primary sludge mixtures to compost for a period prior to application to young seedlings or by reducing application rates.

Economic Assessment (Objective 4)

For poultry litter to be adopted as a nutrient source for pine seedlings, it must cause increase in growth greater than or equal to the standard fertilization practice of applying 125 pounds of diammonium phosphate (18, 46, 0) and the cost of procuring, transporting, and applying litter must be equal to or less than the cost of procuring and applying diammonium phosphate.

At $270 per ton for diammonium phosphate (local dealer price), an application rate of 125 pounds per acre would cost

Table 5—Survival and mean height of surviving seedlings grown in soil amended with three organic residues for 5 months

Amendment	Rate	Leon soil survival	Leon soil height		Orangeburg soil survival	Orangeburg soil height	
		Percent	*Centimeters*		*Percent*	*Centimeters*	
Unamended control		100	19.2	(4.5)[a]	94	25.8	(5.0)
Primary sludge	Low	100	20.9	(4.4)	88	23.4	(5.9)
	High	62	23.2	(6.4)	100	23.1	(2.9)
Primary sludge+poultry manure	Low	100	36.4	(5.9)	88	22.2	(6.8)
	High	25	26.0	(2.8)	38	31.3	(11.5)
Black Kow®	Low	100	23.5	(5.6)	100	25.9	(4.9)
	High	100	25.6	(6.6)	100	27.0	(9.0)

[a] Standard deviation.

Table 6-Foliage nutrient concentrations of seedlings grown in soil amended with three organic residues for 5 months; results averaged across two application rates

Amendment	Nitrogen	Phosphorus	Potassium	Calcium	Magnesium
	Percent				
Unamended control	0.63	0.12	0.54	0.34	0.14
Primary sludge	0.94	0.10	0.63	0.44	0.19
Primary sludge+poultry manure	1.00	0.11	0.77	0.45	0.18
Black Kow®	0.84	0.14	0.76	0.30	0.14

$16.85. Application would add an additional $12 per acre. Therefore, the total cost of aerial application of 125 pounds of diammonium phosphate would be $28.85 per acre.

In areas of North Georgia where poultry litter is readily available, haulers will spread litter for $25 per 6-ton truckload plus $1 per mile of hauling cost from the growing house to the application site. Using an application rate of 1 ton per acre as a nutrient source for pine seedlings, the litter would cost $4.17 per acre plus hauling cost. Each additional mile of hauling would increase per-acre cost by 17 cents. Experience shows that 20 to 25 miles would be a maximum haul of whole litter. This would result in a total litter cost of $8.44 per acre. A county agent in a southeastern Georgia poultry county reported that spread litter costs $5 per ton plus hauling costs. This greater cost of litter in southeastern Georgia would increase the per-acre cost to $9.25. Using poultry litter to fertilize pine seedlings is a nontraditional use of this material. Field trials should be conducted to determine the accuracy of these cost calculations.

Factors limiting the use of poultry litter may include:

1. Could traditional spreader trucks operate in tree plantings? Transfer of litter from trucks to a specialized spreading device would increase costs.
2. Would an increased demand for litter in areas of lesser poultry production cause the cost of litter to increase?
3. Would the convenience of procurement and aerial application of diammonium phosphate offset the cost savings of using poultry litter?

These and other factors should be evaluated prior to deciding to use poultry litter as a nutrient source for pine seedlings.

SUMMARY

Field studies conducted in the Georgia Coastal Plain indicate that pelletized chicken litter applied at a rate of 1 ton per acre did serve as a phosphorus source for pine stand establishment. Pine seedling mortality was observed on the poorly drained wet site associated with the higher treatment rates; one might speculate that anaerobic conditions may lead to excessive ammonia buildup. Leaf tissue nitrogen levels did not increase with increased litter level. The greenhouse study indicates that poultry manure-primary sludge mixtures have potential value as a slow-release nutrient source, but that fresh mixtures of the two materials retain some adverse properties that lead to poor seedling survival in soils amended with fresh poultry manure. This survival problem may be reduced or eliminated by composting poultry-primary sludge mixtures prior to application. Economic analysis indicates that chicken litter applied at a rate of 1 ton per acre would cost $8.44 to $9.25 per acre. This compares favorably with the current diammonium phosphate application cost of $29 per acre. Weed control measures currently used in intensive stand management would minimize the potential increase in weed populations from litter applications.

ACKNOWLEDGMENT

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EFFECT OF FERTILIZATION AND HERBACEOUS WEED CONTROL ON FIRST-YEAR SURVIVAL, GROWTH, AND TIP MOTH INCIDENCE ON LOBLOLLY PINE IN A SANDHILL SOIL

John L. Torbert and Polly-Anne Rantis[1]

Abstract-Although loblolly pine (*Pinus taeda* L.) productivity is often poor on Sandhill soils, these areas can be strategically important to forest industry because of the ability to log them during wet weather. A study was established on a deep, excessively well-drained sandy soil (Lakeland soil series) to test the effects of herbaceous weed control (control vs. 24 ounce VelparL) factorially combined with three fertilizer treatments (control, 250 pounds (Ibs) diammonium phosphate per acre, and a "complete" fertilizer with 350 Ibs micronutrient blend + 330 Ibs ammonium nitrate per acre) on loblolly pine growth and pine tip moth (*Rhyacionia spp.*) incidence using a complete randomized design with three replications. Hexazinone application had a greater effect on tree performance than fertilization. Hexazinone increased first-year ground diameter by 17 percent, which equated to a 50-percent increase in volume index. Tip moth infestation was also lower in the hexazinone treatment. Fertilization did not affect first-year growth. The "complete" fertilizer treatment kept tip moth infestation rates at the control level (51 percent) and lower than the diamnionium phosphate treatment (66 percent).

INTRODUCTION

As southern pine plantation management intensifies, many forest companies are grouping their land based on soil properties in order to develop more intensive, site-specific, silvicultural prescriptions.

The upper coastal plain of Alabama and Georgia consists of many different kinds of soils ranging from deep, excessively well-drained sands to slowly permeable clayey soils. The deep sands are often the least productive since they have a low moisture-holding capacity and are inherently infertile. However, pine plantations on deep sands can be a strategically important source of wood because they can often be logged during wet weather when other soils are prone to deep rutting. As the timber industry strives to comply with best management practices concerning wet weather logging and the AF&PA Sustainable Forestry Initiative, it becomes increasingly important to maximize productivity on sites that can be logged during wet weather.

As part of an attempt to identify the productive potential of deep sandy soils, a study was established in the Georgia Sandhills region. The objective of this study was to determine if herbaceous weed control (HWC) and/or fertilization could substantially improve the establishment and early growth of loblolly pine on a deep, excessively well-drained sandy soil. This paper reports first-year results.

METHODS

The study is located in Macon County, GA, on a Lakeland soil series (Typic Quartzipsamment). The previous pine plantation was clearcut in 1995, chemically site-prepared with hexazinone, burned, and machine planted in early 1996. In April 1996, the experiment was installed.

The study design is a complete randomized design with a factorial combination of two HWC treatments and three fertilizer treatments, replicated three times. The two HWC treatments were: (1) control, and (2) hexazinone (VelparL applied at a rate of 24 ounces per acre). The three fertilizer treatments were: (1) control, (2) diammonium phosphate (DAP) applied at a rate of 250 pounds per acre, and (3) a "complete" fertilization consisting of ammonium nitrate applied at a rate of 330 pounds per acre and a complete fertilizer (O-7-21 with micronutrients. Micronutrient blend analysis: 7 percent phosphorus 205, 21 percent potassium 20, 8 percent calcium, 2 percent magnesium, 9 percent sulphur, 0.5 percent boron, oxygen, 75 percent copper, 1.3 percent manganese, [0.13 percent water soluble manganese], and 0.75 percent total zinc) at a rate of 350 pounds per acre. Treatments were applied in 3-feet bands around each planting row.

Measurement plots were 0.1 acres (66 by 66 feet) within a 0.25 acre treatment area (105 by 105 feet). After the first growing season, seedling survival, height, ground diameter, and tip moth infestation were measured. Tip moth infestation was calculated as the percentage of buds in the terminal and top lateral branches that were infested by tip moth.

Foliage was sampled from 10 dominant trees in each plot (from 2 nonadjacent trees in each of 5 rows). Five fascicles of needles were removed from each of these 10 trees. Foliage was oven dried at 71 °C, weighed, ground, and sent to Waters Agricultural Lab (along with some standard tissue of known concentration) for nutrient analysis.

To assess HWC and fertilizer treatment effects and interactions, data were analyzed by analysis of variance. An arcsine transformation was made to the survival data for assessment of treatment effects, but not to the tip moth data because its distribution appeared to be relatively

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normal. A volume index was determined for each seedling by multiplying ground diameter squared times height. For all foliar nutrient concentration data, a Duncan's multiple range test was performed (alpha = 0.1) to identify treatment effects.

RESULTS AND DISCUSSION

The **Lakeland** soil used in this study is typical of much of the Sandhills. The soil is a deep, coarse, excessively **well-**drained sand with no argillic horizon within 80. inches of the surface. This soil type is not routinely chosen as a candidate for early HWC because the competing vegetation does not seem very vigorous. After the first growing season, this site had approximately 40 percent ground cover and species such as yucca (Yucca *spp.*) and prickly- pear (*Opuntia spp.*) were common.

The effects of hexazinone and fertilizer treatments on tree growth parameters are presented in table **1.** For all parameters, the probabilities of falsely concluding that different means are attributable to treatment effects are presented as **P>F.** For purposes of discussion, a treatment effect will be considered "significant" if the **P>F** value was less than 0.1. There were no significant interactions of HWC and fertilizer treatments for any of the tree growth parameters measured in this study.

Overall, survival was about 89 percent, and not significantly affected by hexazinone or fertilization (table 1).

With respect to tree growth, the strongest treatment effect was the influence of hexazinone on seedling diameter. Ground diameter was significantly greater in the herbicide treatment (0.49 versus 0.42 inches) (table 1). This corresponded with a 51 percent increase in volume index. Fascicle weight was also higher in the hexazinone treatment (5.7 grams versus 4.9 grams). Assuming that higher fascicle weight is indicative of a greater leaf area, it seems likely that the trees in the hexazinone treatment will continue to grow at a faster pace in future years.

The hexazinone treatment also had higher foliar nitrogen (N) concentrations (1.6 versus 1.49 percent) (table 2). It seems unlikely, however, that the increased foliar N concentration observed in this study is the cause of greater growth in the hexazinone treatment, since even the control levels are much higher than the considered threshold levels for N sufficiency of 1 .1 percent to 1.2 percent.

None of the fertilizer treatments had a significant effect on tree growth, fascicle weight, or foliar N or phosphorus (P) concentration. Considering that the N and P concentrations of the control treatment were greater than the deficiency levels of 1.2 percent and 0.1 percent respectively, it is not surprising that the fertilizer treatments did not increase tree growth. It is surprising, however, that the high rate of N applied in the "complete" treatment (100 Ibs N per acre) did not produce a significant increase in N concentration, whereas the application of hexazinone without any added N did increase foliar N. The "complete" treatment did result in significantly higher concentrations of potassium, boron, and manganese (table 2).

As pine plantation management intensifies, concern about tip moth is also increasing. When foresters spend money to accelerate early growth of pine with treatments such as HWC and fertilization, tip moth damage can become a significant problem if infestation is high enough to prevent the benefits of these applications from being realized.

Tip moth infestation was significantly influenced by both HWC and fertilization (table 1). In this study, there were fewer infested buds following the last generation of tip moth (measured in October) in the hexazinone treatment than in the control treatment (50 percent versus 61 percent). With respect to fertilizer treatments, tip moth incidence was

Table l-First-year growth by treatment of loblolly pine on a **Lakeland** soil series in Macon County, GA

Treatment	Survival	Height	Ground diameter	Volume	Fascicle weight	Tip moth infestation
	Percent	*Inches*		*Inches³*	*Grams*	*Percent*
Herbicide:						
Control	90.4	15.5	**0.42a**	**3.3a**	**4.9a**	61a
Herbicide	87.3	16.7	**0.49b**	**5.0b**	**5.7b**	50b
P>F	0.45	0.29	0.02	0.06	0.03	0.04
Fertilizer:						
Control	93.0	15.3	0.43	3.5	5.3	51a
DAP	87.2	16.6	0.48	4.7	5.4	66b
Complete	86.5	16.5	0.45	4.2	5.2	50a
P>F	0.37	0.58	0.38	0.49	0.86	0.02

DAP = diammonium phosphate.

Table 2-Foliar nutrient analyses by treatment of loblolly pine on a Lakeland soil series in Macon County, GA (values followed with different letters are significantly different at $P<0.1$ according to Duncan's multiple range test)

Treatment	Nitrogen	Phosphorus	Potassium	Calcium	Magnesium	Boron	Manganese
	Percent					Parts per million	
Herbicide							
Control	1.49a	0.18	0.48	0.28	0.07	25	981
Herbicide	1.60b	0.17	0.45	0.30	0.07	29	935
Fertilizer							
Control	1.51	0.17	0.44a	0.28	0.07	18a	807a
DAP	1.53	0.18	0.44a	0.29	0.07	18a	987ab
complete	1.58	0.17	0.53b	0.30	0.07	45b	1087b

DAP = diammonium phosphate.

higher in the diammonium phosphate (DAP) treatment than in the control and "complete" treatment.

It is difficult to explain the reasons for these treatment effects on tip moth or speculate about their meaningfulness. It was interesting to note, however, that the "complete" treatment had a significantly lower infestation rate than the DAP treatment. One of the reasons for including this "complete" treatment was to test the hypothesis that micronutrients might play a role in reducing tip moth infestation. These early results warrant further attention to tip moth effects as this study progresses.

CONCLUSIONS

This study was established on a deep, excessively well-drained upper coastal plain site to evaluate the effect of HWC and fertilization on first-year tree growth. Hexazinone application was associated with a greater seedling diameter growth, a greater needle fascicle weight, higher foliar N concentration, and lower tip moth infestation. There were no beneficial treatment effects attributable to fertilization; however, it was observed that fertilization with micronutrients resulted in lower tip moth infestation than fertilization without micronutrients.

The study site used for this experiment had about 40 percent groundcover after the first year, and would not operationally receive an HWC treatment. However, if these first-year growth effects continue in the future, this study may provide justification to begin treating these sites with hexazinone in the first year even though groundcover is not as dense as other soils.

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PILOT STUDY SUGGESTS AN ECONOMIC RETURN TO FERTILIZING LATE-ROTATION LOBLOLLY PINE ON A PIEDMONT SOIL

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Abstract-Economic rates of return for fertilizing early and midrotation loblolly pine (*Pinus taeda* L.) can exceed 15 percent on selected stands. Can similar rates of return on fertilization be achieved on late rotation stands? To determine the answer, 35-year-old, pole-sized planted loblolly pine stands on an eroded Piedmont site were fertilized with 120 pounds of nitrogen and 68 pounds of phosphorus per acre. Five l/lo-acre plots were placed in the treatment area and an associated control area. Foliar nutrient analysis suggests that the fertilizer effects lasted only 4 or 5 years. Because of different initial stand levels of basal area and volume, the data were analyzed using an analysis of covariance. The analysis of covariance showed a $92 per-acre increase in value due to the fertilizer treatment. Due to the large amount of variation, this $92 per-acre increase was not statistically significant. However, the short time between fertilization and harvest caused this $92 increase to create a 12 to 15 percent rate of return on investment. Because the $92 increase is small relative to the estimated standard deviation ($96), future research will need to use larger numbers of plots to get statistically significant results.

INTRODUCTION

Loblolly pine (*Pinus taeda* L.) has come under increasingly intensive management, typically including fertilization at establishment and midrotation (11 to 15 years) (Allen 1987, Bengtson 1979). Common rates of fertilization are 100 to 200 pounds of nitrogen and 25 to 50 pounds of phosphorus per acre. Most fertilization research has concentrated on either newly established stands or stands near midrotation. Very little research has been done on the effects of fertilization of late-rotation loblolly pine stands.

Gent and others (1986) studied the effect of fertilizing loblolly pine stands on poorly drained lower coastal plain soils and found that the nitrogen and phosphorus fertilizer used at establishment was still having a growth effect up to 12 years after fertilization. Fisher and Garbett (1980) and Stearns-Smith and others (1992) found that the volume growth response to fertilization continued up to 8 years after treatment for loblolly and slash pine (*Pinus elliottii* var. *elliotti* Englem.) at midrotation. Duzan and others (1982) and Wells and others (1976) created prediction equations for the effects of fertilization on midrotation slash pine and loblolly pine stands. Because stand growth slows with stand age, the ability of a stand to respond to fertilization also decreases with stand age. This operational scale pilot study was designed to determine if economic results from fertilization found for early and midrotation stands can be achieved with older, pole-sized stands.

MATERIALS AND METHODS

Location and Site Conditions

The study site is located on the Sumter National Forest in Union County, SC. The soils are in the Cecil and Pacolet soil series (Camp and others 1975). The site has a long agricultural history followed by reforestation. The soils within the study area sites have the B horizon at or near the surface, suggesting that the surface erosion had been severe. There is little organic matter in the surface soil horizon. Soil samples from the top 4 inches were consistently acid (pH 4.6 to 5.3), low in soil nitrogen, at least by agronomic standards (281 to 492 parts per million), and low in available phosphorus (1 .O to 14.4 ppm) (Bray P2) (Jackson 1958).

Stand Conditions

Trees were hand-planted with 1-O seedlings around 1951 on a 6- by 1 O-foot spacing. Approximately 200 to 250 trees per acre remained at the time the study was installed. Reductions in stocking since time of establishment have resulted from either thinning or mortality. Records of exact planting dates and thinning intensities are not available. Understory vegetation was sparse in all stands and consisted mainly of broomsedge (*Andropogon* sp.) and brambles (*Rubus* sp.).

Experimental Design

The study area was split into six strips. Three strips were not fertilized. The other three strips were fertilized with a combination of diammonium phosphate and urea as a 35-16-O (nitrogen:phosphorus:potassium) ratio at 400 pounds per acre. The fertilizer was applied on an operation basis, using a helicopter, on April 22, 1986. Five square l/lo-acre measurement plots were located randomly within the three strips for each treatment for a total of 10 plots. Corners of plots were monumented with treated wooden stakes. Trees within plots were identified with numbered metal tags attached to trees with aluminum nails at breast height.

Measurements

Soil samples were collected from the surface 4 inches of the plots. Ten to 15 cores were taken at random from each plot and cornposited. Samples were air-dried and analyzed for pH, total nitrogen (Nelson and Sommers 1973), and available phosphorus (Bray P2) (Jackson 1958).

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Foliage nutrient levels were measured during the dormant season before the fertilizer application and annually for 3 years following fertilization. Foliage samples were collected from the upper third of the crown on the south side of the tree with a shotgun. Material from the first flush of the previous growing season was saved for analysis. Needles were oven-dried for 24 hours at 70 °C and ground to pass a 40-mesh screen. Nitrogen concentrations in the needles were determined by the salicylate-cyanurate method (Nelson and Sommers 1973). Concentrations of phosphorus in the needles were determined by dry ashing a 1.O gram sample at 450 °C, taking up in 0.3 M HN03, and analyzing for phosphorus by the molybdovanadate method (Jackson 1958).

Stem diameters at breast height (d.b.h) were measured before fertilization and annually for 4 years following fertilization to the nearest 0.1 inch with a diameter tape. Heights were measured to the nearest 0.1 foot with a visual caliper in 1987 and 1989.

Computed Variables

Basal areas and stem volumes were calculated from the height and diameter measurements. Per-acre basal area was derived as the sum of stem basal areas per plot and expanded to a per-acre basis by multiplying by a factor of 10. Total volume (cubic feet), inside bark, was calculated using equation 1.

$$TV = 0.00148209 \times dhb^{1.9229} \times height^{1.1105}, \quad (1)$$

where
TV stands for total volume inside bark.

Merchantable volumes (cubic feet) to a 4 inch top were computed using equation 2 from Clutter and others (1984).

$$MV = TV \times (1.0 - 0.5694 \times 4.0^{3.4304} \times dbh^{-3.2395}), \quad (2)$$

where
MV stands for merchantable volume inside bark.

The results of these calculations and their values per acre were summed by 1 -inch diameter classes.

Dollar values for the diameter classes were developed from the Timber Mart South's first quarter 1989 standing timber prices for South Carolina Piedmont and the percentage of stems in various diameter classes found in Broderick and others (1982). The Timber Mart South's prices were: pulpwood at $17.24 per cord, sawtimber at $193 per thousand board feet (mbf) (Scribner), and peelers at $191 per mbf (Scribner). These prices were converted to cubic feet by assuming 2.8 cords per mbf and 5.5 mbf per thousand cubic feet (mcf). The merchantable volume in each diameter class was allocated to the different products according to the percentages given on table 4 of Broderick and others (1982). Volume between the 4-inch top and the minimum end diameters for sawtimber and peelers (6-inch and 8-inch, respectively) were discarded. Because sawtimber went for a higher price than peelers, stems that could be sold as peelers were assumed to be sold as sawtimber. An average price for each diameter class was created by weighting the price of each product class by the percentages of the stems sold as that product, and summing these weighted prices together.

Data Analysis

The experimental unit was the treatment strip. For each treatment, two of the strips had two measurement plots. The data from these two plots were averaged together to create a strip-level mean.

The strips from the two treatment groups had different initial values for basal area per acre, volume per acre, and dollar value per acre. Woollons's (Woollons 1985, Woollons and Whyte 1988) recommendation of using analysis of covariance for adjusting for initial basal area in fertilizer studies was followed. The dependent variable in the analysis of covariance is the change in dollar value per acre. All significance tests used a $p = 0.05$ level of significance.

RESULTS

Foliage Nutrients

The average pretreatment leaf nitrogen levels were 1.27 percent for both the fertilized and nonfertilized plots (table 1). There was no effect of fertilizer on the leaf nitrogen concentrations. The leaf phosphorus levels followed a pattern that was consistent with the fertilizer giving a short pulse of phosphorus that diminished with time. The pretreatment phosphorus levels were .1 22 percent for the nonfertilized plots and .109 percent for the fertilized plots. The first year after treatment, the fertilized plots increased in phosphorus concentration relative to the nonfertilized plots. During the second year, this increase had diminished. By the end of the third year, the fertilized plots had returned to a lower leaf phosphorus concentration than the nonfertilized plots. These responses indicate that the

Table l-Effect of fertilization on foliage nitrogen and phosphorus levels for 3 growing seasons following treatment

Year and treatment	Nutrients Nitrogen	Phosphorus
	———Percent———	
1986 (before fertilization):		
No fertilizer	1.27	.122
Fertilizer	1.27	.109
1987 (1 st year):		
No fertilizer	1.20	.114
Fertilizer	1.21	.125
1988 (2nd year):		
No fertilizer	1.09	.107
Fertilizer	1.06	.113

fertilizer effect on the foliar nutrient concentrations of pole-sized trees is short lived, probably 4 or 5 years.

Stand Growth

The unfertilized stands grew more in height (10.9 feet versus 8.2 feet), basal area per acre (10.0 square feet versus 9.4 square feet), volume per acre (959 cubic feet versus 785 cubic feet), and lost fewer trees per acre (8 versus 18) than the fertilized stands. At first glance, these results suggest that the fertilizer treatments did not increase the yields of these stands. However, the fertilized plots started with taller trees (62.2 feet versus 56.1 feet), more trees per acre (256 versus 230), larger quadratic mean diameter (9.21 inches versus 9.08 inches), more basal area per acre (118.5 square feet versus 103.5 square feet), and more volume per acre (3578.4 cubic feet versus 2867.2 cubic feet) than the unfertilized stands. The fact that the fertilized stands started with larger trees and larger basal areas suggests that these stands were further along in their development and closer to their maximum carrying capacity than the control stands. These differences in initial stand conditions led to the analysis of covariance.

Analysis of Covariance

An analysis of covariance was used to account for these differences in initial basal area, using the change in dollar value as the dependent variable with the initial basal area as the covariate. The analysis was run on the strip averages under the assumption that the measurement plots were subsamples. The standard statistical assumptions for analysis of covariance were used. The adjusted mean increase for the control plots was $596 per acre. The adjusted mean increase for the fertilized plots was $688 per acre. This gives a difference of $92 per acre due to fertilization. The estimated standard deviation was $96 per acre. Because of the large variation between stands and the small number of strips, this $92 per acre difference was not statistically significant ($p = 0.43$).

DISCUSSION

Even though this $92 per acre increase in value is not statistically significant, the short time span between the investment and the realization of the investment caused the investment to have a high rate of return. The fertilizer cost was $52 per acre.[2] The $92 per-acre increase in value caused by fertilization leaves a $40 net profit. Using simple annual compounding, this leads to a 15-percent rate of return if the profit is realized in 4 years, and a 12-percent rate of return if the profit is realized in 5 years. These are fairly high rates of return for the landowner.

The main problem with the rates of return is that the $92 per acre increase is not statistically significant. Statistical significance is a function of three quantities: the size of the effect, the amount of variation, and the number of plots. The number of plots required to obtain a statistically significant result was calculated using the size of the effect ($92 per acre) and the amount of variation ($96 per acre) from this study. To have a 50-percent chance of a statistically significant result, an experiment would have to have at least eight plots: four control plots and four fertilizer plots. To have a 75-percent chance of a statistically significant result would require 16 plots, and to have a 90-percent chance of a statistically significant result would require 24 plots.

SUMMARY

1. The results from this study suggest that late-rotation fertilization of loblolly pine will cause a small increase in dollar value gain ($92 per acre).

2. Because of the short turnaround time between fertilization and harvesting, small dollar increases can cause high rates of return on investment. The rates of return from this study range between 12 percent and 15 percent. The short turnaround time also causes the rate of return to be greatly affected by price fluctuations.

3. Because the suggested gain is smaller than would be observed with early or midrotation fertilization, large study sizes will be needed to obtain a statistically significant result.

4. Stearns-Smith and others (1992) found that price differences between pulpwood and sawtimber were required to make midrotation fertilization of loblolly pine profitable. Our results agree with their analysis. If only pulp prices are used in this study, the $92 per-acre increase due to fertilization drops to a $7 per-acre loss.

5. Results of fertilizing late-rotation loblolly pine will be affected by differences in site and differences in amounts of fertilization. Further research will be required to determine where fertilization is economically feasible.

6. When the study was started, Bill McKee was part of a soil productivity unit. Bill McKee's part of the soil productivity unit was merged into a forested wetlands research unit. Therefore, the authors are no longer studying loblolly pine fertilization, and would like to encourage those who are researching the effects of fertilization on loblolly pine to consider studying late-rotation fertilization.

ACKNOWLEDGMENT

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Physiology

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COMPARATIVE PHYSIOLOGY OF LOBLOLLY PINE CLONES THAT HAVE EXHIBITED A WIDE RANGE IN GROWTH PERFORMANCE

Phil Dougherty and Andy Laviner[1]

Abstract-Net photosynthesis light response and foliage age response curves were developed for three rapid- and three slow-growing clones of loblolly pine. Maximum rates of net photosynthesis were the same for all clones. However, total tree leaf area on the three rapid-growing clones was much greater than that on the three slow-growth clones. Thus, whole tree carbon gain would be much greater for the rapid-growth clones because of their greater total tree leaf area. These results suggest that tree growth potential is more a function of leaf area than potential carbon fixation rates per unit leaf area.

Foliage age response curves were developed in September when multiple flushes were present and at different stages of development. Needles on the last flush were still extending in September and their lengths were less than 20 percent of the length of first flush needles. Net photosynthesis rates of needles with lengths less than 20 percent of maximum were about 50 to 55 percent of the rates observed for needles that had achieved 60 to 70 percent of their maximum size. The longest and oldest needles (usually first-growth flush) actually had lower net photosynthesis rates than second or third flush needles. All six clones exhibited the same net photosynthesis-age trends although actual rates were different for each growth flush. Stomatal conductance trends with age were similar to those observed for net photosynthesis with one exception: needles that were less than 20 percent of the maximum needle length had high stomatal conductance. This suggests that the low rate of net photosynthesis of young developing tissue is not due to stomatal limitations but instead due to lack of development of the photosynthetic system and/or high respiration cost.

INTRODUCTION

Large differences in growth performance of loblolly sources (Wells and Wakeley 1966) and source-families (McKeand and others 1989) have been reported. Similar differences in growth of loblolly pine clones are currently being observed in Westvaco's clonal test. Genetic progeny tests are designed such that growth differences are a reflection of true genetic differences in growth potential and not differences in growth environment. Thus, observed differences in growth potential have to be manifestations of genetic influences on plant phenology, physiology, and/or morphology. Increases in aboveground yield can theoretically result from improvement in many plant factors: increased net carbon gain, nutrient acquisition and utilization efficiency, or carbon allocation into stemwood. In the past, it has not been important to understand which tree morphological or physiological processes were responsible for rapid or slow tree growth rates. It has been sufficient to test for and select the best performing crosses and to enhance their growth by using silvicultural treatments that improve site resource availability. Now forest industry is interested in increasing productivity through application of forest biotechnology. Knowledge about which processes or morphological characteristics determine growth rates is needed to provide direction regarding which compliment of genes it is important to manipulate to further increase growth potential. The objective of this research was to determine if differences in the rates of net carbon gain of foliage might be responsible for observed differences in growth rates.

METHODS

Research Approach

Three good- and three poor-growing clones were selected for comparison of gas exchange rates. The three good-growth clones had attained a height of nearly twice the average height of the poor-growing clones over a 3-year period.

The study site is located in Berkeley County, SC. Soil on the study site is a Goldsboro series, which is moderately well drained. Prior to the establishment of the clonal test in the spring of 1994 the land was used for agricultural purposes. In the spring of 1994, 120 clones of loblolly pine were established on this site using rooted cuttings (Les Pearson and Farrell Wise, personal communication). Three of the best and three of the poorest performing clones after 2 years in the field were selected for comparison of gas exchange characteristics.

Measurements

Five individuals of each of the six clones were selected for measurement of gas exchange characteristics. All foliage gas exchange measurements were made in September of 1996 using a LI-6400 Portable Photosynthesis System.

Light response curves were developed over a 2-day period for all clones. Quantum efficiency was estimated as the slope of the response curve between a light intensity of zero and 250 micromoles per square meter per second. Maximum, light saturated, net photosynthesis was determined as the rate of net photosynthesis at a photosynthetically active radiation (PAR) of greater than 1600 umoles per square meter per second. All light response measures were made in the early morning hours. During each light response curve measurement, cuvette temperature was held at 27 "C, relative humidity at 70 percent, and CO, concentration at 350 parts per million.

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The effects of needle age (development) on gas exchange was also made on five individuals of each of the six clones, Detached shoots were used to determine maximum net photosynthesis and stomatal conductance of each flush of needles present on the growing shoots in September. Ginn and others (1991) previously determined that stomatal conductance of detached loblolly pine shoots does not change over a 30-minute period. Gas exchange measurements in this study were completed within 3 to 5 minutes after removal from the tree. Most shoots had four age classes of foliage. Needles on the first flush were considered as 100 percent full development. Relative needle development of the remaining three flushes were expressed on a percentage basis by dividing their needle length by the needle length of the first flush and multiplying by 100.

Stem Gas Exchange

Net carbon exchange of developing stem material was determined on five individuals of a single clone in September. Relative stem development was based on the length of the needles on each flush relative to that on the first flush in the same manner as described above for foliage. Stem gas exchange was determined under light-saturated conditions (1,500 micromoles per square meter per second), constant cuvette temperature (27 "C) and constant relative humidity (70 percent).

RESULTSANDDISCUSSIONS

Light Response

None of the parameters (dark respiration, quantum efficiency, or maximum net photosynthesis) that were derived from the light response curves shown in figure 1 were significantly different (alpha=.1) between fast- and slow-growing clones. There was a tendency for light-saturated net photosynthesis to be greater for slow-growing clones than for fast-growing clones (fig. 1). Stomatal conductances also tended to be higher for the poorer-growing clones than for the fast-growing clones (fig. 2) but were also not statistically significantly different. Maximum net photosynthesis and stomatal conductance rates observed in this study are lower than those previously reported for loblolly pine (Murthy and others 1996, Teskey and others 1987). At the time these measurements were made available, soil moisture in the upper O-30 cm of the soil profile was low and partial stomatal closure was apparent (fig. 2). The tendency for lower stomatal conductance and light-saturated net photosynthesis rates in the fast-growing clones may be related to the fact that the fast-growing clones had much more leaf area than the slow-growing clones. Recent work by Laviner (personal communications) has shown that at a given soil moisture supply and moderate-to-high vapor pressure deficits that loblolly trees with large leaf area have lower stomatal conductance than smaller trees with lower leaf area. Based on our preliminary results, it would appear that differences in carbon gain capacity between fast- and slow-growing clones are likely to be dictated more by development of greater leaf area than by differences in the rate of gas exchange per unit leaf area.

Foliage Development and Gas Exchange

Net photosynthesis rates at each relative needle development stage, ranging from near 20 percent to 100 percent full development, were not significantly different between clones. All clones exhibited the same response in net photosynthesis as foliage approached 100 percent full development (fig. 3). At near 20 percent development, net photosynthesis was only 50 to 55 percent of the maximum net photosynthesis observed at later stages of development. Stomatal conductance (fig.

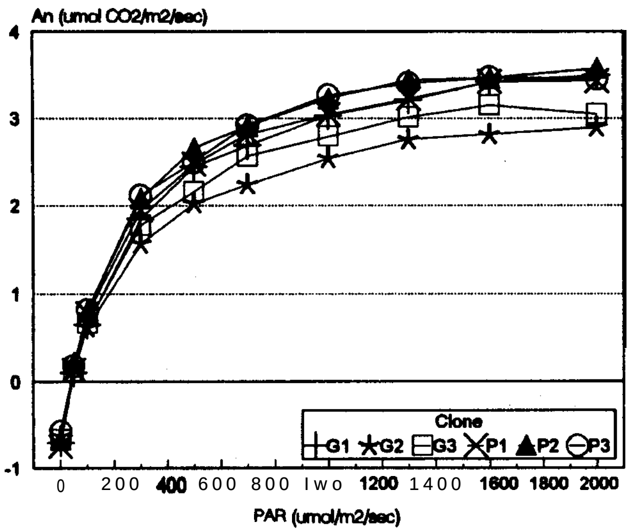

Figure l-Average net photosynthesis (An) of three good-growing loblolly pine clones (G1, G2, G3) and three poor-growing clones (P1 , P2, and P3) plotted as a function of photosynthetically active radiation (PAR). Each point is the average of five measurements.

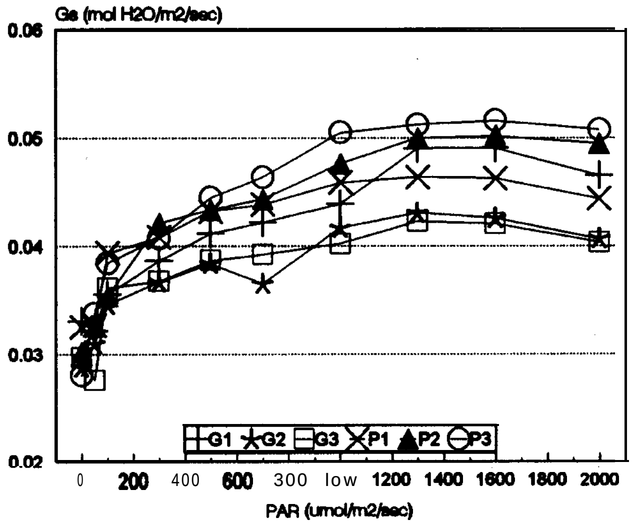

Figure 2-Average stomatal conductance to water vapor (Gs) of three good-growing clones (G1, G2, and G3) and three poor-growing (P1 , P2, P3) clones of loblolly pine plotted as a function of photosynthetically active radiation (PAR). Each point is the average of five observations.

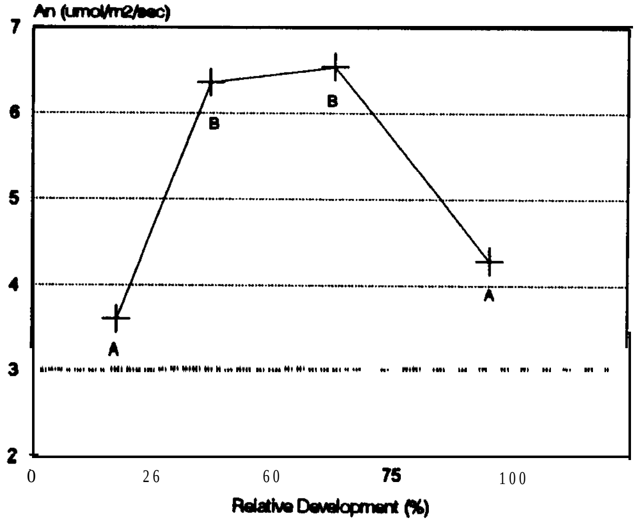

Figure 3-Average light saturated net photosynthesis (An) rates of six clones plotted as a function of relative foliage development. Relative foliage development was obtained by dividing the length of needles on each flush by the length of needles on the first flush and multiplying by 100.

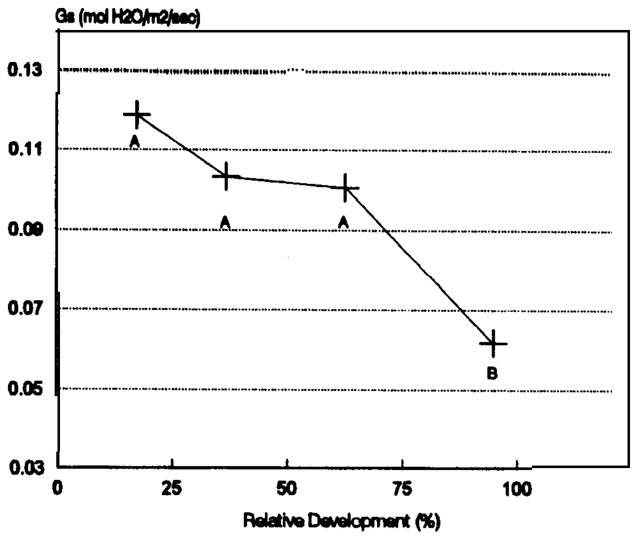

Figure 4-Average light saturated stomatal conductance to water vapor (Gs) of six clones of loblolly pine plotted as a function of relative foliage development. Relative foliage development was obtained by dividing the length of needles on each flush by the length of needles on the first flush and multiplying by 100.

4) at a relative development stage near 20 percent was equal to or greater than that observed for more mature foliage. This suggests that low rates of net photosynthesis at this early stage of development were not due to stomatal limitations. Internal factors related to the development of the photosynthesis process, mesophyll resistance, or high respiration cost are all factors that could result in low net photosynthesis rates at this stage of development. By the time foliage had reached 35 to 40 percent full development, net photosynthesis rates were near maximum. Surprisingly, the rate of net photosynthesis of the most mature tissue was lower than that observed at midstages of development. Previous studies have shown light-saturated net photosynthesis rates tend to remain near their maximum in the year that they are formed (Murthy and others 1996) until environmental conditions result in a decline in net photosynthesis.

Stem Development and Gas Exchange

Stems of young shoots appear green and succulent and should have the capacity to photosynthesize. The observed trend in carbon dioxide exchange rates of developing shoots, which ranged from near 20 percent (needle development) to 100 percent development, from which all needles had been removed, is shown in figure 5. At the earliest stage of development, carbon exchange rates are positive, suggesting that stem photosynthesis may be completely offsetting maintenance and construction respiration cost under high light conditions. Stems which had foliage that had attained near 60 percent full expansion also appear to offset a considerable amount of respiration cost. Shoots with needles that are near 100 percent at their final size do not appear to be able to offset much growth and/or maintenance respiration cost.

CONCLUSIONS

Differences in rates of net photosynthesis per unit leaf area do not appear to be a major factor contributing to differences in the growth of loblolly pine clones. The role of other physiological processes, phenology, and crown morphological factors such as leaf area and distribution will be considered in future studies.

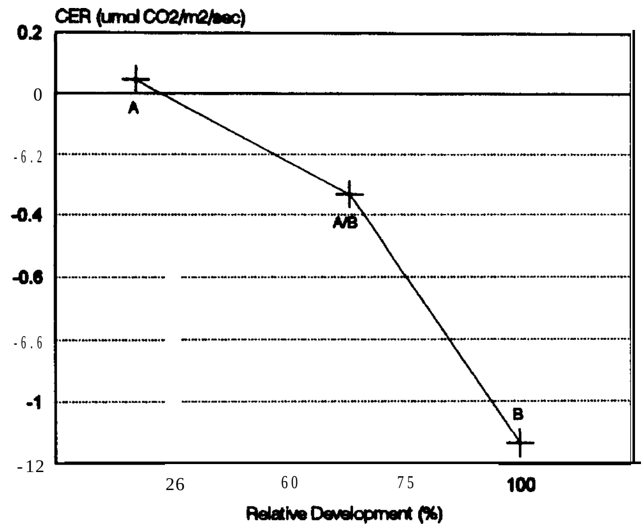

Figure 5-Average stem carbon dioxide exchange rates (CER) of a single clone of loblolly pine plotted against stem relative development. Relative development of each stem section (flush) was determined on the basis of the relative development of needles located on each flush. Each point is the average of five measurements.

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A CONCEPTUAL APPROACH TO STAND MANAGEMENT USING LEAF AREA INDEX AS THE INTEGRAL OF SITE STRUCTURE, PHYSIOLOGICAL FUNCTION, AND RESOURCE SUPPLY

D.A. Sampson, J.M. Vose, and H.L. Allen[1]

Abstract-Stand management involves manipulation of factors that are thought to control ecophysiological mechanisms determining forest growth and function. Stand leaf area index can be used to assess current growth, as well as site growth potential based on the perceived ability of the stand to respond to silvicultural manipulation (e.g., fertilization). We sampled the leaf area index (LAI) in 30 plots for each of six forest cover-types across the Southeast to examine natural variability in LAI. The mean index ranged from 3.5 to 5.1 m^2 m^{-2} (projected); spruce-fir had the lowest while maple-beech-birch had the highest. We present a conceptual model that relates LAI to site resources, occupancy, and shade tolerance to initiate discourse and development of diagnostic tools for evaluating site-specific determinants of forest growth. Simulations from a process model suggest that biologically achievable LAI may not be optimal LAI for maximum growth.

INTRODUCTION

Imposition of silvicultural treatments to improve forest productivity by increasing leaf area index (LAI) has only recently been considered in southern land management. Earlier work in southern pine stands demonstrated that site manipulation to improve soil water availability and fertility increased loblolly pine growth (Fisher and Garbett 1980, Pritchett and Cumerford 1982). Absent, however, has been the physiological basis for increased stem growth following improved resource availability. Managing LAI to increase yield in southern forest ecosystems is an idea long overdue.

Canopy leaf area intercepts photosynthetically active radiation (PAR) and, through photosynthesis, converts absorbed light energy into dry matter (Cannell 1989). The empirical relationship between intercepted PAR and dry matter production suggests that increased radiation absorbed, or increased efficiency of conversion of absorbed radiation to biomass, will increase dry matter produced (Cannell 1989). However, the relationship is curvilinear, with decreased fractional interceptance as LAI increases (Russell and others 1989), indicating decreased interception efficiency as LAI increases. Thus, a reduction in light capture efficiency as LAI increases suggests that a species optimum LAI for maximum productivity may exist. Increasing leaf area will increase PAR interception (Cannell 1989). Therefore, we can manipulate the stand to increase LAI and, subsequently, PAR absorbed. The PAR conversion efficiency is, more or less, species specific and constant (c.f., Cannel and others 1988).

The objectives of this paper are (1) to develop a conceptual approach for discussing the structural and physiological basis of stand LAI in determining productivity of southern pines and hardwoods, and (2) to examine how this approach may be used to design a tool that would aid in stand management decisions.

APPROACH

Our approach is to use a combination of concepts, published and unpublished data, and modeling to establish the foundation for analyses of LAI as the integration of site properties determining stemwood growth. We estimated LAI for six forest cover-types (cypress-water tupelo, blackgum-red maple, sweetgum-yellow-poplar, oak-hickory, maple-beech-birch, and spruce-fir) in North and South Carolina and Georgia. We sampled projected LAI at 25 systematic points in each of 30 stands for each forest type, using a LI-COR LAI-2000 Plant Canopy Analyzer and the 90-degree view cap. Estimates were taken under diffuse sky conditions, or in the dawn or predusk periods during sunny days in closed-canopy stands throughout the summers of 1994 and 1995. Simulation data were obtained from a series of sensitivity analyses conducted with the process model BIOMASS (McMurtrie 1991) that has been adapted for loblolly pine. We examined the interactions among LAI, climate, and gross and net canopy carbon assimilation for three regions across the Southeast (NCSFNC 1996).

RESULTSANDDISCUSSION

Southern Pines

Variability in LAI-The amount, pattern, and duration of southern pine LAI incorporate region-specific characteristics of growing season length and annual foliage cohort retention. Loblolly and slash pine carry an effective maximum of two annual foliage cohorts. As such, they exhibit a relatively stable yearly minimum leaf area in late winter and early spring after needlefall of the previous year's cohort has completed and prior to new foliage production for the current year begins (c.f., Vose and Swank 1990). Peak LAI is generally reached in late August Or early September following completion of elongation Of current year foliage. For southern pines, peak LAI varies considerably, with lower quality mid-rotation loblolly pine stands typically ranging from 0.8 to 2.2 (m^2 m^{-2}; one-half

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total) (Sampson and Allen 1995). For those stands where fertilizer has been applied, LAI may exceed 4 (m^2 m^{-2}; projected) (Vose and Allen 1988). Silvicuitural operations intended to manipulate site characteristics determining LAI must consider and incorporate principles regulating seasonal LAI dynamics to effectively administer and identify treatment responses.

LAI and resource supply and Use-Inadequate soil N supply is the dominant limitation to foliage production in southern pine stands (Vose and Allen 1988, Colbert and others 1990). In addition to N, phosphorus (P) has also been identified as an important element controlling stand LAI (NCSFNC 1991), although the magnitude of response is generally lower than from N. Inadequate water availability has long been thought to limit leaf area production in southern pine stands. However, there are few data that support this hypothesis. Gholz and others (1991) found little interaction between water availability and LAI in slash pine stands. Similarly, a fertilization and irrigation experiment in a young loblolly pine stand growing on an excessively drained sandy soil in North Carolina suggests that water does not limit LAI (Albaugh and others, in review). Apparently, the amount and pattern of rainfall, along with soil water holding capacity, must be considered.

LAI and site occupancy-Stand density, the stage of stand development, and basal area (BA) all influence site occupancy and, therefore, crown closure and LAI. Southern pine plantations under nominal nutrient supply typically achieve canopy closure in 10 to 14 years (Vose and Swank 1990). LAI also increases with stand development, and reaches a maximum that coincides with crown closure and full site occupancy (Vose and others 1994). The amount of canopy in nonfoliated gaps can also be used as an indicator of site occupancy; LAI and canopy gap fraction are negatively correlated.

Loblolly pine LAI increases linearly with increased BA (vis a vis sapwood area support of canopy foliage) (Shinozaki and others 1964) up to approximately 30 to 35 m^2 ha-' (Dougherty and others 1995), after which the relationship becomes asymptotic. Decoupling between basal area and LAI can occur for several reasons, and can include the development of heartwood and, thus, decreased sapwood area relative to basal area (c.f., Long and Smith 1988), a reduction in resource supply, or a reduction in basal area efficiency (basal area growth per unit LAI).

LAI and shade tolerance-Few studies have examined the relationship between shade tolerance and LAI for pine species. However, increased LAI with increased shade tolerance has been observed (Vose and others 1994). Assuming the branch autonomy model (e.g., Sprugel and others 1991), foliage longevity will be related to a time integral of incident PAR and net carbon balance. The ecophysiological mechanism determining the presence of foliage in lower crown positions is related to the activity of meristematic buds for the development of new foliage rather than influencing abscission of current foliage in southern pine species.

We can conclude that inherently high resource supply, or improved soil nutrition (N and P amendments), will result in high LAI. In the Eastern United States, soil water supply appears considerably less important than soil nutrients. In addition, stand development, stand density, and the amount of canopy in gap will all influence LAI. An upper level of LAI will be reached at a basal area considerably less than maximum. Much more work is needed on the role of shade tolerance in determining LAI for southern pine stands. Empirical data suggest that an LAI of 4.0 (m^2 m^{-2}; projected) or more is possible in southern pine stands.

Hardwood Ecosystems

Natural variability in LAI-Leaf area development in deciduous hardwood ecosystems must, by definition, occur within one growing season. Foliage development occurs rapidly, with maximum LAI achieved usually within 4 to 9 weeks of bud break. Maximum LAI for the six forest cover-types studied varied considerably (table 1). Mean LAI ranged from 3.5 for spruce-fir stands to 5.1 for maple-beech-birch forest types (table 1). The low LAI found for spruce-fir was unexpected; shade tolerant conifers generally exhibit greater LAI than deciduous broad-leaf forests (Kira 1975). However, spruce-fir forests of the Southern Appalachian region are in decline, which may explain the low LAI's obtained. Vose and others (1995) examined LAI for five Appalachian hardwood ecosystems where LAI varied from 3.9 m^2 m^{-2} in a high elevation stand dominated by red oak (*Quercus rubra*), sugar maple (*Acer saccharum*), and birch (*Betula* spp.) to 7.3 m^2 m^{-2} in a lower elevation stand dominated by black oak (Q. *velutina* Lam.), chestnut oak (Q. *prinus* L.), and black tupelo (*Nyssa sylvatica*).

LAI and resource supply and use-To our knowledge, no experimental data are available to examine relationships between soil nutrition and LAI of southern hardwood ecosystems. Instead, only anecdotal evidence exists to

Table I-Cover-types and leaf area index statistics for six forest cover-types of the Southeastern United States; data represent a five-State region from Virginia to Alabama

Cover-type	Mean and (range) of LAI (m^2 m^{-2}; projected)		Std. of LAI
Cypress-water tupelo	4.02	(2.68544)	0.89
Blackgum-red maple	3.89	(2.73-5.20)	0.71
Maple-beech-birch	5.05	(2.74-6.30)	0.98
Oak-hickory	3.87	(2.78-5.95)	0.82
Sweetgum-yellow-poplar	4.18	(2.34590)	0.81
Spruce-fir	3.46	(2.20-4.89)	0.68

Note: sample size of 30 for each cover-type.

support patterns similar to pines (i.e., lower LAI on resource-poor sites). For example, in the Southern Appalachians, LAI is lowest (-3) on dry and typically nutrient deficient ridge sites, and highest (-5 to 7) in more mesic midslope and cove sites (J.M. Vose, unpublished data). We hypothesize that LAI of hardwood ecosystems could be substantially increased with fertilization. Studies are underway by industry to examine nutrient and water availability on key hardwood species. These studies will provide important information on single-species versus resource availability relationships; however, responses in mixed species stands will remain unknown.

LAI and site occupancy-We found no relationship between stand basal area and LAI for the six forest cover-types, indicating that basal area may not be a good indicator of LAI in hardwood ecosystems. In addition, stand development for mixed-species forests is considerably more complex than single-species plantation derived forests. After disturbance, hardwood regeneration can come from three sources: seed germination, sprouting, and advanced regeneration. In the Southern Appalachians, the regeneration source depends on topographic position and stand age. For example, in coves, yellow- poplar (*Liriodendron tulipifera*) regenerates from seed in sufficient numbers (e.g., 18,000 seedlings ha^{-1}) to dominate the developing stand for several years (Boring and others 1988). In more midslope positions, sprouting is the primary regeneration method, and it increases in prevalence in younger stands (Boring and others 1988, Elliott and Swank 1994). Advanced regeneration occurs in all slope positions, but is less predictable than either seed or sprouting regeneration.

LAI and shade tolerance-The method of regeneration in mixed hardwood ecosystems influences the time trajectory of **LAI,** and the maximum LAI attainable. If regeneration occurs primarily from seed, then the stand will typically be comprised of light seeded, intolerant species which may dominate the stand for the first 100 years. Maximum LAI will be attained rapidly, but at a lower level than stands of mixed shade tolerance. If regeneration occurs primarily from sprouting, then species of mixed shade tolerance are present throughout the length of the rotation and the relative mixture of shade tolerant versus shade intolerant species changes throughout stand development. As pure stands get older (i.e., > 100 yrs), LAI increases from successful regeneration of more shade tolerant species beneath the predominately shade intolerant canopy. As the intolerant canopy declines, intermediate or shade tolerant species will replace them in the mid- and upper canopy. In mixed stands, increased LAI results from greater dominance of intermediate or shade tolerant species after canopy closure. The rate at which these shifts occur is a complex function of site resource availability, predisturbance species composition, and disturbance intensity and frequency in the developing stand. For example, on poor sites, site resources are inadequate to support resource-demanding and, typically, shade tolerant late successional species. Hence, it is biologically infeasible for a low resource site to support higher resource-demanding shade tolerant species.

LAI and forest productivity-Several common principles relating LAI and forest productivity in both southern pines and hardwoods can be observed. First, we can manage LAI by manipulating those factors thought to limit leaf area production. In some cases, low LAI may not be due to a resource limitation but, rather, stand structural characteristics associated with stand development (i.e., the mix of shade tolerant and intolerant species), natural disturbances, or past stand management practices. Second, for mixed species stands there exists a species mix that optimizes the existing site potential for fixing carbon. Although there are obvious limitations to species associations based on slope, aspect, elevation, etc., we can incorporate management strategies to manage stand LAI by knowing basic principles about species development, light tolerance, and competitive ability. Third, there is evidence to suggest that biologically maximum LAI may not be optimal LAI for maximum net primary production.

Simulations using BIOMASS version 13.0 for loblolly pine suggest decreased net production efficiency with increased LAI. Specifically, although net canopy assimilation (carbon available for partitioning to growth) increases with increased LAI, the relationship is curvilinear, with decreased net carbon per unit LAI as LAI increases (NCSFNC 1996). The concave functional form results in maximum net canopy assimilation at an LAI that is less than biologically attainable; there is less net carbon assimilation at LAI's greater than "optimal." A reduction in net assimilation efficiency is attributed to decreased light interception efficiency as LAI increases, and increased maintenance respiration (R,) costs (relative to gross carbon fixed) of the canopy foliage (NCSFNC 1996). Climate determines the R_m/gross primary production ratio; warmer regions have higher respiratory demands and, thus, less carbon available for growth.

For mixed-species hardwood, relationships between stemwood NPP and LAI depend on the relative mixture of species and their contribution to total stand LAI. For example, species specific leaf photosynthesis (Pnet) (Sullivan and others 1996) and R_m rates indicate that stands with a greater proportion of intolerant species in the upper canopy (high light; >1000 $\mu mol\ m^{-2}\ s^{-1}$) will fix more canopy carbon than stands with a greater intermediate and shade tolerant species. Patterns at low light (<300 $\mu mol\ m^{-2}\ s^{-1}$) are reversed, indicating that without major disturbance during stand development, shade tolerant species will eventually dominate the stand, LAI will increase due to multilayering, and NPP will be reduced. While more complex, the mixture of species may present more opportunities to increase NPP by altering the composition and structure of natural stands through selective thinning.

MANAGEMENT IMPLICATIONS

Conceptual Diagram

The relationships among resource supply, site occupancy, shade tolerance, and LAI can be examined in a Conceptual diagram (fig. 1). Stand level shade tolerance can be defined as a "light compensation ratio" (the ratio Of total LAI

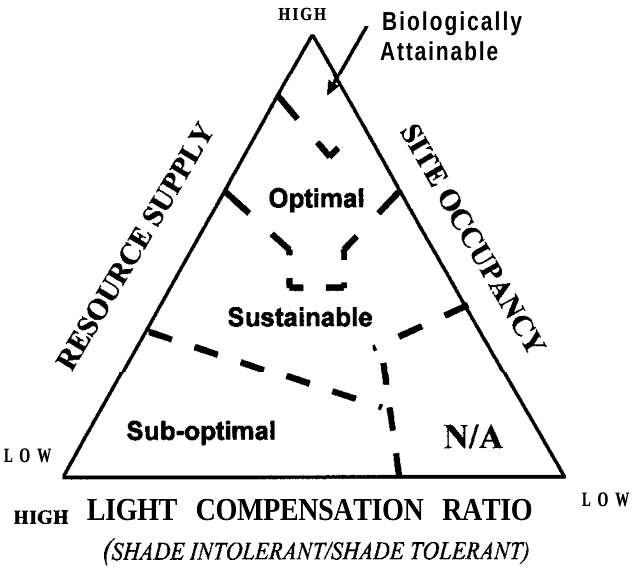

Figure 1-A conceptual representation of the relationships among resource supply, site occupancy, light compensation ratio, and leaf area index (LAI) groupings. The light compensation ratio, as used here, incorporates stand-level shade tolerance described as the ratio of LAI in shade intolerant species to that of shade tolerant species. The category N/A represents not applicable.

in intolerant species to LAI of tolerant species). The region formed by the intersection of lines drawn to opposite corners of the triad conveys a level of LAI (fig. 1). We classify these regions as: (1)suboptimal, (2) sustainable, (3) optimal, and (4) biologically attainable LAI. These will be discussed individually.

LAI Thresholds

Suboptimal LAI corresponds to stands exhibiting marginal growth. Intensive management intervention would likely be required to increase LAI to improve forest yield. Examples for southern pine would be low-site stands (low nutrient supplying soils), and/or intentionally or unintentionally low stocking (< 200 trees ha^{-1} at a basal area of 10 m^2 ha^{-1}). These stands would likely have much understory vegetation and poor crop tree basal area growth rates (c 2.3 m^2 ha^{-1} yr^{-1}). Examples of suboptimal LAI stands for southern hardwoods may correspond to recently thinned stands or stands on poor sites, such as xeric ridges or highly eroded soils with low nutrient supply.

Sustainable LAI infers natural conditions in the general absence of disturbance, but where poor site quality (low nutrient availability), or high competition from nontarget species, restricts leaf area production of desired species. Hardwoods, because of annual foliage production, would have a much more dynamic interaction between existing site resources, and yearly recycling of mineral nutrients.

Optimal LAI would be found on either high-quality sites due to naturally high nutrition, or where moderate nutrient inputs to the stand have occurred. For midrotation loblolly pine, this may correspond to nutrient amendments (200 kilograms nitrogen and 25 kilograms phosphorus ha^{-1} over a repeated cycle of 4 to 6 years). Simulations suggest that an LAI of 3.0 to 3.5 (projected) is optimal for loblolly pine over most of the Southeast. For mixed hardwood stands, optimal LAI may be that found in midsuccessional ecosystems with a mixture of shade-intolerant and shade tolerant species. This mixture may provide for optimal conditions of light use efficiency; i.e., high light-requiring (and productive) species in the upper canopy and lower light-requiring species in the mid- and lower canopy.

Biologically attainable LAI would be that theoretical LAI created from heavy nutrient inputs, either from fertilization or from atmospheric deposition. Biologically attainable LAI has been identified from simulations, or from theoretical relationships between LAI and light extinction (k). Assuming a k of 0.5 to 0.8, and an under-canopy PAR transmittance of 0.05, biologically attainable LAI could range from 3.6 to 6.0 (projected). Gholz (1986) suggests that LAI of slash pine stands could reach six m^2 m^{-2} projected. From simulations, we suggest that an LAI of 4.0 to 4.5 (projected) would be biologically attainable but not optimal for maximum NPP in southern pine stands.

Biologically attainable LAI for hardwood ecosystems has yet to be identified. However, LAI values > six are uncommon in hardwood ecosystems. Where they occur, the general stand conditions include a dense mid- and understory of shade tolerant species (J.M. Vose, unpublished data). While contributing substantially to total stand LAI, low light conditions in the mid- and understory result in only slight increases in NPP. What is not known is whether altering site resources (e.g., via fertilization) would increase LAI in the upper canopy and result in proportional increases in stemwood NPP.

The next step for this approach would be an attempt to quantify the levels of resources, site occupancy, and the canopy light compensation ratio to create a working diagram for use in stand management. The general principles that hold for broad comparisons may not hold for stand level management. As such, region-specific, or ecosystem-specific models may be required.

ACKNOWLEDGMENT

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STEM MECHANICS AS A BASIS FOR BIOMASS ALLOCATION IN SOUTHERN PINES

Thomas J. Dean'

Abstract-The opportunity may exist to increase forest yield beyond what may be possible through site amelioration through a better understanding of biomass allocation within trees. Two general principles currently exist that explain the response of allocation to environmental changes. The first is considered a "goal seeking" approach where the tree maintains a critical ratio between mineral nutrient and carbon concentration within its tissues. Biomass is allocated to the foliage and root system, according to this ratio. The other principal is a physiological approach that relates meristem activity to the combined local concentration of mineral nutrients and carbon. The principal difficulty of the goal seeking approach is that it does not apply well to trees. The principle deficiency of the physiological approach is that simplifying assumptions must be incorporated into the model since not all of the physiological processes involved in nutrient and carbon uptake and in carbohydrate allocation are completely understood. An alternative approach exists that accounts for the allocation between the main stem and fine-root system by treating the main stem as a structural member of the tree. According to this approach, carbohydrate is preempted by the stem in order to counter the increased mechanical stress created by crown growth or by changes in the exposure to lateral wind forces. This approach corresponds with the negative linear relationship between fine-root allocation and stem allocation observed in several coniferous species. It also agrees with differences in allocation patterns seen among genotypes. Possible experiments to test this approach involve manipulating the mechanical stress experienced by the stem. If the hypothesis is correct, fine-root allocation will decrease as greater stress is generated in the stem.

INTRODUCTION

The most common approach to increasing forest yield has been to ameliorate the abiotic limits to growth. In the Southeastern United States, many of the areas available for forest production are naturally low in fertility due to highly weathered soils or past agronomic practices. Thinning has long been used to make more site resources available to crop trees, and fertilization has recently become a standard practice in plantation management. In the near future, several forest industries expect to fertilize and irrigate plantations. Resource use efficiency varies with genotype, and yield can be further increased by carefully matching families with site conditions.

Forest yield is a function of both the total amount of biomass produced (net primary production) and the amount of that biomass allocated to the stem. Many environmental factors such as light availability and soil fertility have been found to influence biomass allocation within trees (Gower and others 1995). Allocation patterns also vary by family in southern pines (Li and others 1991). The interaction between environmental and genetic variation in biomass allocation produces a wide spectrum of allocation patterns and suggests that silvicultural treatments may have the potential of changing conventional site and family associations. Making precise matches between family, site, and silvicultural treatments can be achieved through conventional screening studies in the field, but this approach is slow and cannot include a large range of combinations. A better understanding of the mechanisms controlling allocation would aid in determining the correct combination of family and silvicultural prescription for a particular site.

Gower and others (1995) reviewed the factors that influence biomass allocation in evergreen conifers. However, despite extensive knowledge of factors affecting allocation, no consensus has been reached in the mechanisms responsible for allocation patterns. The purpose of this paper is to present a hypothesis that accounts for this tradeoff between stem and fine-root allocation. The hypothesis is based on the mechanical relationship between the crown and the stem and states that decreases in fine-root allocation result from the stem's preemption of carbohydrate to counteract mechanical loads generated by the crown. Since crown morphology differs among families, the hypothesis should also account for genetic differences in stem and root allocation. Several experimental approaches that could test the proposed hypothesis are also outlined in this paper.

BRIEF SUMMARY OF EXISTING HYPOTHESES

Carbon allocation in trees, and plants in general, exhibits considerable plasticity. This plasticity has been treated as either goal seeking or as a consequence of the principally opposite directions carbohydrate and nutrients move through trees (Cannell and Dewar 1994). From a goal seeking perspective, trees allocate carbon according to the relative supply of resources in order to maintain proper tissue balances of essential elements. From the physiological perspective, the different movement of carbohydrates and nutrients produces changes in the relative abundance of essential elements within the primary and secondary meristems, resulting in different growth and allocation patterns within the tree. Both views result in realistic allocation patterns. The main difference between the two views is that the physiological approach changes

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allocation patterns much more quickly than the goal seeking approach (Thornley 1995).

Goal Seeking Hypotheses

For plants in general, the most common expression of treating allocation as a goal seeking process is the functional-balance equation. This equation combines two simple mass balance equations that state that the fraction Of carbon in the plant is the product of shoot mass and the photosynthetic activity of the shoot, and that the fraction of a soil-mineral nutrient in the plant, most commonly nitrogen, is the product of root mass and the specific uptake rate of the root system for that particular nutrient. The ratio between the fractions of carbon and the soil-mineral nutrient is expressed as

$$f_c/f_n = (M_s\, P_s)/(M_r\, a_n), \qquad (1)$$

where

f_c and f_n = the tissue fractions of carbon and a mineral nutrient,

M_s and M_r = the mass of the shoot and root system, respectively,

P_s = photosynthetic rate, and

a_n = specific uptake rate of the root system for the mineral nutrient.

Equation (1) was first presented by Davidson (1969) for alfalfa and clearly indicates that when photosynthesis increases, more carbon is allocated to the root system, and when specific uptake rate of the root system increases, more carbon is allocated to the shoot. While the functional-balance equation has been the starting point for a number of analytical solutions for optimal allocation (e.g., Hilbert and Reynolds 1991), it does not apply directly to trees because the stem and branches are not photosynthetic, and the stem comprises the majority of the plant mass. Cannell (1985) has suggested that the functional-balance equation may apply to trees only if the foliage and fine roots are considered, but because nutrient concentrations vary by two orders of magnitude among the various tree structures (Switzer and others 1966), and nutrients are retranslocated from older foliage to new foliage (Birk and Vitousek 1986), much more information is needed to use the functional-balance equation to quantify carbon allocation in trees. The value of the functional-balance equation for carbon allocation in trees has been that it supports the reduction in relative allocation to the fine roots often observed when trees are fertilized or are growing on fertile soils.

Genetic differences in carbon allocation also support the goal seeking approach to allocation. Van Buijtenen and others (1976) noted a tendency for families of loblolly Pine from the extreme western portion of the loblolly pine range to allocate greater amounts of carbon to the root system than families from the central portion of its range. Bongarten and Teskey (1987), working with loblolly pine seedlings, found that coastal families allocated less carbon to the root system than interior families when subjected to drought.

Another common variant of the goal seeking approach is the priority hypothesis of carbon allocation developed by Waring and Pitman (1985). According to this hypothesis, foliage allocation has the highest priority, the root system is second, and stemwood allocation is below both foliage and root allocation. This is a difficult hypothesis to test, partly because the hypothesis allows priorities to shift to maintain critical, physiological balances within the tree.

Physiological Hypotheses

The most comprehensive, physiological approach to carbon allocation is the transport-resistance model of Thomley (1991). In this model, carbon is fixed in the foliage and moves basipetally to the fine roots, and nitrogen is taken up by the fine roots and moves acropetally to the foliage. The intrinsic growth rate of the meristems along transport path is proportional to the concentrations of carbon and nitrogen within the meristematic region. A set of rules is defined to keep the structural growth of each component in balance with supporting structures. This model produces realistic results, but it does not include retranslocation of mineral nutrients within the crown.

While the transport-resistance model relates meristematic growth to the concentrations of carbon and nitrogen, the functions that maintain the proper balances among the various tree components are based on hydraulic relationships according to the pipe model of Shinozaki and others (1964). Use of the pipe model as a basis for either constraining allocation or determining allocation, as in the carbon-balance model of Valentine (1988), requires some questionable assumptions. Typically, these models assume that leaf area, sapwood cross-sectional area, and fine-root surface area are all linearly correlated. The relationship between leaf area and fine-root surface area is unsubstantiated, and the relationship between leaf area and sapwood cross-sectional area is curvilinear for several species (Baldwin 1989, Dean and Long 1986a). In addition, some sapwood loss rate must be assumed. If each new ring of sapwood corresponded to each year of foliage production, the loss of sapwood would correspond directly with litter fall. This is not the case, however. Albrektson (1984) has shown that the number of rings in sapwood do not correspond with the number of needle cohorts in Scots pine, and that the number of rings in sapwood changes with position on the stem. Sapwood also serves as a storage organ for carbohydrate, and the carbohydrate storage needs may also determine the quantity of sapwood (Bamber 1976). The majority of water transport occurs in the outer sapwood rings (Shelburne and others 1993) leaving the remainder for carbohydrate storage. This may be the reason why sapwood changes slowly after artificial removal of leaf area (Margolis and others 1988).

MECHANICAL SUPPORTHYPOTHESIS

The dominant shift in allocation in response to soil fertility occurs between the stem and the fine-root system (Beets and Whitehead 1996, Santantonio 1989) (fig. 1): allocation to branches and course roots is comparatively Small and does not appear to influence the tradeoff between stern allocation and fine-root the production (Santantonio 1989).

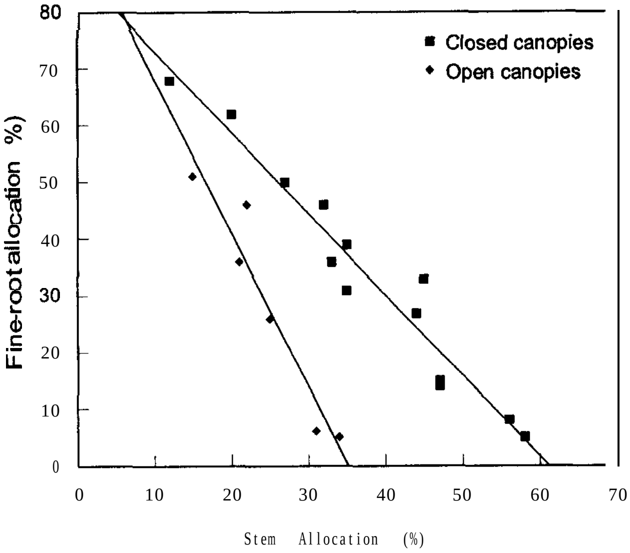
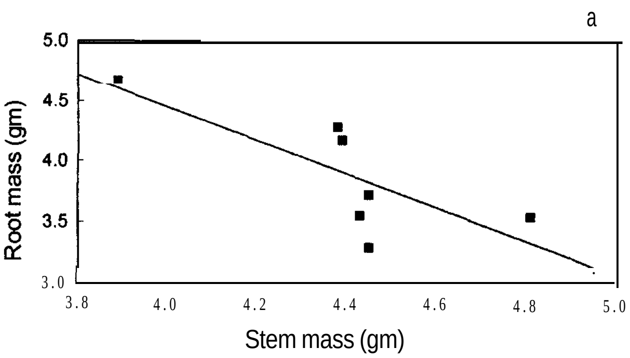


Figure l-Fine-root allocation as a function of stem allocation for various northern coniferous species. Line is from linear regression. Data from Santantonio (1989).

Across a soil fertility gradient, increases in annual stem increment are associated with corresponding decreases in annual fine-root production. Tradeoffs between stem and root allocation can also be seen in loblolly pine seedlings representing a range of seed lots subjected to common moisture regimes (fig. 2). Each additional unit of carbon required to counteract greater mechanical load on the stem may reduce allocation to the fine roots by a proportional amount (Santantonio 1989). The negative relationship between stem and fine-root allocation suggests that stem growth preempts carbohydrate from the root system and corresponds to studies showing that stem and fine-root growth are offset with cambial activity occurring during primary bud and leaf expansion and fine-root growth occurring during the interim, provided adequate soil moisture and temperatures (Reich and others 1980). Preemption of carbohydrate during cambial activity is supported by studies on source-sink relationships showing that sinks closest to the carbohydrate source are the strongest competitors for available supply (Wardlaw 1990).



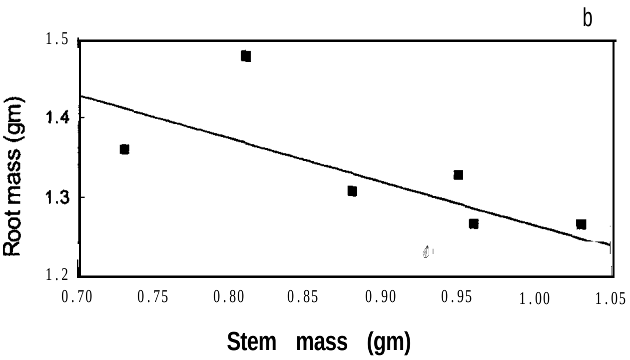


Figure 2—Root mass as a function stem mass for 1 -year-old loblolly pine seedlings. Seedlings represent a range of families and were subjected to moist (a) and dry (b) soil conditions. Data from Bongarten and Teskey (1987).

The most common response to soil fertility or fertilization is increased foliage production (Brix 1983, Colbert and others 1990, Gholz and others 1991, Keyes and Grier 1981). The additional foliage increases the amount of stress generated in the stem by lateral wind pressure and increases the gravitational load on the stem. Since much of the new foliage under normal stand conditions is produced near the top of the crown (Borghetti and others 1986), the increased force is applied higher on the stem adding additional stress to the stem. Stem cross-sectional area increases to counteract this load (Niklas 1992) and may preempt carbohydrate that may otherwise be used for fine-root allocation.

Several lines of evidence indicate that mechanical support is the primary function of the main stem and that hydraulic support develops within the framework established by the mechanical relationships. Long and others (1981) found that stem taper in four Douglas-fir trees representing a range of canopy classes conformed with elementary structural beam theory, and that the amount of sapwood cross-sectional area appeared independent of the total cross-sectional area required for structural integrity. Dean and Long (1986b) found that both stem diameter and taper for lodgepole pine also conformed to structural beam theory. Dean (1991) found that saturated sapwood permeability is affected by the bending stress experienced by the cambium in slash pine seedlings where the entire basal area is needed for water conduction. When supplemented with water and nutrients and allowed to sway freely with the wind, these seedlings had significantly greater mean cross-sectional areas but lower saturated sapwood permeability than similarly treated seedlings that were prevented from swaying.

The effect of lateral and vertical forces on stem size can be described with tapered-beam mechanics and tapered-column mechanics, respectively. Mature trees appear to conform to both tapered-beam and tapered column mechanics; however, sapling stems, with relatively little crown weight, appear to conform only to tapered-beam mechanics (Dean and Long 1986b). For stems that are constructed with uniform material and experiencing a lateral force applied at the top of the stem, the most efficient geometry for the stem is a cubic parabloid where diameter cubed varies directly with height. This geometry produces both equal bending stress and bending strain along the length of the stem. Increases in either height or the applied lateral force requires an increase in cross-sectional area to maintain a specified bending stress or strain.

While sophisticated applications of tapered-beam principles have been derived for trees (Morgan and Cannell 1994), a simplified equation derived by Dean and Long (1986b) provides a good approximation of the relationship between bending stress, stem diameter, and stem taper and clearly identifies canopy variables that influence bending stress. According to this equation, stem diameter at any cross section i (Di) is proportional to the product of the leaf area above i (Ai) and the distance from i to the center of leaf area above i (Si), i.e.,

$$Di = a\ (Ai\ Si)b, \quad (2)$$

where

a = proportionality constant and

b = 0.33 for stems conforming perfectly with the constant-stress model.

Experimental values of b obtained through regression analysis range from 0.28 for lodgepole pine saplings (Dean and Long 1986b) to 0.33 for mature loblolly pine trees (Dean and Baldwin 1996).

Experimental manipulation of bending stress generally indicates increased stem allocation with increased loading (Kellogg and Steucek 1980, Larson 1965) and decreased stem allocation with decreased loading (Dean 1991). Moderate pruning of the lower crown increases the bending moment, represented by S_i in the constant-stress equation and can increase allocation to stem wood if the associated reduction in leaf area is not severe (Larson 1965). Wind exposure also increases the bending moment and may explain why light thinning increases total stand growth over an unthinned control (Lo-Cho and others 1991).

Data from various studies also support the idea that the reduction in relative allocation to the fine roots in response to improved soil fertility occurs by the stem preempting carbohydrate to counter the additional bending stress created by accelerated foliage growth. Data presented by Friend and others (1994) show that additional nitrogen beyond 25 milligrams per liter (mg/l) supplied to Douglas-fir seedlings results primarily in increased shoot growth with little or no increase in fine-root growth. In mature slash pine stands growing in northern Florida, fine-root allocation as determined by root respiration was not significantly different between fertilized and unfertilized stands (Cropper and Gholz 1994) even though fertilization significantly increased foliage biomass (Gholz and others 1991). Linder and Alexsson (1982) supplied a 14-year-old Scots pine plantation with a complete fertilizer solution for 6 years and saw no significant difference in the carbon allocated to fine-roots between the fertilized and unfertilized stands, despite a nearly threefold difference in allocation to the stems and branches in the fertilized stand. Beets and Whitehead (1996), working with radiata pine plantations, saw significant fertilization effects on stem allocation but no significant effects on fine-root allocation.

In some cases, preemption of carbohydrate by the stem in response to soil fertility may result in reduced allocation to fine roots in absolute terms. Keyes and Grier (1981) compared the differences in biomass allocation in 40-year-old Douglas-fir stands growing on a poor site and a good site and on the good site, found a threefold decrease in the amount of biomass allocated to the fine-root system while stem allocation increased nearly twofold. Gower and others (1992) applied various treatments to a 50-year-old Douglas-fir stand including fertilization and found that fertilization reduced root allocation nearly 50 percent and increased stem allocation by 30 percent. Haynes and Gower (1995) compared fine-root production and mortality in fertilized and unfertilized plantations of red pine and found significant reductions in belowground carbon allocation in 2 of the 3 years they collected measurements. Ryan and others (1996) found that fertilization reduced fine-root production by 30 percent and nearly doubled stem production in radiata pine plantations.

POSSIBLE EXPERIMENTS

Several types of experiments could test this hypothesis. The basic premise of the hypothesis is that increased mechanical stress placed on the stem by an increase in crown size causes the stem to preempt carbohydrate that would otherwise be used to produce fine roots. Therefore, treatments that affect only the mechanical stress experienced by the cambium, but not the total amount of carbohydrate produced by the foliage, should result in significant changes in fine-root production. Mechanical stress experienced by the stem can be manipulated several ways. The classical way of minimizing mechanical stress is through tying the main stem to rigid stakes or by guying the main stem. Minimizing wind sway should result in significant increases in fine-root production compared to trees allowed to sway normally with the wind. The mechanical stress can be increased through artificial swaying. Stems can either be bent by hand or wrenched with a mechanical pulley. Increases in the amount of stress experienced by the stem should result in significant reductions in fine-root production.

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BRANCH AND FOLIAGE LEAF AREA OF LOBLOLLY PINE (*Pinus taeda* L.) 6 YEARS AFTER THINNING AND FERTILIZATION

S.F. Yu, J.L. Chambers, and J.P. Barnett[1]

Abstract-Branch and foliage biomass and leaf area were measured at two crown positions (upper and lower crown) of 48 trees that were harvested from a 14-year-old loblolly pine (*Pinus taeda* L.) plantation in conjunction with ongoing physiological studies. The collected data were used to evaluate the cultural treatment effects on foliage and branch characteristics, and will provide part of the information needed as a basis for scaling photosynthesis from the needle to the stand level. The study was conducted on the Palustris Experimental Forest, Rapides Parish, LA, during early spring 1995, six growing seasons after treatment. Thinning (thinned versus unthinned) and fertilization (fertilized versus unfertilized) were randomly assigned to 12 plots in a 2 by 2 factorial design with three replications at the site. Thinning significantly increased branch length, diameter, and foliage biomass and leaf area per branch. Effects of thinning at the branch level mainly occurred in the lower crown. The thinned treatment had twice as many shoots per branch as the unthinned treatment. The vertical distribution of leaf area per branch'was positively related to branch size but negatively related to crown depth after midcrown. Fertilization had no significant residual effects on leaf area and branch size either in the upper crown branch or in the lower crown branch 6 years after treatment. The interaction of thinning and fertilization was not significant for branch and foliage leaf area.

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Plant and Structural Diversity

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FLORAL DIVERSITY FOLLOWING HARVEST ON SOUTHERN APPALACHIAN MIXED OAK SITES

Daniel N. Hammond, David Wm. Smith, Shepard M. Zedaker, David K. Wright, and Jesse W. Thompson'

Abstract-Floral species richness was assessed for three vegetation strata in midsite quality, upland hardwood stands in the Ridge and Valley, and Allegheny Mountain physiographic provinces of Virginia and West Virginia. High variability in richness was found among six study locations which were relatively homogenous in topographic characteristics and overstory species composition and structure. Total species richness of the 35-acre sites ranged from 92 on the Clinch Ranger District of the Jefferson National Forest in Southwestern Virginia to 167 on the Wythe Ranger District. An inverse relationship occurred between overall species richness and percent crown cover in the midstory. Most of the variability was associated with differences in herbaceous communities. The high variability in species richness between sites of apparently similar age, structural, and topographic characteristics could question the validity of the chronosequence approach to the study of species diversity. By using stands of different age but similar site characteristics to represent community development, chronosequence studies are dependent on the assumption that similar sites will develop similar communities. Preliminary comparisons of 1 -year post-treatment species richness to pre-treatment values were made for one of six, 35-acre replicates containing seven 5-acre treatment plots. Treatments were clearcut, two-aged (leave tree), two levels of shelterwood, group selection, chemical understory control, and control/undisturbed. Species richness increased for all treatments. The magnitude of increase followed a gradient of canopy disturbance. The clearcut resulted in a net gain of 26 species while the herbicide treatment mimicked the control with a net gain of 2 species.

INTRODUCTION

Concern over changes in the amount of biological diversity has been increasing during past decades. The Forest Management Act of 1976 (FMA) responds to these concerns by mandating that on federal lands "management prescriptions... shall preserve and enhance the diversity of plant and animal communities... so that it is at least as great as that which would be found in a natural forest" (36 CFR 219.27g). Two questions must be answered in order to successfully abide by this mandate: (1) what is the diversity of a natural forest and (2) how wilt management prescriptions preserve that diversity?

Although the FMA applies to all Federal lands, this study focuses on the Southern Appalachians. Several authors have contributed to answering the first question (Braun 1950, Whittaker 1956, Duffy and Meir 1992, Aulick 1993) for forests in this region; however, these and other efforts have focused primarily on late-successional forests growing on highly productive sites. Little emphasis has been placed on second-growth forests growing on average sites, site index,, 60 to 80, in the Southern Appalachians. Other studies have attempted to illustrate community response to silvicultural disturbances (Horn 1980, Moriarty and McComb 1985, Duffy and Meir 1992, Gilliam and others 1995). Most have focused on the clearcut regeneration system and have taken chronosequence approaches to represent community development. This approach is dependent on the assumption that there is low variability in species diversity on sites which are apparently uniform with respect to topographic characteristics and overstory species composition.

The need to investigate community response to silvicultural practices is clear, and a long-term study which tracks the development of a set of forest stands would best reflect those changes. The objectives of this paper were to () establish baseline data for the characterization of the Vascular plant communities found in mixed oak stands of the Ridge and Valley and Allegheny Mountain physiographic provinces of the Southern Appalachians; and (2) make initial comparisons of species richness between a mature community and the communities which developed following various silvicultural disturbances at one study location.

METHODS

Study Area

Eight study sites have been located within the Ridge and Valley and Allegheny mountain physiographic provinces of southwestern Virginia and West Virginia. The Blacksburg and Clinch Ranger Districts of the Jefferson National Forest contain two study sites each (BB1 and BB2 and Clinch 1 and Clinch 2, respectively); one site is located in the Wytheville Ranger District and one in the New Castle District. Two sites were installed on the Westvaco Wildlife and Ecosystem Research Forest (WWERF) near Cassity, WV. Due to incomplete data, WWERF 2 and Clinch 2 were not included in this analyses. Study sites were selected to represent mid-elevation, southern aspect, mixed oak forests in the Southern Appalachians. Site index,, ranged from 60 to 77. Sites were installed in mature forests that displayed no indications of silvicultural manipulation within the past 15 years. Elevations range from approximately 2,200 feet at BB1 to 3,580 feet at Clinch 1. Mean daily July temperature for BB1 and BB2, Wythe, and New Castle is 72 °F. There are 150 frost-free days and an associated 42 to 48 inches of annual precipitation, with approximately 24 to 32 inches of snow. The WWERF and Clinch sites, located in the Allegheny Mountains, are slightly cooler and moister, with only 130 frost-free days and a mean daily July

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temperature of 65 "F. They receive 50 to 55 inches of precipitation, including 48 to 64 inches of snowfall (Smith 1995). The soils dominating these sites are derived predominantly from sandstone and shale parent material.

Study Design

A randomized complete block design was used, in which each 35-acre site contains seven 5-acre treatment blocks. Treatments include clearcut, group selection, leave tree, two types of shelterwood, chemical understory control, and a control. Due to area constraints, the WWERF 1 site was limited to five treatments, and did not contain the light shelterwood or chemical understory control. Clearcuts consisted of the removal of all merchantable stems and the felling of all residuals greater than l-inch d.b.h. Group selections were installed such that opening diameters would be no more than twice the height of the adjacent canopy trees with three openings per block. Leave tree and shelterwood cuts contain 10 to 20 sq. ft., 20 to 30 sq. ft., and 50 to 60 sq. ft. of residual basal area per acre, respectively. Chemical control consisted of a basal spray application of Garlon 4 to undesirable midstory woody vegetation in order to promote development of oak advance regeneration.

To qualify floral structure, vegetation was divided into three strata based on height: the tree stratum consisted of vegetation greater than 48.75 feet (5 m) in height, the shrub stratum was woody vegetation greater than 3.25 feet (1 m) but less than 48.75 feet (5 m), and the herb stratum was woody and herbaceous vegetation less than 3.25 feet (1 m) in height. The tree stratum was measured on three, randomly located, 78- by 78-foot (24- by 24-meter) plots per treatment block. The species of each tree within the plot was recorded and its diameter (d.b.h., 1.37 m aboveground) measured to the nearest 0.04 inches using a metal diameter tape. Sixteen 19.5- by 19.5-foot (6- by 6-m) subplots were established within each tree plot. Three subplots were randomly selected for measurement of the shrub stratum. Numbers of individuals per species and their respective crown diameters were measured and recorded to the nearest 0.3 foot on each plot. A further division of the 78- by 78-foot plots was used to establish eight 3.25- by 3.25-foot (1- by l-m) plots on which the herb stratum was sampled for numbers of individuals and percent cover by species. Percent cover was visually estimated using a pretransformed scale (Little and Hills 1978). In addition to measurements taken on sampling plots, a walkthrough of each 5-acre treatment plot was done in an attempt to account for all woody and nonwoody vascular plant species present. All strata were sampled mid-May to early June and additional sampling of the herbaceous stratum and walkthroughs occurred in mid-August. The two herbaceous samplings were used to account for within-growing season-variation of the herb stratum. A single data set was created by combining the data from each sample period. All species sampled were included in the combined data set. If a species occurred in both samplings, the larger value for each variable measured was used. The study is designed so that these communities will be periodically sampled throughout an 80- to 100-year rotation. Posttreatment sampling of BB1 occurred one complete growing season after harvest. Future inventories will occur at 3, 5, and 10 years, and at 1 O-year intervals thereafter until rotation age.

DATA ANALYSES

Pretreatment site characterization was based on both topographic and vegetative characteristics. Average slope percent and aspect were calculated from measurements taken at each tree plot center. Overstory basal area, quadratic mean diameter, and percent crown cover of the shrub stratum were estimated based on d.b.h. and crown radii measurements taken from the tree and shrub plots, respectively. ANOVA and Tukeys multiple comparison tests were used to test for between-site differences in tree basal area and percent cover in the shrub stratum. Pretreatment values for each stratum were calculated by averaging across the appropriate plots at each site. Total species richness and numbers of unique woody and herbaceous species were determined for each site, based on the compilation of treatment plot walkthroughs. In calculating richness values, some species (Carex, *Aster, Solidago, Desmodium, Poa, Panicum, Lespedeza,* and *Rubus*) were grouped by genus to account for variations in identification specificity among sampling crews.

In addition to pretreatment comparisons, changes in total richness following treatments were determined for BB1 based on 1 -year posttreatment data.

RESULTS

Site Comparisons

The six study sites evaluated represented aspects between 149 and 270 degrees azimuth with consistent within-site variation (table 1). Slopes ranged from 12 to 38 percent with moderate oak site indexes (table 1). Overstory composition and structure were consistent among the sites with various *Quercus* species dominating between 42 to 84 percent of the basal area (table 2). Overstory richness, compiled from all 78- by 78-foot plots, averaged 26.8 species per site. The greatest richness occurred on BB1 and Clinch 1 with 33 species at each site. WWERF had the least number of

Table l-Site characteristics and associated 95 percent confidence intervals of six study sites located in the Ridge and Valley and Allegheny Mountain physiographic provinces of Southwestern Virginia and West Virginia, based on measurements taken at plot center of 78- by 78-foot tree stratum plots

Site	Aspect	Slope	Oak site index,,	Age
BB1	153 ± 19	16 ± 3	n/a	n/a
BB2	151 ± 14	21 ± 3	72	99
Clinch	149 ± 20	30 ± 3	60	111
NC	150 ± 16	12 ± 4	60	62
Wythe	163 ± 39	18 ± 4	72	70
WWERF	270 ± 7	38 ± 3	77	73

Table 2—Basal area (square feet per acre) of the overstory stratum of six study sites located in the Ridge and Valley and Allegheny Mountain physiographic provinces of Southwestern Virginia and West Virginia, based on measurements taken on 78- by 78-foot plots (totals followed by the same letter were not significantly different at $\partial = 0.05$)

Species	Study site					
	BB1	BB2	Clinch	NC	WWERF	Wythe
Quercus prunus	18.8	49.6	16.6	33.1	20.8	24.9
Q. alba	34.3	12.8	16.9	11.4	0	15.0
Q. velutina	14.5	14.8	2.0	6.7	0	22.3
Q. coccinea	13.2	0.5	0.4	49.6	0	12.2
Q. rubra	2.3	4.3	38.0	0	44.8	1.2
Acer rubrum	8.5	7.9	19.5	3.5	33.1	7.4
Liriodendron tulipifera	4.7	9.1	1.0	0	15.3	1.7
Oxydendron arboreum	0.7	7.4	8.8	3.8	1.2	15.6
Others	19.0	12.6	26.8	11.9	40.8	11.7
Total	116a	119a	130ab	120a	156b	112a

overstory species with 22 (table 3). Slightly more variation occurred in the shrub stratum, with respect to cover and composition. The 48-percent crown cover at Wythe was significantly lower than the 78.3- and 73.7-percent at BB1 and New Castle, respectively (table 4). However, the 30

Table 3—Overstory, midstory, and overall species richness values of six study sites located in the Ridge and Valley and Allegheny Mountain physiographic provinces of southwestern Virginia and West Virginia[a]

Site	Overstory	Midstory	Overall	
			Woody	Herbaceous
BB1	33	33	50	75
BB2	25	29	50	80
Clinch	33	24	44	54
NC	24	17	41	51
Wythe	24	30	52	115
WWERF	22	24	47	88
Average	26.8	26.2	45.7	77.2

[a]Numbers of species in the overstory and midstory are based on the compilation of twenty-one 78- by 78-foot plots and sixty-three 19.5- by 19.5-foot plots respectively at each site. Overall richness is based on compilation of treatment plot walkthroughs at each site.

shrub species occurring at Wythe was higher than the average midstory richness (table 3). Average midstory richness for all sites, 26.2 species, was just less than overstory richness but had greater variation. It must be noted that these richness values for the tree and shrub strata are not directly comparable since sampling area was more than five times greater for the tree stratum. However, with a larger sample area yielding less than one more species on average in the tree stratum, this suggests that midstory richness is greater than overstory richness across these sites. Also, richness values for WWERF are based on a smaller area sampled, due to there only being five treatment plots.

The overall species richness was quite variable among the locations sampled (table 3). New Castle had only 92 species while 167 species were found at Wythe. Since the number of woody species found at each site was relatively homogeneous, herbaceous vegetation accounted for most of the variability in richness values. Of the 275 species identified across all pretreatment communities, 80 herbaceous and 18 woody species were found at only one site (table 5). Wythe and WWERF had not only the greatest richness values, but also had the greatest number of unique (found only at one site) species, with 30 and 27, respectively. Species richness was inversely related to percent cover in shrub stratum. Those sites with high richness had correspondingly low shrub cover, while those with low richness had high coverage in the shrub stratum. No relationship was found between richness and overstory basal area.

Blacksburg 1 Pretreatment versus Posttreatment

As was expected, overall species richness at BB1 increased dramatically following treatment. Total species richness increased from 125 to 291 species, with herbaceous species representing 91 percent of the 166 invading species. Evaluation of the data collected on the 3.25- by 3.25-foot plots illustrates the variability of the effects of individual treatments (table 6). The clearcut resulted in a net increase in richness of 26 species, while only 2 species were gained by the herbicide and control treatments. The magnitude of change in species richness occurred along a gradient of canopy disturbance. As canopy disturbance increased, more species were lost from the community. For example, 26 species were lost following clearcutting but 42 new species were gained. Treatments with less canopy disturbance, such as the shelterwoods, resulted in species losses equal to those in the control. Considering the group selection as a high-disturbance treatment, the seven species lost in this treatment were an exception to the pattern. The indistinguishable difference between the group selection and control in numbers of species lost could be attributed to the nonuniform effects of the treatment creating refugia for species which would be otherwise negatively impacted by canopy removal. Since groups were installed without consideration of plot location, a portion of the plots were located in group openings while the remaining plots were in the residual stand. Therefore, species invading group openings and species in the residual stand were represented in the sample plots.

Table 4-Percentage of cover of the shrub stratum of six study sites located in the Ridge and Valley and Allegheny Mountain physiographic provinces of southwestern Virginia and West Virginia[a]

Species	Study site BB1	BB2	Clinch	NC	WWERF	Wythe
Acer pennsylvanicum	0.1	0	8.1	0	11.4	1.8
A. rubrum	24.5	13.8	9.3	0	7.9	1.8
Betula lenta	0	0.5	2.1	0	5.7	0.2
Castanea dentata	0.4	1.0	10.4	3.5	0.1	8.2
Cornus florida	12.5	8.0	0	4.0	0	1.6
Fagus grandifolia	0	0	0.1	0	19.7	0
Lindera benzoin	3.8	0	0	0	0.4	0
Magnolia frazieri	0	0	7.4	0	0.5	0
Nyssa sylvatica	10.3	7.7	0.8	58.7	0.3	3.3
Oxydendrum arboreum	0.4	6.2	1.9	3.1	0.7	12.1
Pinus strobus	1.7	2.5	0	0	0	4.9
Others	24.6	25.3	25.9	4.4	12.4	6.6
Total	78.3a	63.0ab	66.0ab	73.7a	59.1ab	44.1 b

[a] Species listed were chosen on the basis that they represent the four most common at each site. Totals followed by the same letter were not significantly different at ∂ = 0.05.

Table 5—Number of woody and herbaceous species unique to a site (sites are located in the Ridge and Valley and Allegheny Mountain physiographic provinces of southwestern Virginia and West Virginia)

Site	Species Woody	Herbaceous
BB1	2	9
BB2	2	12
Clinch	3	0
NC	4	9
Wythe	2	28
WWERF	5	22
Total	18	80

Table 6-Changes in woody and herbaceous species richness for seven treatments installed in a mixed oak forest near Blacksburg, VA (values are based on the species represented on eighteen 3.25- by 3.25-foot plots per treatment)

Treatment	Number of species lost Woody	Herb	Number of species gained Woody	Herb	Total change
Clearcut	3	13	2	40	+26
Group selection	2	5	5	22	+20
Leave tree	7	13	5	28	+13
Shelterwood 20-30	2	7	7	19	+17
Shelterwood 50-60	5	4	6	14	+11
Herbicide	2	4	4	4	+2
Control	5	4	3	8	+2

The numbers of woody species lost and gained remain fairly constant across treatments. Herbaceous plants account for the patterns of species invasion. The increase in available light associated with the clearcut and other high canopy disturbing treatments created conditions which favored these species.

CONCLUSION

There was high variability in species richness among communities which appeared homogenous when compared on the basis of topography and overstory species composition and structure. The number one assumption for chronosequence studies is that if site factors and overstory species composition are similar between sites which are at various stages of successional development, then those sites can be used to represent the development of a community through time following a given disturbance. The high variability in species richness found in this study questions the validity of chronosequence studies for comparing treatment effects on species diversity in Southern Appalachian mixed oak forests.

Consistent with Gilliam and Turrill (1993), these data suggest that overall species richness is negatively correlated with percent cover in the shrub stratum. Further analyses of these data will attempt to quantify that correlation and investigate other possible variables which can be used to predict species richness.

For all treatments at BB1 , herbaceous layer species richness increased following treatment. The magnitude of increase followed a gradient of canopy disturbance. Herbaceous species were the majority of those lost and gained. Future work with these data will compare the shifts in species relative abundance and investigate relationships among the species lost and gained as a result of treatment and associated site variables. Future inventories representing the redevelopment of these communities will be necessary to reveal any differences or similarities between treatments.

If silvicultural practices are to survive the scrutiny of current legislation and the environmental community, then scientific documentation of the effects of those practices on all members of a given plant community must be established. Although research such as this can help to identify the changes that take place following silvicultural activities, in no way can we identify which aspects of diversity hold the most ecological significance. Without that ability, societal values will ultimately decide which practices are acceptable, and as scientists we can only provide society with sound information for the basis of that decision.

ACKNOWLEDGMENT

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INFLUENCE OF HARVEST VARIABLES ON WOODY PLANT DIVERSITY IN UPPER COASTAL PLAIN MIXED TYPES

James W. McMinn'

Abstract-Commercial clearcuts and silvicultural clearcuts were applied to upper coastal plain mixed stands in the dormant season and early growing season. The commercial clearcutting removed only merchantable material. The silvicultural clearcutting included felling of all stems 1 inch d.b.h. or larger in addition to the removal of merchantable material. Each combination of season and type of cut was replicated six times. The stands were allowed to regenerate naturally via seedlings and sprouts with no further treatments. Harvest treatments significantly influenced pine seedling proportions and the diversity of foliage cover in the regenerated stands.

INTRODUCTION

This paper presents preliminary results of a study being conducted on the U.S. Department of Energy, Savannah River Site, in the upper coastal plain of South Carolina. Earlier research in the upper piedmont of Georgia demonstrated that harvest season and intensity, alone, could strongly influence the relative species composition of naturally regenerated stands in the oak-pine type (McMinn 1992). However, the degree to which such influences may generalize to other mixed types is open to question. The objective of this study is to determine the influence of harvest season and intensity on subsequent woody species composition and diversity in upper coastal plain mixed hardwood-pine stands.

METHODS

Mixed hardwood-pine stands of from 20 to 60 acres in size were each partitioned into four equal areas to accommodate the four combinations of commercial clearcutting and silvicultural clearcutting in the dormant season and early growing season. The commercial clearcuts removed only merchantable material. The silvicultural clearcuts included felling of all stems 1 inch d.b.h. or larger in addition to the removal of merchantable material. The experimental design is a randomized complete block in which each of six stands constitutes a block. Three blocks were harvested in each of 2 consecutive years, but year was not included as a variable in the analyses reported here. All results reported here are from data within 5 years after treatment. The response variables are number of seedlings by species and foliage coverage by species. Woody plants less than 4.5 feet tall were considered seedlings and were counted on hundredth-acre circular plots spaced at 150 feet on a square grid network. Foliage cover of woody plants at least 4.5 feet tall was estimated from a system of 150-foot line transects. To characterize the general influence of treatments on species composition, species were grouped by oaks, other hard hardwoods, pines, soft hardwoods, shrubs, and miscellaneous species. In the oak group, southern red oak (*Quercus falcata* Michx.), water oak (Q. *nigra* L.), willow oak (Q. *phellos* L.), post oak (C?. *stellata* Wangenh.), and black oak (*Q. velutina* Lam.) were prevalent; turkey oak (Q. *laevis* Walt.) and blackjack oak (*Q. marilandica* Muenchh.) were common; and scarlet oak (Q. *coccinea* Muenchh.), bluejack oak *(Q. incana* Bartr.) and laurel oak (*Q. laurifolia* Michx.) were occasional. Other hard hardwoods included hickories (*Carya* spp.), dogwood (*Cornus florida* L.), persimmon *(Diospyrous virginiana* L.), and American holly (*Ilex opaca* Ait.). Pines included loblolly (*Pinus taeda* L.) and longleaf (*P. palustris* Mill.). Among the soft hardwoods, sweetgum *(Liguidambar styraciflua* L.), blackgum (*Nyssa sylvatica* Marsh.), and black cherry *(Prunus serotina* Ehrh.) were prevalent; winged elm (*Ulmus alata* Michx.) was common; and red maple (*Acer rubrum* L.), sycamore (*Platanus occidentalis* L.), and willow (*Salix* spp.) occurred occasionally. In the shrub group, plum (*Prunus* spp.) and sumac (*Rhus* spp.) were prevalent; blueberry *(Vaccinium* spp.) was common; and occasionals were chinkapin *(Casfanea* spp.), viburnum *(Viburnum* spp.), waxmyrtle (*Myrica cerifera* L.), yaupon (*Ilex vomitoria* Ait.), St. Johnswort *(Hypericum* spp.), and privet *(Ligustrum* spp.). The miscellaneous group included apple (*Malus* spp.) and sassafras *[Sassafras albidum* (Nutt.) *Nees].* Species diversity and evenness for seedlings and foliage cover were calculated using Shannon's indexes (Magurran 1988).

RESULTSANDDISCUSSION

Significant difference by block in the proportion of seedlings or foliage cover for a given species group reflects only a difference among initial stands in the prevalence of that species group (table 1). The only statistical difference attributable to harvest treatment is the proportion of total seedlings that are pine. For the commercial clearcuts, dormant season harvests produced almost nine times the pine proportion as early growing season harvests (table 2). For the silvicultural clearcuts, dormant season harvests resulted in over six times the pine proportions as early growing season harvests. The strong seasonal influence on pine proportions is consistent with results in the upper piedmont (McMinn 1992). Larger proportions of the "other' species following early growing season harvests compared to dormant season harvests are also consistent with the piedmont study.

As with seedling and foliage proportions, significant differences in diversity and evenness by block reflect

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Table l-Analysis of variance results for seedling **proportion** and foliage cover proportions of selected species groups

Species groups	Source of variation			
	Block	Season	Cut	Season x cut
Seedling proportion:				
Oak				
Hard hardwood	-	-	-	
Pine	*a	*		
Soft hardwood	-	-	-	
Foliage cover proportion:				
Oak	*			
Hard hardwood	-	-	-	
Pine				
Soft hardwood	-	-	-	

[a] Asterisk denotes significance at the **.05** level.

Table 2-Seedling percentages by species group and harvest treatment

Treatment Season	Treatment cut	Species group Oak	H. hwd.	Pine	S. hwd.	Other[a]
		Percent				
Dormant	Comm	15.9	10.9	16.1	8.3	48.8
Dormant	Silv.	9.7	16.6	15.3	11.8	46.6
Growing	Comm	6.9	9.5	1.8	8.7	73.1
Growing	Silv.	9.8	12.7	2.4	6.4	68.7

Comm = commercial clearcuts, silv = silvicultural clearcuts.
[a] Includes shrubs and miscellaneous species.

variability among initial stand characteristics (table 3). Foliage cover diversity differed by type of cut and the interaction between type of cut and season. Species richness ranged only from 26 to 28 for seedlings and from 18 to 21 for foliage cover, so any differences among treatments in diversity are attributable to differences in evenness (table 4). The high foliage cover diversity following growing season commercial clearcuts compared to growing season silvicultural clearcuts is likely due to a degree of species stability provided by the residual stand. The low foliage cover diversity following growing season silvicultural clearcuts is likely due to differential sprouting among hardwood species from the harvest timing that introduces the greatest stress. Higher seedling diversity

Table 3-Analysis of variance results for woody species diversity and evenness of seedlings and foliage cover

Trait	Source of variation			
	Block	Season	Cut	Season x cut
Seedlings:				
Diversity	*a			
Evenness				
Foliage Cover:				
Diversity	**		*	*
Evenness				

[a] **Single** asterisk denotes significance at the **.05** level, **double** asterisk at the **.01** level.

Table **4—Woody** species diversity by harvest treatment for seedlings and foliage cover

Treatment Season cover	Treatment cut	Trait Seedlings	Trait Foliage
Dormant	Commercial	1.77	1.60
Dormant	Silvicultural	1.92	1.67
Growing	Commercial	1.77	1.89
Growing	Silvicultural	1.94	1.44

following silvicultural clearcuts compared to commercial clearcuts could, perhaps, be due to differential response of various seedling species to competition from residuals in the commercial cuts.

CONCLUSION

These results suggest that harvest season and intensity do have the potential to influence species composition and woody plant diversity in upper coastal plain mixed types.

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CHANGES IN WOODY STEM SPECIES DIVERSITY OVER TIME FOLLOWING CLEARCUTTING IN THE MISSISSIPPI RIVER FLOODPLAIN

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Approved for publication as Journal Article FA 073-0497 of the Forest and Wildlife Research Center, Mississippi State, MS.

Abstract-Woody species diversity is an important ecological aspect of bottomland hardwood stands in the Mississippi River floodplain. A chronosequence study was established with stands which had been clearcut during different years on Delta National Forest. The stands were chosen with respect to site similarity and ranged in topographical position from ridges to high flats. Stand age ranged from 1 to 50 years since harvest. Several older, adjacent stands were utilized as controls. No intermediate silvicultural treatments had been implemented on these stands. Woody stem measurements were recorded during the summer of 1996 and data were analyzed to determine when woody species diversity reached a maximum following clearcutting. Analysis of three canopy levels showed a peak in total woody species diversity (relative dominance and relative frequency) during the first 10 years following clearcutting. Trends were observed relating to changes in diversity over time. When diversity of the three canopy levels was examined separately, the upper and lower canopy levels exhibited a peak during the first 10 years. The lower canopy level actually exhibited two peaks in the chronosequence, one at 10 years and the other at 35 years. In the lower canopy level, the highest diversity occurred at 35 years. Diversity of the midcanopy level did not peak until 15 years following clearcutting. The diversity of all three canopy levels decreased with age after 45 years.

INTRODUCTION

Within the Mississippi River floodplain, the land area occupied by the bottomland hardwood forest type has diminished drastically during the last 100 years. Land clearing for agriculture has been the primary reason for the decrease (Hodges 1993). Remnants of the original forest are left in areas that are either too wet for efficient farming or were in public ownership. These forested sites were subjected to repeated diameter-limit harvests which were in actuality high grading, and left them in disparaging condition with respect to timber quality and species composition.

During the 1960's, the USDA Forest Service began implementing operational clearcuts on the Delta National Forest in a manner that could be construed as a regeneration technique rather than simply a harvesting procedure (Hurst and Bourland 1976). In southern floodplain forests, clearcuts are an effective regeneration technique and will promote a more desirable species composition if advance regeneration is present. From this time period to the present, an abundance of even-aged stands were created.

Another event that transpired during this time period was the designation of three research natural areas on the Delta National Forest. These areas were originally set aside to preserve important communities, maintain genetic diversity, and serve as reference areas for the study of succession, and are still in existence today (USDA 1976). The research natural areas are valuable examples of areas where mature, unmanaged stands exist, although additional stands may be found throughout the forest that were last harvested during the 1910's and 1920's.

Concerns over the perceived loss of biodiversity are of great importance to scientists, natural resource managers, and the general public (Westman 1990). There is a need to explore the effects of clearcutting on plant diversity and to examine natural succession in bottomland hardwood stands. The objectives of this paper are to examine changes in woody plant diversity over time and to ascertain when, following clearcutting, woody species diversity is most similar to that of mature, unmanaged stands.

STUDY SITE

The Delta National Forest is approximately 59,000 acres in size and is located in Sharkey County at the southern end of the Mississippi River alluvial plain in Mississippi. Both the Little Sunflower River and the Big Sunflower River as well as countless sloughs and bayous run through the forest. The forest is actually within the Yazoo Basin and the elevation is about 90 to 95 feet above sea level (USDA 1976). The forest is subjected to spring flooding from the Mississippi River backwater as well as rainwater runoff from surrounding areas.

Due to differences in hydrology between the north and south ends of the forest, the stands used for this study were all located on the north end of the forest. The south end of the forest is flooded for a longer duration during the growing season. The stands on the north end of the forest occupy high flats or low ridge sites or gradations between the two topographic positions.

Forest types are typical of southern bottomland hardwood forests (Johnson and Shropshire 1983). Commercially important species include Nuttall oak (*Quercus nuttallii* Palmer), willow oak (Q. *phellos* L.), overcup oak (C?. *lyrata*

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Wall.), green ash (*Fraxinus pennsylvanica* Marsh.), sugarberry (*Celtis laevigata* Willd.), sweetgum (*Liquidambar styraciflua* L.), eastern cottonwood (*Populus deltoides* Marsh.), sweet pecan [*Carya illinoensis* (Wang.) K. Koch], water hickory [*C. aquatica* (Michx. f.) Nutt.], boxelder (*Acer negundo* L.), red maple (*Acer rubrum* L.), American elm (*Ulmus americana* L.), and persimmon (*Diospyros virginiana* L.). Important midstory and understory species are rough-leaved dogwood (*Cornus drummondii* Meyer), swamp privet [*Forestiera acuminata* (Michx.) Poir.], buckthorn bumelia [*Bumelia lycioides* (L.) Pers.], deciduous holly (*Ilex decidua* Walt.), hawthorn (*Crataegus viridis* L.), and water elm [*Planera aquatica* (Walt.) Gmelin]. All Latin names follow those used by Smith (1988).

METHODS

Inventory Procedures

Stands were grouped in 5-year age classes based on time since harvest. Thirty-five stands were used with approximately four stands in each of nine age classes. Upper, mid, and lower canopy levels were measured using a nested plot design with 10 plots per stand randomly located. Diameters at breast height (d.b.h.) were measured for all living trees or shrubs in the upper canopy level within a 1 O-acre fixed area circular plot. Diameters at breast height were measured for all living trees or shrubs in the midcanopy level within a 100-acre fixed area circular plot. The same 100-acre plot used for the midcanopy level was also utilized for the lower canopy level, where diameters at the root collar were measured for all living trees or shrubs. Each individual tree or shrub was identified to species.

Canopy level differentiation was based on the authors' observations rather than an arbitrary height. The midcanopy level was not distinguishable as a separate entity in any of the stands until 10 years of age. The basis for separation of the canopy levels was the presence of a distinguishable layer of foliage. Due to the various stages of succession of the stands, the use of a particular size class for a member of a particular canopy level was impractical.

Data Analysis

Relative density by species for each stand was used to calculate Shannon's diversity index. Shannon's diversity index is a measure of the uncertainty of the ability of predicting the species of an individual when that individual is picked at random from the community (Hair 1980). The many stands used for the chronosequence were assumed to represent an average stand on ridge or flat topography in the Delta National Forest. Comparisons were made between the clearcut stands and the mature unmanaged stands. In this case, Sorenson's similarity index was used to compare relative species dominance and relative frequency. Sorenson's index was expressed as a percentage with respect to differences between the clearcut stands and the mature unmanaged stands.

RESULTS

Woody species diversity in the upper canopy level reached a peak during the first 10 years following clearcutting. It had a Shannon's diversity index value of 2.44. This peak was actually somewhat higher than that found in the mature unmanaged stands. Shannon's diversity for the older unmanaged stands was 1.37. The diversity levels of the lower strata seemed to be adversely affected by the diversity levels of the upper canopy in stands older than 10 years of age. As species richness increased in the upper canopy, diminished species richness in the lower strata was a result (fig. 1). Although many species which are generally considered to be midstory species were present in these younger stands, they occupied either lower or upper canopy positions.

Woody species diversity in the lower canopy level actually peaked twice during the chronosequence. The first peak was at about 10 years, with a Shannon's diversity index

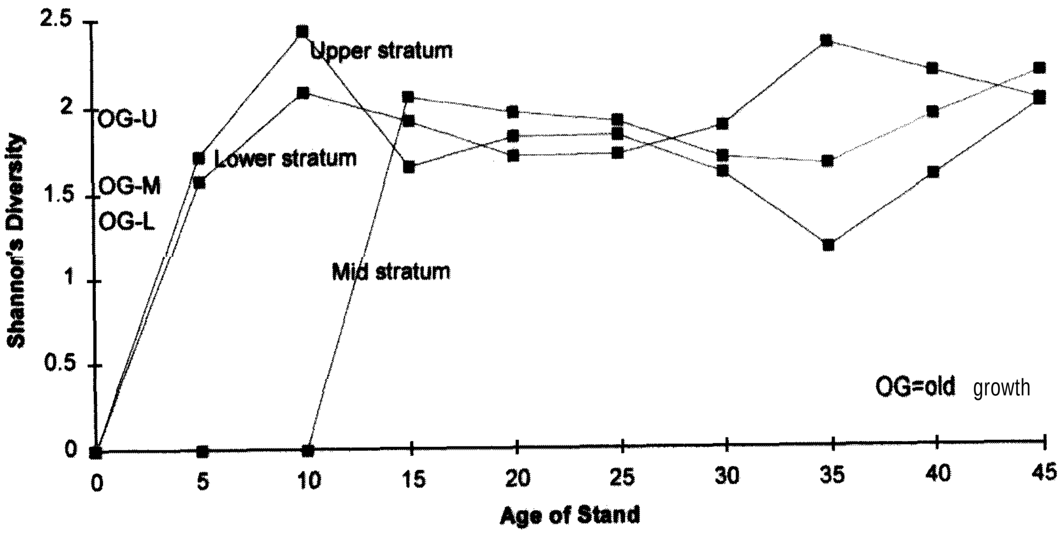

Figure l-Shannon's diversity index for each canopy strata for stands between 1 and 45 years of age.

value of 2.09. The second peak occurred at about 35 years, with a Shannon's diversity index value of 2.37.

The diversity levels of the three strata were averaged together according to 5-year age intervals to determine total site woody plant diversity. Again, diversity levels were highest in the 5- to lo-year age interval (fig. 2). The high diversity levels during this time period were attributed to the high diversity of the lower stratum. Diversity levels in the lower stratum are very dynamic, responding to flood events with drastic decreases. This leads to decreased stability with respect to species diversity within this stratum (May 1977). When the diversity of the lower stratum was excluded from the analysis, diversity was highest during the 10- to lbyear age interval (fig. 3). The lower stratum was the only canopy level that had its highest peak in stands over 25 years of age.

Clearcut stands were compared with older unmanaged stands. After 10 years, diversity in the clearcut stands and diversity in older unmanaged stands was very similar. Ten- to 15-year old stands and 20- to 25-year old stands were 73 percent similar to older stands, and 15- to 20-year old stands were 71 percent similar to their more mature counterparts. Stands between the ages of 25 and 40 ranged from 63 percent to 69 percent similar to the older stands (table 1). Similarity increased steadily after 45 years.

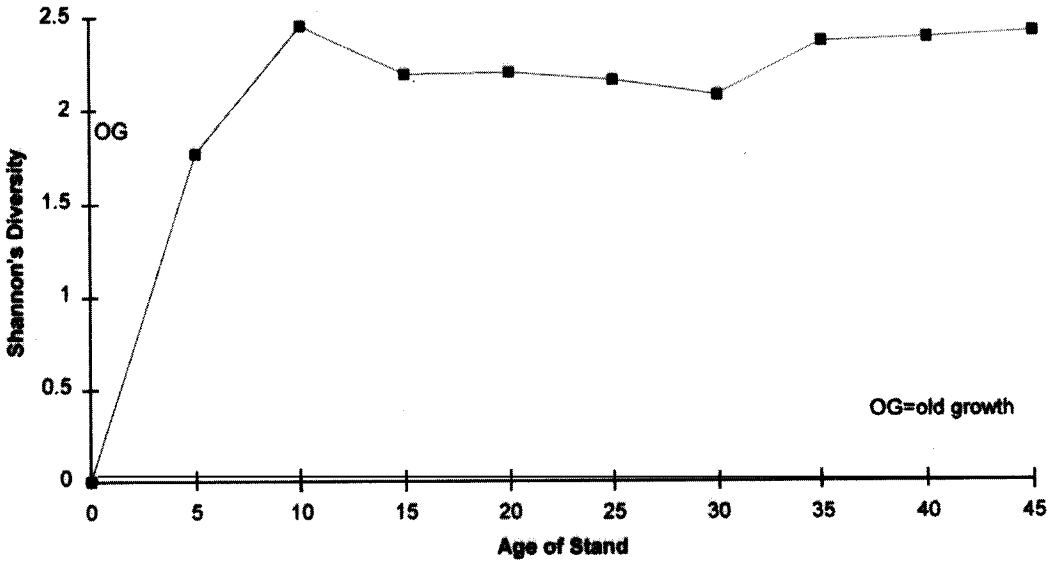

Figure 2-Shannon's diversity index for the average of all canopy strata for stands between 1 and 45 years of age.

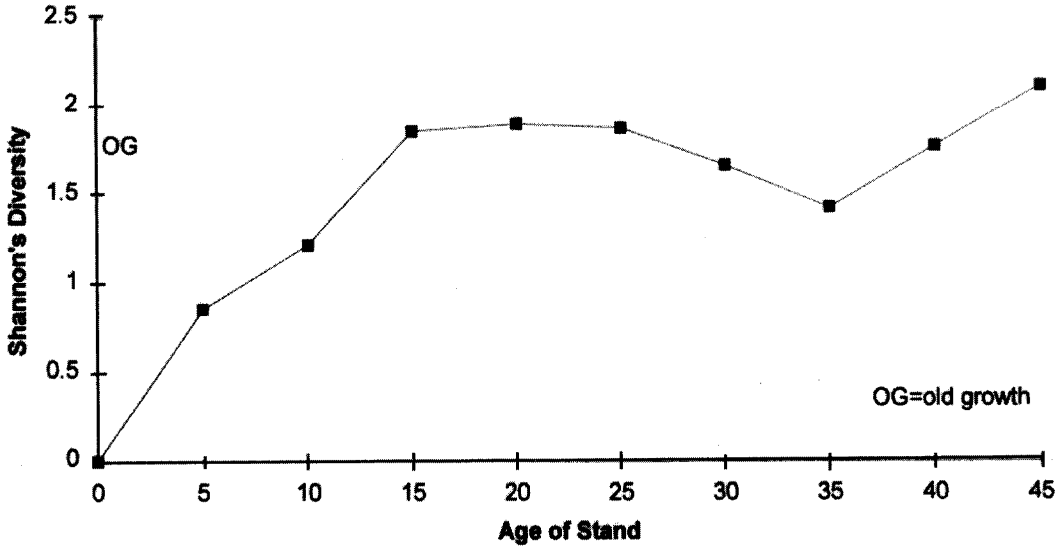

Figure 3-Shannon's diversity index for the average of the mid and upper canopy strata for stands between 1 and 45 years of age.

Table i-Similarity between clearcuts less than 45 years of age and older unmanaged stands for all canopy levels

Age class of clearcut	Similarity to older stands
	------------ Percent ----------
5	46
10	73
15	71
20	73
25	65
30	63
35	69
45	71

DISCUSSION

Oliver and Larson (1990) best describe the stand development patterns that are taking place in this chronosequence. According to their treatment the four stages of stand development are stand initiation, stem exclusion, understory reinitiation, and old growth.

The rapid increase in diversity during the first 10 years was expected. Biological legacies from the preceding stand and pioneer species infiltrating the new stand lead to a rapid increase in the species richness on the site. The diversity peak during the stand initiation stage and subsequent drop in diversity during the stem exclusion stage is well documented (Bormann and Likens 1979, Hibbs 1983, Schoonmaker and McKee 1988). The stands which were examined in this study had higher levels of diversity at about 10 years of age than did stands over 95 years of age. The reduced amounts of light reaching the forest floor and the exclusion of many of the pioneer species found in the younger stands are a probable cause of the differences in levels of diversity (Spurr and Barnes 1964).

Another possible explanation for the reduction in main canopy diversity involves predetermined species stature. Some species exist in the main canopy of the young stand that do not have the capacity to grow to tree stature. These species are excluded in the older stand when they become overtopped by the larger species.

Canopy closure in these stands leads to the stratification of the midcanopy level. At this stage of succession the faster growing species behave like emergents in older stands. They are beginning to form the upper canopy level but have not yet reached upper stratum canopy closure. As the upper stratum approaches canopy closure the less shade tolerant species, which occupy the midstrata position, are lost and a decrease in midstratum diversity occurs. At the end of the stem exclusion stage the upper stratum has increased somewhat in diversity and has become more efficient in its canopy structure and a subsequent loss in lower stratum diversity occurs.

The lower stratum in the southern floodplain forests is very dynamic and subject to more rapid change due to flooding. Flooding is an excellent seed dispersal mechanism for many plant species (Weaver and Clements 1938), and water stress on upper stratum species allows more sunlight to infiltrate the canopy, creating a favorable environment for plant growth when the flood waters recede. The flood effect phenomenon causes fluctuation in the diversity levels of the lower stratum for individual stands and may be confounding this study, where a spatial chronosequence was developed using many stands of varying ages in a single year. The lower canopy level did react to fluctuations in diversity in the upper stratum, decreasing in diversity when the upper stratum increased.

The lower canopy level exhibited its greatest diversity between 30 and 35 years following clearcutting. Thirty to 35 years marks the beginning of the understory reinitiation stage (Oliver and Larson 1990). The lower stratum at this time is composed of both shrub species and regeneration from tree species which persists in the lower stratum but does not exhibit rapid growth. The 30- to 35-year period is also the time in which similarity to older natural stands begins to increase.

The diversity level fluctuations observed during certain successional stages are not unique to southern floodplain forests. Schoonmaker and McKee (1988) observed similar patterns in the Cascade Mountains of Oregon. They found that old-growth forests had lower diversity levels than did early successional stands following clearcutting. They also observed two peaks in diversity during the early stages of succession, as was found in this study.

Spatial chronosequence studies which examine many stands of different ages during a short time period are difficult to implement with great accuracy (Oliver 1982). Factors such as site differences and preharvest stand conditions are extremely relevant (Blackman 1978). Many stands must be sampled to obtain an accurate representation of an average stand on a particular topographic position. The characteristics described in this paper are not meant to describe a particular stand but should prove beneficial in developing a representation of changes in diversity over time in a lower Mississippi River valley bottomland hardwood ecosystem.

ACKNOWLEDGMENT

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DYNAMICS OF COARSE WOODY DEBRIS IN UNMANAGED PIEDMONT FORESTS AS AFFECTED BY SITE QUALITY

John B. Crooks III, Thomas A. Waldrop, David H. Van Lear, and Victor B. Shelburne'

Abstract-Although coarse woody debris (CWD) is accepted as an important component of forest ecosystems, little is known about the changes in CWD loads that might be expected over long periods. This study documents CWD loadings across a chronosequence of 1 OO+-years on three different site types in the piedmont of South Carolina. Seven age classes (0 to 3, 4 to 7, 8 to 15, 16 to 25, 26 to 50, 51 to 100, 100+) and three site types (subxeric, intermediate, and submesic) were sampled on the Clemson Experimental Forest. CWD loads were measured in five stands of each age-site combination using a modified Versiolanar Intersect Method. These data were used to test the FORCAT gap model which was modified to predict CWD accumulation. Field observations showed that CWD loadings varied by age class with smaller amounts found in stands between ages 8 and 25, but the loadings did not vary among landscape ecosystem classification (LEC) units. When comparing FORCAT to field observations, the patterns of CWD loading were similar. However, the model overpredicted CWD loads throughout the simulation period. Predicted CWD loads may have been too high because inputs from harvesting were too high and simulated decomposition rates were too low.

INTRODUCTION

As a forest ecosystem matures and progresses from one successional stage to another, many changes occur. One of these changes is the mortality of trees, which provides coarse woody debris (CWD) to the ecosystem. Nonliving woody material, i.e., any dead fallen or standing tree stem or limb material greater than 3 inches, is called CWD. CWD provides several ecosystem functions such as seed germination sites, reservoirs of moisture during droughts, sites of nutrient exchange for plant uptake, and critical habitat for a number of forest organisms (Harmon 1982, Van Lear 1996, Van Lear and Waldrop 1995). Because of these important functions, CWD should be considered by land managers and incorporated into management regimes. The amount of CWD present on a site may be affected by the type and intensity of silvicultural practices performed on that site.

Although CWD is recognized as an important structural component of forest ecosystems (Harmon and others 1986), little is known about the changes in CWD loads that might be expected over long periods. Most studies in the Southeast have provided short-term "snapshots" of CWD at specific successional stages (MacMillan 1988, Smith and Boring 1990, Muller and Liu 1991). Research on CWD accumulation over time is very limited, with most of it being conducted in the Pacific Northwest (Spies and others 1988, Spies and Cline 1988, Harmon and Hua 1991). However, Hedman and others (1996) have documented loading patterns of CWD by species over a 300+-year chronosequence in Southern Appalachian streams.

Essentially no information is available for long-term CWD dynamics in terrestrial southeastern ecosystems. One study (Waldrop 1996) used the FORCAT gap model (Waldrop and others 1986) to simulate CWD dynamics in mixed-species forests on xeric and mesic sites in east Tennessee. CWD accumulation on the two sites remained relatively low for the first 30 years after clearcutting. From years 30 to 75, there was a rapid increase in CWD accumulation. CWD continued to accumulate after year 75, but at a slower rate, and it reached a maximum at age 90. For the remainder of the 200-year simulation period, decomposition exceeded accumulation and CWD loads gradually decreased. CWD loading on the mesic site decreased much more rapidly than on the xeric site.

The objective of this study was to document CWD accumulation in a chronosequence of selected stands in the piedmont of South Carolina and to examine the effects of stand age and site on CWD accumulation. The results were then used as a rough test to verify the accuracy of the FORCAT CWD model.

METHODS

The study used five replications of a 7*3 factorial arrangement of a completely random design. Factors included stand age (using seven age classes) and site (three site types). Age classes were suggested by the results of Spies and Cline (1988) and Waldrop (1996) and included 0 to 3, 4 to 7, 8 to 15, 16 to 25, 26 to 50, 51 to 100, and over 100 years. All sampled stands in the 100+ age class were between 100 and 125 years of age according to Clemson University records. However, some of these stands were uneven-aged and may have cohorts of trees as old as 175 years. Sites were identified by using the Landscape Ecosystem Classification (LEC) system for the upper piedmont as described by Jones (1991). This system identifies each site type by a combination of soil type, slope position, and aspect. Site types in the upper piedmont include xeric, subxeric, intermediate, submesic, and mesic. In this study, CWD accumulation was measured on subxeric, intermediate, and submesic site types. Differences of CWD accumulation between age classes and site types were detected by analysis of variance (alpha = 0.05) using Duncan's Multiple Range Test for mean separation.

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CWD accumulation was measured in selected stands on the Clemson Experimental Forest in Pickens, Oconee, and Anderson Counties of South Carolina. Sample stands were selected that have similar histories and with little or no management after stand regeneration. Each stand was regenerated (natural or artificial) to pure pine, although-as a result of no management activities-a significant hardwood component was expected in the older stands and on the better sites. Sample stands have no evidence of burning, thinning, herbicide application, or any management activity that would affect natural CWD loadings. Stands to be selected within the younger age classes (0 to 15 years) had no site preparation other than broadcast burning. Although site preparation burning reduces CWD loading to some degree, most of the consumed biomass is smaller than the 3-inch minimum diameter to be considered as CWD (Van Lear 1996). The method of site preparation was not a limitation for selecting sample stands older than 15 years. CWD decomposes rapidly in the Eastern United States and, therefore, CWD loading in stands older than 15 years should not be affected by site preparation technique (Waldrop 1996).

Sample stands for the subxeric, intermediate, and submesic site units were selected by estimating site units on the basis of slope position and aspect (Jones 1991). Once each stand was selected, a more accurate assessment of its site unit classification was made by using methods described by Jones (personal communication). This method uses three measurements to classify site types: soil rating, exposure rating, and terrain surface rating. The soil rating is affected by the depth to the B-horizon and the highest percent clay found in that horizon. The exposure rating is a result of the landform index average of eight clinometer readings from plot center to skylight, and the plot's aspect. Terrain surface rating measures the convexity or concavity of the plot. Measurements in each of these rating areas are taken on each plot, and values from 0 to 10 are assigned in each area with low values associated with mesic indicators and high values associated with xeric indicators. The three values are then summed to produce an environmental score which identifies the plot along an environmental gradient from mesic to xeric. All 105 sample plots were therefore evaluated and assigned a site unit from mesic to xeric.

One sample plot was randomly placed in each stand. Sample plots were square and 1/10 acre in size. Each side was 66 feet long. The corners and the plot center were marked with flags at each point. CWD accumulation in each sample plot was measured by the planar intersect method (Brown 1974). This technique was developed for conditions in the Western United States, but it was adapted for sites on the Clemson Experimental Forest by Sanders and Van Lear (1988). Five 50-foot-long planar transects were located within each l/l O-acre sample plot, one on each side and one along the diagonal between the fourth and second corners.

The diameter and decomposition stage (Maser and others 1979) of each piece of woody material that crossed the plane defined by the 50-foot transect was measured and recorded. The diameter of pieces of CWD larger than 1 .O inch was measured and recorded along the entire 50-foot transect. CWD that was less than 1 .0 inch in diameter was measured for only the first 15 feet of the 50-foot transect. It was assumed that all CWD lies in a horizontal plane. A correction factor was used for slopes over 10 percent (Brown 1974). These CWD data were converted to biomass to produce an estimate of total amount of CWD loading.

If any snags were present in the plot, their diameter, decay class, and species type (pine or hardwood) were recorded. The condition of each snag was determined by placing it into one of five different decay classes (Maser and others 1979), where Class I is a recently dead tree and Class V is a stump with little woody material remaining. These data were then entered into diameter regression equations obtained from Clark and others (1986) and Van Lear and others (1984) to produce biomass values.

RESULTS AND DISCUSSION

A total of 105 stands (seven age classes * three site types * five replications) was selected for this study. Because of the strict criteria placed on stand selection, only 82 of these sample stands were found on the Clemson Experimental Forest. The number of sample stands was evenly distributed across age classes and site units, except for the 4 to 7 age class which had only four plots (table 1). Because the sample size for the 4- to 7-year age class was too small, these plots were excluded from the study. Therefore, this study uses only 6 age classes and a total of 78 sample plots.

Figure 1 shows loadings of CWD for each site unit within each age class. CWD loading of the 1- to 3-year age class is very high, due to logging slash left from clearcutting the previous stand. This slash decomposes very rapidly and the loading decreases to a minimum somewhere between 8 and 25 years of age. CWD loading began to increase in 16- to 25-year-old stands, probably due to canopy closure and increased mortality. This increase in loading is seen throughout the final three age classes, reaching a peak in

Table l-Number of sample plots by age class and landscape ecosystem classification unit

	Landscape ecosystem classification unit		
Age class	Subxeric	Intermediate	Submesic
Years			
0 to 3	5	5	2
4 to 7	1	2	1
8 to 15	5	5	3
16 to 25	5	5	4
26 to 50	3	5	3
51 to 100	5	5	5
1 00+	4	4	5

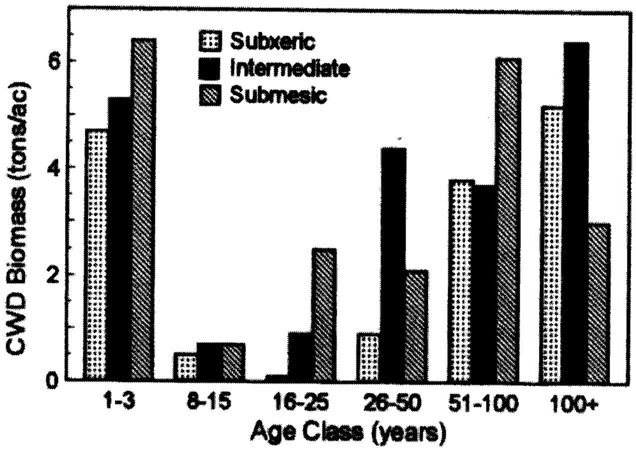

Figure l-coarse woody debris accumulation by age class and landscape ecosystem classification unit.

the 100+ age class. Analysis of variance showed that the loadings of the 8 to 15 and 16 to 25 age classes were Significantly lower (F= 5.05, P= 0.0006) than those of the other four age classes, suggesting that CWD loadings do vary with stand age.

Differences in CWD loadings among LEC units were compared across the age classes. We expected that submesic sites would have the highest CWD loading, due to higher site productivity, and that subxeric sites would have the lowest. This expected trend held true for the first three age classes, but not for all six. A possible explanation for this trend is the different rates of succession that occur among LEC units. Because these stands are unmanaged, species composition changes over time. This change could alter the physical characteristics of the stand, the amount of debris accumulating on the site, and the decomposition rates of the debris. CWD loading may be higher on the more productive sites immediately after disturbance. However, after these periodic heavy loads decompose, the relatively high inputs on productive sites may be balanced by faster decomposition rates.

One of the objectives of this study was to use these field observations as a validation for the FORCAT model. To make a more equal comparison between the two studies, only the subxeric site field observations were used because the FORCAT model simulated loadings on xeric sites. When these two graphs (fig. 2) were compared, there were both similarities and differences. The two curves had the same general pattern of CWD loading over time. Both had a U-shaped pattern for the first half of the time period and a bell-shaped curve for the remainder. The major difference in the two curves is that the magnitude of CWD loading in the FORCAT predictions was greater than that of the field observations. This could be due to the differences in the locations of the two study sites. Since the FORCAT simulations were based on conditions of the Cumberland Plateau of east Tennessee and the field observations were obtained from the piedmont of South Carolina, differences in soil, topography, elevation, and species composition may affect the amount of CWD accumulating on the sites.

The differences in the magnitude of CWD loading could also be caused by an overestimation of the biomass of postharvest slash made by the FORCAT model. To test this possibility, field measurements from a fuel loading study (Scholl 1996) on sites in South Carolina were substituted for those estimated by FORCAT. The result (fig. 3) was that loadings became very similar to the observed field measurements of this study for the first few years after harvest. Therefore, the FORCAT model seems to overestimate postharvest CWD loadings and the need for modifications is indicated.

When comparing the two curves as in figure 2, their minimums are somewhat different. The FORCAT model predicts the minimum about 10 years later than the actual field observations. This difference may indicate that the decomposition rates of the model were too low. If the decomposition rates were too low, then the debris would be on the site longer; therefore, shifting the curve to the right. To test for this assumption, the simulated decomposition rate was increased from 6 percent to 12 percent. With this adjustment, the two curves (fig. 3) become very similar throughout the simulation period. A 12 percent decomposition rate may be unrealistically high for subxeric

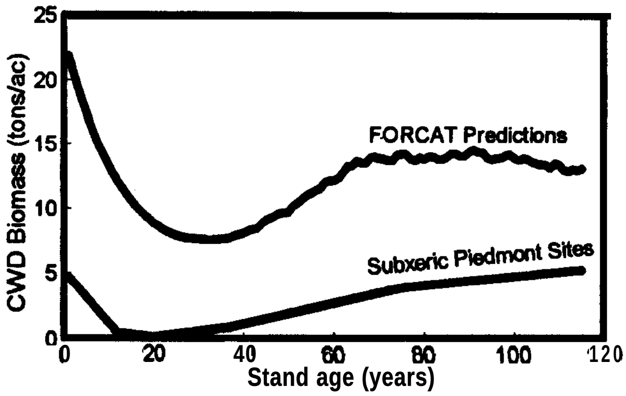

Figure 2-Comparison of coarse woody debris loadings between FORCAT predictions (using a 6 percent decomposition rate) and subxeric piedmont sites.

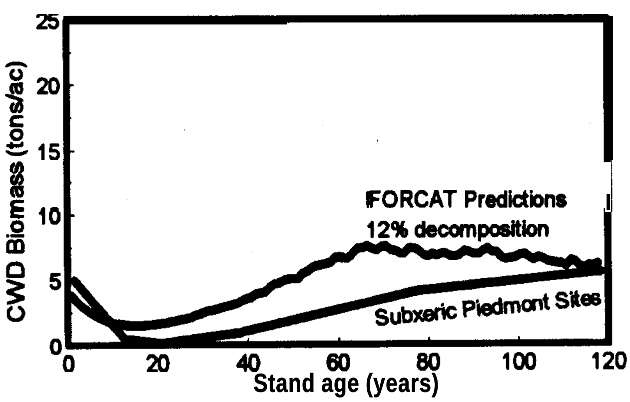

Figure 3—FORCAT loading predictions adjusted to a 12 percent decomposition rate and compared to subxeric piedmont sites.

sites, but its use here for preliminary model testing emphasizes the ability of FORCAT to predict the pattern of CWD loading.

A limitation to the FORCAT simulation study was the lack of accurate mortality and decomposition rates for each species and site type. Since the FORCAT model was tailored for a specific area and not verified by field observations, adjustments would have to be made so that it could be used for other areas. If a database of site characteristics and conditions could be established for a range of site units in different geographic areas, this model could then be adjusted to accurately represent CWD loadings on a wide array of sites.

CONCLUSIONS

For piedmont sites in South Carolina, observed field observations showed that the loading of CWD varied by age class with smaller amounts found in stands between ages 8 and 25. Consequently, these CWD loadings did not vary among LEC units. The pattern of CWD accumulation over time within the study stands was similar to a chronosequence reported by Spies and Cline (1988) and model predictions reported by Waldrop (1996).

When looking at the comparison between the FORCAT model projections and this study's observed field observations, it is seen that the FORCAT model successfully predicts the patterns of CWD accumulation over time, but it overpredicts the postharvest CWD levels after clearcutting. Also, FORCAT predicted the magnitude of CWD loading to be somewhat higher than the field observations. These predictions may have been too high because simulated decomposition rates were too low.

This study is only a preliminary validation for the FORCAT model. The model is not ready to be used immediately as a management tool, but this study does show that there is potential for its use in the future. The key to the model's success is that more research has to be conducted in the areas of decomposition rates and CWD inputs over time for various site types. If a database could be established that incorporates various site characteristics for different geographic areas, models such as FORCAT could be adjusted to compensate for these variables. This would then enable land managers to use these model projections to help determine how to alter the level or timing of their activities to enhance CWD loading on both a stand and a landscape scale.

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EFFECTS OF SITE, DIAMETER, AND SPECIES ON EARLY DECOMPOSITION OF WOODY DEBRIS

James W. McMinn[1]

Abstract-Bolts of loblolly pine (*Pinus taeda* L.) 1 meter long by 20 to 30 centimeters in diameter were placed in contact with the ground on xeric, mesic, and hydric upper coastal plain sites in late April and early May. In addition, bolts of loblolly pine 4 to 6 centimeters and 40 to 50 centimeters in diameter and southern red oak (*Quercus falcata* Michx.) 20 to 30 centimeters in diameter were placed on mesic sites only. There are three replicates of each site and enough bolts to sample periodically for several years. Bolts were destructively sampled at 0, 6, 12, and 18 months to determine wood density as an indicator of decomposition. For the period sampled there was no difference in decomposition among sites, but substantial differences by size in loblolly pine, and between loblolly pine and southern red oak.

INTRODUCTION

Woody debris, comprised of standing dead snags and forest floor material, was probably a significant component of native southern forest communities. Although largely undocumented and untested, there is evidence that woody debris may be a key resource in enhancing local diversity of forest flora and fauna through various mechanisms (Maser and others 1988, Spies and Franklin 1988, McMinn and Crossley 1996). One of the primary consequences of forest management is a reduction in the size, species composition, and quantity of material. The critical role of woody debris clearly depends upon the dynamics of recruitment and decomposition. While there is significant information on the generation of woody debris, there is little on the dynamics of decomposition and how to characterize the state of the material in terms of its functional contribution. The study objectives are to assess the role of primary environmental conditions (landscape position or site) and initial conditions (size and species) on decomposition rates. This paper reports preliminary results through the first 18 months following establishment.

METHODS

The study is being conducted on the U.S. Department of Energy's Savannah River Site in the upper coastal plain of South Carolina. Effects of landscape position are being tested on the basis of three general site moisture categories: xeric, mesic, and hydric. These correspond to the following landscape ecosystem classes after Jones (1991): "xeric to subxeric," "submesic to mesic," and "well-drained bottomland," respectively. Each site category is replicated three times.

Fresh-cut bolts of loblolly pine 1 meter (m) long by 20 to 30 centimeters (cm) in diameter were placed in contact with the ground on all sites in late April and early May of 1995. In addition, fresh-cut bolts of loblolly pine 4 to 6 cm and 40 to 50 cm in diameter, and southern red oak 20 to 30 cm in diameter were placed on mesic sites only. Sufficient bolts were prepared to remove three bolts for each comparison from each experimental unit twice a year for 5 years. At 6-month intervals, bolts are destructively sampled to determine density on the basis of oven-dry weight and water-displacement estimates of volume (Barber and Van Lear 1984). As the study progresses, relative density will be used as an indicator of decay state at each sampled point in time after Christensen (1984).

RESULTS AND DISCUSSION

After 18 months, there were negligible differences among the three sites in decomposition of loblolly pine (table 1). Wood density on all sites was about 90 percent of the initial density. Different temporal patterns and overall decomposition did occur by size of material (table 2). Small material exhibited no detectable decomposition the first 6 months and increasing rates thereafter. This is attributed to rapid drying initially and an early tendency for wood moisture to follow weather patterns up to a certain stage of colonization by decay organisms. Early decomposition of large material is attributed to lower initial drying rates, but after the large bolts dry decomposition rates tend to stabilize for a period. Medium size bolts exhibited a relatively constant rate of decomposition over the observation period. Overall, after 18 months small, medium, and large loblolly pine material was 72, 90, and 80 percent, respectively, of initial density. Southern red oak was denser than loblolly pine initially and exhibited a more rapid decomposition rate (table 3). After 18 months southern red oak specific gravity was 78 percent of the initial value compared to 90 percent for loblolly pine.

Table l-Specific gravity of loblolly pine wood initially and after 18 months on three site types

	Site		
Sample time	Xeric	Mesic	Hydric
Months	Specific gravity (cm)		
0	.473	.489	.482
18	.426	.438	.432

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Table 2—Wood specific gravity of three sizes of loblolly pine bolts through 18 months on mesic sites

	Bole diameter		
Sample time	4-6	20-30	40-50
Months	-------Specific gravity (cm)		
0	.476	.489	.525
6	.476	.471	.462
12	.447	.460	.459
18	.343	.438	.418

Table 3-Wood specific gravity of medium size loblolly pine and southern red oak bolts through 18 months on mesic sites

	Species	
Sample time	Loblolly pine	Southern red oak
Months	Specific gravity (cm)	
0	.489	.576
6	.471	.548
12	.460	.523
18	.438	.451

CONCLUSIONS

For the 18-month observation period there is no evidence that site moisture influences the rate of wood decomposition. There is, however, evidence that different decomposition rates can be expected by size of woody debris and by species.

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EFFECT OF SITE ON BACTERIAL POPULATIONS IN THE SAPWOOD OF COARSE WOODY DEBRIS

Emma G. Porter, Thomas A. Waldrop, Susan D. McElreath, and Frank H. Tainter'

Abstract-Coarse woody debris (CWD) is an important structural component of southeastern forest ecosystems, yet little is known about its dynamics in these systems. This project identified bacterial populations associated with CWD and their dynamics across landscape ecosystem classification (LEC) units. Bolts of red oak and loblolly pine were placed on plots at each of three hydric, mesic, and xeric sites at the Savannah River Station. After the controls were processed, samples were taken at four intervals over a 16-week period. Samples were ground within an anaerobe chamber using nonselective media. Aerobic and facultative anaerobic bacteria were identified using the Biolog system and the anaerobes were identified using the API 20A system. Major genera isolated were: Bacillus, *Buttiauxella, Cedecea, Enterobacter, Erwinia, Escherichia, Klebsiella, Pantoea, Pseudomonas, Serratia,* and *Xanthomonas*. The mean total isolates were determined by LEC units and sample intervals. Differences occurred between the sample intervals with total isolates of 6.67, 13.33, 10.17, and 9.50 at 3, 6, 10, and 16 weeks, respectively. No significant differences in the numbers of bacteria isolated were found between LEC units.

INTRODUCTION

Coarse woody debris (CWD) may influence a site for several decades in the form of snags, logs, chunks of wood, large branches, or coarse roots. Snags create habitat favorable for cavity nesting birds and animals. Logs in contact with ground may serve as habitat for plants, animals, fungi, and other microorganisms. The degradation process recycles nutrients in the soil and creates a fine-textured material which enhances soil nutrient and energy content, thus creating richer soils for tree growth (Harmon and others 1986, Maser and others 1988, Spies and Cline 1988). Mortality and breakage of living trees add CWD to an ecosystem while fire may remove or transform it (Van Lear 1996). Addition of CWD may occur over time as trees age and die or it may occur sporadically due to disturbances such as hurricanes, tornadoes, and insect and disease epidemics.

At a recent workshop on CWD in southern forests (McMinn and Crossley 1996), emphasis was placed on the need to manage CWD to preserve ecosystem function and health. A conclusion of the workshop was that a lack of knowledge of CWD dynamics is a major limitation to managers. With a better understanding of the CWD loads that could be expected at each stage of forest succession, managers may be able to increase loading during critical periods. Research on CWD dynamics in southern forests is limited to one study (Waldrop 1996) which used a forest-succession model to predict loading. That study suggested that CWD dynamics could be strongly influenced if inputs (limbfall or tree mortality) and outputs (decomposition) of CWD were varied between different types of forest sites. Abbott and Crossley (1982) suggested that decomposition rates vary by site quality.

Decomposition of CWD is a relatively slow process. Factors that control the rate of decay involve temperature, moisture, oxygen, carbon dioxide, and substrate quality (Harmon and others 1986). All of these factors affect the organisms that cause decomposition of CWD. Major microbial organisms that cause decomposition include fungi and bacteria. Insects grind woody components into smaller pieces but do not chemically decompose the wood. Microorganisms degrade cell contents of recently dead woody cells (sugars, starches, proteinaceous materials) and cell wall components (lignin, pectin, hemicellulose, and alpha-cellulose) (Harmon and others 1986). Another population of microorganisms develops to live on the degradation products of these dead microorganisms. Fungi have long been given credit for the majority of the decomposition of wood, but bacteria may also play an important role in the primary breakdown of some woody cell wall components and facilitate the entry of fungi to begin the major part of the decay of CWD.

This study examines the populations of bacteria that occur in CWD placed across three forest site types. These sites were defined using the landscape ecosystem classification (LEC) approach developed by Barnes and others (1982) for forests in Michigan and applied to the South Carolina upper coastal plain by Jones (1991).

This study was performed as part of a long-term, larger research project which examines the decomposition of CWD by site class and species across an environmental gradient at the Savannah River Station (SRS), Aiken, SC. The present study specifically determined the bacterial populations present during the decomposition of sapwood of CWD, by site class and species, within the first 16 weeks following placement of freshly cut wood bolts on the sites.

METHODS

Preparation of Bolts

Boles of loblolly pine (*Pinus taeda* L.) and red oak (*Quercus* spp.) between 20 and 30 centimeters (cm) in

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diameter were cut into half-meter-long bolts. The loblolly pine was collected from the Savannah River Station (Barnwell County, SC) and placed on the study plots within 2 days after cutting; the red oak was collected from the Clemson Experimental Forest (Pickens County, SC) and transported to the Savannah River Station the same day and placed on the study plots the next day.

Location of Study Sites

The USDA Forest Service provided the study plots which were located on the Savannah River Station. They were part of a larger study by McMinn (1997) on the decomposition of CWD by site class and species across a landscape environmental gradient. LEC units were chosen based on their average soil moisture regime and associated understory flora (Jones and others 1984). Three sites of each were selected and included: xeric, mesic, and hydric. The xeric sites were located in pine plantations with little or no undergrowth. The mesic sites were also located in pine plantations; however, there was more undergrowth and debris present on these sites. The hydric sites were located in mixed overstory species stands with dense understories. These latter sites were also located near streams and the soil was very moist at all times. These sites were classified and used in studies on CWD decomposition as affected by microarthropods (Bailey 1994) and fungi (Hare 1992). On each LEC unit, a square plot was established and 11 sample bolts of each species were placed on each plot.

Sample Collection

The sample bolts were collected at 3, 6, 9, and 16 weeks after placement. As a control, a separate bolt was processed immediately after the trees were felled. A randomized system for bolt selection was created for the collection of two bolts of each species from each site during the different sampling periods. The bolts were collected and taken to Clemson University for sampling, breakdown, and analysis. Overall, 162 bolts of wood were sampled.

For bacterial isolations, only the face of each bolt in contact with the ground was sampled. After washing the debarked area with ethanol, a sterile increment borer was used to extract approximately 4 to 5 grams (g) of sapwood. The cores were placed in sterilized, preweighed, screw cap tubes that were continuously filled with nitrogen. The tubes were then weighed to obtain the weight of the core sample. After all cores were collected, they were transferred to an anaerobe chamber.

Culture Preparation

Each core was ground for 5 minutes in 20 milliliters (mL) Of anaerobic LPBB (Zeikus and others 1979) using a Sorvall Cmni Mixer. With a sterile syringe and needle, 1 mL of this ground material was used to inoculate 9 mL of an anaerobic THAM broth tube (Schink and others 1981). Then, successive transfers were made to dilute the original inoculum. This was done in triplicate. Then, 10 microliters (μL) and 100 μL of the inoculum were used to inoculate anaerobically conditioned THAM agar culture plates. The inoculum was removed from the anaerobic chamber and used to inoculate aerobic dilution tubes of THAM broth and THAM agar plates. After all the samples were processed, the dilution tubes were incubated for 7 days at 30 °C. The anaerobic plates, which were placed in a GasPak jar, and the aerobic plates were incubated for 24 hours (hr) at 30 °C.

At 24 hrs the THAM agar plates were viewed for isolate selection which were then streaked to fresh THAM agar plates in order to obtain pure cultures. At 7 days the dilution tubes were observed for growth and the most probable number (MPN) was calculated. The last positive tube was then streaked for isolation to THAM agar plates.

Identification of Isolates

The aerobic isolates from the MPN tubes were identified using the Biolog Microstation System (Biolog Inc., Hayward, CA, 1993). Biolog is capable of identifying Gram negative, Gram positive, lactic acid bacteria, and yeasts. All isolates were grown and prepared as per Biolog instructions and incubated in microplates for 4 and 24 hours at 30 °C before readings were taken. The anaerobic isolates were identified using the Analytical Profile Index (API) 20A system (BioMerieux Vitek, 1991) which is based on 21 different biochemical reactions. All isolates were grown and prepared as per API instructions and incubated in ampules of API basal medium.

Statistical Analysis

Because several dilutions were missed on the MPN, the bacterial populations were estimated and averaged over LEC unit and sample interval and over tree species and sample interval. No statistical analysis could be performed on these results. An analysis of variance was performed to compare the number of isolates by LEC unit and tree species. Mean separation was by Duncan's Multiple Range Test. Differences were significant at $\partial = 0.05$.

RESULTS AND DISCUSSION

Aerobic Isolations

All bacteria that were isolated under aerobic conditions and taken from the last positive tube in a serial dilution are summarized in table 1. Overall, 272 organisms were isolated aerobically from the dilution tubes. Of these, 69 were omitted from the identification process for various reasons: 28 did not grow on the medium required for identification, 26 were yeasts, 1 was a fungus, 1 was fastidious, 1 was an actinomycete, and 11 were duplicates. Therefore, 203 isolates were obtained for identification.

Anaerobic Isolations

Only 67 isolates were obtained from the anaerobic dilution tubes, These isolates were also taken from the last positive tube of the dilution series. No strict anaerobes were isolated, only facultative anaerobes similar in genus to the aerobic isolates (table 2). Unlike the aerobic isolates, no yeasts were found. However, *Enterobacter* consisted Of 31.7 percent of the anaerobic isolates, with *Erwinia* at 20.6 percent and *Serratia* at 17.5 percent. The only strict anaerobes found in the bolts were those taken from anaerobically conditioned plates of THAM inoculated with the original inoculum of ground core sample in LPBB under

Table I-Totals by genus of all aerobic isolates and percentages overall of the 257 isolates and the 203 isolates identified by Biolog

Group	Total	Overall	Biolog
		Percent	
Enterobacter spp.	47	18.3	23.2
Serratia spp.	21	8.2	10.3
Xanthomonas spp.	16	6.2	7.9
Klebsiella spp.	15	5.8	7.4
Etwinia spp.	15	5.8	7.4
Cedecea spp.	13	5.1	6.4
Pantoea spp.	13	5.1	6.4
Pseudomonas spp.	11	4.3	5.4
Buttiauxella spp.	8	3.1	3.9
Bacillus spp.	7	2.7	3.4
Escherichia spp.	7	2.7	3.4
Curtobacterium spp.	4	1.6	2.0
Other	8	3.1	3.9
Unidentified	18	7.0	8.9
Yeast	26	10.1	n/a
THAM	28	10.9	n/a

Table 2-Totals by genus of the anaerobic isolates and percentages overall of 63 isolates

Group	Total isolates	Percentage
Enterobacter	20	31.7
Etwinia	13	20.6
Serra tia	11	17.5
Buttiauxella	3	4.8
Pantoea	3	4.8
Bacillus	2	3.2
Clavibacter	2	3.2
Cardiobacterium	1	1.6
Cedecea	1	1.6
Escherichia	1	1.6
N/I	6	9.5

N/I = Biolog could not identify.

anaerobic conditions (table 3). Only 13 anaerobes were isolated and it could not be determined if these bacteria were present in high numbers in the wood. These bacteria were identified using API 20A and only 4 of the 13 could not be matched to the database.

Differences Between LEC Units

To determine if site type affected the bacterial populations, first the total number of organisms was calculated. From serial dilution tubes, the MPN per gram of core sample was calculated for both the aerobic and anaerobic dilutions. Since many of the dilutions were missed, the estimation of bacterial populations should be higher. Using the MPN/g values, calculated averages by sample period and site type were plotted logarithmically (fig. 1). On all sites, the MPN increased dramatically between week 6 and week 10. However, this pattern and the actual MPN values were nearly identical among LEC units. Analysis of variance showed no differences between the LEC units in total isolates (table 4). The only significant difference occurred between the control and the rest of the LEC units with means of 16.5 for the control, 11 .O for mesic, 9.5 for hydric, and 9.3 for xeric. When comparing the tree species, there was no significant difference between the mean total number of isolates and LEC units. For the xeric and mesic sites the p-values are $p>0.7018$ and $p>0.8312$,

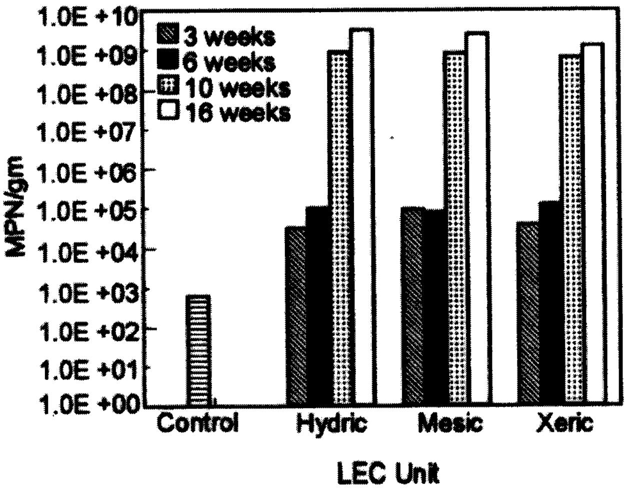

Figure I-Averages of the most probable number of bacteria per gram of cores sampled from sapwooci ot red oak and loblolly pine over sample interval and LEC unit.

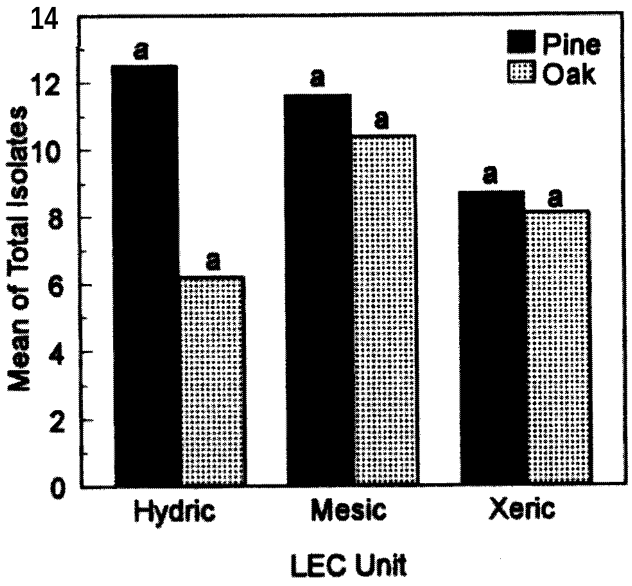

Figure 2-Means of total isolates from the sapwood of red oak and loblolly pine over LEC units. Means within a pair of bars with the same letter are not significantly different at $\partial=0.05$.

Tablo 3—Bacteria isolated anaerobically from plated samples of red oak and loblolly pine using API 20

Isolate number	Tree number	Tree species	Sample group	Site type	Bacterial organism
AA1	o-2	Oak	0	Control	*Bacteroides oralis*
AA2	o-4	Oak	0	Control	*Bacteroides oralis*
AA3	8148	Pine	1	Mesic 2	*Bifidobacillus adolescentis*
AA4	815B	Pine	1	Mesic 2	N/I
AA5	833	Pine	1	Mesic 3	*Bifidobacillus adolescentis*
AA6	975	Oak	2	Hydric 1	*Streptococcus intermedius*
AA7	867	Pine	3	Hydric 1	N/I
AA8	956A	Oak	3	Xeric 3	*Bacteroides oralis*
AA9	873	Pine	4	Hydric 1	*Clostridium beijerinckii*
AA10	895	Pine	4	Hydric 3	N/I
AA11	898	Pine	4	Hydric 3	*Actinomyces israelii*
AA12	813	Pine	4	Mesic 2	N/I
AA13	825	Pine	4	Mesic 3	*Clostridium beijerinckii*

N/I = API 20A could not identify.

Table 4-Mean total number of isolates by LEC unit

LEC unit	Number	Mean
Control	2	16.500 a
Mesic	8	11.000 b
Hydric	8	9.500 b
Xeric	8	9.250 b

Note: Means with the same letter are not significantly different at ∂=0.05.

respectively. Over the hydric sites the p-value is $p>0.0728$, indicating that there is, likewise, not a difference. However, when comparing the mean values over LEC unit the oak is nearly double that of the pine (fig. 2).

If the isolates are grouped by genus, *Erwinia* and *Xanthomonas* are prevalent in the controls (fig. 3). However, *Enterobacter* was the most abundant in all the LEC units, with the largest number isolated from the mesic site. *Serratia* was also prevalent throughout all LEC units, again with most isolates found on mesic sites. This same trend also pertained to the yeasts that were isolated.

CONCLUSIONS

Previous studies suggested that decomposition varies by site quality, possibly due to different populations or numbers of microorganisms (Abbott and Crossley 1982, Bailey 1994, Hare 1994). In this study, however, bacterial populations were not found to vary, suggesting that they play similar roles in CWD decomposition on hydric, mesic, and xeric LEC units. These results may suggest that bacteria play a minor role in CWD decomposition or that they are highly adaptable to different forested environments. This study identified a large number of facultative anaerobic bacteria from the sapwood of loblolly pine and red oak and created an extensive database of bacteria that inhabit decaying wood of these two tree species.

ACKNOWLEDGMENT

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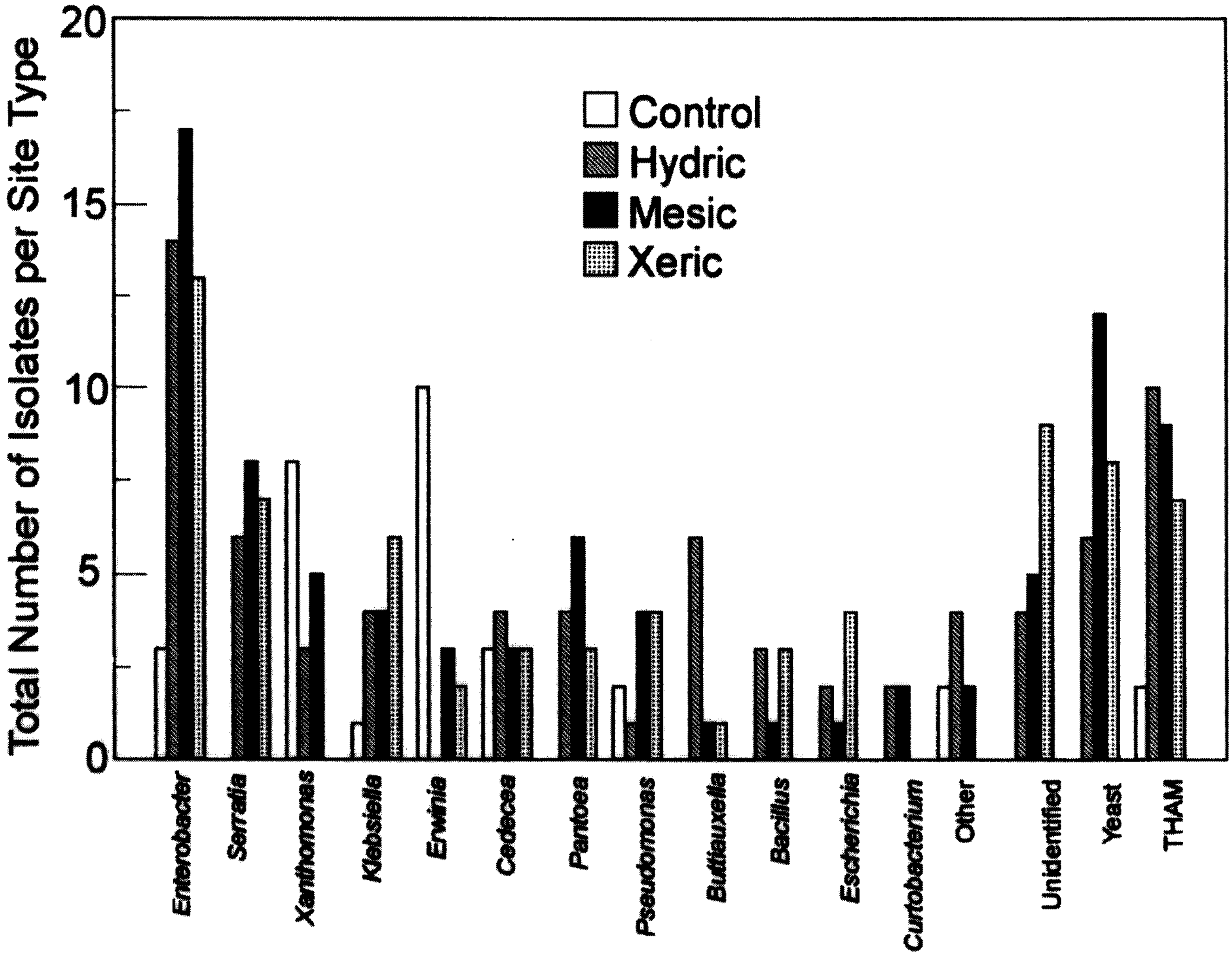

Figure 3-Total number of isolates per LEC unit by genus from the sapwood of red oak and loblolly pine over 16 weeks.

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IMPACT OF ECOSYSTEM MANAGEMENT ON STANDS IN THE PIEDMONT

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Abstract-An ecosystem approach to managing national forests is being used to conserve biodiversity, improve the balance among forest values, and achieve sustainable conditions. This paper reports on a study established to identify the implications of ecosystem management strategies on natural pine stands in the Piedmont. The impact of partial cuts, group selections, seed tree cuts, and no human disturbance on species composition, wood properties, and tree quality of pine stands in the piedmont is described.

INTRODUCTION

In the early 1990's an ecosystem approach to managing national forests was introduced to conserve biodiversity, improve the balance among forest values, and achieve sustainable, healthy conditions while retaining the esthetic, historic, and spiritual qualities of the land. Under ecosystem management, pine and pine/hardwood stands on national forests in the piedmont are being converted from even-aged monocultures to uneven-aged or two-aged pine and mixed species stands.

This paper describes a study established to monitor the effects of ecosystem management strategies on species composition, tree growth, wood properties, and tree quality of natural pine stands on national forests in the Piedmont. The paper also presents initial results on species composition, wood properties, and tree quality.

METHODS

A series of permanent measurement plots have been established in loblolly (*Pinus taeda* L.) and shortleaf pine (*P. Echinata* Mill.) stands on the Oconee, Sumter, and Uwharrie National Forests to monitor the response of these stands to a range of ecosystem management practices. The management practices included: (1) partial cuts, (2) group selection cuts, (3) seed tree cuts, and (4) reserve areas. Included in the partial cuts are single tree selection, salvage cuts, stand improvement cuts, and shelterwood cuts. Reserve areas are stands in which no human disturbance is planned. Each monitoring plot is a cluster group (CG) consisting of three 1/5-acre circular plots and is randomly located within each stand selected for monitoring. Cluster groups were inventoried at establishment, then prior to and following harvest treatments. Cluster groups will also be inventoried every 5 years and after any natural disturbances. Cluster groups were established in stands representative of five 20-year age classes (1, 20, 40, 60, and 80 years) and two broad site-index (SI) classes (SI <80 and SI ≥80) for each management practice. Table 1 shows the distribution of the 49 cluster groups established in the piedmont by management practice, age class, and SI class.

On each 1/5-acre plot, all trees ≥5.0 inches in diameter at breast height (d.b.h.) were located by azimuth and distance from plot center. Species, d.b.h., total height, merchantable height, crown class, tree grade, and defect indicators were recorded for each live and dead tree. Five 1/300-acre microplots were located 30 feet from plot center at 72" intervals within each 1/5-acre plot to tally seedlings and saplings. Seedlings (trees up to 1.0 d.b.h. inches) were tallied by species count. Saplings (trees 1.0 to 4.9 inches d.b.h.) were tallied by species, d.b.h., and total height.

Table 1-Number of cluster groups[a] established in pine and pine/hardwood stands in the piedmont by management practice, site index class, and age class

Age class	Partial cut SI <80	Partial cut SI ≥80	Group selection SI <80	Group selection SI ≥80	Seed tree SI <80	Seed tree SI ≥80	Reserve SI <80	Reserve SI ≥80
Years								
20	2	3		2				
40	2	2	2		1	1		
60	5	5		2	2	3	1	1
80+	3	2		2	3	3	1	1

[a]Cluster group = three 1/5 acre-plots.

Softwoods 5.0 to 8.9 inches d.b.h. and hardwoods 5.0 to 10.9 inches d.b.h. were classified as pole timber. Softwoods ≥9.0- and hardwoods ≥11.0-inches d.b.h. were classified as sawtimber if they contained one or more 16-foot saw log. Softwood sawtimber trees were placed into one of three tree grades based on a pine tree grading system for natural pine developed by Clark and McAlister (1997) and hardwood sawtimber trees were graded using USDA Forest Service hardwood tree grades (Hanks 1976).

Increment cores [5 millimeter (mm) in diameter] for wood properties analysis were extracted from bark to pith at 4.5 feet aboveground from four trees in each 1/5-acre plot. The largest diameter pine at 90" intervals in each plot was selected for boring. Increment cores were analyzed to

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determine tree age, earlywood and latewood annual radial growth, and amount of juvenile wood, sapwood, and heartwood at breast height.

Species diversity and evenness were calculated using Shannon's indexes of diversity and evenness based on species stem counts. (Magurran 1988).

RESULTS

Species Composition

Table 2 shows the average number of stems per acre, species richness, diversity, and evenness by management practice for the natural pine stands sampled. Average number of stems per acre for seedlings, saplings, and pole and sawtimber was highest in the reserve stands and lowest in the seed tree cuts. Species richness and diversity for sapling and pole and sawtimber trees were also highest in the reserve stands and lowest in the seed tree cuts, as would be expected. In the natural stands, the three most abundant species in the seedling class were red maple (*Acer rubrum* L.) (18 percent), loblolly pine (15 percent), and sweetgum (*Liquidambar styraciflua* L.) (13 percent). In the sapling class, the most abundant species were sweetgum (25 percent), loblolly pine (18 percent), and dogwood (*Cornus florida* L.) (11 percent). The most abundant species in the pole and sawtimber class were loblolly pine (57 percent), sweetgum (13 percent), and shortleaf pine (6 percent).

Number of stems per acre in the seedling class in the younger natural pine stands was lower than that found in older stands (table 3). This occurs because the young pine stands have a closed canopy and little sunlight reaches the forest floor. However, when these young stands are thinned, the crown canopy is opened and the number of stems in the seedling class increases significantly. Species diversity and evenness for seedlings, however, decreases in the older stands (table 3). Species diversity and evenness for pole and sawtimber trees was lowest in the young stands and highest in the oldest stands that have been thinned several times.

Wood Properties

The increment cores were analyzed to determine various wood properties. On national forests managing for red-cockaded woodpecker (*Picoides boreales*) (RCW) habitat the effect of management practice, site productivity, and tree characteristics on heartwood formation are important. One result of this long-term study will be increased knowledge on how and where forest managers can expect to find increased heartwood for RCW cavity habitat. The

Table 2-Average stems per acre, species richness, diversity, and evenness for seedlings, saplings, and pole and sawtimber by management practice for natural stands in the piedmont

	Management practice			
Characteristic	Partial cut[a]	Group selection[a]	Seed tree	Reserve
	Number			
Stands sampled	28	2	7	4
Seedlings (trees <1.0 in. d.b.h.)				
Stems/acre	14,992	12,210	10,674	28,960
Richness	19	16	18	20
Diversity	1.9	1.8	2.0	1.6
Evenness	0.7	0.7	0.7	0.6
Saplings (trees 1.0-4.9 in. d.b.h.)				
Stems/acre	446	510	346	630
Richness	5	4	3	7
Diversity	1.2	0.7	0.6	1.4
Evenness	0.8	0.6	0.5	0.7
Pole and sawtimber (trees ≥5 in. d.b.h.)				
Stems/acre	153	115	31	190
Richness	8	6	4	10
Diversity	1.2	1.1	0.8	1.4
Evenness	0.8	0.6	0.5	0.6

[a] Stand conditions before harvest.

Table !&Average stand characteristics and species richness, diversity, and evenness for seedlings, saplings, and pole and sawtimber by stand-age class for partial cut and group selection natural pine stands

Characteristic	Stand-age class 20 years	40 years	60 years	80 years
	----Number----			
Stands sampled	2	4	16	8
Seedlings				
(trees <1 .O in. d.b.h.)				
Stems/acre	5,060	13,295	16,716	14,180
Richness	17	19	20	19
Diversity	2.3	1.9	2.0	1.8
Evenness	0.8	0.7	0.7	0.6
Sapling				
(trees 1 .O-4.9 in. d.b.h.)				
Stems/acre	550	725	310	570
Richness	4	7	4	7
Diversity	1.2	1.5	1.0	1.4
Evenness	0.9	0.8	0.8	0.8
Pole and sawtimber				
(trees ≥5 in. d.b.h.)				
Stems/acre	287	174	122	161
Basal area/acre (ft^2)	77	90	97	113
Richness	5	8	8	10
Diversity	0.2	1.2	1.3	1.5
Evenness	0.1	0.6	0.6	0.7

RCW requires a minimum of 5 inches of heartwood at cavity height to envelop the cavity.

A regression equation developed by Clark (1994) was used to estimate heartwood diameter at 22 feet based on d.b.h., tree age, and heartwood diameter at 4.5 feet. Initial study results confirm that the diameter of heartwood at cavity height (22 feet) increases not only with tree age but with site productivity. The proportion of trees bored that had 25 inches of heartwood at 22 feet was higher for pines growing in stands with SI ≥80. This indicates that managers should concentrate RCW recruitment activities not only in older stands but also on high-productivity sites.

Tree Quality

The impact of harvest operations on volume of trees cut and removed, cut and not removed, accidentally downed, and the health of the residual stand are important. After monitoring plots were established in the mature pine stands, seven of the stands were harvested using some type of partial cut, two harvested using group selection, and four harvested using seed tree cuts. The monitoring plots were remeasured following tree-length harvesting. In the partial cut stands only 1 percent of the basal area marked was cut and not harvested, 1 percent was pushed down during harvest, 65 percent was left standing healthy, but 7 percent was left standing with logging damage (table 4). In the group selection cuts, 5 percent of the initial stand

Table 4—Proportion of initial stocking[a] harvested[b], cut and not removed, down during harvest, residual standing healthy, and standing with logging damage by type of management practice for natural pine stands in piedmont

Stocking before harvest	Trees harvested	Trees cut not removed	Trees down in harvest	Residual standing healthy	Standing logging damage
BA/A ft[b]	---- Percent ----				
Partial cut (N=7)					
105	26	1	1	65	7
Group selection (N=2)					
98	90	5	2	3	0
Seed tree (N=4)					
109	67	0	3	25	5

'Trees ≥ 5 in. d.b.h.
[b] Tree length logging.

basal area marked was cut but not removed. This increase in volume of trees cut and not removed was because the feller-buncher felled all the trees in the 1 1/2-acre openings into a crisscross pile and then the skidder removed the felled trees. When operating in these small openings, it appears best to cut and skid a portion of the stand at a time.

In the stands marked for seed tree cuts, all of the marked trees were removed, 3 percent of the original basal area was pushed over during the harvest, and 25 percent of the initial basal area was left standing and healthy. However, 5 percent of the initial basal area left standing contained logging damage.

SUMMARY

This paper describes a study established to monitor the effects of ecosystem management practices on species composition, wood properties, and tree quality of natural loblolly/shortleaf pine stands in the Piedmont. Variation in species diversity, evenness, and richness by stand-age class and management practice are described. The effect of tree age and site productivity on heartwood formation for RCW cavity habitat is discussed. The impact for various management practices and tree length logging on proportion of basal area cut and not harvested, pushed over during harvest, and left standing with logging damage is discussed.

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DESCRIPTION OF A MONTANE LONGLEAF PINE COMMUNITY ON FORT McCLELLAN, ALABAMA

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Abstract-A montane longleaf pine (*Pinus palustris* Mill.) community on the Main Post of Fort McClellan, AL, was described and characterized. Choccolocco Mountain and its foothills contain relatively undisturbed disjunct longleaf pine populations, shaped by past logging episodes and sporadic presence of fire. Canopy and tree regeneration layers were sampled and overstory pines were aged. Aging indicated historic stand dominance by longleaf pine. Fire suppression and selective logging occurred about 80 years ago. This allowed other pine species to establish. Remnant longleaf pine maintained a seed source, resulting in a longleaf pine-dominated stand with establishment of loblolly (*P. taeda* L.), shortleaf (*P. echinata* Mill.), and Virginia pines (*P. virginiana* Mill.) and scattered large oaks and hickories. Infrequent fires allowed a vigorous hardwood component to establish in the understory. Recruitment of longleaf pine regeneration into the canopy apparently has decreased due to absence of growing season burns.

The Fort McClellan longleaf pine community represented an excellent but deteriorating remnant of the montane longleaf pine ecosystem. Timely implementation of growing season burns should provide for maintenance and restoration of a longleaf pine-dominated stand with scattered hardwoods and other pine species.

INTRODUCTION

Longleaf pine (*Pinus palustris* Mill.) forests have declined from 37.2 million hectares (ha) (ca. 1600 AD) to less than 1.3 million ha today (Landers and others 1995). Historically these communities were maintained by natural and anthropogenic fire. Fire suppression and harvesting, with conversion to agriculture or other tree species [e.g., loblolly pine (*P. taeda* L.)], have led to the widespread decline of this forest type. Currently, this type is considered threatened or endangered and restoration efforts have been initiated (Bridges and Orzell 1989, Landers and others 1995, Means and Grow 1985).

Longleaf pine ecosystems are found throughout the Coastal Plain and Piedmont, and extend into the Ridge and Valley and Mountain Provinces of the Southeastern United States (Boyer 1990). Freezing temperatures and heavy clay soils limit northern extent. Mortality can occur in adult trees that are damaged by ice storms (Lipps 1966), and fall-germinated seedlings can be killed by frost-heaving on heavier soils (Croker 1979). Longleaf pine inhabits the highest elevations (ca. 600 meters) of its range in the Blue Ridge Physiographic region (fig. 1).

Little information exists on the unique montane longleaf pine type, which occurs in the Blue Ridge and Ridge and Valley Physiographic regions of northwest Georgia and northeast Alabama. Longleaf pine occurs on ridgetops and south/southwest slopes in these Appalachian disjunct populations. It occurs in single-species or mixed stands with shortleaf (*P. echinata* Mill.) or Virginia pine (*P. virginiana* Mill.) and blackjack (*Quercus marilandica* Muenchh.) and chestnut oak (Q. *prinus* L.) (Harper 1905, Mohr 1901). Presence is related to fire and edaphic conditions.

Range limits of many Appalachian, Coastal Plain, and Piedmont plants interface in this region, resulting in unique biotic assemblages (Jones 1974, Lipps and DeSelm 1969, Mohr 1901). Plants more aligned with Appalachian or more northern regions include scarlet (Q. *coccinea* Muenchh.) and chestnut oak (Howell 1921), mountain blueberry (*Vaccinium vacillans* Torrey) (Clark 1971), and Virginia pine (Harper 1928). Coastal elements include poison oak (*Rhus toxicodendron* L.), foxglove [*Aureolaria pectinata* (Nuttall) Pennell], sensitive briar [*Schrankia microphylla* (Solander ex Smith.) McBride], and turkey oak (*Q. laevis* Walter) (Anon 1994). These species reach their regional limits by adaptations that allow survival in a more fire-prone habitat, centered around a longleaf pine-dominated overstory.

A study was initiated in summer 1994 to examine the montane longleaf pine community of Fort McClellan, AL (Maceina, 1997). Previous overview surveys indicated that this area contained an excellent but deteriorating remnant of this forest type.

STUDY OBJECTIVES

(1) Research the literature regarding the history of montane longleaf pine in the Blue Ridge and Ridge and Valley Physiographic Provinces of northwest Georgia and northeast Alabama.

(2) Determine the status of the montane longleaf pine ecosystem in Alabama, with emphasis on the community of Fort McClellan Main Post (MP), located in central northeast Alabama.

(3) Describe a montane longleaf pine community on MP. Aspects were: overstory tree composition-species and diameter at breast height (d.b.h.); overstory Pine age structure; and regeneration tree species composition.

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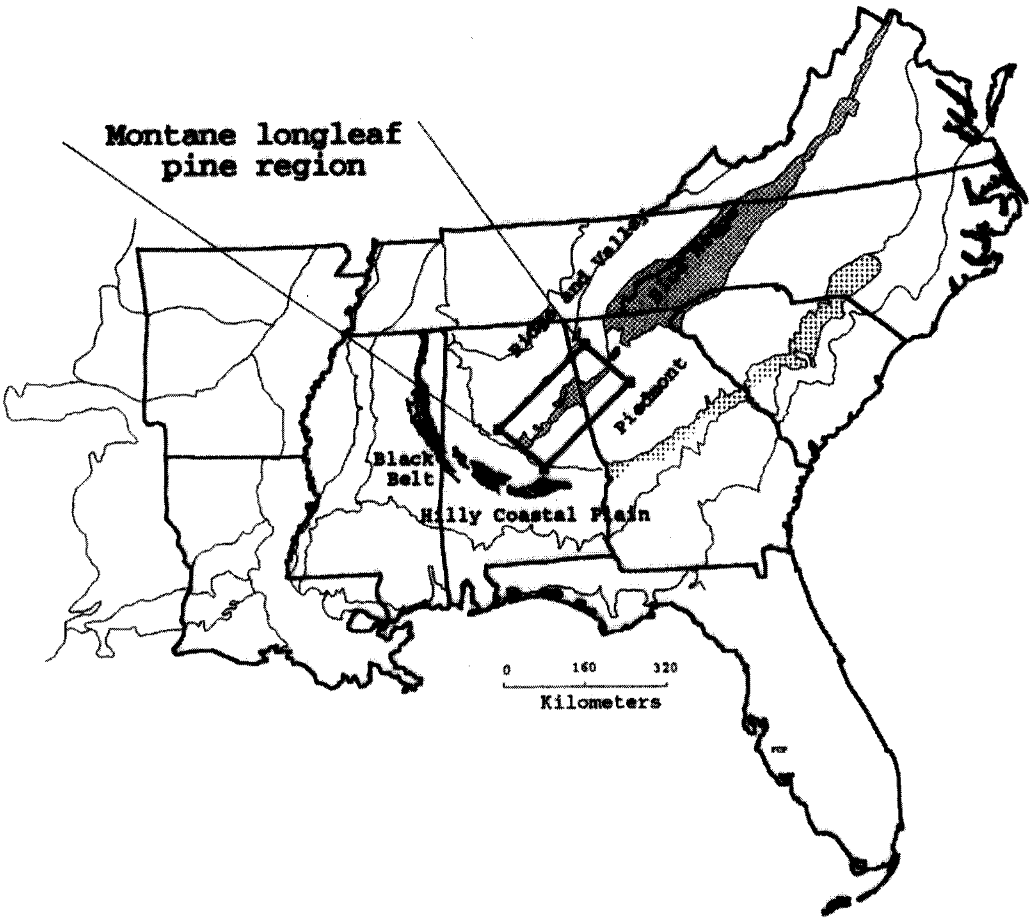

Figure l-Location of Blue Ridge disjuncts in northwest Georgia and northeast Alabama. Fort McClellan is in central northeast Alabama. (Adapted from Miller and Robinson 1994.)

HISTORICAL BACKGROUND OF MONTANE LONGLEAF PINE

History of Georgia Montane Longleaf Pine

Occurrence of longleaf pine in Georgia's highlands was documented by early botanists. They noted that harvesting activities were initiated prior to their observations, but that ridgetop areas were not yet exploited.

> "Some of the long-leaf pines there (Bartow County, GA) are over 2 feet in diameter, and but for their inaccessibility they would probably have been cut long ago." (Harper 1905, p. 57).

The demise of the Georgia montane longleaf pine community was tied to European settlement beginning in the 1830's (Wharton 1978). Timber harvesting took most of the longleaf pine. Fire suppression or annual burning eliminated the conditions necessary for successful regeneration.

> "Notwithstanding the abundance of long-leaf pine in the region under consideration (northwest Georgia), it seems to be very little used for lumber, and not at all for turpentine. A part of the charcoal which is made in considerable quantities in Bar-tow, Floyd, and Polk counties to supply iron furnaces in the vicinity doubtless comes from this species, but in Haralson and Carroll counties the only evidence I saw of its being used in any way was a few logs at a small sawmill in Bremen. It is probably not abundant enough in these highlands to make its exploitation profitable at present in competition with the much greater supply in the coastal plain. A great deal of it was doubtless destroved in clearing the land for agricultural purposes before-its timber was as much in demand as it is-now." (Harper 1905, p. 59-60).

> "The southern slopes (of Floyd County, GA, the inland and upland range limit of longleaf pine) are covered with the remains of great forests of this valuable timber, interspersed with various hardwood trees and with shortleaf pines. They have been repeatedly cut for lumber and burned over by >ground fires= started in spring by farmers to provide a free range for their cattle, but the longleafs continue to reproduce themselves with a pertinacity which, if not too diligently thwarted by the blundering incompetence of county officials and the shortsighted greed of ignorant timber cutters, will in the course of a generation or two repopulate the southern mountain slopes with a new forest growth sprung from the old stock." (Andrews 1917, p. 498).

Today, relict trees are found throughout the Georgia montane longleaf pine region, remnants of a longleaf pine forest that was replaced by less fire-tolerant pine and hardwood species. Establishment of these trees changed the forest composition to a mixed pine-hardwood type.

History of Alabama Montane Longleaf Pine

In Alabama, the Blue Ridge Physiographic Province is surrounded by the Ridge and Valley and Piedmont Physiographic Provinces (fig. 1). These areas had Vigorous longleaf pine forests that extended to steep ridges and slopes. Periodic fires maintained the species dominance.

> "Cur long-leaf pine forests must have been burned originally at least 5 years out of 10, but very likely at irregular intervals. A fire every year on every acre might make it very difficult for any seedlings to survive, but a fire-free period for 2 or 3 years once or twice in a century might be sufficient to give a new crop of trees a start." (Harper 1943, p. 34).

Lower elevation areas were settled, and lands cleared for farming and grazing. Alabama montane longleaf pine stands were not exploited due to their remoteness and inaccessibility on steep slopes (Harlin and others 1961, Harper 1913).

> "At least 90 percent of the Blue Ridge region has never been cleared, the ground being too steep and rocky to offer much attraction to the farmer." (Harper 1913, p. 66).

Contrasted with the loss of much of Georgia's montane longleaf pine, Alabama still contains representative stands of the montane longleaf pine ecosystem. Remnant montane longleaf pine communities in Alabama approach elevational limits of the type, and occur on Shoal Creek and Talladega Ranger Districts of Talladega National Forest (TNF), Cheaha State Park, and Choccolocco Mountain. Shoal Creek is 10 kilometers east, Choccolocco Mountain forms the eastern part of MP, and Cheaha State Park and Talladega Ranger District are south of MP.

STATUS OF ALABAMA MONTANE LONGLEAF PINE

Each of the three main Alabama regions of montane longleaf pine have different management histories and land use plans. TNF ranger districts had a history of timber harvest and species type conversion. Cheaha State Park received fire protection, while MP was subjected to frequent fires.

Cheaha State Park was spared of timber harvesting activities, but fire suppression was initiated with park creation in 1927. Present ridge species are mostly Virginia pine. Upper slopes had longleaf pine pockets, but focus to maintain these stands is weak. Most prescribed fires have been fuel reduction burns in Virginia pine stands.

The montane longleaf pine forest on Shoal Creek Ranger District is now managed for red-cockaded woodpecker (RCW) (*Picoides* borealis) habitat. In the 1960's, restoration of logged ridges and slopes to longleaf pine began. Hardwoods, except flowering dogwood and persimmon, were removed and a fire program was initiated. Intense hardwood control and summer fires produced open, two-layered stands with rich herbaceous growth. Transition from ridge longleaf pine to bottom hardwood was defined by hydric conditions that limited fire extent downslope, allowing development of a dynamic ecotone between pines and hardwoods.

The Talladega Ranger District had logged much of its Original longleaf pine, and replanted with loblolly pine. In the past 5 years, stand conversion to longleaf pine postharvest was mandated, with 120-year rotations to provide RCW habitat. Prescribed fires were mostly during the winter, with growing-season burns planned. Logistical and personnel concerns limited burning.

Fort McClellan Military Reservation was established in 1917. Much of the MP montane longleaf pine stands of Choccolocco Mountain and its foothills were in old-growth age structure when acquired. By the 1960's, logging had removed much of the accessible old-growth longleaf pine, but uncut pockets may remain in more inaccessible areas of MP.

The surviving MP longleaf pine forest contained an excellent remnant of a contiguous montane pine woodland system in Alabama's Blue Ridge region (Anon 1994). Military maneuvers perpetuated fire, which maintained a longleaf pine overstory and provided the conditions necessary for longleaf pine regeneration. Fires also maintained a diverse herbaceous community. Primary MP forest uses were for military maneuvers, watershed protection, and hunting.

METHODS

Stand selection on MP was accomplished with reconnaissance of longleaf pine areas on Choccolocco Mountain and its foothills. A 25-ha midslope tract was selected for detailed study.

Overstory trees were sampled in a systematic grid of circular plots, with 0.08-ha pine and nested 0.04ha hardwood plots. All pines $1.5 centimeters (Cm) d.b.h. and all hardwoods $5.1 cm d.b.h. were included in the overstory sample on 29 plots. Relative density (RD), relative basal area (RBA) and importance value (IV), [(RD + RBA)/2] were determined for overstory trees for each plot. Stand structure was evaluated using diameter distributions of species and species groups across the study area. Pine species were aged using increment cores. Species age-d.b.h. relationships were evaluated to determine stand history.

Four, 0.0002-ha nested subplots in each overstory Plot sampled the tree regeneration. Maximum size for inclusion

In the regeneration sample was <1.5 cm d.b.h. for pine species and <5.1 cm d.b.h. for hardwood species.

Sapling and seedling size/age groups were defined by ability to survive fire. Pine seedlings were defined as fire-tolerant if ground line diameter (GLD) was $0.8 cm or d.b.h. <1.5 cm, and hardwoods if d.b.h. $2.5 cm. Smaller pine and hardwood seedlings were considered fire susceptible.

Regeneration RD was determined for each species by the total regeneration population and by sapling size groups. These values were summed over each set of four subplots per overstory plot.

Community successional status was evaluated by comparison of overstory with sapling and total regeneration groups. Results provided the basis for formulating a fire management plan to restore and maintain the montane longleaf pine community on MP.

RESULTS AND DISCUSSION

Overstory

Stand history was revealed from the coring of pine trees. Ring counts ranged from 9 to 104, with maxima of 104 for longleaf, 70 for shortleaf, 64 for loblolly, and 40 for Virginia pines (fig. 2). The number of individuals per species cored was based on its percentage of total density. Trees were cored across all diameter classes. Of the 298 cores, 201 were longleaf, 43 were loblolly, 32 were shortleaf, and 22 were Virginia pines.

Longleaf pine had a wide range of diameters and ages with many trees in the older age classes, indicating historic dominance. Shortleaf and loblolly pine established on the stand 60 to 80 years ago. This timing coincided with logging on MP and the emergence of a fire-suppression policy which began in the 1920's. Openings and infrequent fire facilitated survival of these less fire-tolerant pine species. Virginia pine, the most fire-sensitive of the pine species on the tract, established about 40 years ago. Under a sporadic fire regime, with frequency >10 years, all pine species could survive (Chapman 1932), as evidenced by the tract's mixed pine overstory.

The pine species diameter size class distribution (fig. 3) illustrates the pattern of pine species establishment and survival on the tract. The size class distribution was a reverse j-shaped curve, with a deficiency in the 2.5 cm diameter class. Longleaf pine regeneration and recruitment into larger size classes is a concern as it represents a potential shift in dominance to other species. The low number in the 2.5 cm class indicated lack of recent recruitment by this species. About half of this size class was made of other pine species, suggesting initial species shifts from longleaf to other pines, under a sporadic and winter fire regime.

Hardwoods <5.1 cm d.b.h. were not sampled in the overstory plots, but the diameter size class distribution

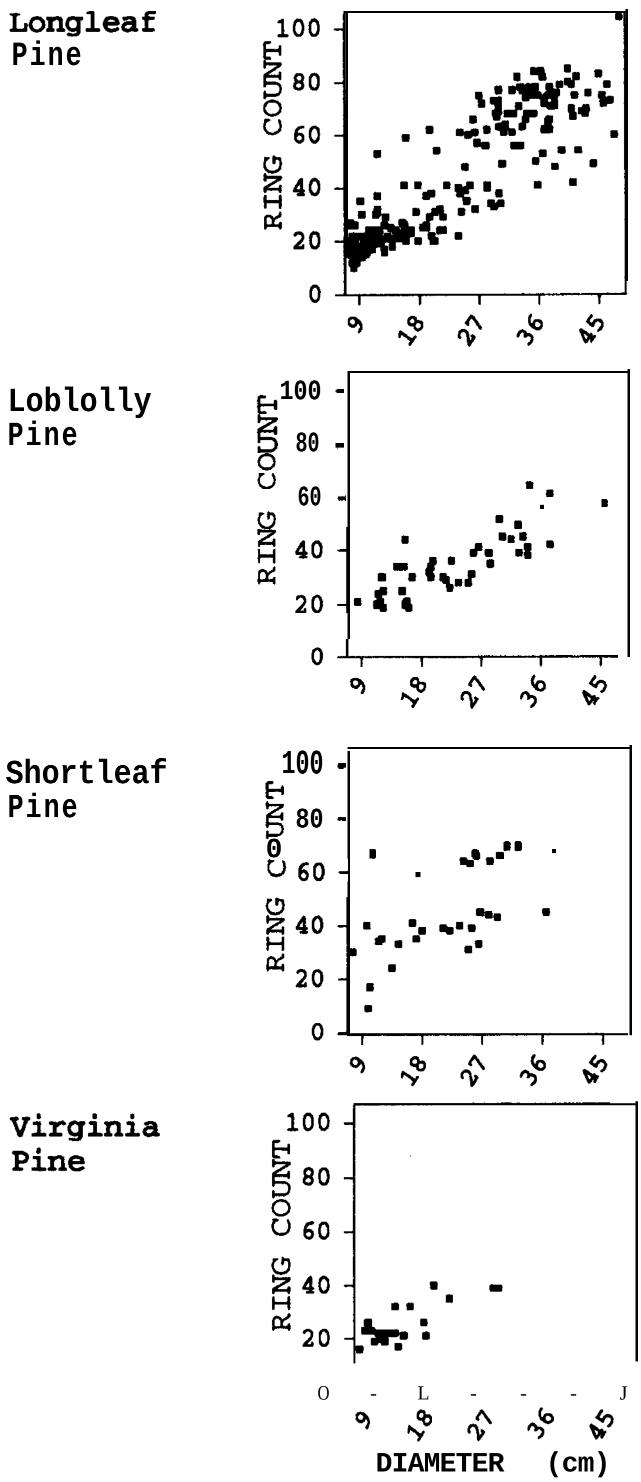

Figure 2-A comparison of diameter-ring count patterns of the four pine species on the study area.

was consolidated into the overstory sample. Most hardwoods were in the 5 and 8 cm diameter classes (fig. 3), inferring recent establishment dates and initial species compositional shifts. Presence was related to irregular and dormant-season fires (Boyer 1990, Brender and Cooper 1968, Heyward 1939, Waldrop and Lloyd 1990).

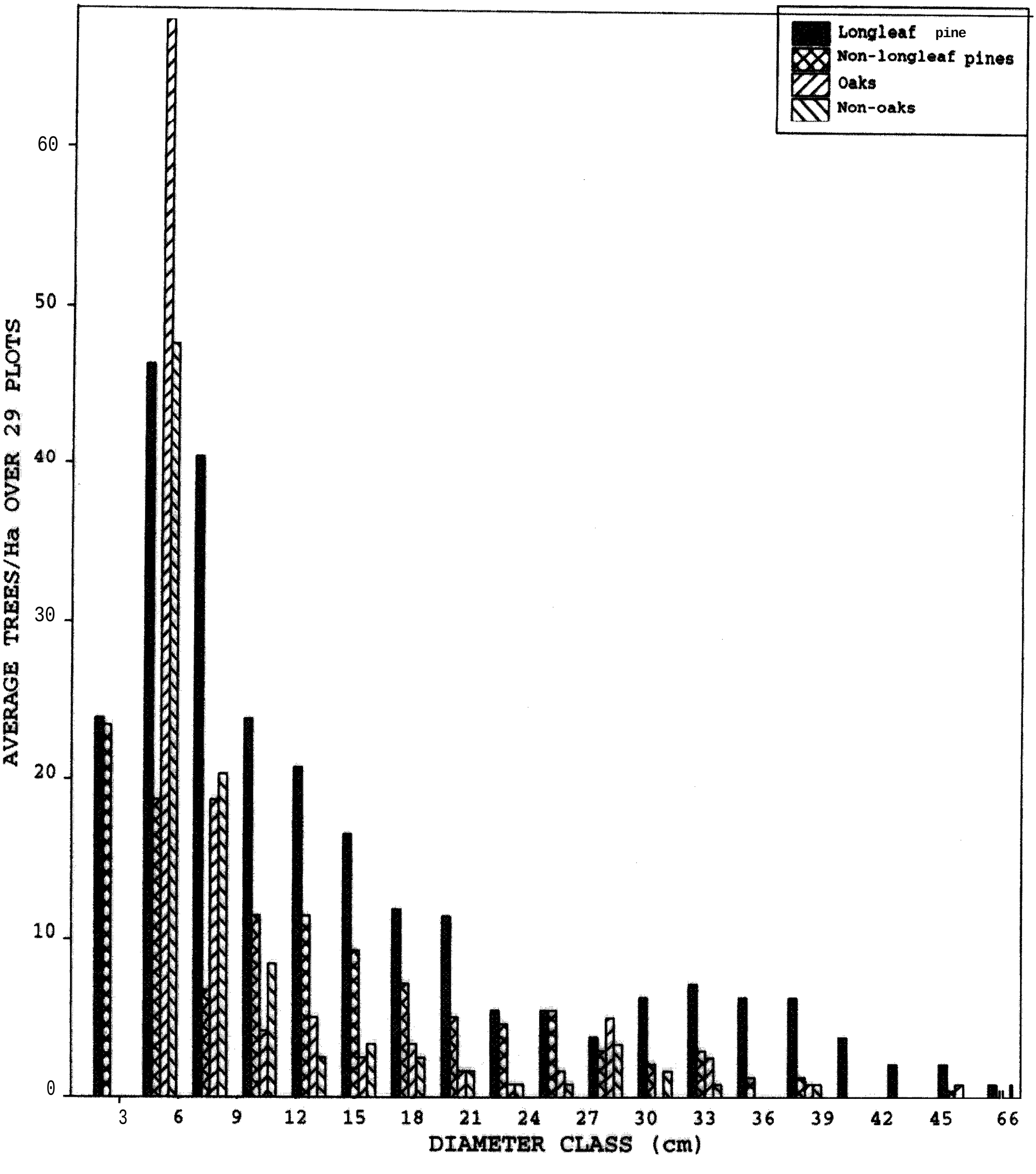

Figure 3-Composite pine and hardwood diameter size class distribution, presented in 2.5-cm increments. Pines were sampled from the 2.5-cm size class, and hardwoods from the 5.1-cm size class. The largest tree was a 65.3-cm mockernut hickory.

Understory

Sapling and overstory species compositions were compared, providing indications of successional status if the current periodic fire regime was continued or increased. Overstory longleaf pine dominated 27 plots, compared with 17 plots for the sapling size class. The longleaf pine component was declining over the tract, measured by comparison of overstory and regeneration species composition. Twelve plots with a longleaf pine-dominated overstory had no saplings in sample subplots (fig. 4). Longleaf pine saplings

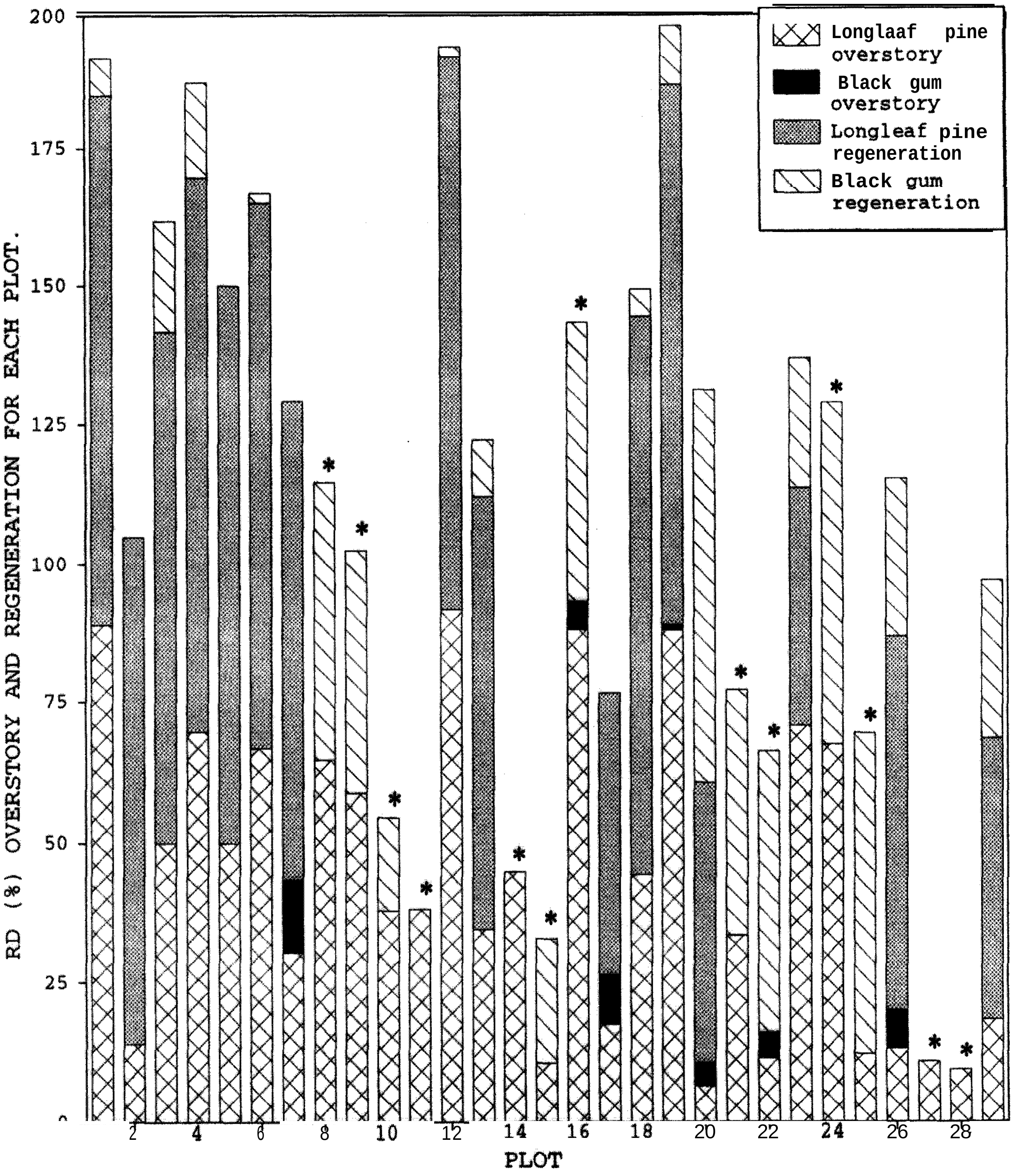

Figure 4—Longleaf pine and blackgum relative density by overstory and regeneration over the 29 plots on the study area.

strongly dominated 16 plots with ≥50 percent sapling RD, ranging from 50 to 100 percent, and 1 plot had 42.9 percent. In the sapling size class, longleaf pine saplings dominated 11 plots, 7 plots had shared pine-hardwood species dominance, and hardwood species dominated 8 plots.

When all regeneration sizes were summarized, results were very different from the sapling size class and revealed not only more plots with other pine species, but large increases in number and variety of hardwoods. Species compositional changes were suggested with sapling data but very apparent with total regeneration RD's, which included smaller sizes. This analysis indicated future overstory composition under an infrequent or dormant season fire regime.

Blackgum regeneration was observed in 25 plots compared with overstory trees in only 7 plots (fig. 4). McGee (1990) reported that blackgum responded vigorously to release, quickly colonizing openings, could grow in shade, and was susceptible to fire. Trees also propagated by root suckers. Seedling establishment on 25 plots indicated past recent sprouting or lack of recent fires.

Species shifts shown by comparisons of overstory and regeneration samples were evidenced by the decline in longleaf pine and the strong emergence of blackgum. This illustrated initial species shifts that resulted from a decrease in fire frequency and a shift to dormant season prescribed fire. The sapling regeneration population has potential to maintain the longleaf pine component over the tract, if increased frequency of fire in the growing season is initiated. The regeneration sample indicated the beginning of a species change from a pine-dominated to a hardwood-dominated forest type.

CONCLUSIONS

Longleaf pine was the dominant overstory species on Fort McClellan's Main Post. With fire suppression and logging, other pine species, followed by hardwoods, were able to establish and grow into the overstory. Evaluation of overstory species composition and size class distributions revealed initial species shifts from longleaf pine to other pine and hardwood species. Comparisons of overstory with regeneration by species composition in sapling and total regeneration size classes showed a decrease in number of plots with longleaf pines. There was an increase in other pine and hardwood species. This species shift was indicated by the strong emergence of blackgum in the regeneration sample.

Prescribed fire or other disturbance will be required to maintain the longleaf pine type and retard hardwood succession in this forest type. Fires should be of low intensity to protect present longleaf pine regeneration, but conducted at frequent intervals during the growing season to control more fire-sensitive species. Without hardwood-controlling fire or other disturbance, the longleaf pine type will not maintain its historic dominance in this system.

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Growth and Yield

Moderator:

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AN INDIVIDUAL-TREE SURVIVAL FUNCTION FOR LOBLOLLY PINE MANAGED UNDER SINGLE-TREE SELECTION

Paul A. Murphy and Michael G. Shelton’

Abstract-Aspects of the growth and stand dynamics of uneven-aged loblolly pine (*Pinus taeda* L.) managed under single-tree selection were investigated as follows. Eighty-one plots were installed in south Arkansas and north Louisiana. Treatments were three basal areas (40, 60, and 80 ft^2/acre), three maximum diameters (12, 16, and 20 inches), and three site classes (site index <81, 81-90, and >90 ft at base age 50 years, loblolly pine). Each treatment combination was replicated three times. The logistic function was selected for the individual-tree survival equation, and tree, stand, and site factors were tested as explanatory variables. Initial individual-tree diameter, ratio of initial individual-tree diameter to quadratic mean diameter, and site index were the best variables. The resulting survival equation was used to examine survival patterns for different uneven-aged stand structures. Implications for management are discussed.

INTRODUCTION

The major components of uneven-aged stand dynamics are recruitment, growth, and mortality of trees. Trees in even-aged stands compete only with members of their own cohort, but trees in uneven-aged stands not only compete with members of their own cohort but also compete with members of older and younger ones. An uneven-aged loblolly pine stand is made up of clumps of trees and looks understocked. The clumps vary in size, but each is made up of trees of generally similar size. Following a disturbance, where a single mature tree or clump of trees is cut or dies, a patch of pine reproduction regenerates in the opened space. These pine seedlings compete with their peers and are also affected by the surrounding overstory trees. As a new cohort develops, some of its members inevitably die as a result of competition or other causes. When the cohort becomes merchantable, cutting reduces its numbers further. Finally, only a few trees of the original patch remain, and these tower over their neighbors and are little affected by competition. However, their surviving counterparts in even-aged stands still have significant peer competition. Thus, in comparison with trees in even-aged stands, those in uneven-aged stands have more competition earlier in life and less competition as they grow.

Vanclay (1994) gives a succinct summary of the various approaches to modeling tree survival. Most survival models relate to natural even-aged stands or plantations; relatively few have been developed for uneven-aged conditions.

Hamilton and Edwards (1976) and Monserud (1976) explain how to use the logistic function to model individual-tree survival. Hann (1980) developed a stand simulator for even-aged and uneven-aged ponderosa pine (*Pinus ponderosa* Laws.). Buchman and others (1983) used a variant of the logistic function to develop survival equations for Lake State tree species. An alternative approach is to model changes in the number of trees in the stand resulting from both ingrowth and mortality. For example, Lynch and Moser (1986) and Moser (1974) estimated change in number of trees by means of a differential equation that was a component of a system of differential equations describing stand growth. More recently, McTague and Stansfield (1995) used a nonlinear projection equation to describe change in the number of trees.

Our intent here was to develop a survival function that could ultimately be a part of an individual-tree simulator for uneven-aged loblolly pine stands. We chose the logistic function for model development because other workers have used it successfully in similar applications and because the methodology is well developed.

METHODS

Treatment Variables

Uneven-aged stand structures are typically defined in terms of basal area, maximum diameter, and a quotient, 9. This quotient is the ratio of the number of trees in a diameter class to the number of trees in the next larger diameter class. For example, if there are 12 trees per acre in the 12-inch class and 10 trees per acre in the 13-inch class, the 9 value is 1.2. The width of the diameter classes affects 9; for example, a 9 value of 1.2 for 1 -inch classes is equivalent to a 9 value of 1.44 for 2-inch classes. Several published guides explain how to use these three variables to describe stand structure (Brender 1973, Moser 1976, Murphy and Farrar 1982).

Although 9 is one of the variables most often used to describe uneven-aged stand structure, experience has shown that it is not very amenable to management, at least initially. Therefore, the other variables were selected for manipulation in this first effort and 9 was fixed at 1.2. Reynolds (1959, 1969) and Reynolds and others (1984) have observed and used this value of 9 in managing loblolly-shortleaf pine stands by uneven-aged methods.

For treatments, we selected target basal areas of 40, 60, and 80 ft^2/acre in trees with d.b.h. >3.5 inches; maximum diameters of 12, 16, and 20 inches d.b.h.; and site index ranges of <81, 81 to 90, and >90 ft (loblolly pine base age 50). The site index classes in this study adequately cover

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the range of site quality that is encountered in the west gulf coastal plain. Each treatment combination was replicated three times, and there are 81 plots in all.

Basal areas are kept lower than in even-aged stands to favor the development of pine reproduction. Reynolds (1959) recommended cutting when stand basal area reaches 75 ft^2/acre to allow pine regeneration to develop. Basal area in uneven-aged loblolly pine stands, therefore, should probably not be much above this level at any time during a cutting cycle. A slightly higher basal area (80 ft^2/acre) was chosen so that we could investigate its long-term effects on loblolly pine growth and regeneration. The lowest basal area treatment level, 40 ft^2, probably represents the lower acceptable density limit for management. Densities lower than this approach understocked conditions in which growth is lost without any offsetting gain in regeneration.

Maximum d.b.h. in uneven-aged management is somewhat akin to rotation age in even-aged management. Selection of a larger maximum d.b.h. implies a longer term investment. A residual maximum d.b.h. of 20 inches probably represents an upper limit for both economic and product-size goals. A 12-inch maximum d.b.h. represents a lower limit for an adequate seed source.

Field Installation and Measurements

Each of the stands chosen for plot installation had at least 70 percent of its basal area in loblolly pine; no evidence of cutting within the last 10 years; no evidence of catastrophic loss caused by insects, disease, weather, or fire; and a site index that did not vary more than 10 ft over a plot. Stands that exhibited a reverse J-shaped stand structure were preferred if available.

The stands represented a gamut of structures: some already exhibited a reverse J-shaped stand structure, while others had a mound-shaped structure more typical of even-aged stands. Most stands had more than one plot installed in them. All 81 study plots are on the Coastal Plain in southern Arkansas and northern Louisiana (fig. 1).

Each square 1 .&acre gross plot included an interior square O.&acre net plot. Before harvest, all loblolly pine trees with d.b.h. >3.5 inches were inventoried by l-inch d.b.h. classes for the 0.5-acre net plots and 1 .1 -acre isolation strips. Plots were then marked for harvest. Marking was designed to give each plot its assigned residual structure as defined by residual basal area, maximum d.b.h., and a q of 1.2 for 1-inch d.b.h. classes. Any shortleaf pines occurring in the plots were cut. All hardwoods with a groundline diameter ≥1 inch or larger were injected with herbicide prior to harvest, if possible, but no later than the first growing season after treatment. Plot installation and harvesting were carried out over a 3-year period beginning in the fall of 1983. All cutting was completed during the early part of the dormant season of each year, and about one-third of the plots were established each year.

Figure l--Study plot locations (locations have more than one plot).

After harvesting, all residual loblolly pine trees with d.b.h. >3.5 inches on the net plot were numbered, mapped, and measured. D.b.h. was measured to the nearest 0.1 inch using a tape. A d.b.h. mark was painted on each tree to ensure consistency in subsequent measurements. Total height and height to the crown base were measured to the nearest foot on a sample of 20 percent of the trees in each 1 -inch d.b.h. class. Five to 10 height-sample trees suitable for site index calculation were identified and their age determined by increment coring. Trees whose ring widths and growth patterns were indicative of past suppression were not used for site index computation. Site index was computed as suggested by Farrar (1973).

The plot trees were remeasured after 4 to 5 years of growth. With the exception of tree age, the same measurements were taken for both surviving trees and ingrowth trees. In addition, tree status (living, dead, ingrowth) was recorded for all trees in both inventories. Cause of death was determined where possible.

Data Summary and Analysis

Trees that were alive at the time of the first inventory were recorded as alive (1) or dead (0) at the second inventory. The following variables were calculated for trees with d.b.h. ≥ 3.6 inches:

P_i^t = probability of survival of the ith tree for t years

D_{max} = maximum d.b.h. (inches) for the plot,

N = stems per acre,

B = stand basal area (ft^2/acre),

D_q = quadratic mean d.b.h. (inches),

S = site index (ft at 50 years, loblolly pine),

D_i = initial d.b.h. (inches) of *i*th tree,

L = basal area (ft²/acre) in trees with d.b.h. equal to or larger than that of the subject tree,

D_i/D_q = ratio of the subject tree's d.b.h. to the quadratic mean d.b.h. for the plot's trees, and

t = length (years) of the growth period.

Means and ranges for the data are presented in table 1. Although the planned treatment basal areas were 40, 60, and 80 ft²/acre, the actual residual densities ranged from 32 to 89 ft²/acre because of logging damage and failure to harvest all marked trees.

In this study, analysis started with the following full logistic model:

$$P_i^t=[1+exp(b_0+b_1D_{max}+b_2B+b_3N+b_4D_q+b_5S+b_6D_i+b_7L+b_8D_i/D_q)]^{-t} \quad (1)$$

where P_i is the annual survival probability, the b_i's are coefficients to be determined, and the other variables are as previously defined.

The procedure LOGISTIC (SAS Institute 1989) was used to initially screen variables by modeling growth period survival probabilities. This procedure uses a stepwise process for variable selection that is based on the adjusted chi-square statistic at the 0.05 probability level. After the initial screening, reduced models for annual survival were fitted by iteratively reweighted nonlinear least squares and compared with each other. A final model was selected based upon a compromise between model parsimony and adequate depiction of survival patterns using the chi-square goodness-of-fit test described by Hamilton and Edwards (1976).

Table l-Descriptive statistics for tree, stand, and site variables at beginning of growth period

Variable[a]	Mean	Minimum	Maximum
Maximum d.b.h. (inches)	16.2	11.6	22.0
Trees/acre	135	50	310
Basal area (ft²/acre)	59.2	31.7	88.6
Quadratic mean d.b.h. (inches)	9.3	6.1	13.7
Site index (ft)	83	56	97
Basal area in larger trees (ft²/acre)	44.2	31.7	88.6
D.b.h. of subject tree (inches)	8.3	3.6	22.0
D.b.h. ratio	0.93	0.28	2.66

[a] Tree variables (basal area in larger trees, d.b.h., and d.b.h. ratio) are based on 5,465 sample trees; stand variables (maximum d.b.h., trees per acre, basal area, quadratic mean d.b.h., and site index) are based on data from 81 0.5-acre plots.

RESULTS AND DISCUSSION

The final model has three independent variables-initial tree d.b.h., ratio of tree d.b.h. to quadratic mean d.b.h., and site index:

$$P_i^t = [1+exp(-7.28518-0.173095D_i-1.46790D_i/D_q+0.0644407S)]^{-t}. \quad (2)$$

This model yielded close agreement between observed and predicted survival probabilities for l-inch d.b.h. classes (table 2). The calculated chi-square statistic for the equation using l-inch d.b.h. classes is 0.343 with 15 degrees of freedom, which has a probability level of >0.999. Thus, the model predicts d.b.h. class survival rates that are not significantly different from actual rates.

The negative coefficients for initial d.b.h. and the d.b.h. ratio in equation (2) indicate that an increase in these variables results in an increase in predicted survival. However, an increase in site index decreases predicted survival. Vanclay (1991) noted the same negative effect of site index on tree survival in north Queensland rainforests. The reverse-J structure characteristic of uneven-aged stands influences the survival probability calculated by equation (2) through the d.b.h.-ratio term, because a

Table 2-Goodness-of-fit statistics for the logistic survival function

D.b.h. class	Observed survival	Observed survival proportion	Predicted survival proportion	Chi-square
	Stems/ac			
4	592	0.866	0.870	0.015
5	572	0.883	0.892	0.066
6	615	0.923	0.914	0.062
7	576	0.937	0.936	0.001
8	560	0.954	0.951	0.007
9	480	0.968	0.965	0.006
10	435	0.982	0.971	0.047
11	393	0.978	0.980	0.003
12	296	0.980	0.984	0.004
13	169	0.983	0.987	0.003
14	142	0.993	0.990	0.002
15	110	0.991	0.993	0.000
16	83	1.000	0.994	0.003
17	42	0.977	0.996	0.015
18	28	1.000	0.997	0.000
19	24	0.960	0.998	0.036
20	12	0.923	0.998	0.073
21	1	1.000	0.998	0.000
22	1	1.000	0.999	0.000
Total	5131	—	—	0.343

stand's quadratic mean diameter is functionally defined by maximum diameter and *q* (Murphy and Farrar 1982). A 9 value of 1.2 for l-inch d.b.h. classes was assumed, and equation (2) was used to calculate survival rates for a reasonable range of d.b.h., maximum diameter, and site index. Resulting values are plotted in figure 2. Annual survival probabilities range from 0.9 to nearly 1 .O and are most strongly affected by the subject tree's d.b.h. and the stand's site index. The survival probability for trees with d.b.h. ≥10 inches approaches 1 .0 regardless of the site index. By contrast, the survival probability of trees with d.b.h. <10 inches is considerably greater on poor sites (about 0.98 where d.b.h. = 4 inches) than on good sites (about 0.90 where d.b.h. = 4 inches).

The negative influence of the site index variable probably reflects the more intense competition that occurs on better sites-fewer trees will survive intensive competition. The relationship between site index and competition has also been noted in previous analyses of this study. Murphy and Shelton (1994) found that mortality in stand basal area increased with site index, while ingrowth in basal area decreased. This probably results from the greater intraspecific competition on the better sites in addition to more aggressive competition from nonpine vegetation. In addition, Shelton and Murphy (1994) noted the powerful effect of site quality on stand regeneration; pine seedlings and saplings tended to have much lower densities on the better sites as a result of aggressive competition from vines and other understory vegetation.

The survival function can be used to assess the first-year survival of trees under different uneven-aged stand structures. One hundred stand tables were randomly generated from the doubly truncated exponential distribution (Murphy and Farrar 1982) for each combination of the following attributes: a residual basal area of 60 ft^2/acre; a 9 value of 1.2 (for 1 -inch d.b.h. classes); maximum d.b.h.'s of 14, 16, 18, and 20 inches; and site indexes of 70, 85, and 100 ft at 50 years. These d.b.h. distributions are typical for uneven-aged loblolly pine stands with a 5-year cutting cycle, and the maximum d.b.h.'s are probably the operational range of diameters in loblolly pine management.

Table 3 shows the mortality rates as numbers of trees for the different combinations of maximum d.b.h. and site index. Mortality rates range from 0.62 to 4.64 percent. Maximum d.b.h. affects mortality rate less than does site index; rates are six times greater on the best sites than on the poorest. These rates seem reasonable for the combinations of site index and maximum d.b.h. used in these simulations. This simulation supports the generally accepted tenet that uneven-aged loblolly pine stands are more difficult to create and maintain on better sites (Baker and others 1996).

The survival model described here is relatively simple but appears to give reliable estimates for stands managed by single-tree selection, as evidenced by the goodness-of-fit test and the simulations. Its full potential can be realized by incorporating it into an individual-tree growth and yield model.

ACKNOWLEDGMENT

Work was done in cooperation with the School of Forest Resources and the Arkansas Agricultural Experiment Station, University of Arkansas at Monticello. The authors

Table 3-Estimated first-year mortality rates for uneven-aged loblolly pine stand initial basal area of 60 ft^2/ac, a *q* value of 1.2, and specified maximum d.b.h. (based upon 100 simulations for each maximum d.b.h.-site index combination)

	Site index (ft)		
Maximum d.b.h.	70	85	100
Inches	*Percent*		
14	0.71	1.76	4.34
16	0.62	1.82	4.52
18	0.69	1.97	4.53
20	0.83	1.67	4.64

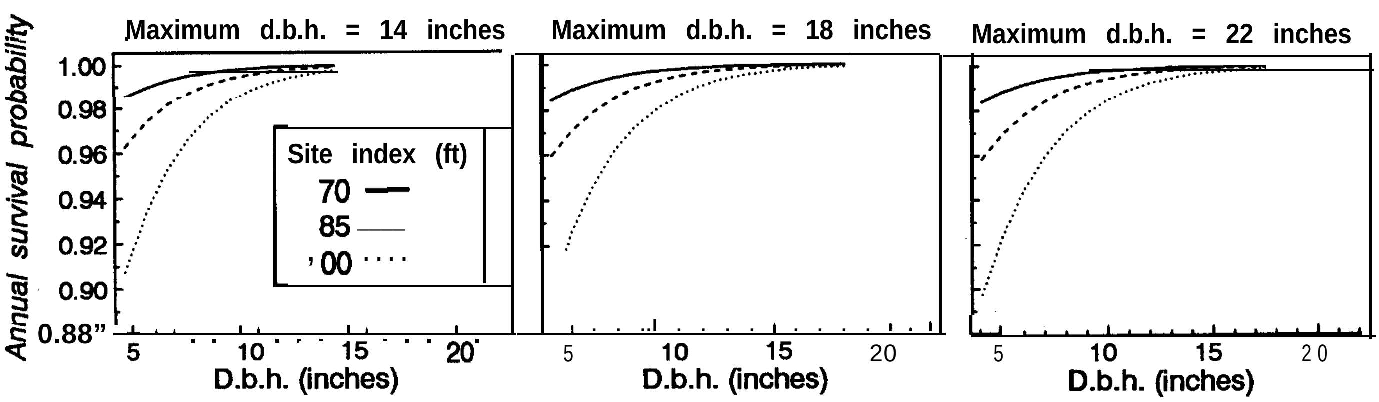

Figure 2-Calculated survival probabilities from equation (2) assuming reverse-J d.b.h.-class distributions with a 9 value of 1.2 and maximum d.b.h. of 14, 18, and 22 inches, which yields quadratic mean d.b.h. of 7.8, 8.8, and 9.2 inches, respectively.

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THE SELF-THINNING RULE AND EXTRAPOLATED RESULTS FROM GROWTH AND YIELD MODELS FOR UNTHINNED LOBLOLLY PINE PLANTATIONS

Quang V. Cao[1]

Abstract-Growth and yield models are often used for short-term projection (5 to 10 years). Nevertheless, knowledge of how well these models behave in long-term simulations can give users more confidence in using the models. In this study, long-term projection from age 10 through age 100 was made using recent growth and yield models for unthinned loblolly pine plantations. Three levels of site index (50, 60, and 70 feet) and initial density at age 10 (500, 1000, and 1500 trees per acre) were included in this simulation. The objective of the study was to investigate the log(Q)-log(N) relationship, where N is surviving trees per acre and Q is quadratic mean diameter.

Except for two models, the growth and yield models did extrapolate well. The stands seem to approach a self-thinning curve, rather than a self-thinning line. Initial stand densities did not affect the shape of the self-thinning curves, whereas site index seemed to affect the level (or intercept) of these curves, but not the slope. It was concluded that most of the existing growth and yield models for unthinned loblolly pine plantations behave reasonably well in long-term projections.

INTRODUCTION

Growth and yield models have played a very important role in managing our forests. Foresters use these models to predict future yields based on current stand conditions, such as stand age, density, and site quality. The forecasts are usually short-term, from 5 to 10 years. Nevertheless, knowledge of how well the growth and yield models behave in long-term projections can give users more confidence in using the models.

In this study, we simulated stands from age 10 to age 100 using recent growth and yield models for unthinned loblolly pine plantations. The objective of the study was to investigate the relationship between tree size and stand density, and to observe if it follows the self-thinning rule.

THE SELF-THINNING RULE

Maximum average plant size for a given density was characterized by Yoda and others (1963) as following a self-thinning line. This line was expressed mathematically as

$$\log (W) = a + b \log (N)$$

where

W = maximum average plant size,
N = stand density,
a = the intercept,
b = the slope, and
log (x) = logarithm base 10 of x.

If the average plant size in the above equation is expressed as Q, the quadratic mean diameter of the stand, a graph of log (Q) versus log (N) shows the reciprocal relationship between quadratic mean diameter and stand density in an even-aged stand (fig. 1). The curve depicts a stand starting at an early age where there is little competition (A), then approaching the self-thinning line as it becomes older (B).

Reineke (1933) found the slope of this self-thinning line to be -1.605 for loblolly pine, when log (N) was plotted against log (Q). If the y-axis is log (Q) and the x-axis is log (N) as presented in figure 1, the slope of his self-thinning line was l/(-l .605) or -0.62. Subsequent authors reported slopes varying from -0.59 to -0.66.

SIMULATION

Long-term projections from age 10 to age 100 at 5-year intervals were made for three levels of site index (50, 60, and 70 feet, base age 25 years) and three levels of initial density at age 10 (500, 1,000, and 1,500 trees per acre).

Ten growth-and-yield models for unthinned loblolly pine plantations used in this study are listed in table 1. Also listed is a description of the data used in developing these models.

RESULTS AND DISCUSSION

Figure 2 shows the stand trajectories from different growth and yield models. There were nine curves for each model,

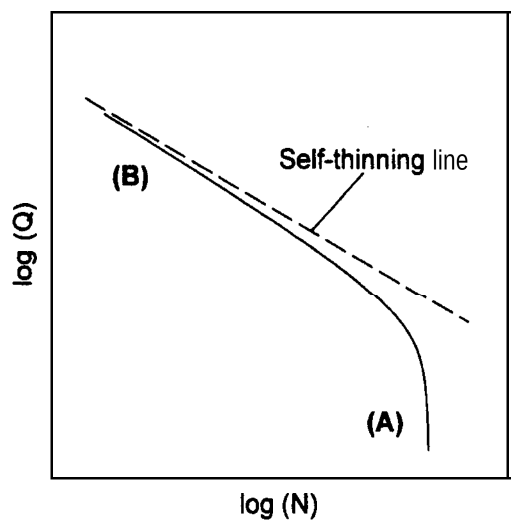

Figure l-Size-density trajectory of an even-aged stand undergoing self-thinning.

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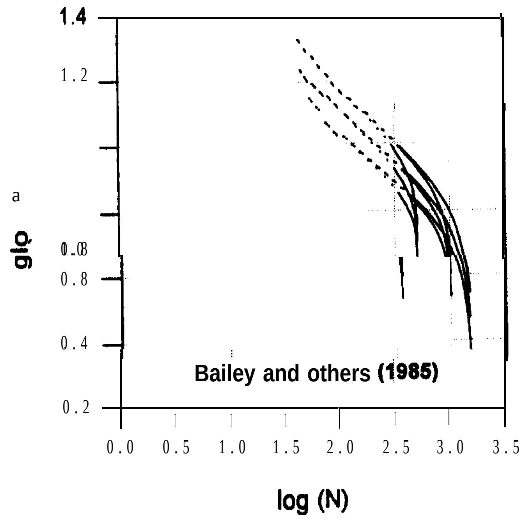
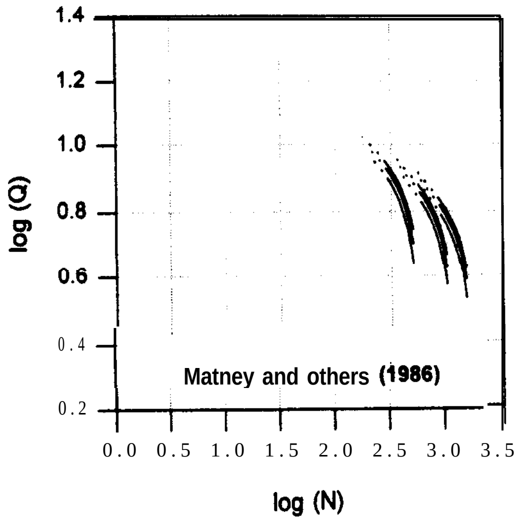
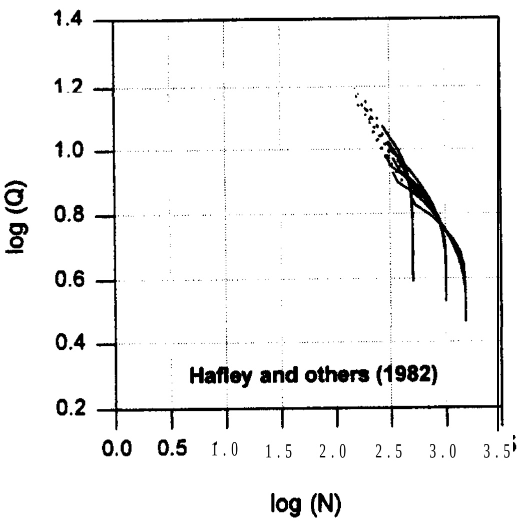
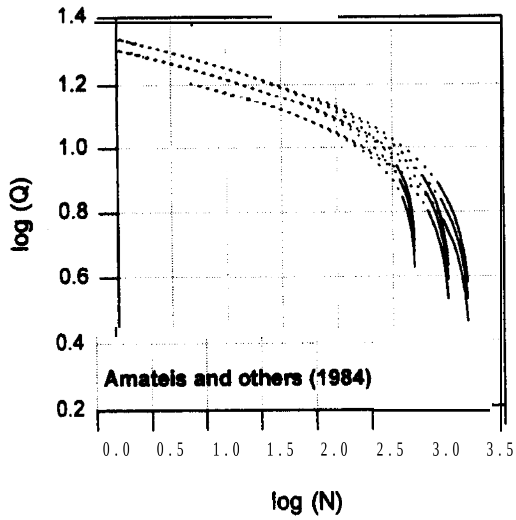
Table I-Description of data used in developing loblolly pine plantation models included in the evaluation

Model	Location	Number of plots	Plot size	Age	Site index feet @ 25 yrs	Trees per acre
			·Acres--------	Years		
Whole stand model						
Coile and Schumacher (1964)	AL, FL, GA, LA, MS NC, SC, TX	398 (Half of the plots were thinned)	0.10 (6-10 yrs) 0.20 (over 10 yrs)	5-35	35-80	—
Weibull diameter distribution models						
Smalley and Bailey (1974)	AL, GA, TN	267 (to fit models) 32 (to validate)	0.05	1 0-31	31-89	202-2240
Feduccia and others (1979)	AR, LA, MS, TX	409	varied, >0.10	3-45	22-78	250-l 500
Amateis and others (1984)	AL, AR, GA, LA, MD, MS, NC, OK, SC, TN, TX, VA	186	0.50	8-25	33-97	275-950
Clutter and others (1984)	FL, GA, NC, SC	226	0.10	1 0-30	40-80	300-900
Bailey and others (1985)	AL, GA, SC	284	64 planting spaces	12-26	39-71	299-l 500
Matney and others (1986)	AL, AR, LA, MS	230	0.25 (214 plots) 0.10 (16 plots)	l-26	51-71	101-801
Baldwin and Feduccia (1987)	LA, MS, TX	85 (unthinned)	—	5-45	40-79	100-2700 (planting)
SB diameter distribution model						
Hafley and othrs (1982)	LA, NC, SC, IL	—	—	5-44	48-93	—
Individual tree simulation model						
Burkhart and others (1987)	AL, AR, GA, LA, MD, MS, NC, OK, SC, TN, TX, VA	186	0.50	8-25	83-90	270-l 000


Bailey and others (1985)
log (N)
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5
1.4
1.2
0.8
0.4
0.2


Matney and others (1986)
log (Q)
log (N)
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5
1.4
1.2
1.0
0.8
0.6
0.4
0.2


Hafley and others (1982)
log (Q)
log (N)
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5
1.4
1.2
1.0
0.8
0.6
0.4
0.2


Amateis and others (1984)
log (Q)
log (N)
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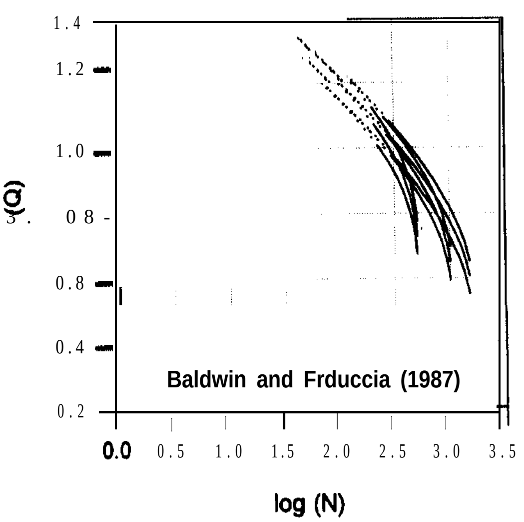
1.4
1.2
1.0
0.8
0.6
0.4
0.2


Baldwin and Frduccia (1987)
log (N)
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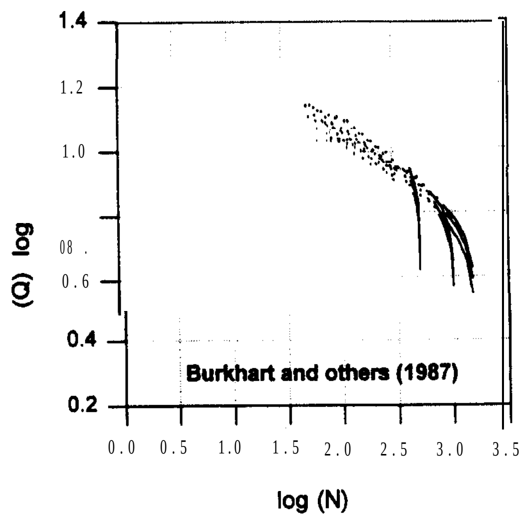
1.4
1.2
1.0
0.8
0.4
0.2


Burkhart and others (1987)
(Q) log
log (N)
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5
1.4
1.2
1.0
0.6
0.4
0.2

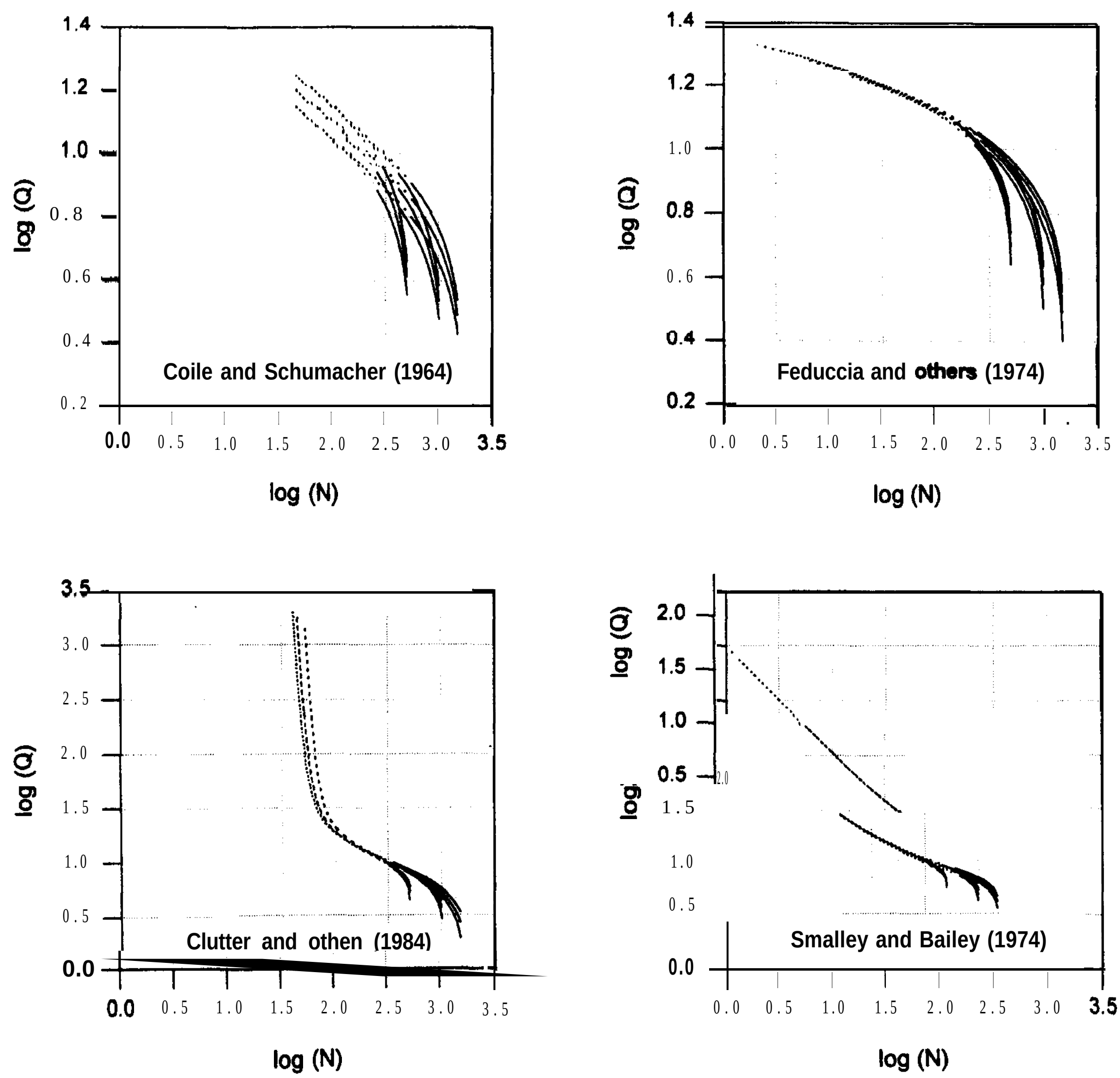


Figure 2-Size-density trajectories of unthinned loblolly pine plantations, simulated from 10 growth-and-yield models. The projections from age 10 to age 100 were made for three levels of site index (50, 60, and 70 feet) and stand density at age 10 (500, 1,000, and 1,500 trees per acre). Solid and dotted lines depict trajectories within and beyond the age range for each model, respectively.

each curve corresponding to a combination of site index (three levels) and initial stand density at age 10 (three levels). The solid lines depict the size-density trajectory within the age range, whereas the dotted lines represent extrapolation beyond the maximum age of the data used to construct that particular model. For example, since the maximum age of Baldwin and Feduccia's (1987) data was 45, solid lines were used for this model from age 10 to 45, and dotted lines from age 45 to 100.

The Self-Thinning Line

For some growth-and-yield models, the stand trajectories were close to a straight line at older ages. The slopes of the self-thinning lines varied between -0.3 to -0.4 (Bailey and others 1985), and between -0.35 to -0.6 (Matney and others 1986). The curves from Hafley and others' (1982) model were not smooth, but they tended to converge to a line having a slope close to -0.5.

For a majority of the growth-and-yield models evaluated here, stands converged at older ages to a curve, rather than a line, as expected from the self-thinning rule. Models exhibiting this characteristic included those from Amateis and others (1984), Baldwin and Feduccia (1987), Burkhart and others (1987), Coile and Schumacher (1964), and Feduccia and others (1974). For example, the slope of the self-thinning "curve" from Coile and Schumacher (1964) decreased (in absolute value) from -0.5 at age 35 to -0.3 at age 100. The curves for Burkhart and others' (1987) model were not smooth, possibly due to the random components in the model. The stand trajectories for this model represented averages of three stands for each combination of site index and initial stand density.

For two growth-and-yield models (Clutter and others 1984, Smalley and Bailey 1974), the stand trajectories behaved properly up to about 10 years beyond the maximum age of the data, then the curves turned upward, resulting in unreasonably high values of quadratic mean diameter at older ages. Both models used the Weibull function to characterize diameter distributions of stands. The Weibull parameters in the models were predicted using regression equations; therefore no constraints were placed on the stand structure. This might cause the inconsistency in the long-term extrapolation attempted here.

Effect of Initial Stand Density

For the same site index, trajectories of stands of different initial stand densities converged to the same curve, as shown by most models evaluated here (Amateis and others 1984, Bailey and others 1985, Baldwin and Feduccia 1987, Clutter and others 1984, Coile and Schumacher 1964, Feduccia and others 1974, Hafley and others 1982, and Smalley and Bailey 1974).

Effect of Site Index

Curves for stands of different site indexes separated'into three levels; a higher site index resulted in larger quadratic mean diameters. This trend was observed in models by Amateis and others (1984), Bailey and others (1985), Baldwin and Feduccia (1987), and Coile and Schumacher (1964). For other models, site index did not affect the stand trajectories (Clutter and others 1984, Feduccia and others 1974, and Smalley and Bailey 1974).

CONCLUSIONS

Since a number of existing growth-and-yield models, especially those developed many years ago, were based on empirical data rather than on biological principles, some foresters might be curious to see if the models behave properly when extrapolated beyond the age range of the data.

Results were encouraging. Except for two models, the growth-and-yield models did extrapolate well. The stands seem to approach a self-thinning curve, rather than a self-thinning line. Initial stand densities did not affect the shape of the self-thinning curves, whereas site index seemed to affect the level (or intercept) of these curves, but not the slope.

I hope that this paper gives foresters some assurance that most of the existing growth-and-yield models for unthinned loblolly pine plantations do a good job of projecting a stand through time, and the new crop of models that incorporate biological principles should perform even better.

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STABILITY OF PARAMETERS THAT PREDICT GROWTH AND YIELD OF NATURAL STANDS OF LONGLEAF PINE (*Pinus palustris* Mill.)

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Abstract-Data from remeasured longleaf pine growth-and-yield plots were modeled at the stand level as well as the individual tree level to evaluate the stability of model parameters over time. Parameter stability analyses were performed using subsets of the database (with nonoverlapping remeasurement periods) where the effects of stand dynamics have been accounted for or isolated as much as possible. Likelihood Ratio tests determined that the model parameters changed significantly from one time period to the next. Further tests also identified the parameters in need of modification to account for the observed changes. The selection of a particular model or model form did not change the fact that the model parameters have changed significantly over the last 25 years. Results were consistent across several dependent variables and several model forms. Results indicate that long-term prediction from growth-and-yield models for longleaf pine will be biased and inefficient without appropriately modifying some of the model parameters.

INTRODUCTION

Linear and nonlinear regression are the primary statistical techniques widely used to quantify biological relationships. Various empirical fits are available to represent biological relationships (Clutter 1963). Somers and Farrar (1991) use biomathematical models that try to explain the biological relationship to a reasonable extent. When a biological relationship is represented by statistical techniques, it is essential to examine the stability of that relationship for a long period of time (Chow 1960). In this context, growth-and-yield models based on periodic remeasurements may be useful to project yield for a certain period of time. The parameters of these growth-and-yield models might be questionable if the projection is for a long period of time. The question of instability of parameters of growth-and-yield models can be answered statistically by testing the parameters over different time periods. This investigation has importance in light of the present concern of growth changes due to climate change (Zahner and others 1989).

DATA

The growth data used in this investigation were part of the Regional Longleaf Pine Growth Study (RLGS) which was initiated by the USDA Forest Service in the mid-1960's (Kush and others 1987). The RLGS data set contains observations from periodically remeasured, naturally regenerated, even-aged longleaf pine (*Pinus palustris* Mill.) stands. Longleaf pine ecosystems once covered vast acreages in the Southeast. These ecosystems provide valuable wood products, unique multiple-use benefits, maintain biological diversity, and supply the necessary habitat for certain rare and endangered wildlife species (Boyer 1991). Plots in the RLGS come from a broad array of physiographic provinces covering a wide range of soil, site, and climatic conditions.

To examine possible productivity changes with respect to time, a series of plots has been established every 10 years in young stands (9-15 years old) on the Escambia Experimental Forest (EEF) in Brewton, AL. These plots are termed the "time replication plots" or "timerep" plots. The plots are purposely located on similar sites and cover similar densities. There are 21 timerep 1 plots (established in the mid-1960's); 15 timerep 2 plots (established in the mid-1970's); and 29 timerep 3 plots (established in the mid-1980's). The plots have been periodically remeasured about every 5 years.

The purpose of establishing the timerep plots was to examine the differences in growth due to differences in the environmental factors after reducing the differences in initial stand characteristics (age, site, and trees/ac) as much as possible. The controlled nature of the timerep plots already isolates most of the stand characteristics included in growth models. For instance, the close proximity of plots to each other and similarity of soil types have isolated most of the effects due to site quality. To help minimize differences between timereps, a subset of nonoverlapping time remeasurements termed as "band" that are similar in site (SI=65 ft), trees/ac (<3000/ac), and ages (15-25 years) were selected from the overall timerep plot data.

In order to check the applicability of the findings from the timerep band data to older age classes, pseudo timerep data sets were created and tested in a similar manner. RLGS observations from nonoverlapping remeasurement years and older age classes were divided into seven arbitrary age classes (e.g., 25-34, 35-44, etc.). These data sets, however, lacked the controlled ranges of site index, trees/ac, and geographical location that were built into the timerep band data.

METHODS

Determining the stability of the parameters in the growth model was a two-stage process. First, differences in the parameters estimated for each of the three timereps were examined using various growth-and-yield models. Tests were conducted to determine whether any or all of the parameters were stable across all the timereps. If

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differences existed, then the parameters would be considered unstable and a specification error was suspected. The second stage attempted to identify which parameter(s) in the models were most unstable.

The models selected to conduct the tests included stand level basal area and volume projection models, stand level increment projection models, and an individual tree basal area increment model.

Thinning Considerations

The effect of thinning was an important factor to be considered prior to the parameter stability analysis. During establishment, plots were assigned a target basal area class of 30, 60, 90, 120, or 150 ft^2/ac. They were left unthinned to grow into that class if they were initially below the target basal area. In subsequent remeasurements, if the basal area of the plots was found to be more than 7.5 ft^2/ac above the target BA the plots were thinned back to the previously assigned class. The thinning was generally of low intensity and from below. Somers and Farrar (1991) found that the thinnings did not significantly impact the functional form of their prediction equations. Similarly, Quicke and others (1994) found that there were no consistent patterns of under- or overprediction in plots of residuals against actual basal area removed in the process. Both of the above studies were based on portions of the same RLGS data.

To test for a difference in growth due to thinning, plots were considered thinned if more than 5 percent of the trees were removed. A likelihood ratio (LR) test was used to test the null hypothesis that a single set of parameters in the projection model was sufficient versus the alternative that separate parameters are needed depending upon thinning history. If the LR test was significant, then an extra parameter would be included in the model to reflect changes in the functional form by thinning.

Stand Level Models

Empirical models were chosen to provide a maximum fit to the data. Dependent variables chosen were: basal area (BA) (ft^2/ac), basal area increment (BAI) ($ft^2/ac/year$), diameteP*height (D^2H) as a surrogate for volume (SV), and D^2H increment (SVI) as a surrogate for volume growth. SV and SVI were chosen since their use eliminates the need to select a specific volume equation and because volume is often a linear function of D^2H.

Stand level projection models-A number of basal area projection models exist that could have been used in this study. One requirement of this study was to select a model flexible enough to fit the timerep band data. After an evaluation of several alternative models, the nonlogarithmic form of the two parameter basal area projection models suggested by Clutter and Jones (1980) was selected:

$$BA_2 = BA_1\left(\frac{A_1}{A_2}\right)^{\beta_0} e^{\beta_1\left[1-\left(\frac{A_1}{A_2}\right)^{\beta_0}\right]} \qquad (1)$$

where

BA, = initial stand basal area (ft^2/ac) at initial age A,,

BA, = projected stand basal area (ft^2/ac) at projected age A_2,

β_0, β_1 = parameters to be estimated.

The analysis based on model (1) was repeated using a second dependent variable SV, with the following model:

$$SV_2 = SV_1\left(\frac{A_1}{A_2}\right)^{\beta_0} e^{\beta_1\left[1-\left(\frac{A_1}{A_2}\right)^{\beta_0}\right]} \qquad (2)$$

Stand level increment models-To further investigate possible changes over time, a linear basal area increment equation including stand characteristics was developed. Stepwise and Maximum R-square procedures were employed when developing the candidate models. Any nonsignificant parameters were dropped from the model. Best candidate models with 2 and 3 parameters were selected.

Individual Tree Models

A distance-independent individual tree basal area increment model developed for thinned, even-aged stands of naturally regenerated longleaf pine was also selected as a candidate model (for further detail see Quicke and others 1994). This model has the following form:

$$bai = a_0 e^{a_1 BA^{0.5}} e^{b_0 BAL} e^{\left[c_1\left(1 - e^{c_2 DBH}\right) - c_0\right] A} \qquad (3)$$

where

bai = annual basal area increment per tree($in^2/year$),

BA = stand basal area (ft^2/ac),

BAL = basal area of all trees >the subject tree(ft^2/ac),

A = mean age of dominant and codominant trees (years),

DBH = tree diameter outside-bark at breast height (in).

Parameter Stability Analyses

Parameters for each of the selected models were tested for stability over different time periods by a series of LR tests. The first series of tests was conducted on the timerep band data set and then repeated on the pseudo timerep data sets. Each series consisted of a general hypothesis that all the parameters were the same for each time period. Rejection of this hypothesis indicated a difference in parameters over the time periods and led to a second series of tests to determine whether each time period required different parameters.

In general, let $\beta 0$, $\beta 1$, and $\beta 2$ be the parameters in a projection or increment model that is fitted from the stand characteristics in the band data. The timereps (1, 2, and 3) are represented by the decomposition of the above parameters β_0, β_1, and β_2 such that

$\beta_0 \rightarrow \beta_{01}, \beta_{02}, \beta_{03}$
$\beta_1 \rightarrow \beta_{11}, \beta_{12}, \beta_{13}$
$\beta_2 \rightarrow \beta_{21}, \beta_{22}, \beta_{23}$

e.g., β_{01} is the β_0 parameter representing timerep 1, and so on.

In order to perform an LR test for an overall difference among the timereps, the following null and alternative hypotheses were used:

(1) H_0: $\beta_{01} = \beta_{02} = \beta_{03} = \beta_0$ $\quad H_A$: $\beta_{01} \neq \beta_{02} \neq \beta_{03} \neq \beta_0$
$\beta_{11} = \beta_{12} = \beta_{13} = \beta_1$ $\quad \beta_{11} \neq \beta_{12} \neq \beta_{13} \neq \beta_1$
$\beta_{21} = \beta_{22} = \beta_{23} = \beta_2$ $\quad \beta_{21} \neq \beta_{22} \neq \beta_{23} \neq \beta_2$

The full model (H_A) and a reduced model $(H_,)$ for the above hypotheses consisted of the parameters respectively: β_{01}, β_{02}, β_{03}, β_{11}, β_{12}, β_{13}, β_{21}, β_{22}, β_{23}, and β_0, β_1, β_2. LR test statistics were used to test the above hypotheses. If F > $F_{(\alpha;\rho,v-\kappa)}$ then H_0 is rejected, where a is the level of significance and r, n-k is the numerator and denominator degrees of freedom for the likelihood F-statistic, respectively. If the above H_0 was rejected (indicating a significant difference among parameters) then the following hypotheses were tested to isolate and identify which individual parameters were candidates for further modification.

(2-β_0) H_0: $\beta_{01} = \beta_{02} = \beta_{03} = \beta_0$ $\quad H_A$ for all H_0's is:
$\beta_{11} \neq \beta_{12} \neq \beta_{13} \neq \beta_1$ $\quad H_A$: $\beta_{01} \neq \beta_{02} \neq \beta_{03} \neq \beta_0$
$\beta_{21} \neq \beta_{22} \neq \beta_{23} \neq \beta_2$ $\quad \beta_{11} \neq \beta_{12} \neq \beta_{13} \neq \beta_1$
$\beta_{21} \neq \beta_{22} \neq \beta_{23} \neq \beta_2$

(2-β_1) H_0: $\beta_{01} \neq \beta_{02} \neq \beta_{03} \neq \beta_0$
$\beta_{11} = \beta_{12} = \beta_{13} = \beta_1$
$\beta_{21} \neq \beta_{22} \neq \beta_{23} \neq \beta_2$

(2-β_2) H_0: $\beta_{01} \neq \beta_{02} \neq \beta_{03} \neq \beta_0$
$\beta_{11} \neq \beta_{12} \neq \beta_{13} \neq \beta_1$
$\beta_{21} = \beta_{22} = \beta_{23} = \beta_2$

Generalization to Pseudo Timerep Plots

To check the consistency of the time-replication analyses, it was desirable to generalize the study to older stands. To accomplish this, the pseudo timerep data sets were used and similar LR tests were performed.

RESULTS AND DISCUSSION

The results presented in this paper deal primarily with the parameter stability analysis, which was performed to determine whether there were any significant changes in the parameters of the selected models during a projection period of 25 years. Candidate models for each dependent variable BA,, SV,, BAI, SVI, and bai were developed and tested for the stability of parameters.

Thinning Considerations

LR tests for the thinning component obtained, using the projection models [equations (1) and (2)], consistently found that there were no significant effects of thinning in the timerep band data. This result was not unexpected since, as already mentioned, thinning was light to moderate and was from below, and previous studies had failed to identify any significant impacts.

Stand Level Models

Stand level projection models-Parameters in projection models [equations (1) and (2)] were estimated using standard nonlinear estimation techniques. The results of the hypothesis tests (1,2-β_0, and 2-8,) are given in table 1.

Stand level increment models-The following candidates for the increment models were developed using Stepwise and Maximum R-square procedures:

$$BAI = \beta_0 + \beta_1\left(\frac{N_1}{A_1}\right) + \beta_2\left(\frac{SI}{A_1}\right) \tag{4}$$

$$SVI = \beta_0 + \beta_1\left(\frac{N_1}{A_1}\right) + \beta_2\left(\frac{SV_1}{A_1}\right) \tag{5}$$

Results of the LR tests for equations (4) and (5) are given in table 2.

Individual Tree Growth Model

A distance-independent individual tree growth model [equation (3)] was fitted using a nonlinear estimation technique. This model fitted well with the timerep band data set (N=23190). The individual tree model [equation (3)] has six parameters and, therefore, decomposing all of its parameters simultaneously to represent three timereps would result in a full model with 18 parameters in the LR tests (as expected, these models failed to converge due to over-parameterization). To overcome this, an LR test was performed by decomposing one parameter at a time to represent different timereps while keeping all the other parameters constant. Table 3 gives the parameters and respective likelihood F-ratios, and their corresponding level of significance.

Parameter Stability Analysis

These analyses used the timerep band data, where effects due to thinning and other stand dynamics are already accounted for or minimized. The projection models [equations (1) and (2)], increment models [equations (4) and (5)] utilizing stand level values were used in the analysis. Table 1 shows the results of the hypotheses tests for all parameters for the above mentioned projection models. The LR test based on hypothesis 1 (table 1) indicated an overall significant difference among the parameters across all three timereps. The overall significant difference was consistent for the surrogate volume projection model [equation 2] (table 1). Results of hypotheses tests 2-β_0 and 2-8, in table 1 further show that the parameter β_0 is the more suitable candidate to represent differences in the three timereps and the parameters β_{11}, β_{12}, and β_{13} can be collapsed to a single parameter β_1.

Analyses performed using the increment models [equations (4) and (5)] (table 2) also indicated an overall significant

Table l-Results of LR tests on three timereps using projection models [equation (1) and (2)]

Hypothesis	BA_2 F-Value/ Prob > F	SV_2 F-Value/ Prob > F	Parameter tested
1. Full model ($\beta_{01}, \beta_{02}, \beta_{03}, \beta_{11}, \beta_{12}, \beta_{13}$) Reduced model ($\beta_0, \beta_1$) H_0: $\beta_{01} = \beta_{02} = \beta_{03} = \beta_0$, $\beta_{11} = \beta_{12} = \beta_{13} = \beta_1$; H_A: $\beta_{01} \neq \beta_{02} \neq \beta_{03} \neq \beta_0$, $\beta_{11} \neq \beta_{12} \neq \beta_{13} \neq \beta_1$	8.6002/ 0.0001	4.1480/ 0.0036	both β_0, β_1
2-β_0. Full model ($\beta_{01}, \beta_{02}, \beta_{03}, \beta_{11}, \beta_{12}, \beta_{13}$) Reduced model ($\beta_0, \beta_{11}, \beta_{12}, \beta_{13}$) H_0: $\beta_{01} = \beta_{02} = \beta_{03} = \beta_0$, $\beta_{11} \neq \beta_{12} \neq \beta_{13} \neq \beta_1$; H_A: $\beta_{01} \neq \beta_{02} \neq \beta_{03} \neq \beta_0$, $\beta_{11} \neq \beta_{12} \neq \beta_{13} \neq \beta_1$	3.5873/ 0.0308	3.66361 0.0287	β_0 only
2-β_1. Full model ($\beta_{01}, \beta_{02}, \beta_{03}, \beta_{11}, \beta_{12}, \beta_{13}$) Reduced model ($\beta_{01}, \beta_{02}, \beta_{03}, \beta_1$) H_0: $\beta_{01} \neq \beta_{02} \neq \beta_{03} \neq \beta_0$, $\beta_{11} = \beta_{12} = \beta_{13} = \beta_1$; H_A: $\beta_{01} \neq \beta_{02} \neq \beta_{03} \neq \beta_0$, $\beta_{11} \neq \beta_{12} \neq \beta_{13} \neq \beta_1$	2.91881 0.0580	2.26401 0.1085	β_1 only

$$BA_2 = BA_1\left(\frac{A_1}{A_2}\right)^{1.44324} e^{5.51592\left[1-\left(\frac{A_1}{A_2}\right)^{1.4432}\right]} \text{ and}$$

$$SV_2 = SV_1\left(\frac{A_1}{A_2}\right)^{1.64644} e^{10.00578\left[1-\left(\frac{A_1}{A_2}\right)^{1.64644}\right]}$$

difference among the parameters across all three timereps. Parameter β_1 was the most suitable candidate for modification (table 2) for the increment models.

The results of the individual tree growth model LR tests (table 3) verify the results found using stand level models. Furthermore, they suggest that any parameter is a suitable candidate for modification.

The timerep analyses clearly indicated that the parameters of the models change across all timereps. This strongly indicates that the parameters of the projection and increment models do not remain stable over the 25-year period. Furthermore, the analysis also indicates that unless the difference is explained by some means, these models may be biased and inefficient when predicting growth for a longer period of time.

Generalization to Pseudo Timerep Plots

Generalization of the timerep analysis was conducted using pseudo timerep data. Hypothesis test 1 was performed using only the basal area increment model [equation (4)] (table 4). In general, the results identified significant differences for all age classes except above 85 years. The pseudo timerep results coincide with the findings obtained in the previous parameter stability analyses and support the generalization of significant growth changes occurring over time within the overall RLGS data set.

CONCLUSIONS

Significant changes in the parameters among three time periods were found in all of the models tested, using a number of model forms and dependent variables. The instability of the parameters might be due to omission of some relevant variable that is attributable for that change. The omitted variable might be identified by correlating several important variables with the residuals from the mis-specified models (for details see Rayamajhi 1996). In the timerep band, most important variables included in a growth-and-yield model were either isolated or accounted for in the model form. The only important variable, which was left out is climate. Inclusion of climate might help stabilize the parameters of these models. The other way of avoiding the instability would be to only project growth-and-yield for short periods of time.

Table 2—Results of LR tests (together and separately for each coefficient) on three timereps using increment models [equation (4) and (5)]

Hypothesis	BAI F-Value/ Prob > F	SVI F-Value/ Prob > F	Parameters tested
1[a]. Full model ($\beta_{01}, \beta_{02}, \beta_{03}, \beta_{11}, \beta_{12}, \beta_{13}, \beta_{21}, \beta_{22}, \beta_{23}$) Reduced model ($\beta_0, \beta_1, \beta_2$) H_0: $\beta_{01} = \beta_{02} = \beta_{03} = \beta_0$ $\beta_{11} = \beta_{12} = \beta_{13} = \beta_1$ $\beta_{21} = \beta_{22} = \beta_{23} = \beta_2$ H_A: $\beta_{01} \neq \beta_{02} \neq \beta_{03} \neq \beta_0$ $\beta_{11} \neq \beta_{12} \neq \beta_{13} \neq \beta_1$ $\beta_{21} \neq \beta_{22} \neq \beta_{23} \neq \beta_2$	2.71311 0.0572	2.73791 0.0161	all β_0, β_1 & β_2
[b]. Full model ($\beta_{01}, \beta_{02}, \beta_{03}, \beta_1, \beta_2$) Reduced model ($\beta_0, \beta_1, \beta_2$) H_0: $\beta_{01} = \beta_{02} = \beta_{03} = \beta_0$ $\beta_{11} = \beta_{12} = \beta_{13} = \beta_1$ $\beta_{21} = \beta_{22} = \beta_{23} = \beta_2$ H_A: $\beta_{01} \neq \beta_{02} \neq \beta_{03} \neq \beta_0$ $\beta_{11} = \beta_{12} = \beta_{13} = \beta_1$ $\beta_{21} = \beta_{22} = \beta_{23} = \beta_2$	0.1913/ 0.9413	1.50811 0.2045	only β_0
[c]. Full model ($\beta_0, \beta_{11}, \beta_{12}, \beta_{13}, \beta_2$) Reduced model ($\beta_0, \beta_1, \beta_2$) H_0: $\beta_{01} = \beta_{02} = \beta_{03} = \beta_0$ $\beta_{11} = \beta_{12} = \beta_{13} = \beta_1$ $\beta_{21} = \beta_{22} = \beta_{23} = \beta_2$ H_A: $\beta_{01} = \beta_{02} = \beta_{03} = \beta_0$ $\beta_{11} \neq \beta_{12} \neq \beta_{13} \neq \beta_1$ $\beta_{21} = \beta_{22} = \beta_{23} = \beta_2$	2.93131 0.0238	3.75451 0.0066	only β_1
[d]. Full model ($\beta_0, \beta_1, \beta_{21}, \beta_{22}, \beta_{23}$) Reduced model ($\beta_0, \beta_1, \beta_2$) H_0: $\beta_{01} = \beta_{02} = \beta_{03} = \beta_0$ $\beta_{11} = \beta_{12} = \beta_{13} = \beta_1$ $\beta_{21} = \beta_{22} = \beta_{23} = \beta_2$ H_A: $\beta_{01} = \beta_{02} = \beta_{03} = \beta_0$ $\beta_{11} = \beta_{12} = \beta_{13} = \beta_1$ $\beta_{21} \neq \beta_{22} \neq \beta_{23} \neq \beta_2$	0.50671 0.7309	3.1693 0.0164	only β_2

$$BAI = 1.44608 + .03009\left(\frac{N_I}{A_I}\right) + .59807\left(\frac{SI}{A_I}\right) \text{ and}$$

$$SVI = 230.02059 + 1.31047\left(\frac{N_I}{A_I}\right) + 1.13628\left(\frac{SV_I}{A_I}\right)$$

Table 3-Likelihood F-ratio and probability levels for testing the sensitivity of individual parameters in the model to changes over time while all other parameters are unchanged for the band data set

Parameter	F-ratio	P > F
a_0	76.5699	0.0001
a_1	96.9675	0.0001
b_0	72.5176	0.0001
c_0	86.9414	0.0001
c_1	89.0613	0.0001
c_2	85.3636	0.0001

Table 4-Generalization of **timerep** analysis using pseudo **timerep** data sets and the increment model [equation **(4)**]

Age range	N	F-value	Prob >F	Conclusion
25-34	142	2.0894	0.0585	Significant at 10% level
35-44	138	2.2212	0.0450	Significant difference
45-54	123	1.8736	0.0913	Significant at 10% level
55-64	143	3.3978	0.0038	Significant difference
65-74	116	1.9939	0.0728	Significant at 10% level
75-84	79	1.8961	0.0936	Significant at 10% level
85-94	55	0.8620	0.5921	No difference

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SIMULATING THE UNEVEN-AGED MANAGEMENT OF SOUTHERN LOBLOLLY PINE: FEATURES OF THE SOUTHPRO COMPUTER PROGRAM

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Abstract-The SouthPro software simulates the growth of uneven-aged stands of mixed pines and hardwoods in the Southern United States. It is based on a density-dependent matrix growth model calibrated from permanent plots of the SO-FIA database. The model was calibrated with out-of-sample plots and predictions of undisturbed growth. The model keeps track of the number of trees in 13 diameter classes for pines and other softwoods, soft hardwoods, and hard hardwoods. Regeneration, growth, and mortality are affected by stand state and by the interaction between trees of different species and size. Stand state also affects tree form and, thus, the standing volumes of saw logs and pulpwood. SouthPro also monitors the Shannon diversity of stands by tree species and size and the income obtained from harvests. The SouthPro software is an Excel add-inn, with features to facilitate data input, error checking, and output interpretation. The output of SouthPro is tabular and graphical. The effects of different residual diameter distributions on diversity and income in loblolly pine stands, given different initial conditions, is discussed.

INTRODUCTION

The 50 million acres of loblolly-shottleaf pine forests in the Southeastern United States contain over two-thirds of the region's standing merchantable volume (Powell and others 1993). These forests are generally managed with even-aged silvicultural techniques; yet there is growing interest in uneven-aged management, particularly among the private nonindustrial owners who control over two-thirds of this acreage (Murphy and Farrar 1983), and within government land management agencies.

Uneven-aged silviculture of this forest type has much to recommend it. It has been used successfully to manage individual stands for more than 50 years (Reynolds and others 1984, Baker 1986). It produces butt logs of comparable volume and form class and of higher grade than logs from even-aged plantations (Guldin and Fitzpatrick 1991), and sawtimber board-foot volumes are at least as high as those from even-aged stands (Guldin and Baker 1988). Williston (1978) notes that uneven-aged management may be particularly appealing to landowners who can afford little capital investment, have few acres to manage, wish to maintain a continuous forest cover, or who desire a more frequent income. He also points out that it is better adapted to steep slopes, fragile soils, very dry sites, and high water tables; maintains genetic variability; and provides the structural diversity favored by many game and nongame species. In addition, it can be used to rehabilitate understocked stands (Baker 1986, Baker 1989, McLemore 1983) or to approximate advanced successional stages (Guldin 1996). Moreover, the present net value of returns from uneven-aged silviculture can be higher than that from even-aged silviculture when interest rates are high (Chang 1981, Redmond and Greenhalgh 1990) or when the initial stand is not valued as a cost (Guldin and Guldin 1990). Finally, selection harvests disturb a smaller percentage of the stand than clearcuts (Kluender and Stokes 1994) and, for many people, are likely to be less esthetically displeasing.

Uneven-aged management of these forests is not a panacea, however. It will likely require greater technical expertise than even-aged management (Hotvedt and Ward 1990). It is more difficult to regulate harvests on an even-flow basis (Williston 1978). And uneven-aged stands are not as efficient at producing pulpwood (Baker and others 1991, Guldin and Baker 1988, Williston 1978). Nevertheless, growing public sentiment against even-aged silviculture and the increasing recognition of the importance of ecosystem management principles suggest that the acreage of loblolly pine managed with uneven-aged techniques is likely to increase.

The SouthPro program was developed to help forest owners and managers evaluate the economic and ecological consequences of alternative uneven-aged management regimes for loblolly pines. This paper discusses the growth model used by SouthPro, describes the SouthPro software, and provides examples illustrating some of its features.

THE GROWTH MODEL

The growth model of SouthPro is an extension of the matrix model of Lu and Buongiorno (1993). The growth matrix describes the effects of standing trees on the ingrowth of different species and on the probabilities that trees of a given size-class and species will stay in their present size-class, grow into the next larger size-class, or die during a 1 -year interval. To express the effect of stand density on tree growth and mortality, the growth matrix is a function of the residual stand basal area (Solomon and others 1986, Buongiorno and others 1995, Lin and others 1996). The growth matrix also varies with site productivity (Lin and others, in press).

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Data

Data from the Southern Forest Inventory and Analysis (SO-FIA) database were used to estimate equations for ingrowth, upgrowth, and mortality. The complete SO-FIA database consists of approximately 18,000 permanent point plots. Plots with more than one age class in the major or dominant species are classified as "mixed age." Site productivity ranges from 1 to 7. A rating of site 7 is used for a potential yield of less than 20 cubic feet/acre/year, site 6 for 20 to 49, site 5 for 50 to 84, site 4 for 85 to 119, site 3 for 120 to 164, site 2 for 165 to 224, and site 1 for more than 225 cubic feet/acre/year.

Calibration plots-A subset of 991 permanent plots was selected for use in calibrating the growth model. It consisted of all the plots that: (1) had been remeasured, (2) were classified as being of the loblolly pine forest type in the previous inventory, (3) were classified as "mixed age" in the previous inventory, and (4) showed no evidence of having been regenerated artificially. Each plot had been measured twice between 1978 and 1994, at an average interval of 7.3 years.

Species groups and size-classes-To estimate the model, trees were grouped as in the SO-FIA species group classifications: pines and other softwoods, soft hardwoods, and hard hardwoods. Within each species group, trees were also classified into 13 diameter at breast height (d.b.h.) size-classes. Size-classes ranged from 2 to 26+ inches at 2-inch intervals. Size-class 2 (the smallest) included trees with diameters ranging from 1 inch to less than 3 inches. Size-class 26+ (the largest) included all trees 25 inches in diameter and larger.

Model Estimation

Each plot gave one observation on ingrowth, upgrowth, and mortality. Ingrowth was defined as the number of trees per acre per year that became larger than 1 inch d.b.h. The transition probabilities and ingrowth were also expressed per year. The parameters of the equations were obtained by multiple regression, across all plots. The upgrowth probability is a function of tree species, residual stand basal area, tree diameter, and site productivity class. The mortality probability is a function of tree species, residual stand basal area, and tree diameter. For a given species, the annual ingrowth is a linear function of the stand basal area and the number of trees of that species (Lin and others, in press).

Model Validation

The growth model was developed from 80 percent of the plots selected randomly from the 991 available. To test its accuracy, the model was then used to predict the state of the remaining plots at the time of their second measurement, given their state at the first inventory and possible harvest. A series of t-tests showed that the predicted mean number of trees in each size-class category was not significantly different from the observed mean, at the 5 percent significance level.

To test the long-term behavior of the growth model, it was used to predict the growth of stands, without harvest, over three centuries. Simulations were performed for a high productivity site and a low productivity site. In both cases, the model predictions were consistent with ecological studies of climax forests of this type (Lin and others, in press).

Tree Volumes and Values

To calculate economic returns, SouthPro multiplies the pulpwood and sawtimber volumes of the average tree in each size-class and species group by the appropriate price per unit of volume and then sums the resulting individual tree values over all trees. For saplings (trees with d.b.h. less than 5 inches), tree values are set to zero. For trees with d.b.h. equal to or greater than 5 inches, the individual tree volumes of sawtimber and pulpwood depended on tree and stand conditions. SouthPro includes equations for calculating tree heights, saw log lengths, pulpwood volumes, and saw log volumes (Lin and others, in press).

The total height of a tree is a function of species, d.b.h., residual stand basal area, and site productivity. The equations were estimated from more than 18,000 trees on the 991 plots used to develop the growth model. Approximately 12,000 trees of saw log length were used to estimate the equations for saw log length, a function of species, d.b.h., and total tree height. SouthPro recognizes two potential sources of pulpwood: pulpwood trees and the tops of sawtimber trees. The volume of pulpwood trees is a function of species, d.b.h., total tree height, and saw log length, based on Clark and Souter's data (1994). The volume of saw logs in cubic feet is a function of species, d.b.h., total tree height, and saw log length, also based on the data of Clark and Souter (1994). SouthPro used Koch's conversion table (1972, p. 1593) to convert sawtimber cubic-foot volumes to board-foot volumes.

THE SOUTHPRO SOFTWARE

SouthPro was written in the Visual Basic programming language and compiled as an add-in program for Microsoft Excel. Once installed and activated, it can be accessed whenever Excel is running, giving the user simultaneous access to both its features and those of Excel. It is available in a Windows and a Macintosh version, each version featuring menu-driven commands and dialog-box interfaces typical of its respective environment. The SouthPro users manual describes the program's features and includes a step-by-step tutorial designed to help new users learn the program (Schulte and others, in press).

Input Data

SouthPro provides an Input Data worksheet for entering the data for a simulation. Required input data include the initial stand state, target stand state(s), cutting cycle parameters, loblolly pine site index, stumpage prices, interest rate, and fixed costs of administration and hardwood control.

The initial stand state or distribution is defined as the number of live trees per acre in each species group and size-class at the start of a simulation. Similarly, a target stand state is the desired number of live trees per acre in each species-size category after a harvest. All trees in excess of the target number in any species-size category are cut at each harvest. To accommodate the simulation of silvicultural systems with an intermediate harvest, SouthPro allows users to enter two target states. In addition, to assist users who practice the BDq method of stand regulation (see for example Baker and others 1996, Farrar 1996), SouthPro includes a BDq Distribution Calculator. It can be used to calculate BDq distributions and copy them to the Input Data worksheet as either initial or target stand states for each species group. Before performing a simulation, SouthPro checks the input data for errors.

Output Worksheets

SouthPro writes the output from each simulation to two worksheets. The Stand Development output worksheet shows, for each year, the size distribution and total basal area of each species group and the Shannon indices of species and size diversity based on the basal area of trees at the beginning of each year and after each harvest.

The Products output worksheet shows, for each harvest year: the basal area cut, the volume of pulpwood and sawtimbers removed by species group, the gross income generated, and the net present value of the harvest. It also reports the total net present value of the stand and its mean annual production in terms of basal area cut and volumes harvested.

Output Charts

SouthPro can generate six different types of charts. Each chart type has a separate dialog box for selecting the years and data series to be plotted. Data on a Stand Development worksheet can be used to create Diversity Indices charts, Size Distribution charts, or Stand Basal Area charts, for pre- and postharvest stand conditions. Diversity Indices charts show changes in the Shannon index of species and/or size diversity. Size Distribution charts show the number of live softwood, soft hardwood, and/or hard hardwood trees in each size-class. Stand Basal Area charts show the per-acre basal area of softwoods, soft hardwoods, hard hardwoods and/or the entire stand.

Data on a Products worksheet can be used to create Basal Area Cut charts, Gross Income charts, or Volume Cut charts, for selected harvest years. Basal Area Cut charts show the total basal area cut, in square feet per acre. Gross Income charts show the gross income generated, in dollars per acre. Volume Cut charts show the cubic-foot volume of pulpwood and/or sawtimber removed from each of the three species groups.

Setup Files

SouthPro also provides dialog boxes for creating, deleting, and loading setup files. Setup Files are collections of related input data, stored together on a Setup File worksheet. Setup files may contain input data for initial stand states, target stand states, cutting cycle parameters, stumpage prices, and fixed costs. Once sets of input data have been stored as setup files, they can be loaded in various combinations to either the Input Data worksheet to run a single simulation or to SouthPro's Batch File worksheet to run a batch of simulations. SouthPro allows batches of up to 500 simulations to be run sequentially.

Stock-and-Cut Tables and Marking Guides

SouthPro can generate stock-and-cut tables from any user-selected preharvest and target distribution. SouthPro's stock-and-cut tables show, for the selected preharvest and target distributions, the cut and residual stand distributions, by species and size. The tables also list the basal area, cubic-foot volume, and board-foot volume of the trees in each species-size category. Additionally, they show the annual cubic-foot growth of stands with the preharvest, target, and residual distributions. Lastly, for each stock-and-cut table, SouthPro calculates the corresponding marking guide: the number of trees to cut, for each species group, in each of four product classes: pulpwood, small sawtimbers, medium sawtimbers, and large sawtimbers.

EXAMPLE APPLICATION OF SOUTHPRO

SouthPro can be used to simulate a wide range of management regimes, from doing nothing to cutting at different intensities and timings. As an example, we summarize the effects of three management regimes, defined by a cutting cycle and target distribution, on stand characteristics and revenues over 120 years. The simulations were performed for a high (site class 3) and a low (site class 5) productivity site. The initial stand state for each simulation was the average species-size distribution at the second inventory of calibration plots with the same site class (table 1), and each simulation used a cutting cycle of 6 years.

Table I-Average number of trees per acre on site 3 and site 5 calibration plots at the second inventory, by species group and size-class

Site 3				Site 5			
D.b.h.	SW	SH	HH	D.b.h.	SW	SH	HH
in				*in*			
2	69.4	147.2	144.6	2	157.8	145.3	290.3
4	35.4	41.7	35.2	4	67.6	23.3	45.8
6	21.2	15.0	11.2	6	40.9	8.8	9.8
8	16.1	6.6	5.9	8	25.9	4.7	6.0
10	11.4	3.0	3.0	10	9.1	1.8	1.4
12	10.2	1.5	1.7	12	6.8	0.7	1.6
14	7.9	0.6	1.3	14	3.9	0.3	1.2
16	5.2	0.3	0.9	16	1.4	0.1	0.0
18	3.3	0.2	0.5	18	0.7	0.1	0.7
20	1.6	0.1	0.3	20	0.2	0.0	0.3
22	0.8	0.0	0.2	22	0.1	0.0	0.2
24	0.4	0.0	0.1	24	0.1	0.0	0.2
26+	0.3	0.0	0.1	26+	0.1	0.0	0.1

D.b.h. = diameter at breast height.
sw = pines and other softwoods, SH = soft hardwoods, HH = hard hardwoods.

Target States

The target distribution for the "diversity" regime (table 2) had a merchantable (5 inches d.b.h. and larger) basal area of 55 square feet per acre. The basal area was distributed evenly among each size-class and species group, giving it the largest possible values of Shannon's diversity index by species (1 .10) and size (2.56).

The "income" regime used as a target for softwoods a BDq distribution with a merchantable basal area of 55 square feet per acre, a maximum diameter of 15 inches, and a q-ratio of 1.3. It assumed that all hardwoods were cut at each harvest and that no submerchantable softwoods were cut (table 2).

The "compromise" regime used BDq distributions for all three species groups. Each distribution had a maximum diameter of 15 inches and a q-ratio of 1.3. The merchantable basal areas for the softwoods, soft hardwoods, and hard hardwoods were 47.5, 2.5, and 5 square feet per acre, respectively. No submerchantable tree was cut (table 2).

Simulation Results

Table 3 shows the present value of gross income, timber productivity, and diversity values, by site and management regime. A real interest rate of 3 percent per year and 1996 average stumpage prices for Southeastern States (Timber Mart-South, 1st Quarter 1997) were used to calculate the present value of gross income. Gross, rather than net, revenues were used because costs were not known. However, sensitivity analysis showed that, in each case, the net present value would decrease by $6 for each additional $1 in fixed costs. The present value produced by the income guide was 1.7 times larger than that produced by the diversity guide for good sites and over 3 times larger for poor sites; whereas the present value produced by the compromise guide was only 5 percent less than that produced by the income guide for good sites and 9 percent less for poor sites. Regardless of regime, the present values were about $2400 per acre larger on good sites than on poor sites.

For both sites, the income and compromise guides cut similar amounts of basal area and volumes, but the composition of the harvest was quite different, with the compromise guide producing a much higher proportion of hardwoods. The diversity guide also produced a high proportion of hardwoods, but cut considerably less basal area and volume than the other guides.

The diversity guide produced the largest average diversity of tree size and species over 120 years. The species diversity obtained by the income guide was very low, dropping to zero for pos-harvest stand states. By leaving some trees in each species at all times, the compromise guide produced stands with species diversity approaching that produced by the diversity guide. The income and compromise guides each resulted in stands with moderate size diversity.

Table 2—Target number of trees per acre after a cut, by species group and size-class

	Diversity guide			Income guide			Compromise guide		
D.b.h.	SW	SH	HH	SW	SH	HH	SW	SH	HH
in									
2	9.0	9.0	9.0	*	0.0	0.0	*	*	*
4	6.9	6.9	6.9	*	0.0	0.0	*	*	*
6	5.3	5.3	5.3	36.2	0.0	0.0	31.3	1.6	3.3
8	4.1	4.1	4.1	27.8	0.0	0.0	24.0	1.3	2.5
10	3.1	3.1	3.1	21.4	0.0	0.0	18.5	1.0	1.9
12	2.4	2.4	2.4	16.5	0.0	0.0	14.2	0.7	1.5
14	1.9	1.9	1.9	12.7	0.0	0.0	10.9	0.6	1.2
16	1.4	1.4	1.4	0.0	0.0	0.0	0.0	0.0	0.0
18	1.1	1.1	1.1	0.0	0.0	0.0	0.0	0.0	0.0
20	0.8	0.8	0.8	0.0	0.0	0.0	0.0	0.0	0.0
22	0.7	0.7	0.7	0.0	0.0	0.0	0.0	0.0	0.0
24	0.5	0.5	0.5	0.0	0.0	0.0	0.0	0.0	0.0
26+	0 . 4	0.4	0.4	0.0	0.0	0.0	0.0	0.0	0.0

D.b.h. = diameter at breast height.
* = Size-classes without a cut, SW = pines and other softwoods, SH = soft hardwoods, HH = hard hardwoods.

Table 3— Income, timber productivity, and Shannon diversity of stands managed under three different harvest regimes, over 120 years

	Diversity guide		Income guide		Compromise guide	
Site class:	3	5	3	5	3	5
Present value of gross income ($/acre):	3556	1149	6230	3796	5947	3457
Basal area cut (ft^2/ /acre/year):	1.9	1.6	3.0	2.8	3.5	3.0
Annual productivity (ft^3/acre):						
Softwood sawtimber	22.3	12.1	78.2	62.6	61.6	47.7
Softwood pulpwood	3.7	3.7	2.2	3.5	1.7	2.9
Soft hardwood sawtimber	1.7	0.8	0.4	0.1	2.0	1.7
Soft hardwood pulpwood	1.1	0.3	1.1	0.5	10.1	3.7
Hard hardwood sawtimber	5.0	2.4	0.8	0.3	3.5	2.0
Hard hardwood pulpwood	2.7	1.3	1.3	0.7	7.6	5.7
Average diversity:						
Species	1.09	1.08	0.09	0.10	0.96	0.96
Size	2.50	2.49	2.01	2.00	2.04	2.01

Summary Charts

Figures 1 and 2 illustrate two of SouthPro's charting options. Figure 1 shows the basal area growth of a stand managed with the compromise regime on a poor site. The basal area of softwoods increased over the first 30 years, then declined thereafter. The basal area of the soft hardwoods and hard hardwoods increased gradually over the 120-year period, with hard hardwoods remaining dominant to soft hardwoods throughout.

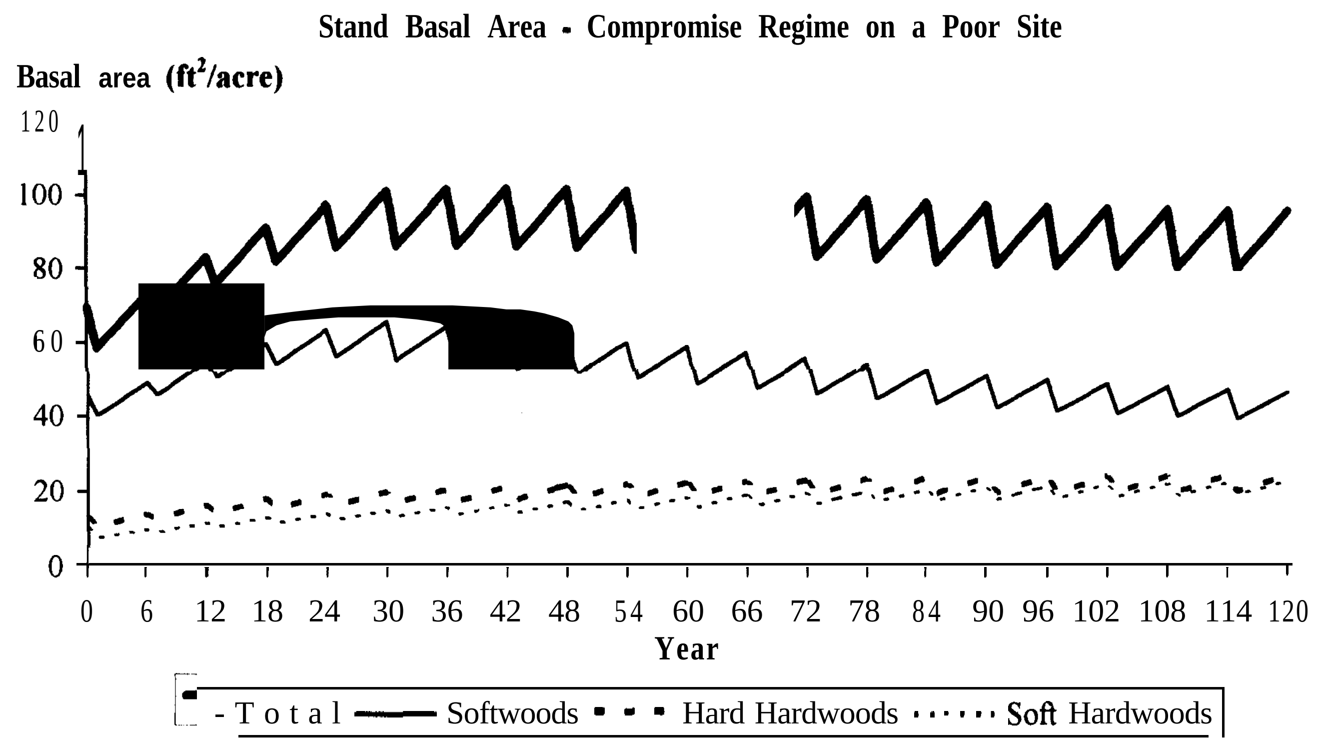

Figure l-Basal area growth of a loblolly pine stand managed with the compromise regime on a poor site.

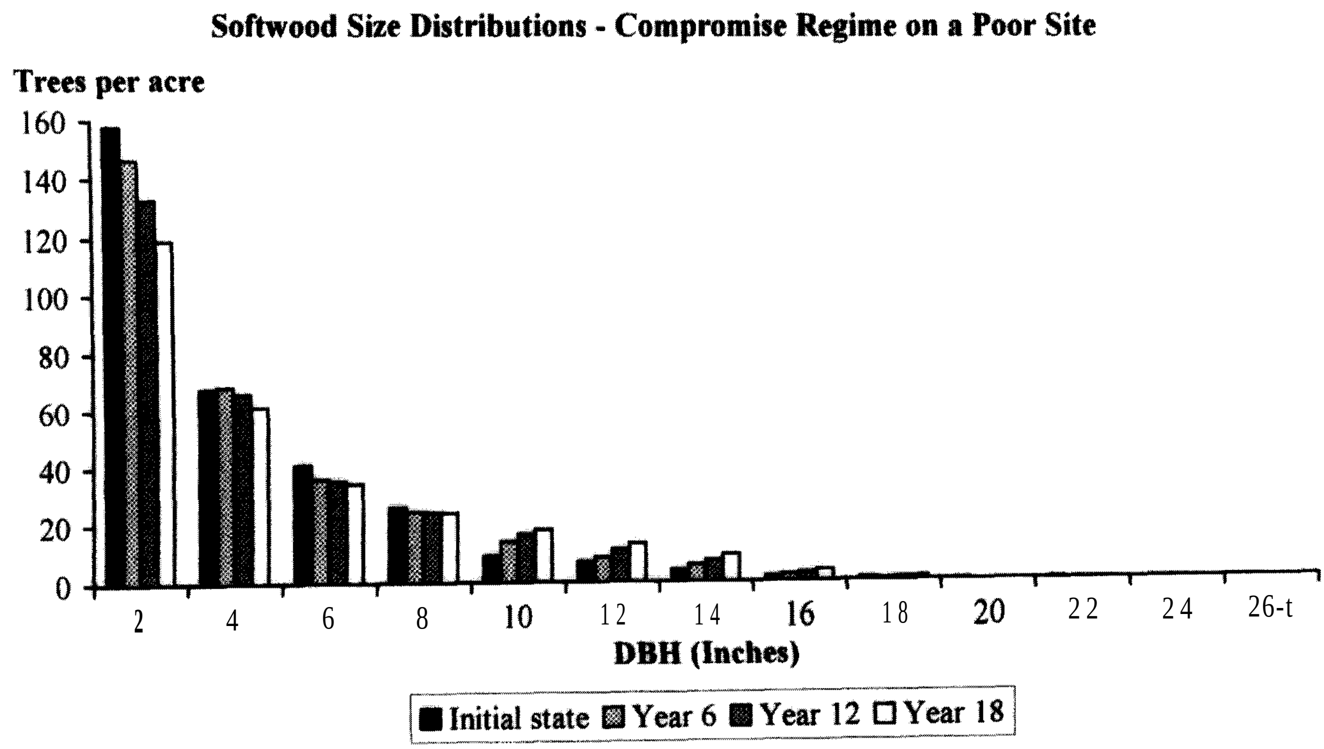

Figure 2-Preharvest size distributions of softwoods for a stand managed with the compromise regime on a poor site.

Figure 2 shows, for the same stand, the number of softwood trees per acre in each size-class for the first four pre-harvest states. The number of softwoods in the four smallest size-classes decreased over this interval, whereas the number of softwoods in the remaining size-classes increased. SouthPro can produce similar charts for the hardwood species.

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AN INDIVIDUAL TREE BASAL AREA GROWTH MODEL FOR UNEVEN-AGED STANDS OF SHORTLEAF PINE (*PINUS ECHINATA* Mill.) IN THE OUACHITA MOUNTAINS IN ARKANSAS AND OKLAHOMA

Onesphore Bitoki, Lawrence R. Gering, Thomas B. Lynch, and Paul A. Murphy[1]

Abstract-A distance-independent individual tree basal area growth model was developed for natural, uneven-aged stands of shortleaf pine in the Ouachita Mountains of Oklahoma and Arkansas; the data came from permanent inventory plots located on private industrial forests of the Deltic Farm & Timber Company, Inc. There were 452 plots established in 1965-66; in 1983 and 1988 there were, respectively, 132 and 236 additional plots established in order to cover all forest conditions found in the region. Only plots that have basal area between 30 and 90 ft^2/acre were used for this study. This resulted in 3,663 observations which were divided into two subsets: one for calibration (2,892 observations) and the second for validation (971 observations). A potential-modifier type model was chosen as the best individual tree basal area growth model for uneven-aged stands. The model had the lowest and most uniform deviations when predicted values were compared to observed values. The model explained 44.01 percent of the total variations and had a mean square error value of 0.000069. The model tended to overestimate basal area growth of trees with d.b.h. equal to or larger than 16 inches. The overestimation might have been due to having few sample trees in the larger d.b.h. classes. This model can be incorporated into a system including ingrowth and mortality functions in order to assess global stand growth dynamics in uneven-aged stand conditions. The model should be limited to conditions similar to the area of study.

INTRODUCTION

Modeling growth and yield of shortleaf pine (*Pinus echinata* Mill.) in the Southern United States has concentrated on even-aged stands. However, recently there are more concerns in managing forest stands by adopting an uneven-aged system in order to respond to an ever increasing desire of noncommodity products from public and private forests. Baker and others (1996) developed silvicultural guidelines for uneven-aged stands of loblolly and shortleaf pine stands to respond to new trends. In order to facilitate planning, a model for predicting future yields in such stands needs to be used. A literature survey showed little has been done in terms of individual tree modeling for uneven-aged stands of shortleaf in the Southern United States. However, a recent publication presents an individual-tree basal area growth model for loblolly pine (*P. taeda* L.) stands in Arkansas and Louisiana (Murphy and Shelton 1996).

Basal area of individual trees is used in mathematical models to estimate the volume of standing trees by measuring diameter at breast height (d.b.h.) and total or merchantable height. The aggregation of tree basal areas on a given unit area gives an indication of the degree of stocking, a useful description of stands and their development over time. The availability of sophisticated data analysis procedures has made the development of individual tree basal area models feasible.

The objectives of the study were (1) to develop a distance-independent individual-tree basal area growth model for natural uneven-aged stands of shortleaf pine in the interior highlands of Arkansas and Oklahoma, (2) to validate the model with data from an independent data set, and (3) to make recommendations regarding use of the model. The model predicts future individual-tree basal area growth for trees with d.b.h. equal to or greater than 5 inches.

DATA

The data came from 0.2-acre continuous forest inventory (CFI) plots established by the Deltic Farm & Timber Company, Inc., on forest lands located in the Ouachita Mountains of Arkansas. A total of 452 permanent plots were established between 1965-66 and were remeasured every 5 years until 1993. There were 132 and 236 additional plots installed in 1983 and 1988, respectively, in order to get a more representative data sample of all stand conditions found in the study area. A total of 820 permanent plots were installed in the uneven-aged stands, from which the data for the current study were drawn.

Individual tree records were maintained for all trees with d.b.h. 5.0 inches and larger. Pertinent information collected included (1) d.b.h. to the nearest 0.1 inch, (2) total merchantable height, (3) saw log height, (4) merchantable height for sawtimber trees, (5) tree history, and (6) crown position. Site index at base age 50 was estimated for each plot for shortleaf pine. Six basal area classes and four site index classes were selected to cover all major conditions found in the region of study. Stand basal area was estimated by aggregating all individual shortleaf basal area estimates per plot by class, and then multiplying by an expansion factor of five to obtain values on a per-acre basis. Summary statistics are provided for site index class and merchantable basal area class combinations for the shortleaf pine data set (table 1).

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Table I-Summary of treatment combinations comprising six classes of basal area per acre and four classes of site index (base age 50) for Deltic data set

Variable	Class Range	Midpoint
Merchantable	<11	
Basal area	11-29	20
(ft^2/acre)	30 - 49	40
	50 - 69	60
	70 - 89	80
	>89	
Site Index	<45	40
(Base age 50)	46 - 55	50
	56 - 65	60
	>65	70

Table 1 illustrates a potential of 24 treatment combinations, similar to Murphy and others (1985), with slight variations. Sawtimber basal area as used by Murphy and others (1985) was not included when creating the combinations because the purpose of the study was to develop an individual-tree basal area growth model without regard to product classification. Plots retained for model development were in natural uneven-aged stands with relatively uniform spacing of trees. All plots had at least 70 percent of basal area in shortleaf pine and less than 10 percent mortality of initial plot basal area. There had been no harvesting or thinning activities during the entire growth period.

Elimination of all the plots that did not meet this selection criteria left 319 plots. Many of these plots had basal area less than 30 or more than 90 ft^2 per acre. However, very few plots were present in merchantable basal area classes less than 11 ff per acre and classes greater than 90 ft^2 per acre. The same is true for all combinations of site index less than 45 and greater than 65. Baker and others (1996) suggested that uneven-aged stands having less than 30 ft^2 of basal area per acre are understocked while those with more than 90 ff are overstocked. Therefore, the data were balanced by further eliminating plots having less than 30 or more than 90 ft^2 basal area per acre of shortleaf pine at the beginning of the growth period.

The remaining plots were randomly assigned identification numbers. An unbalanced condition of data was expected since the data were collected from ordinary forest inventory operations, not from controlled permanent research plots. When establishing research plots, all forest conditions are represented with equal frequency in each condition, consequently requiring no further data balancing. For each merchantable basal area class, the maximum number Of plots allowed was restricted to 25. Because the data were mainly concentrated in a few site index and basal area classes, a restricted set of observations was randomly chosen to obtain a more uniform sample across the range of data. This procedure was also adopted by Murphy and Farrar (1985). The final selection reduced the total plots to 157, from which a total 3,663 observations (individual trees) were available for model development. Seventy-five percent of the total observations (2,692 observations) were randomly selected for calibrating the model and the remaining 25 percent (971 observations) were used for validation. Summary statistics are presented for variables used in the individual-tree basal area growth model development for the combined, calibration, and validation data sets (tables 2, 3, and 4, respectively).

The purpose of dividing the original data set into two subsets is to allow the development of estimates of the regression parameters using the calibration data set. Once the final model had been selected, the validation data set could then be used to determine the robustness of the model. It is important that two data sets contain variables that have common statistical properties, while remaining independent and mutually exclusive of each other. Tests of hypothesis about the mean for each variable concluded there were no

Table 2—Summary of descriptive statistics for seven variables included in the complete data set (3,663 observations) used for individual tree basal area growth model development

Variable at midpoint	Minimum	Maximum	Mean	Std Dev	Cv
					Percent
Site index (feet at base age 50)	35.00	73.5	56.34	7.35	13.06
Stand basal area (ft^2/acre)	37.08	115.23	72.71	17.07	23.48
Diameter at breast height for shortleaf pine (inches)	5.20	19.8	9.14	2.50	27.38
Quadratic mean diameter (inches)	6.35	12.95	8.93	1.22	13.66
Individual tree basal area (ff)	0.1475	2.1409	0.4911	0.2788	56.77
Average annual individual tree basal area growth (ft^2)	-0.00422	0.06849	0.0164	0.0111	67.24
Proportion of plot basal area of all trees as large or larger than the subject tree	0	0.99141	0.5866	0.2816	48.02

Table 3—Summary of descriptive statistics for seven variables included in the calibration data set (2,692 observations) used for individual tree basal area growth model development

Variable at midpoint	Minimum	Maximum	Mean	Std Dev	Cv
					Percent
Site index (feet at base age 50)	35.00	73.5	56.39	7.34	13.03
Stand basal area (ft^2/acre)	37.08	115.23	72.27	17.07	23.61
Diameter at breast height for shortleaf pine (inches)	5.25	19.8	9.11	2.50	27.49
Quadratic mean diameter (inches)	6.35	12.95	8.92	1.22	13.71
Individual tree basal area (ff)	0.1504	2.1409	0.4884	0.2779	56.91
Average annual individual tree basal area growth (ff)	-0.00419	0.06849	0.0164	0.0110	67.31
Proportion of plot basal area of all trees as large or larger than the subject tree	0	0.99141	0.5888	0.2813	47.78

Table 4-Summary of descriptive statistics for seven variables included in the validation data set (971 observations) used for individual tree basal area growth model development

Variable at midpoint	Minimum	Maximum	Mean	Std Dev	Cv
					Percent
Site index (feet at base age 50)	35.00	73.5	56.51	7.38	13.14
Stand basal area (ft^2/acre)	37.08	115.23	73.91	17.03	23.05
Diameter at breast height for shortleaf pine (inches)	5.20	19.2	9.21	2.45	27.06
Quadratic mean diameter (inches)	6.35	12.95	8.97	1.21	13.52
Individual tree basal area (ff)	0.1475	2.0115	0.4987	0.2812	56.40
Average annual individual tree basal area growth (ft^2)	-0.00422	0.05970	0.0167	0.0112	67.08
Proportion of plot basal area of all trees as large or larger than the subject tree	0	0.98690	0.5804	0.2826	48.68

significant differences (0.05 level) between corresponding variables, therefore, allowing the use of one subset for model development and the other for model validation.

MODEL DEVELOPMENT

Most individual-tree basal area growth models that have been developed are for even-aged stands and can be classified into two categories: direct and indirect models. An example of a simple direct basal area growth model is fully described by Wykoff (1986) in PROGNOSIS. Several variants of direct and indirect models were tried to establish the best to fit the data (Bitoki 1996). The basic structure for the individual-tree basal area growth model adopted was of the potential*modifier form. Theoretically, the potential growth model sets an upper limit size that a given tree cannot exceed (Hann and Leary 1979).

A potential*modifier function model is created in two stages. In the first step, a potential function is developed based on growth theories. Secondly, a modifier function is developed to adjust the potential growth to the actual growth achieved. The modifier function reflects environmental stress on the tree. These two steps produce a complex model having the following form:

Individual tree growth = (potential)*(modifier).

Several researchers have used this technique to produce an individual-tree growth model (Shifley 1987, Fairweather 1988, Belcher and others 1982, Hitch 1994). The potential function used was described by Shifley (1987) and is a version of the Chapman-Richards growth function.

$$Pot = b_1(BA)^{b2} - b_1/M^{(1-b1)}*BA \qquad (1)$$

where

pot = potential basal area growth,

BA = individual tree basal area (ft^2),

M = parameter, maximum tree basal area, and

b_i = parameters to be estimated.

This Chapman-Richards potential growth function ordinarily has three parameters, but only two need to be estimated with this version because the specification of maximum tree size fixes one of the parameters (Shifley and Brand 1984). This fixed parameter (M) represents the maximum size a tree can achieve and, therefore, is mathematically the maximum asymptote, where growth equals zero. The value of the parameter M equals 7.068384 (adapted from Hitch 1994).

The modifier function adopted was previously described by Murphy and Shelton (1993, 1996). This type uses individual tree competitive status in the stand, expressed by the total basal area of all trees per acre as large or larger than the subject tree (BAL) to adjust the potential growth to the growth actually achieved. The following general form was adopted:

$$\text{Modifier function} = 1/\{1 + \exp(b_1 BAL + b_3 BA + ..\text{add'l vars})\} \quad (2)$$

For a tree growing without competition, its actual growth equals the potential growth. Consequently, the modifier function has a maximum value of one, which is approached at an asymptotic rate, when the exponential term approaches zero. Alternatively, if the tree receives extensive competition, the modifier function approaches zero; this occurs when the exponential term grows to infinity. Parameters of the function are estimated by linear or nonlinear regression. The use of linear regression was accomplished by rearranging the equation as:

$$BAG = POTBAG/\{1 + \exp[b_1 BAL + b_2 BA + ..\text{add'l vars}]\} \quad (3)$$

and,

$$\ln[(POTBAG/BAG) - 1\} = (b_1 BAL + b_2 BA + ..\text{add'l vars}) \quad (4)$$

where

POTABAG = potential basal area growth (ft^2/yr),

BAG = individual tree basal area growth (ft^2/yr),

BA = individual tree basal area (ft^2), and

BAL = proportion of basal area per acre of all trees as large or larger than the subject tree.

Equation (4) is in a form where multiple linear regression can be applied. It is flexible so that additional variables that explain basal area growth can also be included; those not significant may be removed through stepwise techniques. The final implicit form obtained was:

$$AABAG = \frac{b_1 BA^{b2} - b_1/M^{(1-b2)} * BA}{1 + \exp(b_3 + b_4 SBA + b_5 BAL + b_6 SI + b_7 d.b.h.)} \quad (5)$$

where

aabag = annual average basal area growth (ft^2),

BA = individual tree basal area (ft^2),

M = individual tree maximum basal area,

SBA = stand basal area (ft^2/acre),

BAL = proportion of basal area of all trees per acre of all trees as large or larger than the subject tree,

SI = site index (base age 50), and

d.b.h. = diameter at breast height (in).

The fit index for this model was calculated as following:

$$\text{Fit Index} = 1 - \left\{\frac{\text{Error Sum of Squares}}{\text{Corrected Total Sum of Squares}}\right\} \quad (6)$$

The model had a fit index value of 0.43129 when fitted to the calibration data set and was consistent in terms of parameters when checked with the validation data set. Although this fit index may be low compared to other studies, it is reasonable because the data came from normal inventory plots, not from research plots where variation is controlled. This statistic measures the proportion of variation of the dependent variable accounted for by the model. Other statistics used to test the model were mean square error and average deviations. When fitted to the entire data set, the following explicit model (with a fit index value of 0.44016 when used with the entire data set) was obtained:

$$aabag = \frac{0.179337BA^{0.861911} - 0.179337/7.068384^{0.138089} * BA}{1 + \exp(-1.161198 + 0.015529SBA - 0.012761SI + 1.026556BAL - 0.013322dbh)} \quad (7)$$

Residual plots for the model by d.b.h. class were examined to detect any model bias and the model performed well throughout all d.b.h. classes (fig. 1). However, it must be noted that, due to having few trees represented in diameter classes 16 inches and greater, these trees were combined into one class to assess the model performance. The minimum tree diameter observed was 5.0 inches and the maximum tree diameter observed in the data of study was in the 20-inch d.b.h. class. Therefore, this model should not be used to predict growth of trees having sizes not represented in this study.

Similar plots were also analyzed by site index class and, again, the model performed well for all classes (fig. 2). Finally, the residuals were examined to detect model bias for stand basal area class and the model performed reasonably well across all classes (fig. 3). It can also be observed that average basal area growth deviations decrease as the stand basal area increases. The model shows that individual tree basal area growth decreases as the stand basal area increases, which is in agreement with forest growth theories (fig. 3).

RECOMMENDATIONS

Forest managers concerned with uneven-aged stands of shortleaf pine in the Ouachita Mountains of Oklahoma and Arkansas are the primary potential users of this model. This is the first individual-tree basal area growth model for uneven-aged shortleaf stands in the region, and should be a useful tool to predict future growth to provide needed

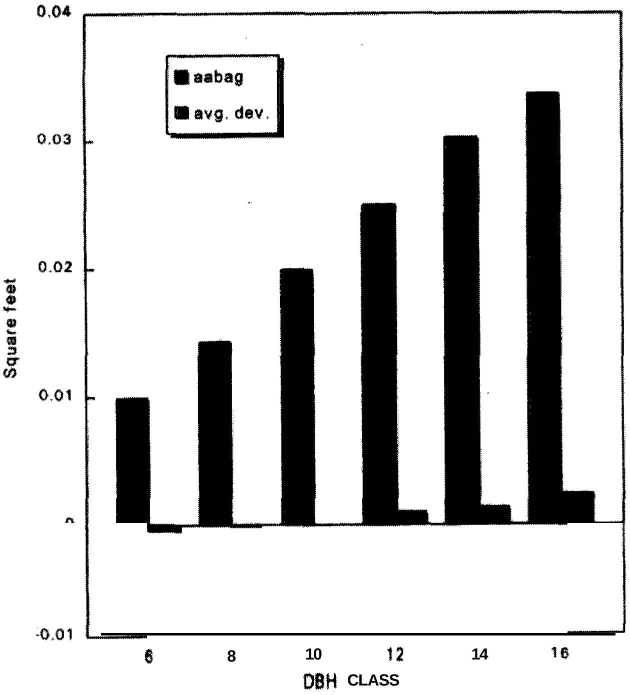

Figure l-Average deviations and mean annual basal area growth (aabag) by d.b.h. class (2-inch classes) for the model when fitted to the entire data set.

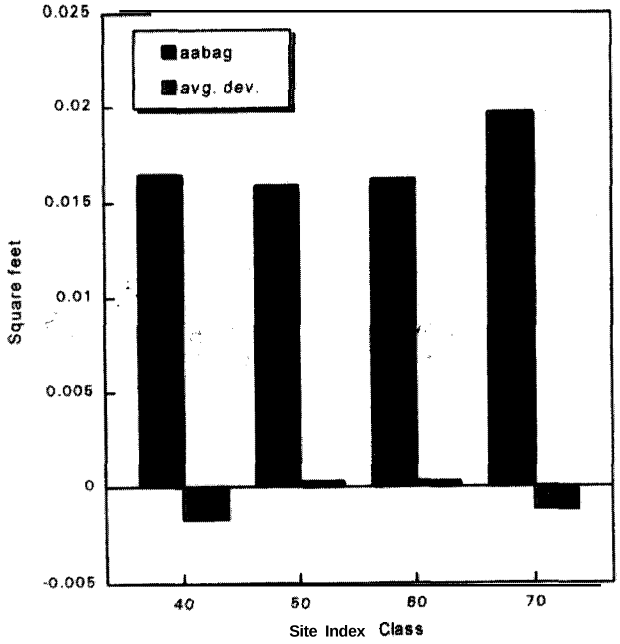

Figure 2-Average deviations and mean annual basal area growth (aabag) by site index class (base age 50 years) for the model when itted to the entire data set.

information for management decisions. This model can be incorporated with other functions such as survival and ingrowth models to predict uneven-aged shortleaf pine growth dynamics in the Ouachita Mountains. The model should be restricted to the region represented by the data used for the model development. Therefore, users are

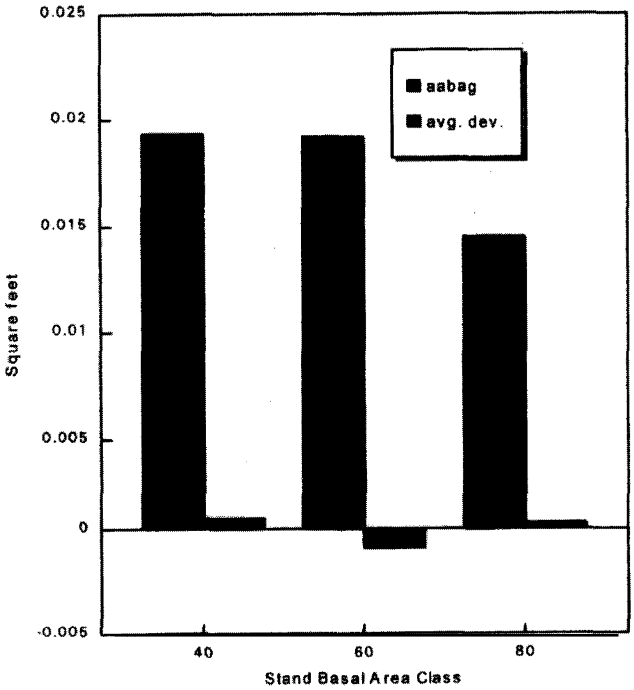

Figure 3-Average deviations and mean annual basal area growth (aabag) by stand basal area class (ft^2/ac) for the model when fitted to the entire data set.

encouraged to check and compare their stand characteristics to the data described in this study in order to discern whether their conditions are similar to the study area.

The data used for this study were from ordinal inventory permanent plots, not research plots. The data, therefore, may not have equally represented all possible stand conditions. Trees with a large d.b.h. (>16 inches) were not well represented in the data set; therefore, this model may not perform correctly for other stands that do have large trees. Also, site index classes 40 and 70 were not adequately represented. The user of this model should take into account these shortcomings. The equation presented here could also be improved in the future by collecting more data on sites with site index of less than 45 and by refitting the model to well-balanced data, especially from research plots.

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DETECTING RESPONSES OF LOBLOLLY PINE STAND DEVELOPMENT TO SITE-PREPARATION INTENSITY: A MODELING APPROACH

Mingguang Xu, Timothy B. Harrington, M. Boyd Edwards'

Abstract-Data from an existing site preparation experiment in the Georgia Piedmont were subjected to a modeling approach to analyze effects of site preparation intensity on stand development of loblolly pine (*Pinus taeda* L.) 5 to 12 years since treatment. An average stand height model that incorporated indicator variables for treatment provided an accurate description of responses to site-preparation intensity, with steepness of the height trajectory increasing with site-preparation intensity. Stand basal area and volume varied similarly among treatments as found for height, with their development increasing with treatment intensity.

INTRODUCTION

It has been widely accepted that development of stand height follows a certain pattern that can be described bv the following model (Clutter and others 1983):

$$\ln(H)=a+b/AGE \qquad (1)$$

where

H is stand height,

AGE is stand age, and

a and b are estimated parameters.

Similarly, growth of stand basal area (BA) and stand volume (V) follow a similar pattern as:

$$\ln(Y)=a+b/AGE \qquad (2)$$

where

Y is stand basal area or stand volume, and

a, b, and AGE are as defined previously.

The growth pattern of stand height, basal area, and volume can vary with site quality, species, and silvicultural treatments, such as site preparation. For a given species and site, effects of treatments can be detected by incorporating their effects into this model:

$$\ln(Y)=a+b/AGE+cTRMT \qquad (3)$$

where

TRMT represents treatment effects,

c is an estimated parameter, and

a, b, and AGE are as defined previously.

In this study, an indicator variable was specified for each treatment to detect effects of site preparation intensity on stand development.

DATA

The data were from an existing site preparation study of loblolly pine (*Pinus taeda* L.) initiated in 1980 in the Georgia Piedmont. After clearcutting mature loblolly pine, the six site-preparation intensities were applied, ranging from absence of site preparation to combinations of mechanical, herbicide, and fertilizer treatments. The treatments are listed as follows in order of increasing intensity:

(1) Clearcut only.

(2) Chainsaw. All residual trees greater than 2.5 centimeters diameter at breast height (d.b.h.) were felled with a chainsaw in August 1981.

(3) Shearing of residual trees with a KG blade mounted on a D7 tractor in September 1981 and chopping of woody debris with a single pass of a rotary-drum chopper in November 1981.

(4) Shear, chop, and herbicide. Treatment 3 plus application of 0.5 cubic centimeters Velpar (TM) Gridball pellets (hexazinone at 10 percent active ingredient) in a 0.6-meter x 0.6-meter grid pattern at a rate of 2.8 kilograms per hectare in March 1982.

(5) Shear, rootrake, burn, and disk. Residual trees were sheared and rootraked into windrows in September 1981 and burned in October 1981. The remaining debris and ash were scattered with a dozer blade and the plots were disked with an offset harrow to a depth of 15-20 centimeters in October 1981.

(6) Shear, rootrake, burn, disk, fertilize, and herbicide. Treatment 5 plus a broadcast application of ammonium- nitrate fertilizer at 114 kilograms N per hectare and a 1 .2-meter band application of Oust (TM) (sulfometuron) at 0.42 kilograms active ingredient per hectare in March and April 1983.

Each treatment was replicated five times in a randomized complete-block design. In January and February 1982, seedlings of loblolly pine were hand-planted at a spacing of 1.8 meters x 3 meters. After establishment of the stands, measurements of d.b.h. (centimeters) and height (meters)

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of each Planted pine were taken 5, 8, 10, and 12 growing seasons after treatment, from which stand average height (H), basal area (BA) (square meters per hectare), and volume (V) (cubic meters per hectare) were calculated. All models were fitted with linear regression using a 95 percent significance level.

RESULTS AND DISCUSSION

Stand Average Height

Fitting stand average height to model (3) resulted in the following equation:

$$\ln(HT)=3.26-9.84/AGE-0.415T1-0.256T2-0.126T3-0.316T4-0.0991T5 \quad (4)$$

where

T1, T2, T3, T4, and T5 are indicator variables that represent treatments 1 to 5, respectively.

For example, $T1=1$ if treatment is 1, otherwise $T1=0$.

Equation (4) indicates that development of average height differed significantly among treatments, with rate increasing with site-preparation intensity. Average height of untreated stands was significantly less than that of treated stands ($P\leq0.05$).

Numerous studies have reported increases in stand height in response to site preparation (Glover and Zutter 1993, Harrington and Edwards 1996, Pienaar and Rheney 1995, Thomson and McMinn 1989). Since stand height is relatively similar for a wide range of stand densities, increases in the rate of height development probably are more attributable to improvement in site quality due to site preparation. Measurements of soil properties on this site demonstrated that the treatments improved growing conditions for pine by decreasing bulk density and increasing pore space (Miller and Edwards 1985).

Stand Basal Area

The following equation resulted from fitting stand basal area to model [3]:

$$\ln(BA)=4.75-919/AGE-1.52T1-1.04T2-0.308T3-0.477T4 \quad (5)$$

The fitted equation (5) indicates that development Of stand basal area also increased with treatment intensity, with the clearcut only treatment having the slowest rate of basal area development.

Stand Volume

Model [3] also was used to test responses of stand volume to treatment:

$$\ln(V)=6.28+24.4/AGE-1.68T1-1.09T2-0.326T3-0.617T4 \quad (6)$$

Stand volume differed significantly among site-preparation intensities, with the clearcut-only treatment having the slowest rate of volume development (fig. 1). Development

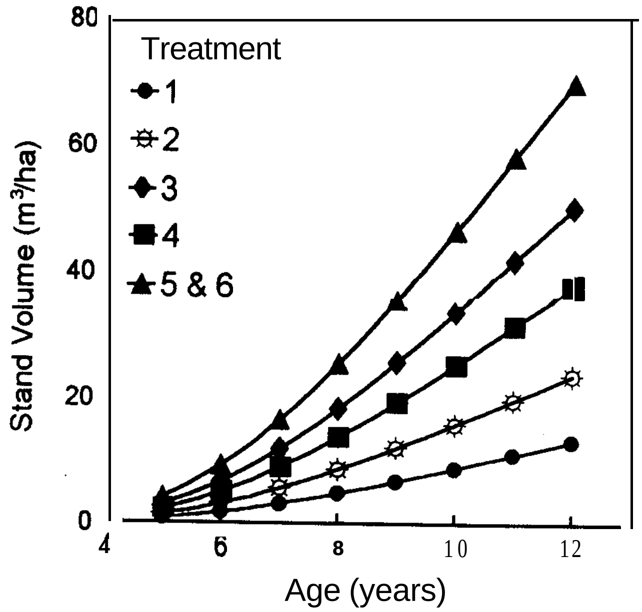

Figure l-Effects of increasing site-preparation intensity on development of stand volume of loblolly pine.

of stand volume did not differ significantly ($P\geq0.05$) between treatments 5 and 6-the two treatments having the greatest rate of stand development.

CONCLUSIONS

Effects of site preparation on stand development were modeled as adjustments to a growth model for stand average height, basal area, and volume. This approach provided an accurate description of stand responses to site-preparation intensity. Results suggest that the more intensive site preparation treatments lead to greater rates of stand development.

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TESTING FOR PREDICTION BIAS WHEN PROJECTING GROWTH FROM INCREMENT CORES

F.T. Lloyd, A.K. Goodnough, V.B. Shelburne, and J.G. Williams'

Abstract-Predictors of periodic basal area growth are derived from each of two data sources, one using breast-high diameters, and increment cores measured at the same time, and another using breast high diameters measured at two points in time. The increment cores are used to estimate diameters of merchantable-sized (d.b.h. > 4.5 inches) survivor trees at a point in the past (in this case, 5 years before the age at measurement). Although this first approach requires more work at the initial measurement, it has the advantage of not requiring a revisit to the site at some future time, and yields immediate information on the periodic growth of survivor trees. We investigated whether regression prediction equations yielded similar parameter estimates when fitted to the two data sets using the same mathematical formulation of initial basal area stocking and initial stand age. Comparisons between the two were not statistically significant when compared on a parameter-by-parameter basis, which supported the conclusion that using increment-core growth this way is an efficient, unbiased way to develop a periodic basal area growth predictor. Although the individual parameters were not statistically different, the fitted models were statistically different when predicted basal area growth was compared at a common initial basal area stocking and initial stand age. Specifically, the model using the 1991-96 data over predicted the model fit to the 1986-91 data by 0.79 ft^2 per 1/5-acre (or approximately 4 ff per acre) for the 5-year period. Adjusting for mean monthly growing season rainfall reduced the difference to 0.19 ff per 1/5-acre (or approximately 1 ff per acre). This adjusted difference was not statistically significant, suggesting that a simple adjustment procedure using growing season rainfall works.

INTRODUCTION

We often Want to use temporary inventory plots to develop predictions of periodic growth, or when installing permanent growth plots, we might want to analyze growth without having to wait for the first remeasurement. One objective of this research is to investigate the suitability of using increment-core derived periodic basal area growth in the development of a periodic basal area growth predictor. For example, Lloyd and Waldrop (1993) used such an approach in their analysis of the relative growth dynamics of the pine and hardwood components in mixed pine and hardwood stands in the Piedmont physiographic region. A second objective is to test the accuracy of using increment-core derived basal area growth from the period prior to plot measurement to project survivor growth for the period immediately following plot establishment. Our hypothesis is that a linear expression of initial basal area stocking and initial stand age fit to'increment-derived growth is the same model derived from remeasured diameters, that is, has the same parameter estimates. This analysis uses a subset of the data from a more comprehensive study of growth dynamics in natural, mixed pine and hardwood stands (Lloyd 1991).

METHODS

The permanent plots were installed in naturally regenerated pine-hardwood stands located on the Piedmont Ranger District of the Sumter National Forest and on the Clemson University Experimental Forest. The study design consists of 39 circular, 1/5-acre plots located in even-aged mixed pine-hardwood stands ranging from 25 to 61 years of age. A stand was deemed to be a pine-hardwood mixture when the pine component made UP between 10 percent and 70 percent of the merchantable basal area. The 10 percent lower limit was selected on the subjective criterion that this is not enough pine to meaningfully affect stand dynamics. The 70 percent upper limit was used as a criterion to assure that at least a portion of the generally shorter hardwood stand component received direct light from above. In other words, that the pine was not so densely stocked that it formed a closed overstory canopy.

Attention was paid to choosing sample stands that had no identifiable evidence of natural or man-imposed disturbance. Plots would be dropped from further analysis if mortality appeared to be caused by forces other than self-thinning due to competition effects. No such rejections where necessary for this 1 O-year growth cycle. All merchantable-sized trees were identified by species, marked by paint with a number, and located by azimuth and distance from the plot center. At plot establishment in 1991, increment cores were extracted from all merchantable-sized trees, and 5- and 1 O-year radial increment was accurately measured on a digital ring measurement device. Tree diameter accuracy was maintained by measuring all trees (merchantable and nonmerchantable) at a painted mark at breast height. Height growth patterns were examined using stem analyses of a dominant oak and pine selected near each permanent plot, but only the ring count from the stump of the stem-analyzed pine was used in this analysis as the stand age. Within the plot, total tree height was obtained on a subsample by choosing every fifth tree within each 1-inch diameter class within the pine and hardwood species categories. One sample tree height was always taken in any diameter classes with less than five trees. None Of the height data were used in this investigation.

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All tree attributes (except increment cores) were remeasured during the 1995 dormant season, and the tree identification numbers of merchantable-sized trees were repainted. Total tree height was remeasured on the sample trees established at plot installation, except in instances of sample height tree mortality. When a sample tree would die, another tree of the same species (if possible) or species genus (for sure) and approximate diameter was substituted by measuring its total height. Any ingrowth trees between 1991 and 1996 were assigned a number and measured the same way as other merchantable trees.

The data used in this analysis are the 1991 diameters measured at plot establishment in 1991, the 1996 remeasured diameters, and the 5-year radial growth from the increment cores that were extracted in 1991. The increment core measurements for all trees alive at the 1996 remeasurement were multiplied by 2 and subtracted from the 1991 diameters to estimate 1986 diameters! The three diameter measures for 1986, 1991, and 1996 were used to compute periodic plot basal area growth for the 1986-91 and 1991-96 periods.

Five-year periodic basal area growth was fit by least squares estimation to the model form:

$$b_i = a_{i0} + a_{i1}t + a_{i2}B \qquad (1)$$

where

t = stand age at the beginning of the growth period,

B = basal area at the beginning of the growth period of all trees alive at the end of the growth period, and

a_{i0}, a_{i1}, and a_{i2} are parameters, which are estimated using periodic growth data from the ith period (that is, 1986-91 or 1991-96.) The simple linear form for the stand age variable (t) was used in equation (1) because curvilinear expressions (such as the reciprocal of stand age) proved unstable due to a lack of data in the middle of the observed stand age range. This design defect was an artifact of the areas in which we initially searched for stands. The plan is to improve the study design by installing additional plots in the deficient age classes. The models to be compared are:

$$b_1 = a_{10} + a_{11}t + a_{12}B \qquad (2)$$

for the 1986-91 period, and

$$b_2 = a_{20} + a_{21}t + a_{22}B \qquad (3)$$

for the 1991-96 period.

Our hypothesis asserts that the models in equations (2) and (3) have the same parameter values. Therefore, the first analytical step was to test the three null hypotheses:

$$H_0: a_{10} = a_{20}, H_0: a_{11} = a_{21}, H_0: a_{12} = a_{22}. \qquad (4)$$

The statistical tests for the hypotheses expressed in equations (4) were performed by least-square analyses using the combined data from both periods. The parameters in this combined model [equation (5) below] are presented in terms of the parameters in the separate models in equations (2) and (3). The purpose of doing this is to make it clear how the combined model is working. Periodic basal area growth for the combined data set is expressed as:

$$b = a_{10} + a_{11}t + a_{12}B + (a_{20} - a_{10})D + (a_{21} - a_{11})Dt + (a_{22} - a_{12})DB, \qquad (5)$$

where all variables are as previously defined, except the new variable D, which is an indicator variable (Gujarati 1995) that takes a value of 0 for the 1986-91 period and a value of 1 for the 1991-96 period. Of course, the $(a_{2j}-a_{1j})$ parameters are estimated as single values of the respective differences.

RESULTS

The results of fitting equation (5) to the combined data set are found in table 1. The three null hypotheses in equations (4) for the individual parameters are tested with the t-statistics for the parameter differences identified in the parameter identifier column of the table. The test statistics of 1.216, -1.352, and 0.303 associated with these differences are not statistically significant, so the assertion of no difference in parameters is not rejected; in other words, our hypothesis is supported. No effort was devoted here to evaluating the power of these statistical tests because our measurement methods were as good as can be obtained from established technique, and thus our ability to detect differences cannot be improved. Table 2 is included to aid interpretation of the statistical tests resulting from the least-squares analysis of equation (5). It contains the parameter estimates for equations (2) and (3) fitted separately to the data sets for periods 1986-91 and 1991-96. Comparisons between tables 1 and 2 verify that the differences in table 1 are in fact the ones we wanted to analyze.

Although the null hypotheses in equations (4) were not rejected, this does not mean that other linear functions of these parameters might not be deemed statistically significant. One such linear function expressed as the null hypothesis is:

$$H_0: (a_{20} - a_{10}) + (a_{21} - a_{11})t_c + (a_{22} - a_{12})B_c = 0 \qquad (6)$$

which is the difference in predicted basal area growth between the two fitted models at the common initial stand age t_c and initial basal area stocking B_c. The value used for t_c is the overall mean age for both periods (34.3 years) and the corresponding 1/5-acre value for B_c is the average stocking across both periods (21.4 ft^2 or 107 ft^2 on an acre basis). These values and the parameter estimates from table 1 are substituted into the linear function in equation (6) to produce the estimated difference of:

$$(4.318-3.371) + (-0.07889+0.06786)(34.3) + (0.1094-0.09882)(21.4) = 0.79 \text{ ft}^2. \qquad (7)$$

Table 1-Regression statistics using both periods to fit the combined model

Parameters	Parameter estimates	t-statistics	Probability >|t|
a_{10}	3.371414	6.637	0.000
$(a_{20}-a_{10})$	0.946511	1.216	0.228
a_{11}	-0.67869	-11.618	0.000
$(a_{21}-a_{11})$	-0.011031	-1.352	0.181
a_{12}	0.098822	3.627	0.000
$(a_{22}-a_{12})$	0.010540	0.303	0.763

Table 2-Regression statistics for models fitted separately to the period data

1986-91 period		1991-96 period	
Parameter	Estimate	Parameter	Estimate
a_{10}	3.371414	a_{20}	4.317925
a_{11}	-0.067860	a_{21}	-0.078891
a_{12}	0.098822	a_{22}	0.109362

The value of the test statistic for this linear combination of parameters is 42.85, which is highly significant. In other words, pairwise comparisons of parameters between periods were not significantly different, but a difference in predicted periodic basal area growth between fitted versions of equations (2) and (3) evaluated at t_c and B_c was significantly different from 0.

The cause of these differences might be a drought in the Piedmont physiographic region during the 1986-91 period. We asked whether making a simple adjustment for rainfall differences between 1986-91 and 1991-96 might account for the observed difference. The approach was to compute an index (I) defined as the cumulative mean monthly rainfall (in inches) for the months of May, June, July, and August, where the "mean" was from monthly values over the 5-year period. Our plots clustered near two permanent weather stations, so the index took on one of four values, depending on the growth period from which the data came and the location of the plot. The indexes were appended to the combined data set through use of a variable called I. The indexes were incorporated into the intercept term of the combined model found in equation (5). The reasoning behind only modifying the intercept term was based on the apparent equality of the parameter estimates for the individual variables suggested by the failure to reject the hypotheses in equations (4). This meant that we expected the significant effect to be due to a difference in elevation between the two parallel plains representing the growth relationships between periods. This assumption yielded the new model:

$$b = i_{20}I(D) + i_{10}I(1-D) + a_{11}t + a_{12}B + (a_{21}-a_{11})Dt + (a_{22}-a_{12})DB, \quad (8)$$

where all variables are as previously defined, and the coefficients i_{10} and i_{20} are for the modified intercept terms. The associated null hypothesis is:

$$H_o: (i_{20}-i_{10})I_c + (a_{21}-a_{11})t_c + (a_{22}-a_{12})B_c = 0, \quad (9)$$

where Ic is the mean rainfall index across both periods. The least-squares estimated parameters for the modified model in equation (8) are listed in table 3. As with the first combined model [equation (5)], the separate fitted models are presented in table 4 to aid interpretation of table 3. Note in table 3 that the differences (a,,-all) and $(a_{22}-a_{12})$ are still not significant, as was the case in the first combined model in table 1. The adjusted (for rainfall) basal area growth between periods is:

$$(0.2658-0.2562)(16.905) + (-0.09234+0.08742)(34.3) + (0.1123-0.1031)(21.4) = 0.19 \text{ ft}^2, \quad (10)$$

where 16.905 is the average rainfall index across both periods (the variable I, in [equation (9)]. The value of the test statistic for this linear function is 2.67, which is not statistically significant.

Table 3-Regression statistics for the combined model with modified intercepts

Parameters	Parameter estimates	t-statistics	Probability >|t|
i_{10}	0.256190	6.241	0.000
i_{20}	0.265770	6.971	0.000
a_{11}	-0.087421	-12.617	0.000
$(a_{21}-a_{11})$	-0.004919	-0.494	0.623
a_{12}	0.103144	3.863	0.000
$(a_{22}-a_{12})$	0.009201	0.256	0.799

Table 4-Regression statistics for modified intercept models fitted separately to periods

1986-91 period		1991-96 period	
Parameter	Estimate	Parameter	Estimate
i_{10}	0.256190	i_{20}	0.265771
a_{11}	-0.087421	a_{21}	-0.092340
a_{12}	0.103144	a_{22}	0.112345

CONCLUSION

This research examined two hypotheses. The first one is that increment cores can function in an unbiased way in estimating future periodic basal area growth of survivor trees. Stating this first hypothesis differently, the null assertion is that the same regression estimates result whether periodic basal area growth of survivor trees is measured from radial growth on increment cores, or obtained from diameter remeasurements made after waiting a time equivalent to the length of the growth period. The consistent non-significance of the parameter differences a_{21}- a,, and a_{22}-a_{12}, combined with the fact that we used the best measurement technique, is strong support for using the increment core data this way. A second hypothesis was supported which asserts that simple expressions of rainfall differences can be used to adjust the fitted growth projections when the projection model is fit to growth from one time period and used to estimate growth for the time period in the immediate future.

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Stand Development and Dynamics

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VALUE OF TREE MEASUREMENTS MADE AT AGE 5 YEARS FOR PREDICTING THE HEIGHT AND DIAMETER GROWTH AT AGE 25 YEARS IN LOBLOLLY PINE PLANTATIONS

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Abstract-Early growth measurements of pine plantations are often used to predict the productivity of the stand later in the rotation when assessing the effect of management on productivity. A loblolly pine (*Pinus taeda* L.) study established at 36 locations (2 to 3 plots/location) was used to test the relationship between height measurements at age 5 years and productivity at age 25. Mean heights of dominant and codominant trees at age 25 were used to represent site index at a location; basal area growth per tree from ages 20 to 25 was used as an index of individual tree growth.

The plot data showed a relatively weak relationship (r^2=0.40) between heights at age 5 and site index. Ranking age-5 heights and using only taller trees did little to improve the relationship. The fit of the regression equation changed gradually from an r^2 of 0.45, when only the tallest tree was used, to an r^2 of 0.43 when the tallest one-half of all trees was used. Using more trees did not degrade that relationship. As all trees must be measured to determine the tallest group, little is gained by attempting to designate dominant and codominants or crop trees for use in analyses and interpretations. Overall, predictions of stand productivity at age 25 using only individual tree parameters based on height at age 5 were of little value, accounting for only about 20 percent of the variation. Although plot location and rank of the tree within a plot each accounted for about 10 percent of the variability at age 25, a nearest-neighbor competition index and height at age 5 accounted for less than 0.1 percent each. However, rank by height at age 5 was an excellent predictor of individual tree survival, with 95-percent survival at age 25 for the tallest pines and almost no survival for the shortest pines. Based on the results of this study, we surmise that accurate modeling of stand development from early measurements probably requires more site information, such as amount and type of competing vegetation, soil properties, and a history of the land management.

INTRODUCTION

A major problem in evaluating new techniques for pine stand establishment and management manipulation is the long time required for the crop to reach harvest age. Even in short-rotation, intensively managed plantations, the rotation period closely matches that of scientists' careers. Thus, there is a need to reliably use early measurements to make projections about subsequent stand development. While there are several ways to make projections, the methods have not been validated.

Equations developed from site index curves can be used to predict relative growth at later ages from early measurements. This method has several disadvantages. First, local curves may not be available, and regionwide curves must be used (Shoulders 1976). Second, site index curves may be valid only for older stand ages and not be useful below age 10 (Farrah 1973). Third, when anamorphic site index curves are used, projecting heights from a young age to a site index is simply multiplying the mean heights by a constant. Thus, the manipulation adds no new information or changes the relative differences between treatment means. Finally, the use of anamorphic curves is based on the assumption that relative rates of growth are constant, and the falseness of this assumption is shown by studies in which treatments did change the rate of height and diameter growth (Cain 1978).

Identifying crop trees using heights at age 5 or other measurements from early ages is another method sometimes used to project stand development forward. The crop trees are trees in the stand at the early measurement period that are expected to develop into dominants and codominants at rotation age. The crop trees may be identified as a fixed percentage of the number of living trees or on a fixed-area basis such as using the tallest 247 trees per ha (Mann and Derr 1970). One disadvantage of this method is that the size of the neighboring trees is not taken into account. Secondly, like the anamorphic site index curves, the method assumes that all trees develop at the same rate. Wakeley (1971) found that trees of superior size at age 30 were usually of above-average size at early ages. However, a number of trees changed from being below average at younger ages to superior at age 30. There were sufficient trees in the late-surging population so that the correlations of heights at age 30 to heights at age 5 ranged from 0.31 to 0.47 for loblolly pines (*Pinus taeda* L).

In a preliminary examination of a loblolly pine data set, we also found that using plot means of heights at age 5 was a poor predictor of the actual site index (base age 25) on the same plots, accounting for only 40 percent of the variation. In this paper, we are using data from plantations located on a wide range of sites and measured over a period of 25 years to examine ways of using early measurements in predicting the size of the stand at later ages. First, we use ranked heights of all the trees on each plot to find the optimum number of large trees to identify as crop trees. Secondly, we use the heights, rank within the stand, competition index of nearest neighbors, and stand location to evaluate which tree and stand parameters at young ages are the most useful in predicting future tree size, stand structure, and survival.

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METHODS

Sites and Measurements

The data set used is a subset of a larger one from a study that compared the performance of different pine species on a wide range of sites in Louisiana and Mississippi (Shoulders 1976). Originally, 47 sites were planted in Louisiana in 1954-58 with each site consisting of three replicates each of loblolly, slash (*P. elliottii* Engelm.), and longleaf pine (*P. palustris* Mill.). Shortleaf pine (*P. echinata* Mill.) was also planted at some of the northern Louisiana locations. The sites were mostly on open, cutover forest land that had not been tilled but had been kept in grass by frequent fires after the original forest was cut in the 1920's. Each plot consisted of 11 rows of 11 trees planted at a 1.83-m spacing. Seedlings grown from unimproved seed lots in a State nursery were graded by Wakeley's (1954) rules, and only seedlings graded 1 or 2 were used. Only the loblolly data collected in Louisiana are used in this paper. By age 25, only 29 of the sites still had all three replicates with sufficient surviving loblolly pines to measure, 5 sites had two surviving replicates and 2 sites had only one replicate. This left a total of 99 plots for use in this paper. Heights of the center 49 planting positions were measured at ages 5 and 10. The d.b.h. of these same trees was measured at ages 10, 15, 20, and 25. At ages 15, 20, and 25, heights of at least 10 dominant or codominant trees were measured on each plot. Mean height of dominant and codominant trees at age 25 was used to represent site index of a plot. The d.b.h.'s were used to calculate basal area growth per tree from ages 20 to 25 for use as an index of individual tree growth.

Site Index Predictions

To find the optimum number of larger pines at an earlier age needed to predict site index at age 25, all measured trees in each plot were ranked by their height at the earlier age. Before ranking, a random value, less than 1 percent of the height, was added to the height of each pine. This transformation prevented ties in the ranked heights without affecting other statistics. The height of the largest pine in each plot at the earlier age was selected as the independent variable in a regression, having SI_{25} (site index at base age 25 years) as the dependent variable. Then the regression was rerun including the earlier-age heights of the two largest trees, three largest trees, and so on until the heights of all measured pines were included.

Basal Area Growth Predictions

To predict stand productivity at age 25, age-5 parameters were used in a general, mixed linear model. The model used was

$$BAG_{I-F} = f(HT_5, R_{HT5}, CI_{HT5}, LOC) + E,$$

where

BAG_{I-F} = annual basal area growth between initial and final age,

HT_5 = pine height at age 5,

R_{HT5} = rank of pine in plot based on heights at age 5,

CI_{HT5} = competition index based on height of pine and its neighbors,

LOC = location, and

E = unaccounted -or variation.

The competition index is based on Hegyi's index (Hegyi 1974), except that total pine height was used instead of diameter to compare the tree to its neighbors. In the CI calculations, the four nearest pines in the rows (distance=1.83 m) and the four pines in the diagonal (distance=2.59 m) were used. Because the pines in the border rows were not measured, only the 25 center pines were used to calculate the competition and subsequently used in the regression with stand productivity. Stepwise fits of the model were used to find the relative importance of each independent variable. The model was then refitted with all independent variables included in the order suggested by the stepwise fits. The same order was used for all growth periods tested. To model survival, a cubic equation was fitted between the height-based rank within a plot and survival at age 25.

RESULTSANDDISCUSSION

Site Index Predictions

The mean height of all live pines on each plot at age 5 is a poor predictor of SI_{25}, accounting for only 40 percent of the variation. At age 10, the mean height accounted for more of the variation, increasing to 69 percent. Age-15 height was not as useful as age-10 height when used in the model to predict site index, accounting for only 65 percent of the variation. Beginning at age 15, heights were measured only on sample trees, and this may account for the weakened relationship. Age-20 height, based on sample trees chosen by the same criteria used to select trees at age 15, was much more useful, accounting for 88 percent of the variation. The regression between all trees measured at age 25 and those identified as dominants and codominants had an r^2 of 0.95. The variation in site index between locations by heights at younger ages is similar to results for loblolly pine in the Florida Parishes of Louisiana (Wakeley 1971). In earlier reports (Ferree and others 1958, Wakeley and Marreo 1958), the 5-year-growth increment after pines had reached breast height was more closely related to site index than were total heights at young ages. However, in the present study, the height increment from age 5 to age 10 was not a better predictor than total height at age 10, accounting for 70 percent of the variation.

Ranking age-5 heights and using only taller trees did little to improve the relationship (fig. 1). The fit of the regression equation changed gradually from an r^2 of 0.45, when only the tallest tree was used, to an r^2 of 0.43 when the tallest one-half of all trees were used. The relationship was similar for other ages, with the amount of variation accounted for increasing with the age of the pines but not changing with the number of taller pines used. Thus, the prediction of future growth cannot be improved by selecting tallest or crop trees at early ages. As all pines must be measured to

Figure l-Effect of percentage of largest pines included as independent variable on regression coefficient between age 5 heights and age 25 heights.

determine the tallest group, little is gained by attempting to designate dominants and codominants or crop trees for use in analyses and interpretations.

Detailed analysis of the changing ranks of pines with time can help explain why selecting larger pines at early ages does not improve the prediction of size at older ages. Ranks by ages are shown in figure 2 for two plots that show extremes in rank changes. Rankings of pines on plot 134-2 are relatively stable. For example, pine A is the tallest tree at age 5 and was still ranked number 5 by d.b.h. at age 25. Pine B was ranked number 45 by height at age 5 and had changed by age 25 to ranking 32, or last, because other small pines died. By contrast, ranks on plot 139-3 changed dramatically with age. Pine C was in rank 41 by height at age 5, but had climbed in stature to having the 4th largest d.b.h. by age 25. Pine D, which was the tallest at age 5, ended in 23rd place by age 25. As the number of intersections of lines in the ranking diagrams indicates, most of the changes in rank seem to take place in the 5th through 10th years of the plantation. While mortality was concentrated in the lower ranks, the pines often moved from higher to lower ranks before dying.

Using a somewhat different analysis also aids in understanding the relationship between rank by height at age 5 and relative position in the stand at index age. Consider the population consisting of the tallest tree on each plot at age 5. At age 25, the mean ranking by diameter of this population was 5.1 (fig. 3A), with a range of 1 to 26. As the ranking at age 5 moves from large to small pines, the mean ranking at age 25 increases in a linear fashion. However, while the mean indicates a good relationship between rank at age 5 and rank at age 25, the large variation nullifies its utility as a predictor. Indeed, the population of pines ranked 36th at age 5 has nearly the same range of 4 to 39 as lower ranked trees (fig. 3A) even though the mean ranking by diameter has increased to 24. This wide range explains why selecting only a larger fraction of pines, based on age-5 heights, does not improve the predictability of SI_{25} (fig. 1). When ranks based on

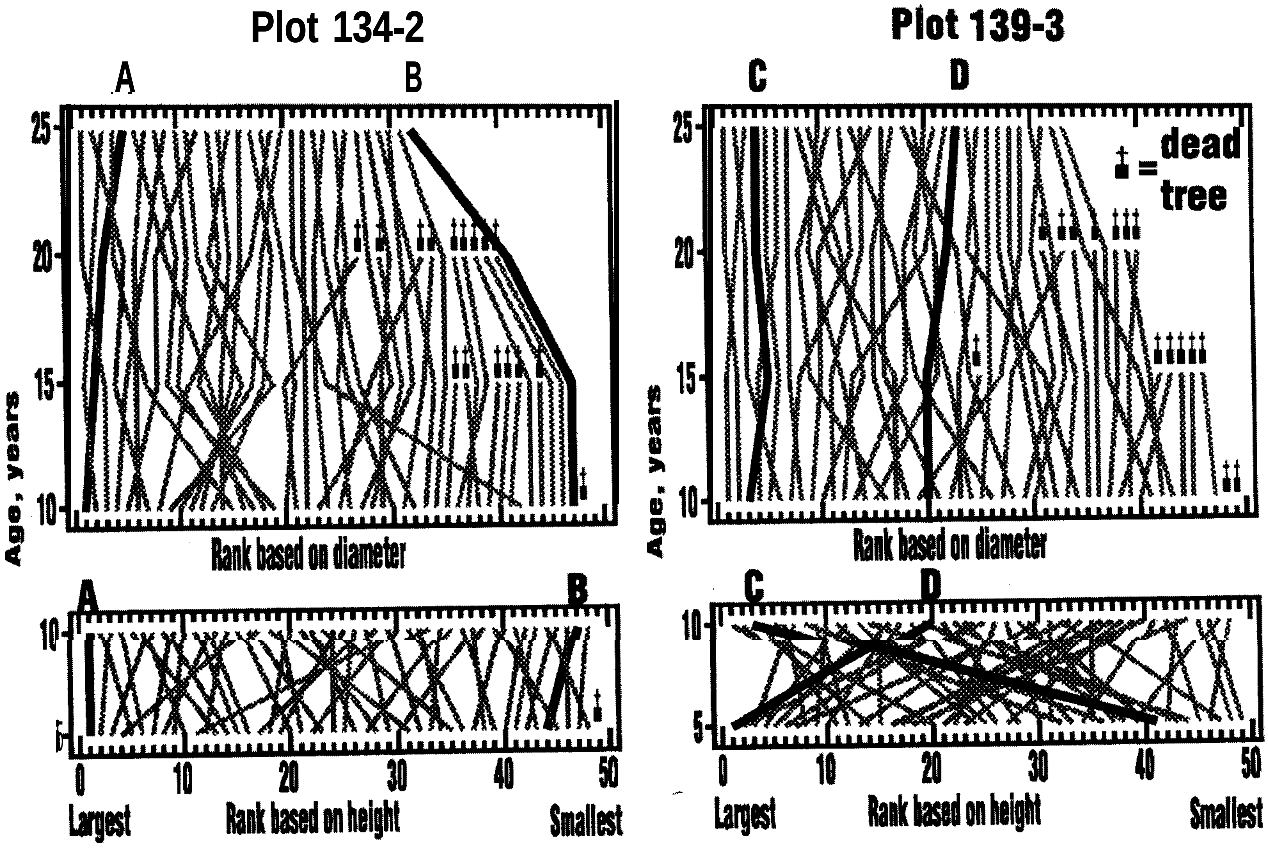

Figure 2-Pine ranks by heights and d.b.h. at different ages for two of the plots used in the analysis.

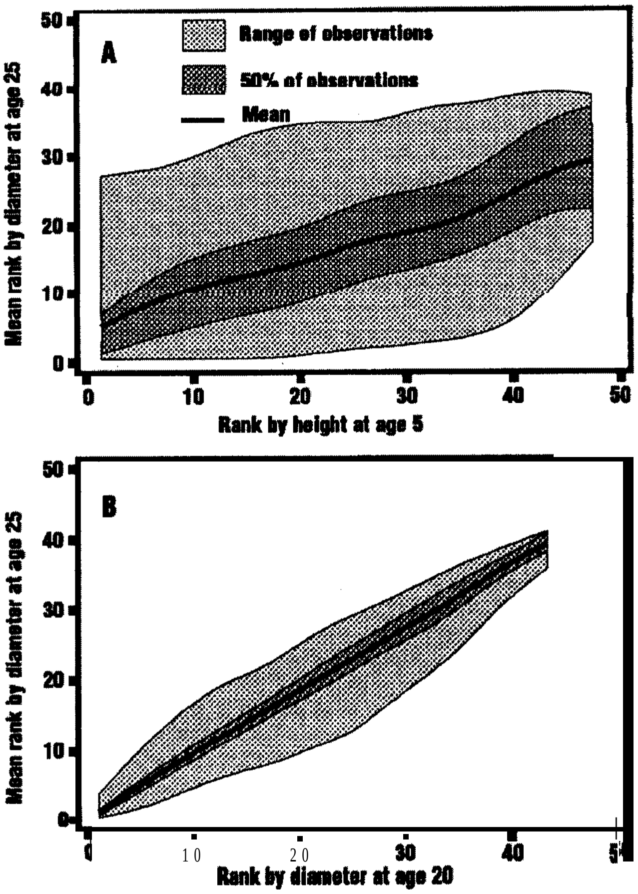

Figure 3--Relationship between rank by height at age 5 (A) and d.b.h. at age 20 (B) to mean rank by diameter at age 25.

diameter at age 20 are compared to ranks based on diameter at age 25, the mean ranking is remarkably similar to that at age 5 (fig. 3B). However, the range at all rankings at age 20 is much lower. This narrower range is expressed as a much higher r^2 in figure 1.

Basal Area Growth Predictions

Parameters for individual trees based on height at age 5 were of little value in predicting basal area growth of individual pines at later ages (table 1). The model accounted for about 35 percent of the variation in basal area growth between the ages of 10 and 15, but the model accounted for only about 20 percent for the age-20 to age-25 period. Height at age 5 accounted for less than 1 percent of the variation when included with the other variables in the model. Competition index, based on the height of a pine and its neighbors at age 5, was slightly more useful at the earlier ages, but by the age-20 to age-25 period, accounted for less than 1 percent of the variation. Ranking by height within plots was the only variable that was a better predictor at later ages than at earlier ones, accounting for 5.6 percent of the variation for the 1 O-l 5 age period and 9.9 percent of the variation for the 20-25 age period. Location was a good predictor for the 1 O-l 5 age period, but after age 15 it accounted for only 10 to 12 percent of the variation in basal area growth.

Table 1— Variation in basal area growth of loblolly pines of three ages accounted for by variables measured at stand age 5 years

	Sum of squares accounted for by variable at stand age		
Source	IO-15	15-20	20-25
	Percent		
Height	0.54[a]	0.03	0.07
Competition index	1.66	2.21	0.45
Rank in plot by height	5.55	10.76	9.91
Location	27.64	11.66	10.16
Unaccounted (error)	64.61	75.3	79.41

[a] Percentage of total sum of squares (Type I).

Survival Prediction

Ranking by height at age 5 was an excellent predictor of individual tree survival (fig. 4). Of the pines that were the tallest on each plot at age 5, 95 percent were still surviving at age 25. In contrast, pines that were ranked near the bottom at age 5 had nearly all died by age 25.

CONCLUSIONS

Pine heights at age 5 accounted for about 40 percent of the variation in SI_{25} indicating that projections based only on age-5 heights should be used with caution. Predictions or decisions based on age-5 results should be considered tentative and need to be reevaluated as later measurements become available. None of the parameters based on height at age 5 was independently useful in modeling individual pine basal area growth. Little is gained by attempting to

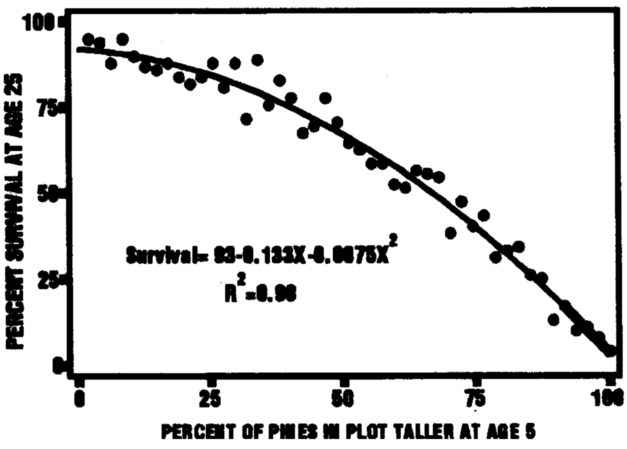

Figure 4-Relationship between rank of pines within each plot, based on height at age 5, and survival at age 25.

designate dominant and codominant or crop trees at age 5. A notable exception is that rank at age 5 was very useful in predicting survival of individual trees at age 25.

Predicting the site index or modeling stand development using early measurements probably requires more site information than is normally documented in research studies. Additional measurements need to be made to account for these factors, including competition, soil properties, past land management, and genetics. Competition at early ages may be an important factor in later stand size and structure. Pines on sites that have severe herbaceous competition may grow slowly in the first 5 to 10 years but grow more rapidly once the stand shades the competition (Haywood and Tiarks 1990). Soil properties may affect the rate of height growth by restricting root penetration or limiting water availability (Zahner 1962). The effects of soil properties may not be fully apparent until the stand has fully occupied the site. Past land management such as agricultural uses or prescribed fire may affect the amount and kind of woody competition and soil fertility. Some of the variation may be the result of differences in genotype, with some trees able to grow better after crown closure than before (Wakeley 1971).

We recommend that additional measurements be made beginning at age 5. These include diameters of the bole, both near the ground line and at breast height; the length of the crown; and a description of the amount and kind of competition. Studies should be located on sites that have uniform soils and have received common management in the past. More detailed studies should include crown diameter as well as a detailed measurement of the competition (Miller and others 1991). Unfortunately, the utility of these additional measurements will not be known until studies that have included these early measurements approach rotation age. Until then, studies testing new management practices should have a plot size large enough to allow measurement through rotation age.

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EFFECTS OF CLEARCUTTING ON STAND COMPOSITION AND STRUCTURE AFTER 17 YEARS OF REGROWTH IN A SOUTHERN APPALACHIAN STAND

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Abstract-The effect of clearcut regeneration with whole-tree yarding on plant composition and structure was examined after 17 years of regrowth. Shrub and tree strata were sampled 1 year prior to harvest and at 7 and 17 years after harvest. Species richness was highest 7 and 17 years after harvest in the shrub and tree strata, respectively. Invasion of pioneer (*Liriodendron tulipifera*, *Betula lenta*, and *Prunus serotina*) and regeneration of disturbance-dependent (*Pinus pungens*) species added to the species pool in both strata. Comparing species richness of preharvest to the 17th year data, species richness increased by one in the shrub stratum, while all preharvest species, plus an additional eight, were found in the tree stratum. The time for ingrowth accounts for the offset in the peak species richness between the two strata. Relative dominance (based upon basal area) for each species was not significantly different between the preharvest and 17 year data in either strata. Preharvest vertical stand structure was reflected in the 17 year data in both strata. In the tree stratum, stem density and basal area were high on better quality sites but low on poor sites. In the shrub stratum, stem density and basal area were high on poor quality sites but low on better sites. The faster growth rate on the better sites has resulted in stand closure which has limited light to the understory and caused density-induced mortality. After 17 years, clearcut regeneration has not significantly changed the composition and structure of forest stands; however, woody species diversity has increased.

INTRODUCTION

The Southern Appalachian Mountains are one of the two most biologically diverse areas of North America (Whittaker 1972). It is not uncommon to have 15 or more commercially important tree species on a given site (Smith 1994). The Ridge and Valley Physiographic Province contains most of the species and forest stand types of the region (Thompson 1992, Johnson 1992). The great diversity of this region is due to its unique topography, geology, and continental climatic conditions (Whittaker 1972).

Disturbance is another factor that has led to the high tree species diversity of the region. Since the turn of the century, major events, human and natural, have shaped the structure of the forest stands of the Southern Appalachians. These events include the nearly complete harvesting of the forests around the turn of the century, introduction of exotic pests [such as the gypsy moth (*Lymantria dispar*) and American chestnut blight (*Ednothia parasitica*)], and suppression of wildfires, The practice of clearcutting has caused significant controversy due partly to the aesthetic appearance of forests after harvesting (McGee 1970). More recently, questions have been raised on the effects that clearcuttino has on the biodiversity (plant diversity) in forests (Gilliam and others 1995). Diversity is often tied to the sustainability of forests. Sustainability, in this case, means the maintenance of a productive, stable, and diverse forest system capable of providing desirable goods (i.e., food, wood, wildlife, recreation, etc.) in perpetuity.

Few studies have evaluated the effects of clearcut regeneration on forest stand structure and diversity in the Southern Appalachians (e.g., Beck and Hooper 1986, Elliot and Swank 1994). In most cases, these studies have been conducted in mesic, higher site-quality stands. Clearcutting is a viable, biologically sound, and often used regeneration system on most sites for many reasons. Since the majority of the commercial tree species found in the Southern Appalachians are intolerant to intermediate of shade (Burns and Honkala 1990a, 1990b), clearcutting provides the forest floor conditions that are an ideal environment for them to regenerate. The majority (78 percent) of the Southern Appalachian mountain range is owned by private, nonindustrial landowners holding 400 acres or less (Smith 1992) and they tend to own land as an investment. Clearcut regeneration on these lands is the predominant regeneration technique since it is usually the most economical and profitable method (Cubbage and others 1993), and results in the most desirable new stand. The majority of stands in the Southern Appalachians are 70 to 100 years old, containing large and valuable trees that are of sufficient size for harvest depending on landowner objectives. Finally, they are old enough such that natural mortality is becoming an important factor in determining the future direction of the stand.

Little is known about the effects clearcut regeneration has on diversity with respect to the composition and structure of forest stands in the Southern Appalachians. Even less is known about this effect on the more typical stands (site index,, of <75 for upland oak, base age 50) of this region. This study will report on the interim results (17 years) of a longer-term study that addresses the question of how clearcut regeneration affects woody plant species composition and structure after implementing clearcut regeneration silviculture on these typical stands.

STUDYAREA

The study area is located on the George Washington and Jefferson National Forest on Potts Mountain in Craig

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County, VA. The elevation is approximately 2,400 feet with stands located at midslope, with slopes ranging from 8 to 45 percent and having east to southwest aspects. Soils are classified as mesic, arenic or typic Hapuludlts with a generally coarse texture of mainly siliceous mineralogy derived from residual or colluvial sandstone and/or shale parent material (Morin 1978).

Four forest types were delineated based on visual criteria of overstory and understory composition (McEvoy 1980). Stands were classified as one of the following: (1) cove hardwood overstory with no ericaceous understory, (2) mixed oak with a light ericaceous understory, (3) mixed oak-pine with moderate to heavy ericaceous understory, and (4) mixed pine with heavy ericaceous understory. For additional descriptions, see Ross and others (1983) and Blount and others (1987).

METHODS

Plot Establishment

In the original study, nine 0.4-acre permanent plots were distributed among the vegetation types in three harvested blocks. These plots were evaluated for site quality using site index (SI_{50} base age 50 for upland oak) (Olson 1959) and ranked from very poor (SI_{50} = 37) to moderately good (SI_{50} = 71). The vegetative composition of each of these types was subsequently found to be correlated to a soil moisture-site quality gradient (Meiners and others 1984). One of the plots was used as a control to detect any significant nonanthropogenic disturbances that occur over the life of the study. For the present study, five of the original plots were remeasured.

Between August 1978 and March 1979 the study area was clearcut using whole-tree harvesting and a cable yarding system. Cable yarding was used to minimize harvesting impacts on the steep slopes. All areas in which the plots were located were harvested during the dormant season except one plot which was completed in September 1978.

Data Collection

Five plots, one from each vegetation type and the control, were sampled in this study. Nested plots were used to sample the tree and shrub strata. A complete sampling (100 percent intensity) of sixteen 1,076 ff tree subplots where all woody stems >16.4 feet in height were measured. Nested within the tree subplots were four 269 ft^2 shrub sub-subplots where all woody stems 3.3 to 16.4 feet in height were measured. In the shrub stratum, a rank set sampling scheme was used to measure 25 percent of the area in each plot. The original sampling period (preharvest) occurred between April of 1977 and March of 1978. Post-harvest sampling occurred in 1986 and 1996 (7th and 17th year after harvesting, respectively) during March and April of each year. [Refer to Blount and others (1987) for detailed description of stand regeneration between years 1977 and 1986.1

For the tree strata, measurements varied between the years. Preharvest measurements in the tree stratum included recording the scientific name, diameter (to nearest 0.1 inch) at 4.9 feet above ground level, and total height (to nearest 0.1 foot) of each individual stem. For post-harvest measurements, the diameter was measured at 4.5 feet above ground level and only the height of every fifth tree of each species was measured. Measurements for the shrub stratum (in all measurement periods) for each individual included scientific name, diameter (to nearest 0.1 inch) at 5.9 inches aboveground level, and total height (to nearest 0.1 foot).

Methods of Analysis

To quantify the changes in plant species composition over time, species richness lists and relative dominance were compared among each of the three sampling periods. Relative dominance was based on basal area and was calculated for each species in each stratum. ANOVA was used to test for significant differences (alpha = 0.05) in relative dominance for each species between the preharvest and 17th-year data. Basal area and stem density, plotted over time for each stratum, were used to examine any changes in the vertical structure of the forest stands.

RESULTS AND DISCUSSION

Species Composition

Species richness in the shrub stratum increased by the 7th year after harvest, then decreased to preharvest levels at 17 years (table 1). A total of 29 species were found over the time of the study period. The increase in species richness in the 7th year was mainly due to the invasion of pioneer or disturbance-dependent species. These included yellow-poplar (*Liriodendron tulipifera*), black birch (*Betula lenta*), black cherry (*Prunus serotina*), and Table mountain pine (*Pinus pungens).* From the 7th to 17th year, three species, serviceberry (*Amelanchier arborea),* black cherry, and northern red oak (*Quercus rubra*) were lost from the site while black birch, blacklocust (*Robinia pseudoacacia*), and striped maple (*Acer pensylvanicum)* grew out of the shrub stratum and into the tree stratum.

Table l-Changes in woody species richness in the shrub stratum over three sampling periods in forest stands on Potts Mountain, Craig County, VA (0.4 acres total sample area)

Sampling periods			Species	
From	To	Initial total	Gained	Lost
Preharvest	7th yr	21	6	1
7th yr	17th yr	26	2	6
Preharvest	17th yr	21	4	3

No. of spp in 1996 = 22.
Total no. of spp from 1977 to 1996 = 29.

Species turnover in the shrub stratum between preharvest and 17th year remained low. Four species were added while three species were lost. Yellow-poplar, Table mountain pine, Virginia pine (*Pinus virginiana)* and sugar maple (*Acer saccharum*) were new while striped maple, blacklocust, and mockernut hickory (*Carya tomentosa*) were no longer found in the understory. Some of the species were previously on site but not represented in the shrub strata. For example, prior to harvest, Table mountain pine was found in the tree stratum but not in the shrub stratum. Additionally, species such as yellow-poplar were now found mainly on more mesic sites presumably from seed sources in adjacent stands. Species such as blacklocust were no longer found in the understory, probably because the light is too low for regeneration as some stands have developed or are approaching a closed canopy.

Species richness in the tree stratum remained virtually the same from preharvest to the 7th year then increased by the 17th year (table 2). From preharvest to the 7th year, there was a loss of four species and a gain of three. Three of the species that were lost [Table mountain pine, pitch pine (*P. rigida*), and black oak (Q. *velutina*)] tend to be found on the less productive sites and had not yet had time to grow into the tree strata. Two of the three species gained (yellow-poplar and black birch) were found in the more mesic stand areas. These pioneer species with their fast growth rate and in combination with increased light are able to reach the tree stratum quickly. By year 17, all preharvest species plus an additional eight, were found in the plots. Individuals, such as pitch pine and black oak, on the poorer quality sites have had enough time to grow into the tree strata. Additionally, pignut hickory (*Carya glabra*), mockernut hickory, and American elm (*Ulmus americana),* intermediate to later successional species, had grown into the tree strata.

The dominant species (expressed as relative basal area) in both the tree and shrub strata have not significantly changed over the study period though their rankings might have changed (figs. 1 and 2). There was one exception in the tree stratum in which the dominance of black oak was

Table 2-Changes in woody species richness in the tree stratum over three sampling periods in forest stands on Potts Mountain, Craig County, VA (1.6 acres total sample area)

Sampling periods			Species	
From	To	Initial total	Gained	Lost
Preharvest	7th yr	13	3	4
7th yr	17th yr	12	9	0
Preharvest	17th yr	13	8	0

No. of spp in 1996 = 21.
Total no. of spp from 1977 to 1996 = 21.

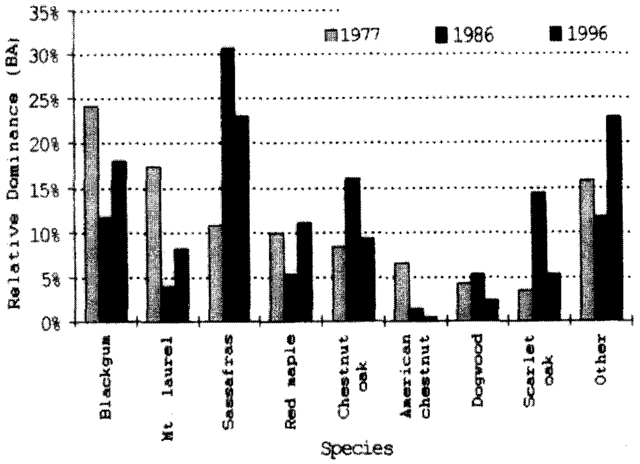

Figure l-Dominant species (based on relative basal area) in the shrub stratum for all three sampling periods in forest stands on Potts Mountain, Craig County, VA (all site quality plots pooled).

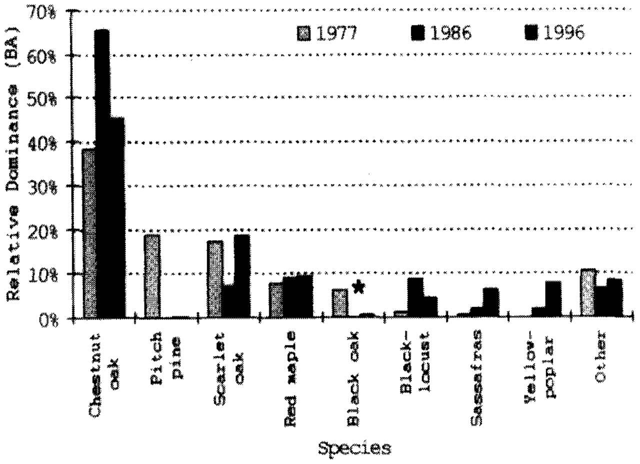

Figure 2-Dominant species (based on relative basal area) in the tree stratum for all three sampling periods in forest stands on Potts Mountain, Craig County, VA (all site quality plots pooled; * = significant difference between years 1977 and 1996 (alpha = .05)).

significantly different ($P < 0.02$) between the preharvest and 17th year. In the shrub stratum, blackgum (*Nyssa sylvatica*), mountain laurel (*Kalmia latifolia*), sassafras (*Sassafras albidum*), red maple (*Acer rubrum*), and chestnut oak (*Q. prinus*) have remained the dominant species. In the tree stratum, chestnut oak, scarlet oak (Q. *coccinea*), and red maple remained dominant species. The significant difference in black oak is probably a result of stand conditions affecting its regeneration ability. Sander and others (1984) found that black oak sprouting ability was greatly reduced for old trees on poor sites. Stump sprouts should have provided faster growth for black oaks to reach the tree stratum more rapidly.

There are some observations in changes in species dominance that are of interest to report. Table mountain pine and pitch pine are increasing in dominance in the shrub stratum on poor quality sites. This is probably as a result of the harvesting disturbance exposing mineral soil (the preferred regeneration medium). The apparent decline in the abundance of the pines is probably a result of the reduction in the fire frequency in the area (Ross and others 1982), an event which often exposes mineral soil. Yellow-poplar and sassafras, typically found on better quality sites, have increased in dominance. Yellow-poplar, on higher quality sites, should become a significant portion of the stands, since it is currently the dominant species along with red maple. This trend has also been observed in other studies (Beck and Hooper 1986, Elliot and Swank 1994). Sassafras, though still a component in the tree stratum, is reducing in dominance in the shrub stratum. As Blount and others (1987) predicted, sassafras should continue to decrease. American chestnut decreased, probably because of the confounding factor of chestnut blight.

Stand Structure

Since the study plots represented different vegetation types and, therefore, site qualities, the structure of each stand varied. In the shrub stratum, basal area peaked first in the higher site quality stands (fig. 3). By year 17, the shrub stratum basal area in the highest site-quality stand had returned to preharvest levels. Note that by year 7, the peak in basal area for the highest quality stand had probably already occurred. Stands with the highest productivity have the fastest in- and outgrowth from one stratum to the next. This would explain the sudden increase ,then decrease, in understory basal area on these better sites. The same trend also occurred for stem density (fig. 4). By year 17, the lower quality sites, usually located on exposed ridgetops with shallow soils, may only achieve the equivalent of stand closure in the shrub stratum.

In the tree strata, 17 year basal areas, for all site qualities, reflected preharvest conditions (fig. 5). The high quality sites (preharvest basal area of 121 ft^2 per acre) had the most basal area in the 7th and 17th years (16 and 85 ft^2 per acre, respectively). With respect to stem density, the higher quality sites had the highest density in both post-harvest samples (fig. 6). In year 17 though, the highest quality site did not have the most stems per acre. This is probably attributed to the stand achieving a closed canopy resulting in density-induced mortality. The high basal area is now being distributed among fewer individuals. The lower quality sites (preharvest basal area of 88 ft^2 per acre) still have not reached stand closure, therefore, they should continue to increase in basal area (7th and 17th year basal areas of 0 and 9 ft^2 per acre, respectively) and stem density for many years. The second highest quality site has probably reached stand closure and future sampling will show a decrease in stem density and a leveling off of basal area.

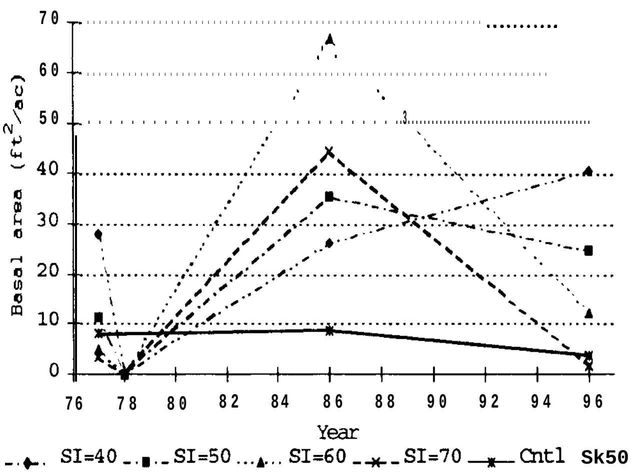

Figure 3-Changes in shrub stratum basal area over time in four different site quality forest stands on Potts Mountain, Craig County, VA [site quality based upon site index (ft) of upland oaks base age 50 (Olson 1959)].

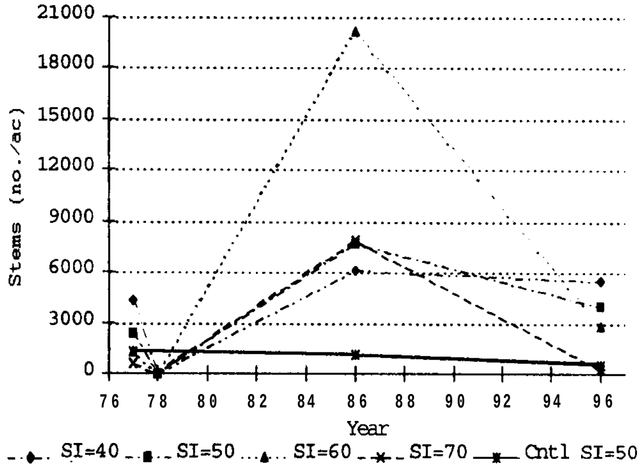

Figure 4-Changes in shrub stratum stem density over time in four different site quality forest stands on Potts Mountain, Craig County, VA [site quality based upon site index (ft) of upland oaks base age 50 (Olson 1959)].

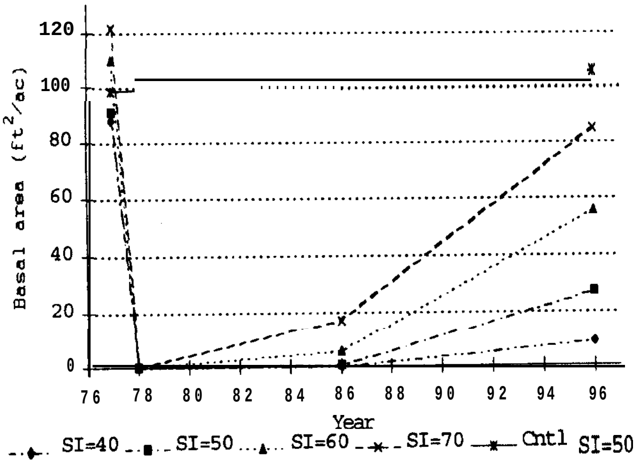

Figure 5-Changes in tree stratum basal area over time in four different site quality forest stands on Potts Mountain, Craig County, VA [site quality based upon site index (ft) of upland oaks base age 50 (Olson 1959)].

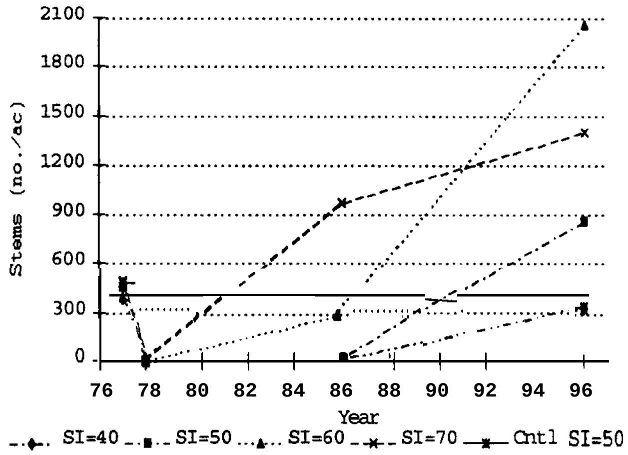

Figure 6-Changes in tree stratum stem density over time in four different site quality forest stands on Potts Mountain, Craig County, VA [site quality based upon site index (ft) of upland oaks base age 50 (Olson 1959)].

CONCLUSIONS

Among harvesting disturbances, clearcut regeneration can mimic natural disturbances that promote tree diversity in forest stands. In stands of the Southern Appalachians, clearcut regeneration has not significantly changed the composition and structure. Tree species richness has increased as a result of this disturbance in both the tree and shrub strata. The mesic stands have had the fastest stand development and have already achieved stand closure. Future stand compositions on these better sites are predicted to change. Oaks, once prominent on the better sites, are bring replaced by yellow-poplar. Basal area and stem density are highest in the tree strata on the better sites. The poorer quality, drier sites, are still progressing to stand closure and have minimal changes in stand composition. They continue to be dominated by oaks and/or pines. The majority of the basal area and stem density is in the shrub stratum on these sites.

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BOTTOMLAND RED OAK STAND DEVELOPMENT WITH IMPLICATIONS FOR MANAGEMENT AND FUTURE RESEARCH

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Abstract-Stand development involves changes in stand structure over time. Knowledge of stand development patterns is crucial for effective forest management, especially southern bottomland hardwood forests. These forests contain more than 70 tree species, many of which have commercial value. In this paper, stand development patterns in bottomland red oaks (Quercus spp.), especially cherrybark oak (Q. pagoda), are reviewed although examples from other oak forest types are included. These studies were divided into three broad categories: even-aged mixed genus, even-aged single genus, and uneven-aged mixed genus. Categorization by genus was necessary because of the lack of knowledge about interspecific and intergenus competition within and between red oak species. Management implications based on these development patterns are discussed, including the importance of many of the non- or less-commercial species during stand development. Areas for future research are also suggested to increase the knowledge base on bottomland hardwood stand development.

INTRODUCTION

Stand development, or dynamics, involves changes in stand structure over time (Oliver and Larson 1996). These changes occur in both a horizontal sense, or distribution of stems, and a vertical sense, or distribution of tree heights, within a stand (Kittredge 1986). An understanding of how stands develop is required for the long-term management of forests, not only for timber production but also for wildlife, water, and recreation uses. The need for more stand development knowledge has led to an increased number of studies and even to recent acceptance of stand development as a discipline unto itself (Oliver and Larson 1996). This paper will review past stand development studies involving bottomland red oaks (*Quercus* spp.), especially cherrybark oak (*Q.* pagoda). Studies of northern red oak (*Q. rubra*) dynamics will also be included with results being inferred for cherrybark oak. Implications from these study results are presented as suggestions for more efficient management of bottomland red oak stands. Also, suggestions for future research in stand development of bottomland red oaks will be put forth in an effort to better understand the dynamics of bottomland hardwood forests.

STUDIES OF BOTTOMLAND RED OAK STAND DEVELOPMENT

Few studies have been conducted involving bottomland red oak stand development. Of these, only two have dealt with natural, even-aged, mixed genus stands typical of southern floodplains. Although few in number, these studies have provided valuable information into how bottomland red oak stands develop and they suggest that forest managers and landowners must reconsider their perceptions on oak stand management. These studies have been divided into three broad categories: even-aged mixed genus, even-aged single genus, and uneven-aged mixed genus stands.

Even-Aged Mixed Genus Stands

Only one detailed study of cherrybark oak stand development in natural, even-aged, mixed bottomland hardwood stands has been conducted. In this study, Clatterbuck and Hodges (1988) used a combination of the chronosequence and the reconstruction techniques (see Oliver 1982 for a review of techniques in stand development research) in mixed cherrybark oak-sweetgum (*Liquidambar styraciflua*) stands growing on old-field sites. Their results depicted three patterns of cherrybark oak development depending upon the average spacing between a central (crop) cherrybark oak and adjacent sweetgum. The patterns were "restricted," "unrestricted," and "overtopped."

In the restricted pattern of development, the spacing between a central cherrybark oak and neighboring sweetgum was approximately 6 to 18 feet. This spacing resulted in cherrybark oak height being initially lower than that of sweetgum. Then, 20-23 years after stand initiation, cherrybark oak overtopped sweetgum and emerged into the canopy overstory. Cherrybark oak emergence was the result of a decrease in the rate of sweetgum height growth along with an increase in the rate of cherrybark oak height growth. Clatterbuck (1985) suggested several reasons for this:

(1) crown architecture-sweetgum exhibits an excurrent crown form while cherrybark oak exhibits a semi-excurrent crown form when competing with sweetgum but changes to a decurrent, spreading, form after emergence into the overstoty;

(2) crown abrasion-sweetgum twigs are smaller and more brittle at a given age as compared to cherrybark oak twigs, thus, during wind events, the terminal buds and twigs of sweetgum tend to break when scraped against twigs of neighboring cherrybark oak stems;

(3) high initial sweetgum density-a high initial sweetgum density may delay intraspecific (within species) crown differentiation thus leading to stagnation (Johnson 1968); and

(4) phenology-bud break in cherrybark oak, though occurring several days later than in adjacent

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sweetgum, occurs basipetally from the top of the crown while bud break in sweetgum occurs acropetally beginning at the base of the crown (Young 1980).

In the unrestricted pattern of development, the spacing between a central cherrybark oak and neighboring sweetgum was greater than 18 feet or the cherrybark oak was several years older than the sweetgum. Cherrybark oak, growing in these conditions, was essentially free to grow and thus experienced little crown competition from sweetgum following stand initiation. This condition is depicted in the height growth patterns in which cherrybark oak is always taller than adjacent sweetgum.

In the overtopped pattern of development, the spacing between a central cherrybark oak and neighboring sweetgum was less than 6 feet. Under these conditions, cherrybark oak stems were subordinate to adjacent sweetgum and stood little chance for survival (Clatterbuck 1985).

A comparison of the restricted and unrestricted patterns showed that the distance of neighboring sweetgum, i.e., the amount of interspecific (between species) competition, affected the carbon allocation patterns of cherrybark oak. With relatively small distances to neighboring sweetgum, more photosynthates were allocated to height growth as the oak tree competed for dominance: a survival mechanism. After emergence, or stratification, cherrybark oak height growth rate slowed but crown and basal, or diameter, growth increased. This change reflects the spreading habit of emergent oak crowns which increase leaf area thus leading to greater photosynthate production.

The spreading habit of oak crowns following stratification has also been noted by Kittredge (1988). This study, involving mixed stands of northern red oak, black birch (*Betula lenta*), and red maple (*Acer rubrum*) combined the reconstruction and chronosequence techniques. Stands chosen were approximately 40-60 years of age, a time in which northern red oak had recently stratified above birch and maple. The stands differed primarily in the density of oak present in the overstory. Since cherrybark oak and northern red oak may have similar patterns of development (Hodges and Janzen 1987), this study may shed light on cherrybark oak development as well.

Kittredge (1988) found that the number of trees within a 10-meter radius of a central northern red oak did not have a negative impact on 5-year basal area growth. On the other hand, the amount of neighboring oak basal area and number of oak trees had a significant negative effect On central oak basal area growth. Total basal area also had a negative effect on central oak basal area growth, but to a lesser extent than neighboring oak basal area. The major reason for this growth reduction involved intraspecific competition between oak crowns in the upper canopy following stratification. Crown expansion and subsequent basal area growth of individual oaks was greater in the presence of few oak competitors rather than many, a result of decreased intraspecific competition for growing space sooner in the upper canopy. Kittredge (1986) suggested that this effect was due to:

(1) wider crowns (lower oak density) have a greater surface area and are thus exposed to a higher quantity and quality of sunlight;

(2) increased crown surface area in full sunlight produced a higher sun:shade foliage ratio and thus increased photosynthate production; and

(3) smaller crowns (higher oak density) have an increased incidence of crown abrasion with stout twigs of neighboring oaks and possibly within individual crowns itself; therefore, an individual oak will allocate more photosynthate defensively to branch thickening at the expense of bole thickening.

Clatterbuck and Hodges (1988), Kittredge (1988), and Oliver (1976) have demonstrated the phenomenon of oak stratification through the chronosequence and reconstruction techniques. But only one study has given unequivocable evidence to bottomland red oak stratification through the use of the permanent plot technique.

Johnson and Krinard (1988) found that 28 years after stand initiation, bottomland red oak species [cherrybark oak, water oak (*Q. nigra)*, and willow oak (*Q. phellos*)] began to emerge above sweetgum. They stated this situation was hardly predictable after 9 years when the overstory was composed primarily of sweetgum, river birch (*Betula nigra)*, and American hornbeam (*Ostrya americana).* But, during normal stand development, the river birch began to die due to increasing competition, while the American hornbeam was relegated to an understory position. The authors postulated that red oak would exceed sweetgum in height within 30-35 years after stand initiation. The difference in time of stratification between this study and Clatterbuck and Hodges' (1988) study was probably due to the cutover sites utilized by Johnson and Krinard (1976, 1983, 1988) compared to the old-field sites utilized by Clatterbuck and Hodges. Similar results were reported by Bowling and Kellison (1983) in mixed stands of water oak, sweetgum, blackgum (*Nyssa sylvatica* var. *biflora*), and American hornbeam.

In summary, these studies suggest that cherrybark oak, and possibly water oak and willow oak, can reach a dominant or codominant position in even-aged, mixed genus bottomland hardwood stands. If given some direct overhead sunlight during the early years of stand development, bottomland red oaks will eventually surpass species such as river birch, American hornbeam, and sweetgum through intergenus competition. Once in the overstory, intraspecific (or intragenus) competition between oaks plays a major role in regulating growth and development of individual oak trees. But recent studies in other mixed-genus stands have shown that cherrybark oak (and probably other bottomland red oaks) will not stratify above species such as sycamore (*Platanus occidentalis*) (Clatterbuck and others 1987), loblolly Pine (*Pinus taeda*) (Clatterbuck 1989), and possibly yellow-Poplar (*Liriodendron tulipifera*) (O'Hara 1986) in stream and river floodplains. Clearly, there is much still to learn about managing such complicated stands.

Even-Aged Single Genus Stands

The occurrence of natural, even-aged, single genus stands of bottomland red oak is believed to be the result of fortuitous events early in the life of the stand, such as fire and grazing, that eliminated competing species (Aust and others 1985). While pure stands of water oak and willow oak can be found on certain sites, pure stands of cherrybark oak occur much less frequently. Studies of how such stands develop provide useful insight into how bottomland red oaks interact when confronted with intraspecific (or intragenus) competition throughout their life. At present, only one study has been conducted involving stand development in single genus stands of bottomland red oaks, primarily cherrybark oak. Aust (1985) used the chronosequence technique to identify factors important in determining red oak structure.

Stratification in these pure stands differed from that of even-aged mixed genus stands. In single genus red oak stands, increased intraspecific competition among oaks may result in individual trees growing taller with lower live-crown percentages as compared to oaks from mixed stands. Such conditions could lead to increased lengths of branch-free boles through continual natural pruning by neighboring oak stems. Kittredge (1986) found that the height to the base of the main fork was positively related to the amount of northern red oak present in prestratified stands, which suggests that intraspecific competition early in a stand's development produced longer merchantable bole lengths. But similar results were not found by Aust (1985) in relatively pure bottomland red oak stands under either narrow or wide spacing between oak stems. Furthermore, early intraspecific competition between bottomland red oaks may increase stress within individual oaks stems, thereby increasing the probability of epicormic branching (Meadows 1995).

The major differences between single genus and mixed genus stands, in terms of growth and development of an individual oak stem, are (1) the intensity and onset of intraspecific competition between oaks and (2) the lack of interspecific competition in single genus stands. Aust (1985) concluded that pure oak stands had no major advantages or disadvantages over mixed-genus oak stands in terms of growth and yield. On the contrary, individual stems in mixed-genus stands will probably have larger diameters containing high quality wood. On a per-acre basis, fewer red oak stems of higher quality may be worth more than red oak stems grown in relatively pure stands. At present, this is speculative.

Uneven-Aged Mixed Genus Stands

In general, most research and management practices for bottomland red oak stands have assumed that stands are even-aged (Hodges 1987). Development of uneven-aged bottomland red oak stands has been largely neglected. This is due to several factors such as the relative scarcity of uneven-aged stands relative to even-aged ones, their more complicated stand structure, and even the sense that uneven-aged silviculture in bottomland oaks is not viable (DeBell and others 1968, Hodges 1987).

However, Guldin and Parks (1989) conducted a stem analysis study in an uneven-aged cherrybark oak stand. The study consisted of 0.2-acre plots, each of which contained three distinct age classes of cherrybark oak. Their data suggested that cherrybark oak stratification occurred within canopy gaps created by the removal of large overstory trees. Two types of stratification were depicted. The first occurred within an age class, particularly the oldest age class, in which a single cherrybark oak seemed to dominate. The second type of stratification occurred between age classes. This was expected, given that younger stems start below older stems. Of particular interest were the developmental patterns between the tallest cherrybark oaks in each of the three plots. The dominant cherrybark oak in one plot was taller than neighboring stems early in its life. Therefore, the lack of more direct intraspecific competition as compared to the tallest cherrybark oak in the other plots may have led to its lesser height. This difference does not take into account the effects of the older, residual trees surrounding these gaps which should affect development within gaps.

Based on these results, Guldin and Parks (1989) stated that the development of cherrybark oak in gaps might be similar to the even-aged developmental dynamics as outlined by Clatterbuck and Hodges (1988). They also suggested that the absence of cherrybark oak in gaps created by single-tree and group selection cuts might be due to the lack of sufficient advanced regeneration at the time of harvest, rather than to the inability of existing advanced growth to develop.

MANAGEMENTIMPLICATIONS

Management of bottomland stands containing red oak is not complicated once stand development patterns have been recognized. Important considerations include the species composition and the ability of the forest manager to elucidate development patterns early in the stand development game, i.e., large-sapling to small-pole stage of development. Crop trees should be selected at this stage. The following suggestions for bottomland red oak management are based on neighboring species composition. These suggestions assume intermediate stand conditions; therefore, no consideration for regeneration is given. Also, biological maturity is assumed instead of economic maturity for rotation length due to an inherent bias for large saw-timber and benefits of large trees for wildlife.

Even-Aged Mixed Genus Stands

The key to managing bottomland red oak in even-aged mixed genus bottomland hardwood stands is the spacing between neighbors and the crop tree, beginning with the sapling to small-pole stage of development.

If neighboring trees are shade-tolerant species, such as ironwood, sugarberry (*Celtis laevigata*), elm (*Ulmus* spp.), or less shade-tolerant species which contain small-diameter twigs, such as river birch or sweetgum, then bottomland red oaks (especially cherrybark oak) should stratify above these species. It is possible that stratification Will occur in two stages. First, the bottomland red oaks would stratify above the more shade-tolerant species, most of which are relegated to a subordinate position when competing against less shade-tolerant species. Following a short period of time, bottomland red oaks would then emerge above the less shade-tolerant species and comprise the main canopy. Once the oaks have stratified above the other species, crown expansion would begin leading to increased diameter growth. The limiting factor on diameter growth would then depend on the onset of intraspecific competition between oak crowns in the upper canopy.

Under this development scenario, deadening or thinning the competing species before the oaks gain dominance would not be necessary since the oaks will gain dominance regardless (Kittredge 1986). Thinning these "trainer' species may lower merchantable height and bole quality of the oaks, thereby reducing their ultimata value. An assumption to this management option of basically doing nothing is that individual bottomland red oak stems attain some direct overhead sunlight throughout most of the early stages of their development.

If neighboring trees are less shade-tolerant than the oaks or equally shade-tolerant and have strong twigs and branches, such as yellow-poplar, sycamore, loblolly pine, and green ash (*Fraxinus pennslyvanica*), then it is less likely that bottomland red oaks can stratify above these species. Therefore, these species are the key competitors of bottomland red oaks. In the early stages of stand development it would be of benefit to the oaks if these key competitors were removed from the stand by deadening or thinning. Since ash crown dynamics seem to be similar to that of oaks (Kittredge 1986), and given the current stumpage value for premium ash, stems of this species may be considered as crop trees also.

If neighboring trees are other oak species, then spacing is especially critical. While the effects of other oak species competing with each other are not yet clear, it is reasonable to assume that intraspecific (or intragenus) competition will be more intense than intergenus competition. If neighboring oak trees are relatively close to crop trees, but not close enough to compete before stratification above other species, then intraspecific competition will begin soon after stratification. This competition for space in the upper canopy will decrease growth of the crown, and thus the bole. Therefore, two options exist to either avoid or alleviate early intraspecific competition following stratification. One is to deaden some of the future oak competitors early in the life of the stand. This option is heavily dependent upon the forest manager's ability to pick crop trees at a young age. A second option is to conduct a thinning operation following emergence of oak into the overstory. Such an operation is risky given the destructive nature of harvest operations on residual crop trees, especially in relatively young, dense stands (Meadows 1993).

If neighboring oaks are so close as to cause intraspecific competition early in the life of the stand, then development Will be similar to that of a pure oak stand. This possibility will be discussed in the section on development in single genus stands.

An optimum range of spacings between bottomland red oaks and its various neighboring species has yet to be determined except for cherrybark oak-sweetgum mixtures. Therefore, crop trees should be selected early in the development of a mixed stand and neighboring composition identified. Species such as yellow-poplar, sycamore, and loblolly pine should be deadened if they will compete directly with the oaks in the future. Deadening may consist of simple girdling. Subsequent sprouts of the hardwood species may not be able to compete starting underneath a larger sapling to small pole-sized stand. Many of the remaining species, i.e., shade-tolerants or small-twigged shade-intolerants, should be left. These species will enhance the development of bottomland red oaks by acting as "trainer" species.

Even-Aged Single Genus Stands

Stratification in relatively pure bottomland oak stands differs from that in mixed-genus stands, leading to red oak crowns codominating in the overstory since they usually will not emerge above one another. Management in relatively pure red oak stands also differs from that in mixed-genus stands. Due to a lack of intergenus competition, the forest manager will have to rely on intragenus competition to act as trainers of crop trees. This will result in smaller crowns and bole diameters, maybe even lower bole quality, in crop trees. Therefore, several thinning operations will be needed to promote good growth of crop trees. As previously mentioned, such operations increase the risk of damage to both boles and crowns of crop trees. Thinning may also increase the incidence for epicormic branching, further lowering bole quality (Stubbs 1986, Meadows 1995).

Development of relatively pure bottomland red oak stands seems to be the result of disturbance early in the life of the stand (Aust and others 1985), which should be avoided. Conventional wisdom suggests that it is better to have too much oak than none at all. But attempts should probably be made to control disturbances that promote the establishment and development of relatively pure red oak stands, in favor of retaining mixed-genus stands if high-quality saw logs are the desired product.

Uneven-Aged Mixed Genus Stands

Management of bottomland red oak in uneven-aged stands is hampered by the scarcity of information about development of such stands. At present, it may be best to view red oak development in the gaps of uneven-aged stands as development of small, even-aged mixtures. Guldin and Parks (1989) noted that the trees developing in a gap were of relatively the same age. Since plots ware selected for cherrybark oak, the data also depicted intense intraspecific competition within a gap. Furthermore, these oaks probably competed with trees of older age classes with larger crowns. Therefore, red oak crop trees have two conditions of intraspecific competition: within a gap and from around the gap. While intraspecific competition within a gap may produce crop trees with smaller crowns, the periodic removal of trees around the gap may allow crop trees to spread their crowns. Therefore, such trees may have more desirable characteristics as compared to those grown in even-aged single genus stands. Obviously, more information is needed on bottomland oak development in uneven-aged stands before more definite silvicultural prescriptions can be made.

FUTURE RESEARCH

There are many areas worthy of future research in stand development of southern bottomland red oaks. What follows is a list briefly describing several of these areas.

Stand Development

Future stand development studies should use combinations of the chronosequence and reconstruction techniques to better understand development patterns. Variations of these techniques could include point-chronosequence using stands of similar ages but with varying amounts of oak density (similar to Kittredge 1988). Another variation could include using gaps of different ages as a chronosequence within a stand for studying development in uneven-aged stands. These studies should include the following situations:

(1) different sites within floodplains, such as ridges and fronts on small river bottoms, and within the loessial hills;

(2) different species compositions such as green ash, hickory (*Carya* spp.), etc.; and

(3) varying densities of bottomland red oak species.

Mixed-Species Plantations

At present, much effort is being expended on reforestation activities to convert former agriculture land to forest (Kennedy and Allen 1989). These activities involve establishing relatively pure bottomland oak stands or mixing several oak species. Based on reviews of previous stand development studies, such plantations may suffer in the long run as oak trees of lower bole quality may be produced (unless such stands are judiciously thinned). Therefore, stand development patterns need testing using a mixture of tree species with artificial regeneration techniques, such as planting and direct seeding. Such plantations could potentially produce more biomass compared to single-species plantations as different species occupy different canopy layers (Kelty 1992). One research effort studying mixed-species plantations and the effects of intraspecific and interspecific competition is underway using mixtures of Nuttall oak (*Q. nuttallii*), water oak, and green ash in an elaborate experimental design (Goelz 1995). Additional studies need to include other less-desirable species (from a timber standpoint) such as sweetgum, American hornbeam, and sugarberry to determine if such species can contribute significantly to increased bole quality in addition to the added benefit of increased species diversity.

Crown Architecture

More study on the role of crown architecture in determining stand development patterns is warranted. Based on the previously discussed studies, the ability of a crop tree to compete successfully in the upper canopy depends on how well it can occupy physical growing space in the canopy. Future studies should include tests of relative twig and branch strength between species. Studies could also be conducted on crown expansion rates, foliage type (sun versus shade), and foliage distribution within a canopy.

Whole Tree Physiology

How well a crop tree competes ultimately depends on its ability to increase carbon allocation when more growing space becomes available. Therefore, information is needed on whole-tree leaf area and gas-exchange, i.e., net photosynthesis and transpiration. This information would not only increase knowledge on how bottomland red oaks grow but also provide insight into how they respond to competition from different species. Such a study has recently been completed with northern red oak, red maple, and black birch (Moser 1994).

Permanent Plots

While establishing more permanent plots to specifically study stand development would be desirable, the costs of such projects are probably prohibitive. Therefore, efforts should be made to expand data collection in existing growth and yield plots to encompass testing hypotheses about stand development. Furthermore, efforts should be made to retain permanent plot data when long-term studies are terminated. Such data may contain as yet unrealized benefits regarding stand development patterns.

CONCLUSIONS

An understanding of how bottomland red oak species develop is essential to making effective silvicultural recommendations for forest managers and landowners who own and manage bottomland hardwoods. The fact that oaks can exist for decades beneath other species and yet can ultimately dominate the stand reflects the dynamic and robust nature of the genus. Recommendations for intermediate silvicultural treatments must reflect these unique developmental dynamics.

The fact that oak developmental dynamics are so different from those of the southern pines is part of the challenge for forest managers and landowners is the South. For example, if pines lag behind other species, they generally cannot recover. Forest managers who are accustomed to thinning and releasing pines from competing species at young ages might be tempted to apply similar tactics in young mixed-species bottomland hardwood stands-and they might be making poor silvicultural decisions if they did.

The studies cited here epitomize how silvicultural recommendations must reflect the best scientific information available for the species being managed. Although forest management ultimately depends on the objectives of the landowner, it is up to the forest manager to advise on how to best meet these objectives. Finally, knowledge of stand development patterns is rewarding in itself, in simply knowing how a stand grows and in being able to predict how it will look in the future.

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Footnote

To avoid repetition, intraspecific competition within a bottomland red oak species also refers to intragenus competition between bottomland red oak species unless otherwise noted.

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HARDWOOD PLANTATIONS AFTER 20 YEARS ON A MINOR STREAM BOTTOM IN SOUTHEAST ARKANSAS: SURVIVAL, GROWTH, AND VOLUNTEER INGROWTH

D.W. Carlson and J.C.G. Goelz[1]

Abstract-Eight hardwood species were planted in May 1976 on a minor stream bottom at 8x8-foot and 12x1 P-foot spacings. Tree species planted include: green ash (*Fraxinus pennsylvanica* Marsh.), American sycamore (*Platanus occidentalis* L.), sweetgum (*Liquidambar styraciflua* L.), swamp chestnut oak (*Quercus michauxii* Nutt.), cherrybark oak (Q. *falcata* var. *pagodifolia* Ell.), water oak (Q. *nigra* L.), eastern cottonwood (*Populus deltoides* Bartr. ex Marsh), and Nuttall oak (Q. *nuttallii* Palmer). In both spacings, sycamore, sweetgum, and green ash had the best survival, diameter, and height by age 6. At age 20, sweetgum was the largest in d.b.h. and height, and cherrybark oak, water oak, and Nuttall oak were larger and taller than green ash and sycamore. Survival at age 20 was highest for sweetgum (96 percent) in both spacings and also high for green ash and water oak. For other species, survival was variable between spacings, with Nuttall oak having the lowest survival (42 percent) in the 8x8- foot spacing. Volunteer ingrowth into all plantations was primarily loblolly pine (*Pinus taeda* L.) and sweetgum. For either spacing, green ash plantations had the most volunteer ingrowth and water oak had the least. On average, the oak plantations had more sweetgum than pine volunteer ingrowth, and green ash, sycamore, and sweetgum plantations had more pine volunteers.

INTRODUCTION

Plantations of southern bottomland hardwoods have been established by public agencies, private nonindustrial landowners, and forest product companies. Many of these plantations have been established within the last 10 years. Research on plantation establishment has provided guidelines for establishment. However, information on growth and yield for midsouth oak plantations 20 years or older is limited (Krinard and Johnson 1988).

METHODS

The study site is located approximately 9 miles south of Monticello, AR. Prior to study initiation, the site consisted of 75 acres of mixed hardwood-pine forest that was harvested, cleared, root raked. and disked in the fall of 1975. The experimental design used was a randomized complete randomized block with four replications. Within each of the four replications, an 8x2 factorial design was used with two factors: species and spacing. Each study plot had 169 planting spots, arranged in a 13x13 row configuration. The soil type is Arkabutla, with pH between 4.9 and 5.3; the soil is poorly drained in some areas.

Eight tree species were planted at spacings of 8x8 foot and 12x12 foot. The eight species planted were: green ash (*Fraxinus pennsylvanica* Marsh.), American sycamore (*Platanus occidentalis* L.), sweetgum (*Liquidambar styraciflua* L.), swamp chestnut oak (*Quercus michauxii* Nutt.), cherrybark oak (*Q. falcata* var. *pagodifolia* Ell.), water oak (Q. *nigra* L.), eastern cottonwood (*Populus deltoides* Bartr. ex Marsh), and Nuttall oak (Q. *nuttallii* Palmer). The planting stock used was purchased from the State nursery. Planting started on May 10, 1976, and was completed by May 18th.

After planting, weed control was accomplished by disking five times for the first growing season. For years 2 and 3, mowing was done monthly during the growing season. After year 3, mowing was done before each measurement until 1989. All mowing and disking was done in a single direction because the original study included plots with narrower spacings (2x8, 3x8) than the 8x8-foot spacing this paper is reporting. Shumard oak (Q. *shumardii* Buckl.) was originally planted but the nursery stock contained a mixture of different oaks. These plantations were cleared and Nuttall oak was planted after the first growing season. Therefore, the age of Nuttall oak is 1 year less than all other species. After the fifth growing season, plots containing cottonwood were dropped from the study. The species had good survival up to age 3, but by age 5 most trees were dead.

For the first 8 years, mean annual increment (MAI) was calculated. At age 8, the MAI in the 8x8-foot and 12x12-foot plantations had peaked for sweetgum, green ash, and sycamore. At this time, trees in every other diagonal row were cut and removed from the plots. The oak plantations have not been thinned. Therefore, comparisons will be made between thinned plots of green ash, sycamore, sweetgum, and unthinned plots of the oaks.

The study has been measured annually by taking measurements of survival, stump diameter [15 centimeters (.5 feet) above ground line], d.b.h., and total height. These measurements were done during the dormant season on each planting location within the interior 5x5 rows of each plot. Beginning in 1995, all volunteer ingrowth with a d.b.h. greater than 5 centimeters (2.0 inches) was recorded by species and measured for height and d.b.h. We will report survival, growth (height and diameter), and volunteer ingrowth at age 20.

Data were analyzed by ANOVA followed by Tukey's test for mean comparison (alpha = 0.05). Survival percentages ware transformed by arcsin (square root) prior to analysis.

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RESULTS AND DISCUSSION

Survival

Initial survival in the 8x8-foot spacing (fig. 1) was good for all species; at age 19, Nuttall oak had the lowest survival, (42 percent). One of four Nuttall plots had excellent survival (100 percent) but the other three had poor survival (less than 25 percent). However, in the 12x12-foot spacing (fig. 2), Nuttall oak was among the species having the highest survival (91 percent). Green ash, sycamore, and sweetgum were among the species having the highest survival for the 12x12-foot spacing; swamp chestnut oak had the lowest survival (62 percent). Mortality for all species generally occurred within the first 2 years with an occasional tree lost thereafter. However, after age 16, mortality of several stems had occurred in sycamore plots in both spacings and green ash in the 8x8-foot spacing (figs. 1 and 2).

Species, spacing, and species-by-spacing interaction terms are significant, Species having significantly lower survival rates than sweetgum in the 8x8-foot spacing (table 1) were cherrybark oak and Nuttall oak. In the 12x12-foot spacing (table 1), survival was significantly less for swamp chestnut oak when compared to sweetgum, green ash, and Nuttall oak. Only Nuttall oak had survival rates that differed significantly between spacings, but across species, survival tended to be lower for the 8x8-foot spacings.

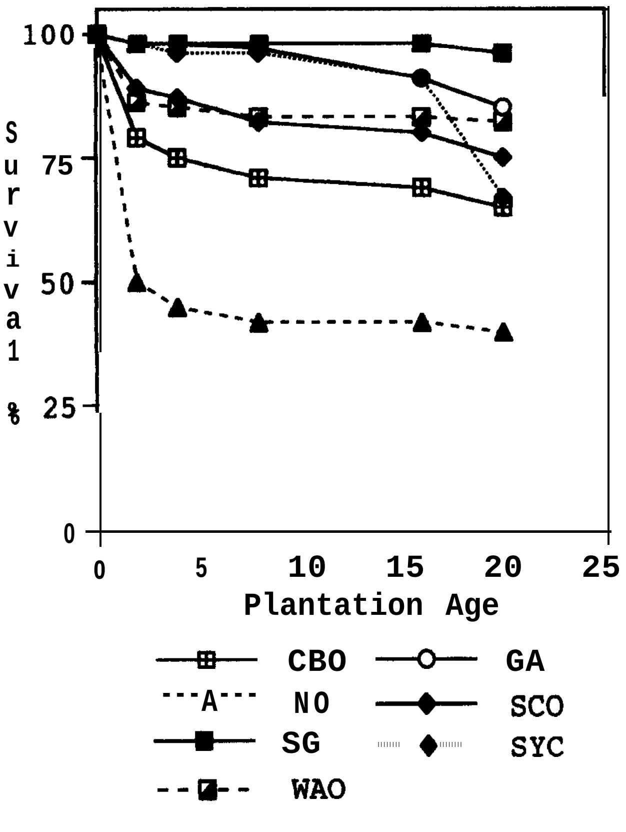

Figure l-Average survival over time for the 8x8-foot spacing plantations. Species codes are: CBO = cherrybark oak; GA = green ash; NO = Nuttall oak; SCO = swamp chestnut oak; SG = sweetgum; SYC = American sycamore; WAO = water oak.

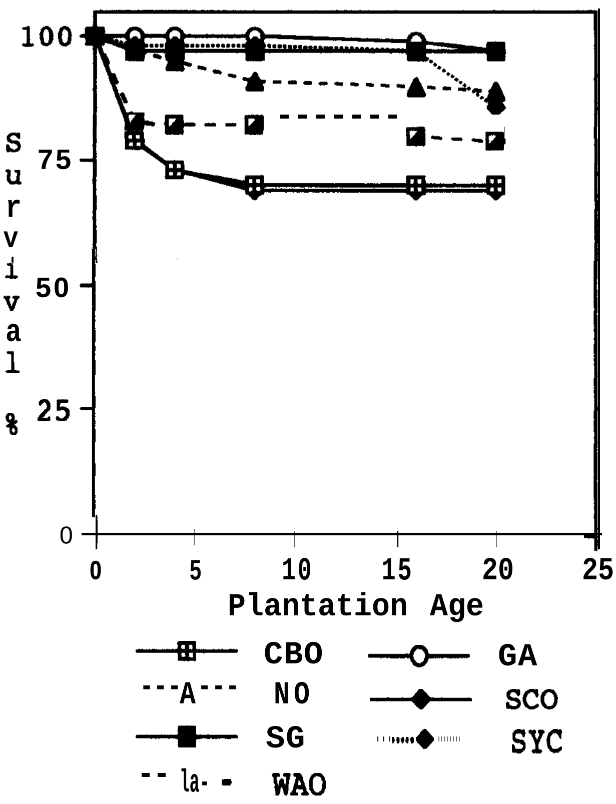

Figure 2-Average survival over time for the 12x12-foot spacing plantations. Species codes are: CBO = cherrybark oak; GA = green ash; NO = Nuttall oak; SCO = swamp chestnut oak; SG = sweetgum; SYC = American sycamore; WAO = water oak.

Table 1— Average survival, height, and diameter at age 20 for plantations on a minor stream bottom site in southeast Arkansas [letters signify results of Tukey's test for mean comparison (alpha = 0.05) and apply to both spacings for a given variable]

	Spacing					
Species	8x8	12x12	8x8	12x12	8x8	12x12
	Pct. survival		---Height (ft)---		----D.b.h. (in)----	
CBOa	65b	71ab	39b	47ab	4.6de	6.9ab
GA	85ab	97a	25c	36bc	3.1e	5.3bcd
NO	41b	91a	35bc	44ab	5.3bcd	5.9abcd
SCO	78ab	62b	28c	29c	3.8de	5.2bcd
SG	97a	96a	43b	52a	5.7bcd	8.1a
SYC	69ab	90ab	26c	35bc	3.0e	4.7cde
WAO	81ab	79ab	39b	45ab	4.4de	6.9abc

Species codes are: CBO = cherrybark oak; GA = green ash; NO = Nuttall oak; SCO = swamp chestnut oak; SG = sweetgum; SYC = American sycamore; WAO = water oak.

Mechanical damage from disking and mowing could have caused higher mortality on the 8x8-foot spacings. Some differences in initial survival may be a result of site variability. When the site was planted, there were places where mineral soil was exposed, mostly by erosion and clearing.

Diameter

Sweetgum, sycamore, and green ash were among the fastest growing species in diameter for both spacings (figs, 3 and 4) at age 6. At age 20, sweetgum was the largest species in both spacings, although not significantly different from cherrybark, Nuttall, and water oak. Swamp chestnut oak, sycamore, and green ash were among the smallest for both spacings. Average diameter appears to be decreasing for sycamore in the 8x8-foot spacing (fig. 3). This was caused by stem die-back below breast height followed by sprouting. Nuttall oak in the 8x8-foot spacing (fig. 3) was among the largest oak species. However, three replications had low survival, providing less tree competition and thus greater diameter growth. Water oak in both spacings was among the fastest growing species in diameter by age 10. At age 20, cherrybark oak diameter was slightly larger than water oak in the 8x8-foot spacing and equal in the 12x12-foot spacing (figs. 3 and 4) however, the difference is not significant (table 1). Diameter was greater in the 12x12-foot spacing for all species although the difference was not significant for Nuttall oak, swamp chestnut oak, and sycamore. Results of the ANOVA and Tukey's test for diameters are displayed in table 1.

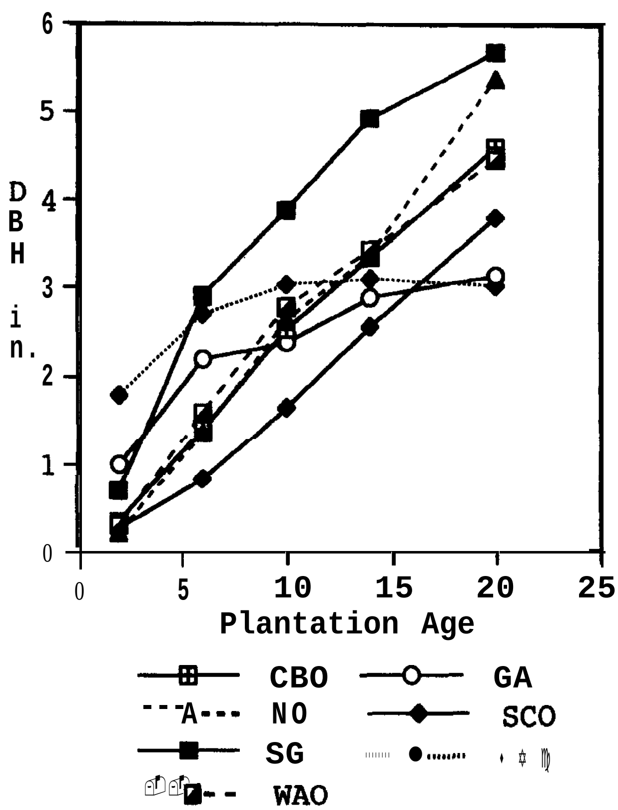

Figure 3-Average diameter over time for the 8x8-foot spacing plantations. Species codes are: CBO = cherrybark oak; GA = green ash; NO = Nuttall oak; SCO = swamp chestnut oak; SG = sweetgum; SYC = American sycamore; WAO = water oak.

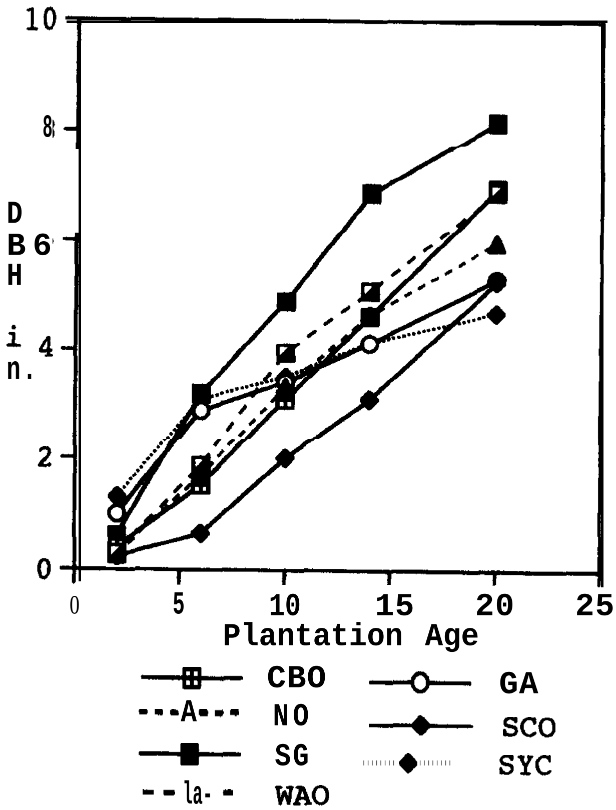

Figure 4-Average diameter over time for the 12x12-foot spacing plantations. Species codes are: CBO = cherrybark oak; GA = green ash; NO = Nuttall oak; SCO = swamp chestnut oak; SG = sweetgum; SYC = American sycamore; WAO = water oak.

Height

Sweetgum, sycamore, and green ash were among the fastest growing species in height by age 6 (figs. 5 and 6). By age 20, sycamore and green ash average height increment had become negligible or negative. Water oak in both spacings had the fastest initial height growth among the tallest species. At age 20, cherrybark oak was slightly taller in the 12x12-foot spacing (fig. 6, table 1) however, the difference was not significant. In the first 2 years, average height for all species was greater in the 8x8-foot spacing. At age 20, average height was greater in the 12x12-foot spacing for all species, although this was only significant for sweetgum (table 1).

Possible reasons why green ash and sycamore were among the lowest in height and diameter growth at age 20 may be the result of low soil nutrients. Soil tests were taken and results revealed that nutrient availability for this site is poor and would be rated infertile for hardwoods; the levels were below or barely reaching acceptable levels for potassium, phosphorus, and calcium (Kennedy and others

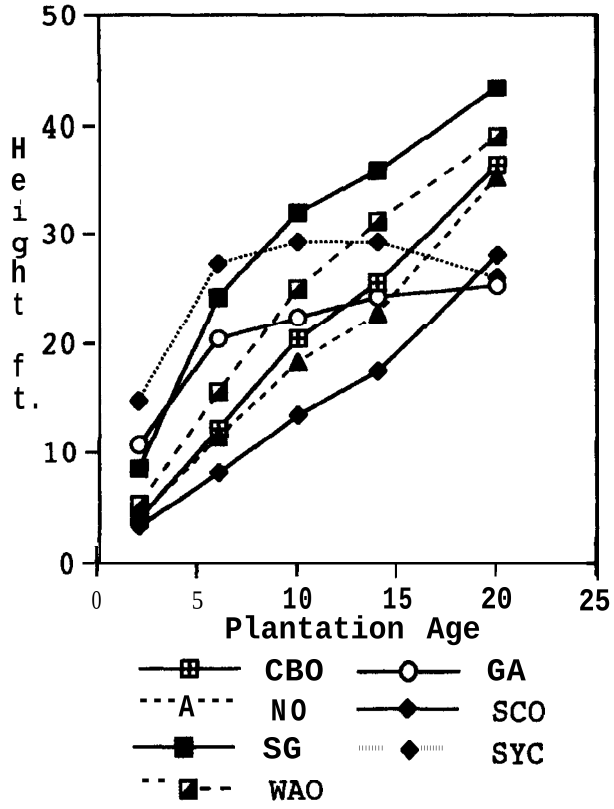

Figure 5—Average height over time for the 8x8-foot spacing plantations. Species codes are: CBO = cherrybark oak: GA = green ash; NO = Nuttall oak; SCO = swamp chestnut oak; SG = sweetgum; SYC = American sycamore; WAO = water oak.

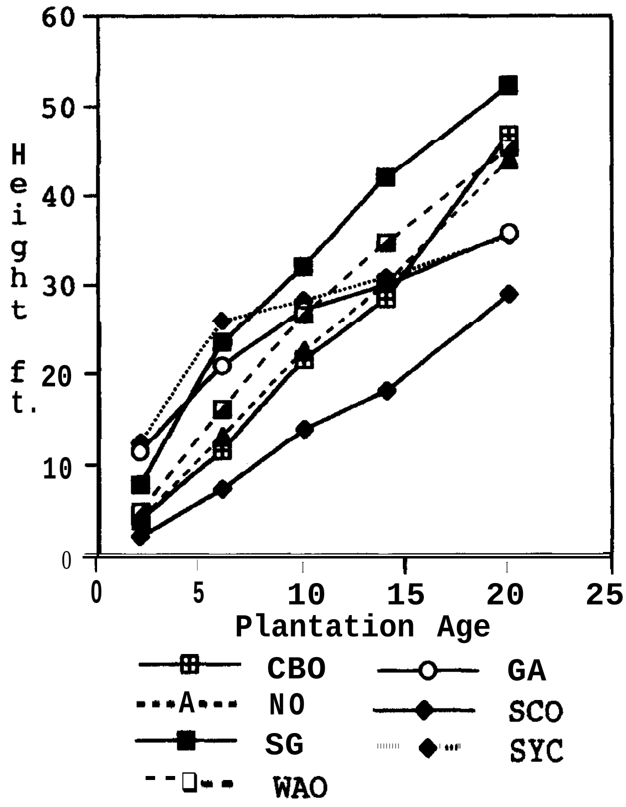

Figure 6-Average height over time for the 12x12-foot spacing plantations. Species codes are: CBO = cherrybark oak; GA = green ash; NO = Nuttall oak; SCO = swamp chestnut oak; SG = sweetgum; SYC = American sycamore; WAO = water oak.

1987). Green ash has shown good survival on acidic sites (soil pH 5.4 or below), but low annual height growth rates of 1 foot have been reported (Kennedy 1991). Sycamore may have low productivity on specific microsites within the Arkabutla soil series when the soil physical condition, nutrient availability, moisture availability, and soil aeration are poor (Briscoe 1969).

Volunteer Ingrowth

Most volunteer ingrowth occurred within the row due to disking and mowing being done in a single direction. Volunteers are primarily loblolly pine (*Pinus taeda* L.) and sweetgum. In both spacings, the green ash plots had the greatest basal area of pine volunteers (table 2); water oak plots were among the lowest for pine and hardwood volunteers. Significant differences in volunteers were found among species but not spacings or species-by-spacing interaction. Generally, plots of species that survived and grew well had less volunteer ingrowth than plots where survival or growth was low. When the basal area of planted trees and basal area of volunteers were summed, there was no significant difference in total basal area between spacings or among species (table 2).

Table 2-Volunteer ingrowth in basal area per acre and total basal area of planted and volunteer trees at age 20 in plantations on a minor stream bottom site in southeast Arkansas [letters signify results of Tukey's test for mean comparison (alpha = 0.05) and apply to both spacings for a given variable]

	Basal area		
Species	Pine	Hardwood	Total
CBOa	5.3b	7.7ab	75.2a
GA	51.2a	12.3ab	89.5a
NO	13.5b	6.3a	69.1a
SCO	17.8b	14.1a	75.7a
SG	10.5b	0.003b	77.1a
SYC	22.8b	16.1a	61.7a
WAO	O.lb	3.3ab	72.3a

Species codes are: CBO = cherrybark oak; GA = green ash; NO = Nuttall oak; SCO = swamp chestnut oak; SG = sweetgum; SYC = American sycamore; WAO = water oak.

CONCLUSIONS

Green ash and sycamore initially had good survival and grew well; however, growth was minimal over the last 10 years and mortality was increasing. Volunteer ingrowth was greatest in the green ash plots and lowest in the water oak plots. When the volunteer basal area was added to the planted basal area, there was no significant difference between spacings or among species. This may indicate that given sufficient influx of volunteers, the total basal area at age 20 was determined by the capacity of the site. We expect that in the future, total basal area for plantations of different species will differ due to natural stand dynamics. Even though soil nutrient availability was low, growth of cherrybark oak, water oak, and Nuttall oak was good. At age 20, sweetgum, cherrybark oak, and water oak were the best species, based on survival, height, and diameter.

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ABOVEGROUND BIOMASS AND LEAF AREA DYNAMICS OF INTENSIVELY MANAGED, 3-YEAR-OLD SWEETGUM COPPICE

Glenn W. Gladders and Klaus Steinbeck[1]

Abstract-Sweetgum coppiced in April of 1994 has been growing at a 1.2x2.4-m spacing on an intensively managed plantation in Tattnall County, Georgia. Four treatments consisting of two levels of fertilization (570 and 1,140 kg of 20-10-10 per hectare per year plus micronutrients) and two levels of moisture (natural rainfall and rainfall + 150 cm per growing season through drip irrigation) are being applied annually. The partitioning of aboveground biomass among foliage, bark, stem wood, and branch wood was determined through destructive sampling of approximately 150 trees. Regression equations predicting percent biomass of each component from diameter at breast height were developed. Additionally, the cumulative area of fallen leaves was estimated through monthly collections of leaf litter from 1x1-m leaf traps. No significant differences between treatment means were found for any measured variables after 3 years. Dominant trees averaged 5.4 m in height three growing seasons after coppicing. Average dry weight of aboveground biomass was 37.2 t/ha, representing a mean annual increment of 12.4 t/ha/year. At the stand level, about 55 percent of that biomass was stem wood, and the remaining 45 percent was divided equally among branch wood, bark, and foliage. Cumulative leaf area index of fallen leaves for the entire growing season averaged 7.2 for all treatments.

INTRODUCTION

Demand for hardwood fiber has increased rapidly due to the increased manufacture of coated board and fine papers (Cubbage and others 1995, Howell and Hartsell 1995). Much of the existing hardwood supply is found on bottomland sites, where wet winters restrict logging operations. Mills must be supplied year-round and this has led to interest in growing hardwood plantations on upland sites which can serve as emergency reserves during supply crises. In the South, this interest centers on the Coastal Plains because of the high pulp mill capacity located in this geographical area.

Uplands usually are not the best sites for hardwoods. Cultural treatments, especially fertilization and weed control, are needed for their satisfactory growth (Wittwer and others 1978). The study reported here is part of a larger experiment in which sweetgum (*Liquidambar styraciflua*) and sycamore (*Platanus occidentalis*) coppice are being grown on an upland under cultural treatments designed to supply optimal nutrition and soil moisture. The study reported here was designed to determine the total, aboveground biomass production of sweetgum grown on an upland site for 3 years after coppicing. Allocation to stem and branch wood, stem and branch bark, and foliage, as well as changes in foliar mass during the growing season, were estimated.

MATERIALS AND METHODS

Site Description

The study site is located in the Middle Coastal Plain in Tattnall County, GA. Topography is flat with some minor local variation. Average rainfall is about 115 cm per year. Previous to this study, the site was an agricultural field and Christmas tree plantation. Soils are in the Leefield and Fuquay series of Arenic and Plinthaquic Paleudults. These soils typically have a 60-cm thick loamy sand A horizon and a B horizon consisting of sandy clay loam and sandy loam. Both soils are acid throughout, with pH between 4.5 and 5.0. Site index (base age 50) for loblolly pine is 25.3 m. Organic matter content and inherent soil fertility are low, but fertilization of these soils can make them suitable for hardwood plantations.

Plant Material

In 1978, bare-rooted 1-O nursery-run sweetgum seedlings were purchased from the Georgia Forestry Commission and planted at a 1.2x2.4-m spacing. In April 1994, all of these trees were clearcut, allowing regeneration through stump sprouting. In June 1994, all plots received 1,820 kg of 1 O-l O-l 0 per hectare to stimulate rapid growth of the new sprouts. Early in the second season of growth, Roundup was applied to control competing vegetation. Canopy closure was achieved later that year, so no further herbicide applications were needed.

Treatments

Two irrigations and two fertility levels were used in this study. The field was divided in halves and one side received natural rainfall only, the other rainfall plus 150 cm of water by drip irrigation, during each growing season. Within each irrigation treatment were four plots, about 1/4 hectare in size (48.8x54.9 m). Each of these plots was split to receive estimated optimum nutrition (570 kg 20-l O-l 0 and 0.2 kg Cu, 0.3 kg Mn, and 1.1 kg Zn per hectare per year) on half of each plot and double these amounts on the other half. Granular fertilizer was broadcast on the nonirrigated plots at the beginning of each growing season. The irrigated plots received their fertilizer in liquid form injected into the irrigation water throughout the growing season. The entire field was also treated with 2.5 tonnes of calcitic limestone and 28 kg of elemental magnesium broadcast per hectare in 1996.

Data Collection

Biomass study—In order to develop regression equations relating diameter at breast height (d.b.h.) to biomass of

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stem and branch wood, foliage, and bark, whole trees were harvested in June and again in August of 1996. Approximately 75 trees were cut on each of these two collection dates, equally distributed over five l-cm diameter classes ranging from 2 to 6 cm. Equal numbers of trees were cut in irrigated and nonirrigated plots. Because no morphological differences due to fertility level were expected, trees were cut from border rows between fertility treatments. Sprouts were severed at ground level with shears or chainsaw, placed on a trailer, and brought to University of Georgia facilities in Athens for separation into component parts.

Subsampling was necessary in the field to ensure that an accurate estimate of leaf mass was obtained, as a large Percentage of leaves were stripped from branches during transport from the site. Two of the 5 trees in each diameter class, or 30 trees on each date, were subsampled. Every third branch was removed and all branches from each subsampled tree were sealed in a plastic bag for transport. Subsamples were stored at 5 °C until leaves and branches could be separated. Leaves and branches were dried separately in an oven at 60 °C to constant weight. Dry weights of branches and foliage were multiplied by three to obtain an estimate of whole-tree dry branch and foliage biomass. SAS software was used to develop a regression equation relating foliage biomass to d.b.h.

Remaining trees were separated into stems and branches. Stem bark weight was estimated by removing bark from a subsample of 10-cm sections cut from each stem at l-m intervals and drying bark and wood separately. Simple ratios were then used to estimate stem bark mass. For branch bark, 25 branches representing the entire range of branch diameters were stripped completely of bark, and a regression equation was derived to estimate branch bark and branch wood biomass from branch diameter. The diameters of all branches on 40 trees were then measured, and a final regression equation was derived to predict the mass of all branch wood and all branch bark from tree d.b.h.

In January 1997, diameters and heights were measured. Biomass of each component was estimated for each measured sprout using regression equations. Per-hectare estimates were then obtained through multiplication with the appropriate conversion factor.

Leaf area study—In order to estimate the mass Of abscised leaves, 48 1x1-m litter traps were installed in June of 1996. Three traps were placed within each fertility/irrigation treatment plot. Approximately every 4 weeks, the contents of all traps were collected dried, and weighed.

A subsample of leaves from the June whole-tree harvest date was used to develop a regression equation to estimate fresh leaf area from dry leaf weight. Leaves from various crown positions in all treatments were measured for leaf area on a Li-Cor meter. These leaves were then dried to constant weight and an equation was developed.

RESULTS

No significant differences were found between treatment means for any of the measured variables after three growing seasons (table 1). No significant interaction effect was found on any variable for the different fertilization/irrigation treatment combinations.

After three growing seasons, aboveground biomass averaged 37.2 t/ha (table 2). This represents an increase of 14.6 t/ha during year 3, and corresponds to a mean annual increment of 12.4 t/ha/year. Height of the dominant trees for all treatments averaged 5.4 m, an increase of 1.2 m during the third growing season (table 1). Aboveground biomass was produced at an increasing rate.

As d.b.h. increases, the proportions of stem wood and branch wood increase, while those of bark and foliage decrease (fig. 1). Stem wood is the largest component of a given sprout across the entire range of diameters observed, generally comprising over one-half of a sprout's dry weight. These data show how aboveground allocation changes with growth for a single sprout rather than for the stand as a whole.

At the stand level, the proportion of total biomass found in each component part depends on sprout diameter distribution. After three growing seasons, an average of 55 percent of total aboveground biomass was stem wood. The remaining 45 percent was divided approximately equally among branch wood, bark, and foliage (fig. 2). Of the 37.2 t/ha aboveground biomass, nearly 85 percent, or about 31.8 t/ha, is wood and bark.

Table I-P-values for mean total biomass and height after three growing seasons, all treatments

Term	Total biomass	Height
Model	0.63	0.79
Fertilization	0.53	0.56
Irrigation	0.26	0.74
Interaction	0.99	0.45

Table 2—Mean height and aboveground standing biomass after two and three growing seasons, all treatments

No. of growing seasons	Height	Yield
	m	*T/ha*
2	4.2	5.4
3	22.6	37.2

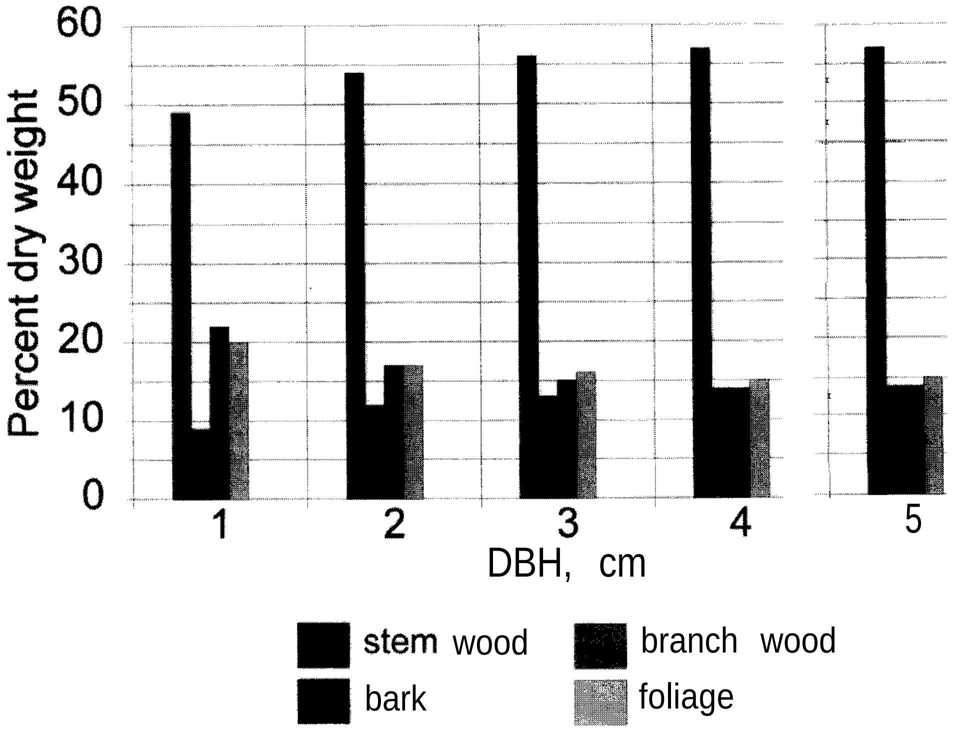

Figure l-Accumulation of biomass in stem, bark, branch, and foliage for trees in five diameter-at-breast-height classes.

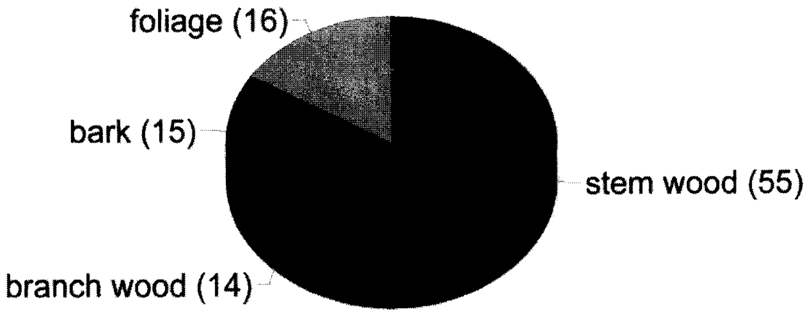

Figure 2-Average percent aboveground dry matter accumulation by tissue component 3 years after coppicing.

The estimated cumulative leaf area index of the leaves caught in the litter traps at the end of the third growing season was about 7.2 (fig. 3). Day 0 in figure 3 represents June 30, when the litter traps were installed. Leaves fell most rapidly during November and December, although senescence occurred to some extent year-round in these plots. Decagon's linear ceptometer device, AccuPAR, gave an estimated leaf area index (LAI) of 4.0 in late July of the third growing season.

DISCUSSION

Smith and others (1975) estimated that hardwoods growing in major river bottomlands in the South produce an average of about 5 tons/ha/year aboveground woody biomass. The sweetgum trees in the present study are producing about 12 tons/ha/year on a fertilized and irrigated upland site. The difference is due, in part, to the cultural treatments. Furthermore, coppice regeneration grows on an established root system with its carbohydrate reserves and immediate access to soil resources.

The lack of treatment effects is not particularly surprising. All 3 years after coppicing were relatively wet, so water has not been limiting even in the nonirrigated plots. The optimum fertilization level is rather high; the twice-optimum level was included to ensure that the major nutrients were not limiting growth.

It might be suggested that these sweetgum trees have attained their maximum growth rates. However, numerous studies (Cannell 1989, Cannell and Smith 1980, Stott and others 1982) involving intensively managed hardwood

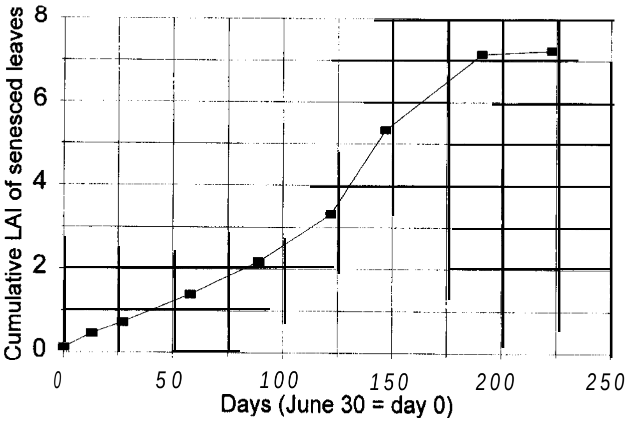

Figure 3-Cumulative leaf area index of fallen leaves during the third growing season.

species have shown production rates in the range of 15-20 t/ha/year in temperate zones of North America and Europe. Over 20 t/ha/year were produced with irrigation and N fertilization in Sweden using *Salix* (Cannell 1989), not typically considered an exceptionally fast grower. It seems reasonable to conclude that the sweetgum used in this study should be able to produce more than the current 12 t/ha/year.

Some other limiting factor is probably present at the study site. Nutrient analyses are being carried out on plant tissues at this time. Low supply of a micronutrient is a possible limiting factor, although any of a number of factors may be responsible for limiting growth.

Regression equations show that as d.b.h. increases, the proportion of stem and branch wood increases while that of foliage and bark decreases (fig. 1). A recent study (Wang and others 1996) showed similar results in *Betula papyrifera*, and these trends are applicable to tree growth in general. On a cross-sectional basis, stems and branches will increase in area more rapidly than in circumference, so the proportion of bark will decrease as trees grow. The foliage of small seedlings consists of a few large leaves but may represent over 50 percent of its aboveground biomass. Over time, stems and branches will accumulate biomass at rates exceeding the increase in leaf biomass. Eventually, mutual shading limits further increases in leaf biomass, especially after canopy closure is reached.

About 85 percent of aboveground biomass after three growing seasons is wood and bark usable for pulp, similar to results from other studies using hardwoods grown for pulp (Hook and others 1990). Within the aboveground portion, any increase in proportion of woody biomass would have to come from a decrease in allocation to leaves. Leaf area is strongly correlated with growth rate, so a decrease in allocation to leaves would be undesirable.

The large difference between instantaneous LAI (4.0) and total LAI of fallen leaves for the entire growing season (7.2) indicates a high within-year leaf turnover rate. Fertilization apparently causes increases in rates of both leaf production and leaf turnover. The optimum LAI for dry matter production is usually about 5.0 (Doley 1984), further evidence that these trees are capable of producing biomass at rates higher than the current 12 t/ha/year.

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STAND DENSITY EFFECTS ON BIOMASS ALLOCATION PATTERNS AND SUBSEQUENT SOIL NITROGEN DEMAND

Christopher A. Dicus and Thomas J. Dean'

Abstract-Growth and yield data from a loblolly pine plantation in southeastern Louisiana were obtained yearly from 1993 to 1996 on numbered trees within two stands initially planted on a 1.22- by 1.22-meter spacing, and two stands planted on a 2.44- by 2.44-meter spacing. Using allometric equations derived from a 1994 on-site destructive harvest, cited nitrogen concentrations of various tree tissues, and accounting for foliar nitrogen retranslocation, stand growth and soil nitrogen demands were determined.

Results showed that production of all aboveground tissues increased as stand density index (SDI) increased. Annual soil nitrogen demand increased with SDI primarily as a result of an increase in nitrogen-rich foliage on the denser sites. Belowground production, as estimated from minirhizotron censuses, also increased as SDI and aboveground nitrogen demands increased. More fine-root production per unit aboveground nitrogen demand was observed on less fertile plots. Stemwood production per unit leaf biomass decreased with increasing SDI, and is assumed to be the result of a greater percentage of total net primary production being partitioned to fine-root production in the denser plots.

The results of this study suggest that the density of forest stands may influence nutrient demands from the soil and subsequent belowground productivity through differential aboveground biomass allocation patterns and tissue nitrogen concentrations.

INTRODUCTION

The underlying mechanisms of plant biomass partitioning are of great importance to the study of forest productivity. As gains are made in understanding the fundamental principles of photosynthate allocation to various tree components, the potential exists to manipulate forest stands to increase the production of merchantable wood despite constant site productivity, thereby increasing economic return for forest landowners.

The ultimate objective for production foresters is to maximize allocation of photosynthate to merchantable stemwood. Strides have been made in improving yield through various silvicultural practices. In many agricultural crops, enhanced yields have resulted primarily from a shift in carbon allocation to harvestable parts, rather than an actual gain in total productivity (Evans 1976).

The mechanisms for aboveground productivity and tissue carbon allocation are becoming more readily understood. Knowledge of belowground productivity patterns, however, lags far behind that of aboveground productivity. If enhancing productivity of merchantable aboveground tree components includes reallocation of available photosynthate from unharvestable belowground sinks, then the study of carbon allocation in the whole forest stand, both above- and belowground, is necessary. The objective of this preliminary study was to determine if there is evidence that different aboveground stand structures resulting from varying stand densities influence soil nutrient demand and subsequent belowground productivity.

CARBONALLOCATIONPATTERNS

Stand density is a factor that has significant influence on stand carbon allocation. Stand density is known to influence tree crown morphology (Dean and Baldwin 1996a), which influences carbon allocation among stems, foliage, and branches (Ford 1982). These relations are complicated because both stand structure and productivity are associated with differences in age and site quality (Assmann 1970). However, Dean and Baldwin (1996b) have shown that stand density index (SDI), a measure of growing stock that includes quadratic mean diameter and trees per hectare (Reineke 1933), may be predicted solely from foliage density, mean live crown ratio, and canopy depth.

There is a positive relationship between stand density and stand foliage production. For a stand of a given stand density, the amount of foliage in a closed canopy stand is a function of the site quality. However, an increase in stand density has been shown to increase leaf area index (LAI) in loblolly stands (Dean and Baldwin 1996a). Stand density has also been shown to positively influence yearly needle fall, a measure of foliage production, in other pine stands (Gholz and others 1985, Gresham 1982).

There is also a positive relationship between stand density and stand stemwood production that is related to changes in canopy structure. Canopy structure is the result of many simultaneous processes including light penetration, height growth, crown lifting, and intercrown abrasion (Dean and Long 1992). After the onset of competition at crown closure, foliage is driven to the top of the canopy as a result of the natural pruning of lower branches (Mar:Mohler 1947). Wind action on the crown of a tree creates a bending stress on the stem, and as the crown midpoint becomes higher, coupled with an increase in the amount of foliage associated with increasing stand density (Dean and Baldwin 1996a), there is an increased load placed on the stem (Dean and Long 1986). Bending of the stem also

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increases the resistance to flow of water in the stem so that more sapwood is needed to transport the same amount of water to the foliage (Dean 1991). Therefore, as stand density and the subsequent physical load on the stem is increased, the carbon sink strength of the stem increases.

The amount of stand branchwood produced, however, is negatively related to stand density. Trees in sparser stands have deeper and wider canopies than do those in denser stands (Dean and Baldwin 1996a) and, therefore, must allocate a greater percentage of total net primary production (TNPP) toward the production and maintenance of branches to support the equilibrium level of foliage. In summary, then, as stand density increases, stand foliage and stemwood biomass production increase, while stand branchwood production decreases.

Another major sink for carbohydrates is production of the fine-root system. Indeed fine root production has been estimated to consume 30-70 percent of TNPP (Santantonio 1989) and has been shown to be inversely related to nutrient and water availability (Gower and others 1992).

On sites of equal nutrition, the belowground proportion of TNPP should correlate with the aboveground demand for nutrients and water according to the functional balance equation (Davidson 1969), which states that as aboveground nutrient demands increase, fine-root production will increase to meet that demand. Nutrient demands will vary during ontogeny (Imsande and Touraine 1994) with the greatest demands being placed on the nutrient reserves of a site during the early stages of stand development when the stand is approaching maximum leaf area (Switzer and others 1968). All else being equal, though, stands with a higher aboveground nutrient demand should allocate more carbon to belowground productivity to meet that demand and maintain a functional balance.

Switzer and others (1968) found that the nitrogen concentration of foliar, branch, and stemwood tissue to be 1.08 percent, 0.23 percent and 0.06 percent nitrogen, respectively, in 18-year-old loblolly pine trees, exhibiting little change with stand age. Foliar nitrogen concentration was 18 times greater than that of stemwood, representing the greatest portion of a stands nutrient requirements, averaging 80 percent for all nutrients (Switzer and Nelson I 972). Because stand density influences the proportion of different aboveground tree tissues in a stand and those tissues vary In nitrogen concentration, stand density should also affect nutrient uptake and subsequent belowground biomass production if a functional balance exists. This preliminary study investigated the above hypothesis to determine if evidence existed to warrant a conclusive study.

METHODS

The study site was located on the Lee Memorial Forest in southeast Louisiana. The site annually receives 1620 mm precipitation, and has a mean low and high temperature of 12.5 °C and 25.5 °C, respectively. Soil there is a Ruston series fine-loamy, siliceous, thermic typic paleudult.

Four 25x25-m plots were established after a 1981 clearcut and planted with loblolly pine (*Pinus taeda* L.) seedlings, two on a 1.22x1.22-m spacing, and two on a 2.44x2.44-m spacing. Prior to data collection, understory vegetation on the plots was felled and drug off-site. Then plots were treated with the herbicide imazapyr to reduce variability from interspecific competition. To minimize edge effects, measurements were restricted to an inner 20x20-m plot.

Each tree in each plot was numbered and measured for outside bark d.b.h., total height, and height to the base of the live crown before the 1993, 1994, 1995, and 1996 growing seasons. Allometric equations were derived from an onsite destructive harvest in November 1994, when leaf area consisted primarily of foliage produced in the previous growing season, and served to give estimates of biomass for each of the aboveground tissue types and leaf area. Annual stand-level, aboveground production for each tissue type in each plot was calculated as the difference in biomass (as determined from the allometric equations) between two measurement periods. Trees that died between measurement periods were assumed to contribute no growth to stand-level production.

Nitrogen concentrations of each of the aboveground tissue types were taken from values cited by Switzer and others (1968), in which the foliar, branch, and stem nitrogen concentrations were 1.08 percent, 0.23 percent, and 0.06 percent nitrogen, respectively. Foliar retranslocated nitrogen that was assumed to be available for a single growing season was estimated to be 58 percent of the total nitrogen located in foliage that senesced the previous fall (Birk and Vitousek 1986). Stand-level nitrogen demand of the soil for a growing season in each plot was then calculated as the sum of the production of each tissue type for that growing season, multiplied by the nitrogen concentration of each tissue type, and then subtracting the estimate of nitrogen retranslocation.

Belowground root production was estimated by two minirhizotron censuses taken in the summer of 1996. For each of 10, clear PVC tubes placed randomly within each plot, fine roots that intersected one of three transects were counted and summed to give a total number of fine-root intersections per tube.

Since differences in stand age and fertility affect relations between production and leaf area (Gholz and others 1986, Waring and Schlesinger 1985), analysis was limited to Plots of identical age and similar site quality (Smith and Long 1989). However, data were blocked into two sites as a result of a fertility gradient across the study area. Both sites 1 and 2 included a 1.22x1.22-m spacing plot and a 2.44x2.44-m spacing plot, but unpublished data show site 1 to have a greater nitrogen availability.

RESULTS AND DISCUSSION

Results, using a 3 year mean of the 1993, 1994, and 1995 growing seasons, showed that as SDI increased, total aboveground production increased (fig. 1). As predicted, on both sites, as SDI increased, foliage and stemwood

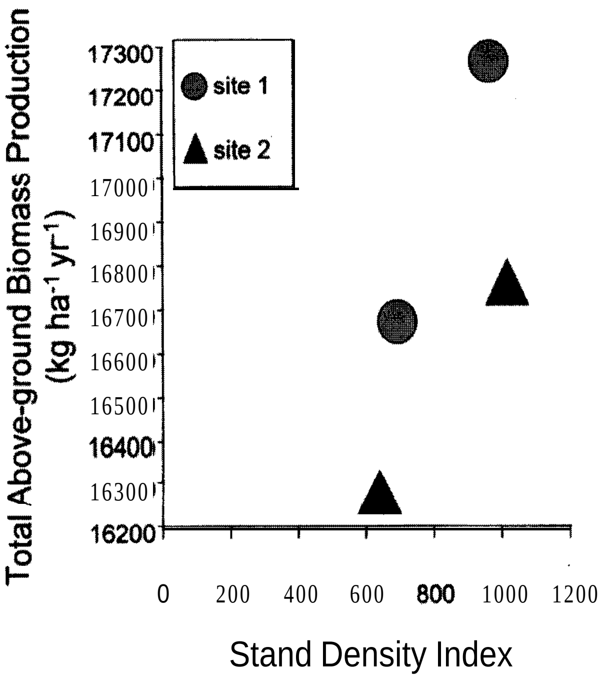

Figure l-Total stand level aboveground biomass production as a function of stand density index.

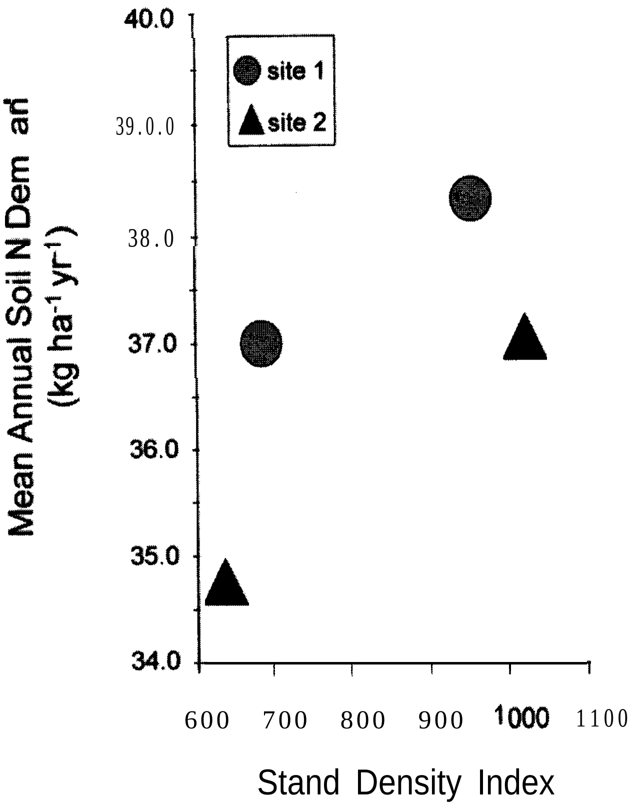

Figure 2—Stand level aboveground nitrogen demands as a function of stand density index.

production increased while branchwood production decreased. It was also found that the more fertile site 1 plots produced more aboveground biomass in all tissue types than the less-fertile site 2 plots.

As SDI increased, soil nitrogen demands also increased (fig. 2), primarily as a result of increased production of nitrogen-rich foliage on the denser plots. Indeed, over 85 percent of the total annual nitrogen demand in each plot was attributed to foliage. Again, the more fertile site 1 plots had a greater aboveground nitrogen demand.

Belowground fine-root intersections increased as SDI and aboveground nitrogen demands increased (fig. 3), giving support for a functional balance. Also, a greater number of root intersections per unit of nitrogen demand were recorded on the less-fertile site 2, suggesting that on these plots, a greater percentage of TNPP was allocated to fine-root production to meet aboveground demands.

Although total annual stemwood production and stemwood production per unit of leaf area increased with increasing SDI, as has been shown in previous studies (Long and Smith 1990, Smith and Long 1989), stemwood production per unit leaf biomass decreased with increasing SDI (fig. 4). This is assumed to be the result of a greater percentage of TNPP being partitioned to fine-root production in the denser stands. Santantonio (1989) has shown that a strong, negative relationship exists between fine-root and stemwood production in closed canopy stands. Although there is a greater amount of foliage biomass produced in the denser plots, it appears that foliage there is less efficient at producing photosynthate, perhaps as a result of an increase in self-shading caused by increased foliar density, a characteristic of denser stands (Dean and Baldwin 1996a).

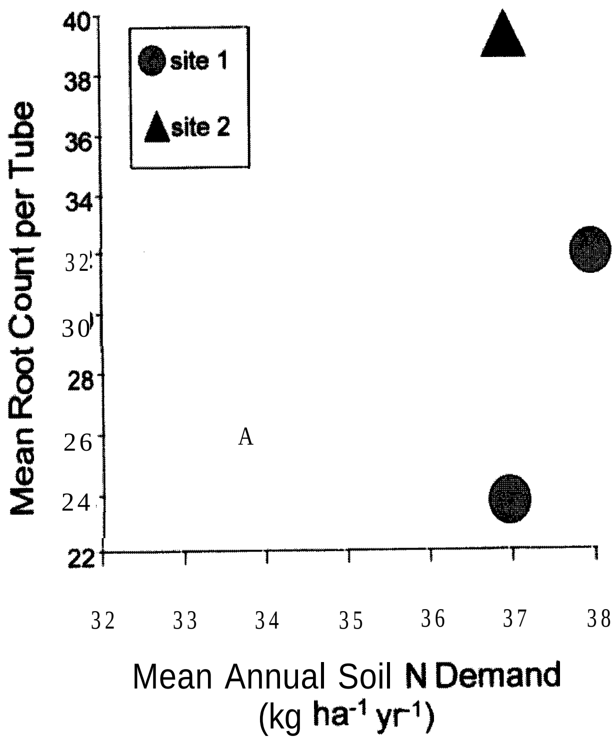

Figure 3—Mean number of root intersections counted as a function of aboveground nitrogen demand.

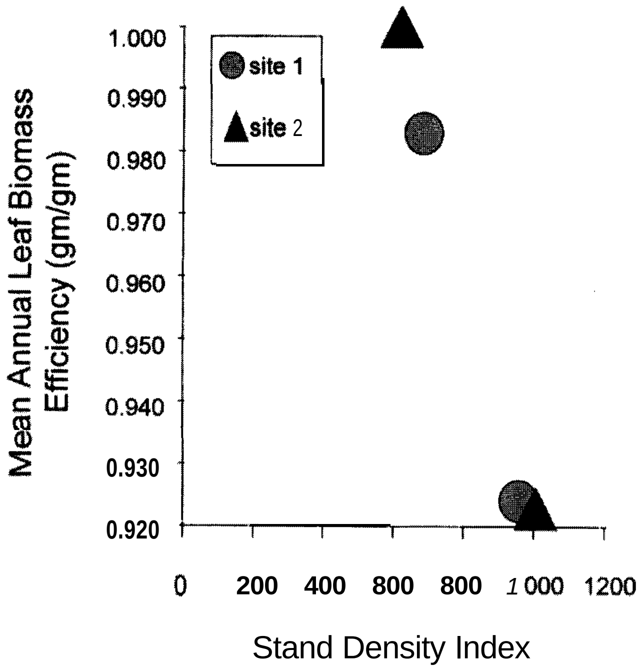

Figure 4-Mean stemwood produced per unit of leaf biomass as a function of stand density index.

One means of reallocating carbon from unharvestable belowground sinks to harvestable aboveground stemwood, then, may be by increasing foliar efficiency through various silvicultural means. For example, foliage does not contribute to stemwood production until maintenance respiration requirements of supporting branches are met (Ford 1975). Foliage in the shaded lower crown, then, would contribute little to production as a result of lowered photosynthetic rates and increased branch maintenance, yet would retain a carbon cost associated with production of fine-root biomass to meet foliar nutrient requirements. By pruning lower branches, a forester may lose little in production, but gain significant amounts of carbon that would have been allocated to fine-root production that supported the low efficiency foliage, thereby gaining in net carbon that could be used for stemwood production.

CONCLUSIONS

Results showed that as stand density increases, changes in aboveground carbon allocation increases both nitrogen demand and belowground productivity to meet that demand. Also, more belowground production is needed on less fertile sites to meet similar demands, decreasing photosynthate that could potentially be used in aboveground production. Therefore, more photosynthate may be available to aboveground sinks as sites become more fertile (through fertilization) or as foliage become more efficient.

The lack of plots in this preliminary study limited statistical analysis, but did provide insightful data. Therefore, a more conclusive study is in progress that will have greater statistical power and include analysis with additional stand densities and species.

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IMPACT OF NANTUCKET PINE TIP MOTH ATTACK ON LOBLOLLY PINE— A SOUTH-WIDE SUMMARY

Roy Hedden[1]

Abstract-The Nantucket pine tip moth (*Rhyacionia frustrana* Comst.) is the most important insect pest of young loblolly pine (*Pinus taeda* L.) in the Southern United States. Trees less than 10 ft. tall can be heavily infested by this insect. The greatest growth impact occurs during the first two to three growing seasons after planting. This paper presents a summary of 24 tip moth impact studies from 9 States (Arkansas, Florida, Georgia, Louisiana, Maryland, Mississippi, South Carolina, Tennessee, and Texas). Sixteen of the 24 were measured in more than 1 year. The plantation ages at the time of measurement ranged from 2 to 16 years. Comparisons were made between the untreated check plots and insecticide-treated plots in each study. Differences in height between treated and check plots averaged 2.4 ft./tree and ranged from 0 to 9.5 ft./tree. Differences in diameter averaged 0.5 in./tree and ranged from 0 to 2 in./tree. Average cubic foot volume per tree impact was 0.5 ft^3./tree while there was an average difference in volume/acre of 4.0 cords. Few of these studies have any meaningful documentation of tip moth infestation levels; therefore, it is not possible to relate growth impact to tip moth attack. Consequently, estimates of impact represent averages for variable and unknown levels of tip moth damage, overestimating impact where infestation levels are low and underestimating impact where attack levels are high. In addition to growth impact, tip moth attack results in some product degrade due to an increase in the number of knots per linear foot of lumber, and an increase in the volume of compression wood leading to reduced pulp yields. Intensive loblolly pine plantation management is apparently related to the severity of tip moth impact; therefore, the Nantucket pine tip moth will remain a serious insect pest that forest managers will have to deal with in the future.

INTRODUCTION

The Nantucket pine tip moth (NPTM) (*Rhyacionia frustrana* Comst.) is one of the most important insect pests of young loblolly pine (*Pinus taeda* L.) in the Southern United States. Trees less than 10 ft tall can be heavily infested by this insect. The greatest growth impact occurs during the first two to three growing seasons after planting. Historically, the NPTM has been considered a minor pest of loblolly pine. However, it is now perceived as an important pest in young pine plantations. This change has coincided with the increase in the number of loblolly pine plantations and the intensity of management in these newly planted stands.

Information on the cost and benefits of managing of this insect is necessary before a control program for the NPTM can be implemented. Of special importance is information on NPTM impact on loblolly pine growth and yield. Several growth impact studies have been published; however, there has been no systematic attempt to analyze this data. This paper is an attempt to assemble and summarize the existing data on the impact of the NPTM on loblolly growth and yield.

METHODS

The literature on NPTM was searched to identify studies on the impact of attack on its pines. To be included in this analysis the studies had to meet certain criteria. These criteria were that data from untreated check and insecticide-treated plots be available for a single location, that the pine species included loblolly pine, and that the trees were planted. Information on height, diameter, and volume were summarized for each site. These data were subjected to statistical analyses which included calculation of means and standard deviations of the variables of interest. The data was also analyzed by age class since the studies included trees of various ages. Measurement data from different years at the same site were available for a few studies. The data were grouped and analyzed by measurement period. Specific detail on the data for each individual study can be found in the appendix.

RESULTS AND DISCUSSION

Data were obtained from 24 separate studies that met the criteria for inclusion in this paper. These studies resulted in 42 observations on height growth (table I), 37 observations on d.b.h. (table I), 16 for cordwood volume/acre (table 3), and 13 for cubic foot volume/tree (table 2). The average difference in total tree height is 2.4 ft/tree (sd=1.93, n=42), in d.b.h. it is 0.5 in./tree (sd=0.38, n=37), in volume/acre it is 4.0 cords (sd=4.8, n=16), and in volume/tree the difference is 0.5 cu. ft. (sd=0.50, n=13). These studies represent a variety of sites varying in cultural treatment, site productivity, intensity and frequency of tip moth control, and unknown but varying levels of tip moth infestation levels. Consequently, these average differences will probably overestimate tip moth impact where infestation levels are low, and underestimate impact where infestation levels are high.

Changes in Height and Diameter Over Time

Since these means are over all sites and ages, it is of interest to stratify the data by age classes. Table 4 shows the statistics for height and diameter grouped into four classes with median ages of 3, 5, 8, and 15 years. However, any trends in this table are difficult to interpret since many of the sites in each age class came from separate studies. Therefore, the data were further

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Table I-South-wide summary of growth response of loblolly pine to tip moth control

	Height				Diameter at breast height.			
Location	Age	Trt.	Chk.	Dif.	Trt.	Chk.	Dif.	Note[a]
		---------- Ft ----------			---------- In ----------			
Calhoun, TN	5	7.0	6.6	0.4				(1)
Warren, AR	8	18.2	16.3	1.9	3.6	3.1	0.5	(2)
Beltsville, MD	4	9.8	4.9	4.9				(3)
Beltsville, MD	10	24.5	16.5	7.9	5.5	3.5	2.0	(3)
Clemson, SC	2	3.6	3.3	0.3				(4)
Louisville, GA	3	8.4	6.6	1.8	0.9	0.5	0.4	(5)
Louisville, GA	5	17.8	14.6	3.2	3.1	2.4	0.7	(5)
Rincon, GA	3	11.3	9.9	1.4	1.8	1.5	0.3	(5)
Rincon, GA	5	21.4	20.0	1.4	3.8	3.6	0.2	(5)
Owensville, AR	6	12.0	10.0	2.0	1.8	1.5	0.3	(6)
Owensville, AR	8	16.0	13.5	2.5	3.0	2.5	0.5	(6)
Owensville, AR	12	27.5	25.0	2.5	5.1	4.6	0.5	(6)
Umpire, AR	6	11.0	9.0	2.0	1.6	1.2	0.4	(6)
Umpire, AR	8	16.0	13.0	3.0	2.9	2.4	0.5	(6)
Umpire, AR	12	28.5	27.0	1.5	5.2	4.8	0.4	(6)
Homer, LA	5	18.6	16.3	2.3				(7)
Homer, LA	14	44.4	43.9	0.5				(7)
Crossett, AR	6	12.0	9.9	2.1	2.1	1.5	0.6	(8)
Crossett, AR	16	39.0	39.0	0.0	6.6	6.4	0.2	(8)
Oxford, MS	6	20.0	17.3	2.7	3.5	3.2	0.3	(8)
Oxford, MS	16	52.0	47.0	5.0	7.5	7.2	0.3	(8)
Alexandria, LA	5	8.6	7.9	0.7	1.4	1.3	0.1	(8)
Alexandria, LA	15	47.0	44.0	3.0	6.5	6.4	0.1	(8)
Brewton, AL	5	14.8	14.3	0.5	1.9	1.6	0.3	(8)
Brewton, AL	15	46.0	46.0	0.0	7.2	6.9	0.3	(8)
Harrison, AR	5	10.9	10.2	0.7	1.8	1.6	0.2	(8)
Harrison, AR	15	36.0	35.0	1.0	6.9	6.6	0.3	(8)
Marianna, FL	5	11.4	7.5	3.9	1.7	1.4	0.3	(8)
Marianna, FL	15	27.5	18.0	9.5	5.4	3.6	1.8	(8)
Nacogdoches, TX	5	18.0	15.4	2.5	3.1	2.7	0.4	(8)
Nacogdoches, TX	15	51 .o	48.0	3.0	7.1	6.8	0.3	(8)
Sewanee, TN	5	11.2	11.3	-0.1	1.8	1.8	0.0	(8)
Sewanee, TN	15	45.0	45.0	0.0	7.8	7.5	0.3	(8)
Hope, AR	6	16.5	11.4	5.1	3.5	2.3	1.2	(9)
Hope, AR	13	35.0	30.5	4.5	6.6	6.1	0.5	(9)
Hope, AR	8	24.2	20.2	4.2	5.6	4.7	0.9	(10)
Hope, AR	16	44.4	42.9	1.5	9.7	8.9	0.9	(10)
El Dorado, AR	7	20.4	17.4	3.0	4.0	3.7	0.3	(11)
Hot Springs, AR	4	11.0	7.4	3.6	1.8	0.9	0.9	(12)
Paron, AR	5	8.7	7.4	1.3	1.3	1.0	0.3	(12)
Alikchi, OK	5	12.4	11.6	0.8	2.4	2.1	0.3	(12)
Winthrop, AR	3	11.8	9.9	2.8	2.0	1.3	0.7	(12)

[a] Notes are located in the appendix.

restricted to measurements at two time periods for the same site. The early measurement (T1) occurred when trees had been in the field for 5 to 8 years. The ages at the second measurement (T2) occurred at 12 to 16 years. The difference in tree height at T1 was 2.20 ft/tree (sd=1.53, n=13), while at T2 it was 2.58 ft/tree (sd=2.68, n=13). Difference in d.b.h. at T1 was 0.42 in/tree (sd=0.32, n=12), while at T2 it was 0.49 in/tree (sd=0.46, n=12). This analysis shows that height and diameter differences are maintained through time.

Table 2—South-wide summary of tip moth control cubic foot volume per tree

Location	Note[a]	Age	Trt.	Chk.	Diff.	Pct. diff.
			Cubic feet			
Louisville, GA	(5)	5	0.42	0.21	0.21	100
Fiincon, GA	(5)	5	0.91	0.73	0.18	25
Beltsville, MD	(3)	9	2.29	0.60	1.69	282
Umpire, AR	(6)	12	1.58	1.31	0.27	21
Owensville, AR	(6)	12	1.47	1.14	0.33	29
Alexandria, LA	(8)	16	3.77	3.30	0.46	14
Alexandria, LA	(8a)	16	3.58	3.30	0.28	8
Brewton, AL	(8)	16	3.24	3.02	0.22	7
Crossett, AR	(8)	16	2.77	2.61	0.16	6
Gulfport, MS	(8)	16	4.74	4.45	0.29	6
Harrison, AR	(8)	16	2.97	2.33	0.64	27
Many, LA	(8)	16	4.86	5.28	(-0.42	(-9)
Marianna, FL	(8b)	16	1.43	0.25	1.18	472
Marianna, FL	(8c)	16	0.59	0.09	0.50	555
Nacogdoches, TX	(8)	16	5.38	4.27	1.11	26
Oxford, MS	(8)	16	6.26	4.78	1.48	31

[a] Notes are located in the appendix.

Table 3-South-wide summary of tip moth control cordwood volume per acre

Location	Note[a]	Age	Trt.	Chk.	Diff.	Pct. diff.
			Cords			
Louisville, GA	(5)	5	3.4	1.7	1.7	100
Rincon, GA	(5)	5	7.3	5.8	1.5	26
Owensville, AR	(6)	12	11.2	9.2	2.0	22
Umpire, AR	(6)	12	11.1	8.3	2.8	34
Hope, AR	(9)	13	26.1	22.0	4.1	19
Hope, AR	(10)	13	44.5	33.0	11.5	35
Alexandria, LA	(8)	16	32.5	29.7	2.8	9
Alexandria, LA	(8a)	16	[illegible]	[illegible]	2.0	[illegible]
Brewton, AL	(8)	16	[illegible]	[illegible]	(-4.7)	(-185
Crossett, AR	(8)	16	[illegible]	[illegible]	0.7	3
Gulfport, MS	(8)	16	[illegible]	[illegible]	(-1.4)	(-4)
Harrison, AR	(8)	16	23.2	17.9	5.3	30
Many, LA	(8)	16	38.6	37.0	1.6	4
Marianna, FL	(8b)	16	11.1	2.0	9.1	455
Marianna, FL	(8c)	16	5.0	0.7	4.3	614
Nacogdoches, TX	(8)	16	36.7	24.7	12.0	46
Oxford, MS	(8)	16	49.7	37.9	11.8	31
Sewanee, TN	(8)	16	36.1	34.8	1.3	4

[a] Notes are located in the appendix.

Table 4-Average loblolly pine height and diameter at breast height (d.b.h.) differences for insecticide-treated and untreated check plots by age class

		Height diff.			D.b.h. diff.		
Median age	Range	Mean	SD	N	Mean	SD	N
Years		*Feet*			*In*		
3	3-4	2.40	1.83	5	0.53	0.18	3
5	5-6	1.90	1.34	18	0.39	0.28	16
8	7-10	3.75	2.17	6	0.78	0.62	6
15	12-16	2.46	2.68	13	0.49	0.46	12

Prediction of Differences in Height and Diameter

The data for differences of height and diameter for the early time period can be used to predict the difference in height and diameter at the later time period. This could be useful for calibrating growth and yield models to estimate long-term impact of NPTM attack on loblolly pine yield. Two equations were estimated using linear regression. The dependent variables were height/tree (H2) and d.b.h./tree (D2) at ages 12 to 16 years. The independent variables were height/tree (H1) and d.b.h./tree (D1) at ages 5 to 8 years. These equations were each based upon 12 observations. The equation for the height difference/tree is: $H2 = 0.888 + 2.767(H1) - 10.087(D1)$ ($R\text{-square}=0.86$). The equation for the difference in d.b.h./tree is: $D2 = 0.182 + 0.385(H1) - 1.280(D1)$ ($R\text{-square}=0.60$). This is just one example of the types of analyses which can be performed using the data from table 1.

Long-Term Volume Impact of Tip Moth Attack

The oldest NPTM studies that contain volume data are for 16-year-old stands of loblolly pine (table 3). The average volume difference at these sites ranged from -4.7 to 12 cords per acre. Only 2 of the 12 sites had negative volume differences. There is no evidence to suggest that the insecticide treatments were the cause of more volume in untreated check plots; therefore, it can be assumed that a negative value indicates there was no volume difference between treatments. Using this assumption, and substituting values of zero for the negative differences at these two sites, the average volume difference is 4.2 cords/acre (sd=4.4, n=12). This value is probably representative of the impact in loblolly pine stands subjected to low-intensity plantation management. These data also illustrate the high degree of between-site variability in impact which is typical of pine stands where the NPTM has been controlled.

Cade and Hedden (1987) used data from tip moth impact studies in two loblolly pine plantations in Arkansas to project volume impact at rotation. They projected the volume loss at a rotation age of 30 years in an unthinned stand to be 2 to 6 cords/acre. Volume loss in a stand thinned once at age 20 and harvested at age 35 was projected to be 1 to 3 cords/acre and 300 to 700 b.f./acre. Hedden and others (1991) also used a growth-and-yield model to project volume loss from NPTM attack. The estimated volume loss in an unthinned stand at age 30 years was 6.2 cords/acre. They also projected that the volume loss in a stand thinned at age 20 with a final harvest at age 30 to be 0.6 cords/acre and 900 b.f./acre. This represents a loss of about 10 percent of the potential sawtimber yield for the stand. However, it should be noted that the actual yields at rotation may be greater or less than those projected in these studies, depending on many factors including level of tip moth control, site productivity, the type and intensity of plantation management, and local tip moth population levels.

Impact of Tip Moth on Product Quality

Volume loss due to tip moth attack is only one aspect of impact (Berisford and others 1989). The NPTM also causes significant product degrade. The larval stage of the moth mines both the terminal and lateral shoots of the tree. When the terminal bud is killed, the tree responds in one of two ways. A lateral branch will replace the dead terminal, or a fascicular bud will be released on the terminal. In the case where a lateral branch replaces the terminal, severe stem deformity and extensive formation of compression wood will occur. Where a fascicular bud is released, little deformity but significant compression wood formation will occur. Moreover, since attack on the terminal leader retards height growth, the branch whorls will be closer together which results in an increase in the number of knots per unit of height and, again, in an increase in the amount of compression wood due to knots.

The only study (Hedden and Clason 1979) that has attempted to quantify the impact of NPTM attack on product quality showed that 21 -year-old loblolly pines attacked by pine tip moths, when compared to insecticide-treated trees, had twice as much compression wood in the lower 16 ft log. Based upon this study, pulp yields in the bottom of the 16 ft log of untreated trees would be reduced by 1.5 to 2.5 percent. Longitudinal shrinkage due to compression wood could result in studs with 3 to 5 times more crook than studs without significant compression wood (Gaby 1972). Studs from trees attacked by the NPTM had 11 percent fewer boards graded as 2D or better than studs from insecticide treated trees. Furthermore, degrade due to knots was much higher in logs from attacked trees. After trimming, studs from untreated trees were degraded due to knots 51 percent of the time, but degraded only 20 percent of the time in studs from treated trees. Consequently, tip moth control should result in an increase in both product quantity and quality.

CONCLUSIONS

Nantucket pine tip moth attacks in young loblolly pine plantations result in a significant loss in the yield at harvest. Reductions of pulpwood volumes due to attack are projected to average 2 to 6 cords/acre. Losses in stands managed for sawtimber are estimated to range from 1 to 3 cords/acre and 300 to 1000 b.f./acre. Moreover, tip moth attack reduces sawtimber quality and pulp yields due to an increase in compression wood level and the number of knots in the lower stem. Actual impact from NPTM will ultimately depend upon the intensity of young plantation management, site productivity, the product being managed for, and many other interacting factors. However, control of the NPTM in young loblolly pine plantations should result in both enhanced quality and quantity of pine yield.

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APPENDIX

(Notes for table 1)

(1) Mason, R.R. 1958. Study of tip moth effects on height growth in loblolly pine plantations: two year results. Hiwassee Forest Res. Note 3. Hiwassee Land Company. Calhoun, TN. 2 p. (5-year-old trees were sprayed three times during the summer of 1956.)

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(3) Lashomb, J.H.; Steinhauer, A.L.; Douglas, L. 1978. Impact studies of Nantucket pine tip moth populations on loblolly pine. Environ. Entomol. 7: 910-912. (Trees caged for 1 year and sprayed for 1 year. Data on early height growth is presented.)

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(4) Hedden, R.L.; Haugen, D.A. 1986. Impact of pine tip moth attack on loblolly pine seedlings. In: Phillips, DR., ed. Proceedings of the fourth biennial silvicultural research conference. Gen. Tech. Rep. SE-42. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station: 535-537. (Tip moth controlled during the second year in the field.)

(5) Berisford, C.W.; Godbee, J.F.; Ross, D.W. 1989. Impact of pine tip moth control, weed control, and fertilizer on growth and form of loblolly pine. In: Alfaro, R.I.; Glover, S.G., eds. Insects affecting reforestation: biology and damage. Forestry Canada, Pacific Forestry Centre, Victoria, BC, Canada: 130-136. [Tip moth controlled first 3 years in the field. Check means were the average of the no treatment and the fertilizer + herbicide (F + H) treatment. Treatment means were the average for the tip moth control (TMC) and the TMC + F + H treatments. Results for Rincon and Louisville in the fifth year are courtesy of C. W. Berisford.)

(6) Cade, SC.; Hedden, R.L. 1987. Growth impact of pine tip moth on loblolly pine in the Ouachita Mountains of Arkansas. Southern Journal of Applied Forestry. 11: 128-l 33. (Tip moth controlled second, third, and fourth growing seasons in the field. Treated means are the averages for the granule and spray-granule treatments.)

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(8) Beal, R.H. 1967. Heavy tip moth attacks reduce early growth of loblolly pine. Res. Note SO-54. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station. 3 p. (Effective control during second and third growing seasons in the field. Phorate, 10 grams of 10 percent granular, was applied in fourth, fifth, and sixth seasons, but this rate was not high enough for effective control at these ages.)

Williston, H.L.; Barras, S.J. 1977. Impact of tip moth injury on growth and yield of 16-year-old loblolly and shortleaf pine. Res. Note SO-221. New Orleans, LA: U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station. 5 p. [Sixteen year results are presented. Local volume tables were developed giving cubic volumes inside bark to a 3-inch top d.i.b. for all trees 3.6 inches in d.b.h. and larger. Plot volumes (cu. ft.) were converted to a per-acre basis by multiplying by 27.7, and then converted to cords by dividing by 75. (8a) plots were treated only 1 year. (8b) plots were site-prepared by chopping. (8c) plots were site-prepared by rootraking.]

(9) Warren, L.O.; Young, J. 1972. Long-term effects of pine tip moth control. Ark. Farm Res. 21(2): 4. (Trees were treated for first two growing seasons in the field-see note (11) below for the source of the sixth-year results.)

(10) Young, J.; Warren, L.O.; Stephen, F.M. 1979. Pine growth and yield: influences of pine tip moth control. Ark. Farm Res. 28(2): 7. (Loblolly and shortleaf pines were planted in 6x6-f-t and 1 0x1 0-ft spacing. In half of the plots, vegetation was controlled using combinations of cultivation, hoeing, and mowing for 13 years. Weedy vegetation was allowed to grow unhindered in the noncultivated plots. Tip moth was controlled in 5 subplots of 25 trees in the second through fifth growing seasons. Tip moth treatment means are the average for all spacing and vegetation control treatments. The eighth-year results are from the 1972 research report of the University of Arkansas Southwest Branch Station, edited by C.M. Bittle and H.A. Holt.)

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(12) Unpublished. Weyerhauser Co. tests were established by J.D. Walstad. (Trees were treated second and third year in the field.)

THE NOT-SO-SUDDEN RESULTS OF THE SUDDEN SAW LOG STUDY— GROWTH AND YIELD THROUGH AGE 45

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Abstract-The Sudden-Saw Log Study, located near Crossett, AR, was established to test the hypothesis that loblolly pine plantations can produce sawtimber on good sites in 30 years. Study measurements reported at stand age 33 years showed that the hypothesis is true. Fortunately, the study was not terminated at that time. Inventory data were also collected at stand ages 36, 39, and 4.5 years. By stand age 45, average Doyle board-foot volume sawtimber yields for all treatments were not significantly different, averaging 21,889 bf/acre, although the mean diameter of trees that received intensive management (20.4 inches) was 38 percent greater than that of trees receiving the control treatment (14.9 inches). The control treatment always produced the greatest cubic-foot volume (9,422 ft^3 at age 45), and after age 33 led all other treatments in predicted financial returns.

INTRODUCTION

In February 1954, a g-year-old loblolly pine (*Pinus taeda* L.) plantation located on an abandoned cotton field near Crossett, AR, was selected for use in a growth-and-yield study (Burton 1982, Burton and Shoulders 1974). The stand had been planted at a spacing of 6 ft by 6 ft (1,210 trees/acre) in 1945. By 1954, survival averaged 1,100 trees/acre, and the 50-year site index was projected to be between 90 and 100 feet. The study objective was "...to determine whether a plantation on a good site (site index = 90) could be managed to produce good quality sawtimber on a short rotation by combining early thinning, understory vegetation control, and pruning" (Baker and Bishop 1986).

The study was officially closed at age 33. Results were reported in Burton and Shoulders (1974), Burton (1982), Taylor and Burton (1982), and Baker and Bishop (1986). However, the stands were never cut and the trees were remeasured at ages 36, 39, and 45. Management, except for occasional mowing of the plots to facilitate tours, had discontinued at age 30. This paper reports the effects of stand treatments on growth and yield since study inception, with emphasis on results at the later ages.

METHODS

Four thinning treatments were replicated three times in randomized blocks. Two treatments began immediately (at age 9) and two began at age 12, when the average tree had attained merchantable pulpwood size. The four treatments were:

Sawtimber only-All noncrop trees and all but 100 crop trees/acre were cut at age 9. Stands were thinned every 3 years thereafter to 76 trees/acre by age 19 and to 41 trees/acre at age 30.

Sawtimber pulpwood-Thinnings at age 9 and 12 removed noncrop trees whose crowns were within 5 feet of crowns of the 100 crop trees. The last noncrop trees were removed at age 15. Further thinnings at 3-year intervals left 80 trees/acre at age 19 and 52 trees/acre at age 30.

Delayed sawtimber-Stands were reduced to 100 crop trees/acre at age 12 and thinned every 3 years thereafter until 45 trees/acre remained at age 30.

Control-Plots were thinned, mainly from below, to a basal area of 85 ft^2/acre at age 12 and every 3 years afterward through age 30. The thinnings reduced stand density from 712 stems/acre at 12 years to 116 stems/acre at 30 years.

The timing and severity of later thinnings were based on periodic d.b.h. growth. Crop trees in the intensive-treatment plots were pruned from the ground to about one-half their total height after the first thinning and every 3 years afterward until clear length averaged 33 feet at age 24. Also, beginning at age 19, the woody understory was mowed every 2 years in the intensively managed plots.

MEASUREMENTSANDANALYSIS

The d.b.h. of all trees was obtained at every measurement date. Total height and height to the base of the live crown, for all crop trees, were measured from age 12. Volumes reported in earlier papers were read from a standard volume table (USDA Forest Service 1976) for stands aged 12 to 18 and were calculated by the STX Program (Grosenbaugh 1967) for stands aged 21 to 33. All total inside-bark cubic-foot volumes and Doyle inside-bark board-foot volumes (merchantable height to an 8-inch inside-bark top diameter) reported here were calculated by means of volume and taper equations (Baldwin and Feduccia 1991). The Doyle board-foot volume measure was selected because its use is mandated by law in timber sales in most of the Southern United States (Baker and Bishop 1986). Volume yields included the accumulated cut yields for each of the treatments.

Yield curves were developed by fitting nonlinear regressions to the volume yield data. The model was yield $= a[1 - \exp(b^*age)]^c$, where a, b, and c are the parameters estimated. Mean and periodic annual volume increments, MAI and PAI, respectively, were then calculated from these smoothed curve values. The mean diameters reported are

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prethinning values for each measurement period; the use of prethinning values minimizes the effect that thinning from below has on diameter. Differences among treatment means were tested by analysis of variance and Duncan's multiple-range test at the a=0.05 level (SAS Institute 1989).

Pretax soil expectation values (SEV's) for harvest ages 30, 33, 35, 39, and 45 were calculated for each treatment so that the economics of the treatments could be compared. Current costs of management activities were gathered from forest managers, scientists, and vendors of forestry services. Louisiana stumpage prices for sawtimber and pulpwood were taken from estimates made by Timber Mart South, Inc. For each harvest, stumpage prices over a 2-year period were averaged to minimize the impact of stumpage price fluctuations on the analysis. The stands were not fully merchandized for quality products that might be obtained from stands of heavily pruned larger diameter timber. A more definitive analysis might include analysis of timber quality and a more thorough consideration of the impact of logging costs.

Some of the procedures or practices employed in the study and reflected in the economic analysis, such as the close 6-ft by 6-ft planting density, frequent mid-rotation mowing to control vegetation, and a two-log pruning regime, are not considered cost effective and thus are not utilized in the present economic climate. The fixed costs of holding the land in forestry-property taxes and miscellaneous management costs-were also not considered in this analysis. The total investment costs of the sawtimber-only, sawtimber-pulpwood, and delayed-sawtimber treatments exceeded $660/acre, whereas the total investment cost for the control treatment was only $161/acre. A real discount rate of 4 percent was used to calculate SEV's. The assumption was made that all prices and costs increased at the rate of inflation.

RESULTS

Only the control treatment was thinned to a target basal area before age 27, so the residual basal areas for the other treatments varied, mainly according to the number of trees cut at each thinning. Basal area was always highest for the control treatment. At age 45, basal area for the control treatment was about 40 ft^2/acre more than basal areas for the sawtimber-only and delayed-sawtimber treatments (98 ft^2 and 102 ft^2, respectively), and about 30 ft^2/acre more than the basal area for the sawtimber-pulpwood treatment (109 ft^2).

Quadratic mean diameter (d.b.h.) was highest for the sawtimber-only treatment throughout the study. The age-45 diameters for all of the intensive treatments did not differ significantly from treatment to treatment (fig. 1). The mean diameter for the control treatment (14.9 inches) was 27 percent less than the average for the other three treatments (20.4 inches). Thus, trees in the intensively managed stands reached sawtimber size before the others did and maintained at least a 27-percent size advantage from age 18 through age 45.

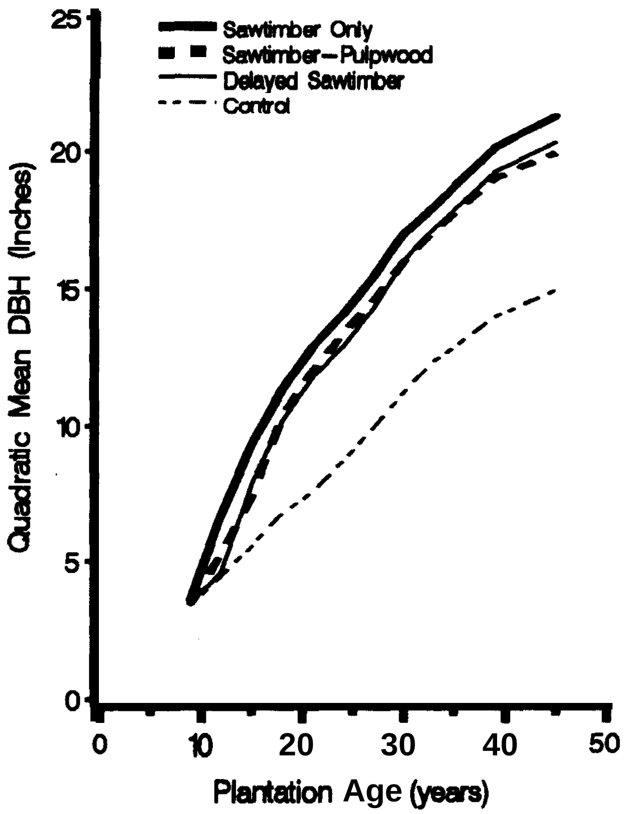

Figure I-Trends in prethinning quadratic mean diameter. Lines join data points for the remeasurement years.

There was no significant difference in mean total crop-tree height between treatments at any remeasurement year. Height averaged 94 feet at age 45. Extrapolation of these results suggests that total height will be near 100 feet at age 50, indicating that site index for the study plots is at the upper end of the range predicted (90 to 100 feet) at study installation (Burton 1982).

As would be expected, the control treatment always carried the highest total cubic-foot volume because it had the most trees per acre throughout the study. At age 45, total volume yield for the control treatment was 9,422 ft^3/acre, compared to an average yield of 6,642 ft^3/acre for the intensively managed treatments. These treatment yields, and those reported below, include all volumes cut at earlier ages.

At age 30, when this study was designed to end, the intensive treatments had produced about twice the board-foot volume produced by the control treatment (table 1). Fifteen years later, however, board-foot volume for the control treatment, (19,778 bf/acre) had nearly caught up with the average volume yield of the other treatments (22,592 bf/acre) and was not significantly different from the other yields. Board-foot volume production of the control stand may even exceed that of the intensively managed stands in a few years (fig. 2). However, all treatments were near their predicted maximum level of annual board-foot volume productivity, so quantitative extrapolations are not warranted. Mean annual increment for cubic-foot volume maximized at age 32 for the delayed-sawtimber treatment, while the

Table l--Saw log volume yield[a] in Doyle board foot peracre for each measurement age and treatment

	Treatment[b]			
Plantation age	Sawtimber only	Sawtimber pulpwood	Delayed sawtimber	Control
Years				
9	0	0	0	0
12	0	0	0	0
15	176	0	13	0
18	2,008	1,007	869	24
21	3,998 a	2,836 b	2,937 b	116 c
24	6,329 a	5,228 b	5,378 b	995 c
27	8,955 a	7,897 b	8,078 ab	2,846 c
30	11,415 a	10,402 a	10,335 a	5,151 b
33	13,527 a	12,903 a	12,699 a	8,034 b
35	14,811 a	14,636 a	14,577 a	9,928 b
39	18,663 a	18,759 a	18,468 a	14,614 b
45	22,622 a	22,611 a	22,544 a	19,778 a

[a] Yield is the total board-foot volume at the listed age plus the sum of all previously harvested volume
[b] Treatment means for ages 21 and above were tested for statistically significant differences with =0.05 using Duncan's multiple-range test. Means in the same row succeeded by the same letter are not significantly different (SAS Institute 1989).

maximum was achieved at age 35 for all other treatments. The maximums for Doyle board-foot volume are projected to occur at about age 48 for the intensively managed treatments and at age 52 for the control treatment (fig. 3).

Despite the very high investment costs of the intensive-management treatments, the SEV's of these treatments were high and reached a maximum at plantation age 39 (table 2). The delayed-sawtimber stand had the highest SEV ($1,892/acre) among the three high-investment treatments, followed by sawtimber-pulpwood ($1,867/acre) and sawtimber-only ($1,732/acre). The control treatment, which was inexpensive to establish, had the highest SEV ($2,049/acre).

DISCUSSION AND CONCLUSIONS

The most significant change since the report by Burton (1982) at stand age 33 was the increase in board-foot volume and value of the timber in the control-treatment plots. That treatment passed the others financially after 33 years of growth. Of course this trend was not unexpected—only the time of occurrence was unknown. In their report of the age-30 results, which included an analysis showing that the intensive-management treatments were the best financial investment, Baker and Bishop (1986) stated: " . ..if the rotation were lengthened to 40 or 50 years, the results of the financial analyses would change markedly, with the

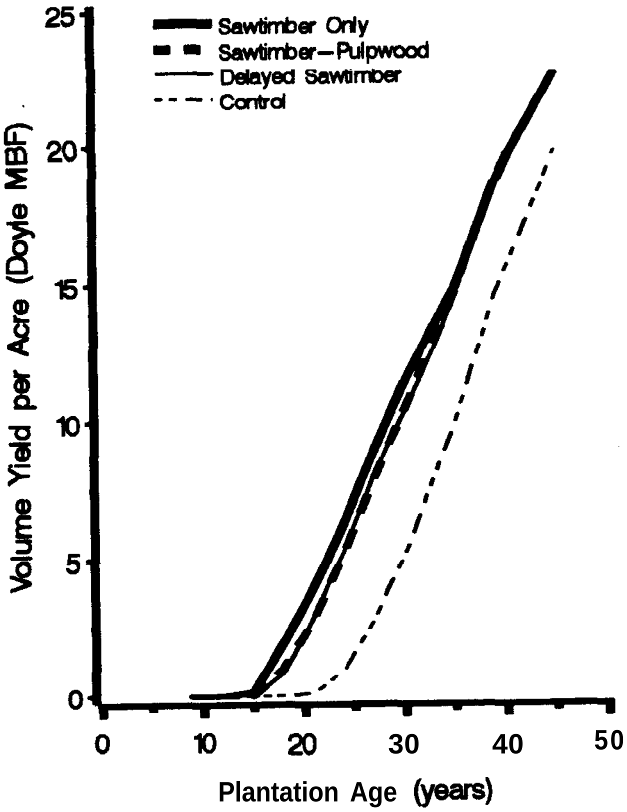

Figure 2-Trends in inside bark, Doyle board-foot volume yield per acre through age 45. Lines join data points for the remeasurement years.

Table 2-Soil expectation values (4-percent discount rate) for each treatment at each inventory starting from age 30

	Plantation age (years)				
Treatment	30	33	35	39	45
	Dollars				
Sawtimber only	1,502	1,591	1,606	1,732	1,636
Sawtimber-pulpwood	1,535	1,674	1,737	1,867	1,727
Delayed sawtimber	1,548	1,683	1,775	1,892	1,791
Control	1,482	1,721	1,828	2,049	2,036

conventional management undoubtedly improving in investment ranking."

However, our financial analysis does not necessarily show that intensive management does not pay. Management costs could be lowered considerably. For example, the intensive-management plots could have been established with fewer trees/acre, pruning fewer times to a one-log height, and mowing less often or not at all. Also, it may be the case that the proportion of export-quality sawtimber is higher for the intensive treatments than for the control treatment, thus implying higher value of the intensive

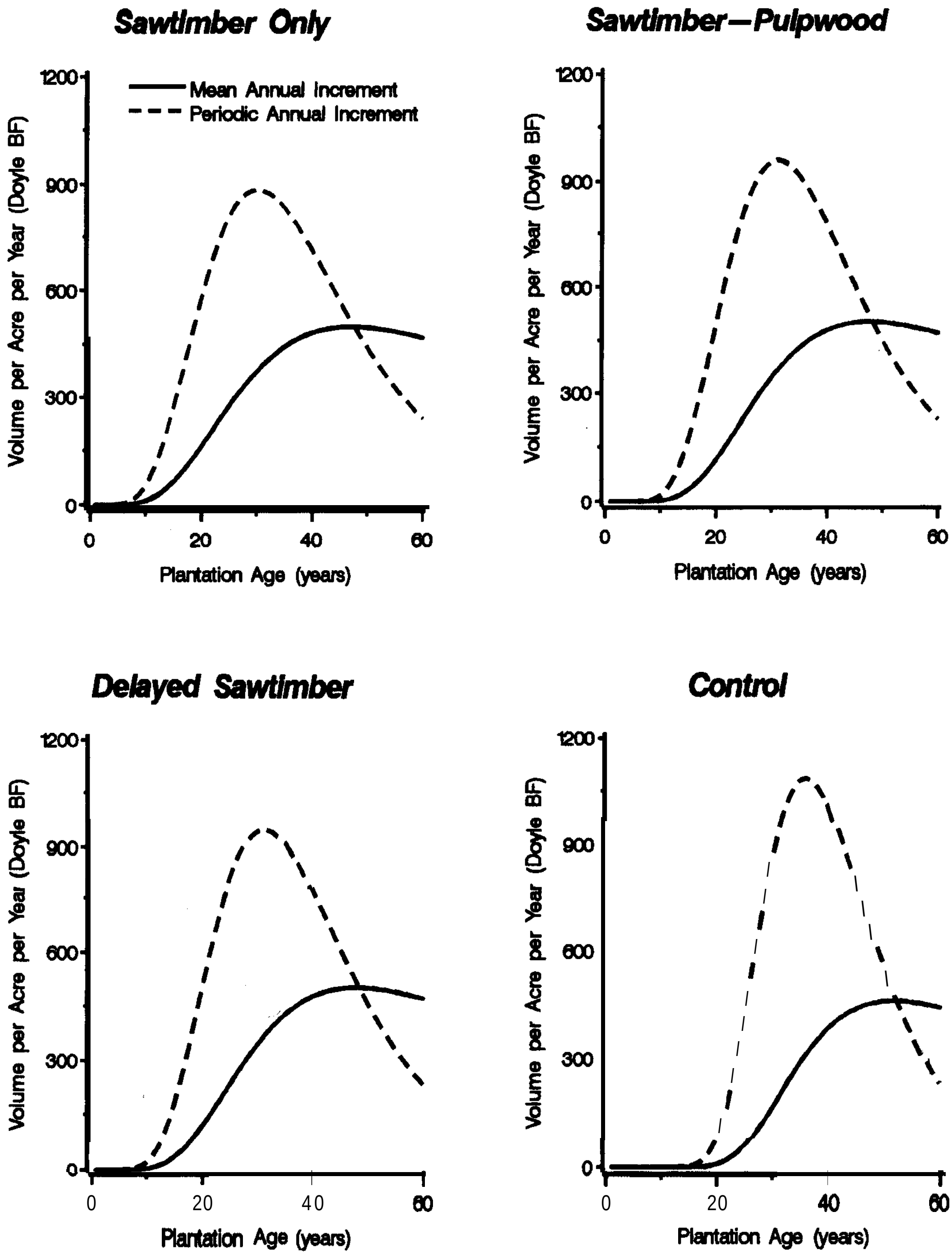

Figure 3--Regression curves for mean and periodic annual increment in Doyle board-foot volume per acre. Curves are extrapolated to stand age 60.

treatment products. Any of these adjustments could make the intensive management scenarios more profitable.

The objective of achieving sawtimber-sized loblolly pine on good sites in 30 years or less is indeed obtainable and can be obtained profitably. However, measurements made at older stand ages show that overall profits can be greater for conventionally managed stands than for intensively managed ones if stands are not harvested by age 33. It is recommended that, as Baker and Bishop (1986) proposed earlier, landowners employing sudden-saw log silviculture use wider planting spacings, commercial thinnings only, pruning of only the very best trees to just one log-length, and early understory control to insure maximum production. Additionally, site preparation and fertilization should be considered for use on cutover lands.

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DIAMETER DISTRIBUTIONS AND BASAL AREA OF PINES AND HARDWOODS 12 YEARS FOLLOWING VARIOUS METHODS AND INTENSITIES OF SITE PREPARATION IN THE GEORGIA PIEDMONT

Timothy B. Harrington and M. Boyd Edwards[1]

Abstract-Twelve years after various methods and intensities of site preparation in the Georgia Piedmont, diameter distributions and basal area (BA) of pines and hardwoods varied considerably among treatments. Site preparation reduced hardwood basal area to 36 percent of that observed in clearcut-only plots. As a result, planted-pine BA in the presence of site preparation was 2.7 times that observed in its absence. Site preparation by manual cutting of residual trees resulted in a volunteer-pine BA of over three times that observed in mechanically prepared plots. We inferred that tillage treatments increased planted-pine BA through improvements in soil characteristics. In treatments in which the planted pines were under severe competition from hardwoods or volunteer pines, their diameter distributions were positively skewed (many small and few large individuals). In treatments of greater site-preparation intensity, diameter distributions approached a normal distribution.

INTRODUCTION

Silviculture often mimics natural disturbances to create desirable stand structures (Smith and others 1997). Specifically, silvicultural treatments select for the growth form, size, or species of trees that have the greatest competitive advantage during specific stages of stand development (Oliver and Larson 1996). An appropriate time for manipulating stand structure of pine plantations is after crown closure and during stand differentiation, when potential crop trees can be identified and recruited into the upper crown classes.

In this paper, we compare diameter distributions and basal area of pines and hardwoods among various methods and intensities of site preparation in the Georgia Piedmont. The results we describe supplement the findings of a previous paper on these data (Harrington and Edwards 1996).

METHODS

Study Site and Treatments

The study was conducted at an existing site-preparation experiment in the lower Piedmont of Georgia located on the Hitchiti Experimental Forest, 18 miles north of Macon. In spring 1980, the previous old-field stand of loblolly pine (*Pinus taeda* L.) was clearcut and nonmerchantable trees (primarily hardwoods) were left standing. Thirty 2- acre plots were located, and one of the following treatments was randomly assigned to each:

(1) Clearcut only: absence of site preparation; residual (nonmerchantable) trees retained.

(2) Manual cutting: residual trees of d.b.h. (diameter at breast height, 4.5 feet above ground) > 1 inch were cut with a chainsaw (August 1981).

(3) Shear-chop: residual trees were sheared with a KG blade, and debris was masticated with a rotary chopper (September and November 1981).

(4) Shear-chop-hexazinone: treatment 3 plus application of hexazinone herbicide (Velpar (TM) Gridball pellets) at 2.5 pounds of active ingredient per acre (March 1982). Heavy rains soon after application accelerated herbicide spread and uptake, resulting in subsequent first-year mortality of approximately 35 percent of the planted pines and an 80 percent reduction in first-year cover of associated woody and herbaceous species (Edwards 1994).

(5) Shear-root rake-burn-disk: residual trees were sheared, rootstocks were raked into windrows and burned, remaining debris was scattered with a bulldozer blade, and plots were disked with an offset harrow to a depth of 6-8 inches (September and October 1981).

(6) Shear-root rake-burn-disk-fertilize-sulfometuron: treatment 5 plus a broadcast application of ammonium-nitrate fertilizer at 102 pounds of elemental nitrogen per acre and a banded application of sulfometuron (Oust (TM)) herbicide at 6 ounces of active ingredient per acre (March and April 1983).

Each treatment was replicated five times in a randomized complete-block design. In January and February 1982, 1-0 bareroot seedlings of loblolly pine were hand planted at a spacing of 6 ft x 10 ft. Pines that had died in treatment 4 were replanted with new seedlings of the same stocktype in January and February 1983.

Vegetation Measurements and Statistical Analysis

At the center of each treatment plot, a 0.2-acre measurement plot was located. In fall 1993, 12 years after treatment, d.b.h. (nearest 0.1 inch) and species of hardwood and pine trees were recorded for each stem of d.b.h. > 1 inch rooted within a given measurement plot. Data were separated into categories of planted pines (tagged at planting), volunteer pines (not tagged), and hardwoods. Measurement plot values of stand basal area (BA, square feet per acre) were calculated for each category of trees.

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Stand basal area data were subjected to analysis of variance and the following orthogonal contrasts (95 percent significance level):

I. Absence versus presence of site preparation: treatment 1 versus the mean of treatments 2-6.

II. Manual cutting versus mechanical site preparation: treatment 2 versus the mean of treatments 3-6.

III. Absence versus presence of hexazinone: treatment 3 versus treatment 4.

IV. Absence versus presence of tillage (i.e., root raking and disking): the mean of treatments 3 and 4 versus the mean of treatments 5 and 6.

Stem frequencies (trees per acre) were plotted against 1-inch d.b.h. classes to illustrate the effects of the site preparation treatments on diameter distributions for each of planted pines, volunteer pines, and hardwoods.

RESULTS AND DISCUSSION

Absence versus Presence of Site Preparation

By removing aboveground portions of residual trees, site preparation reduced hardwood BA to about 36 percent of that observed in clearcut-only plots (fig. 1A). Although some of the site-preparation treatments caused abundant sprouting of the hardwood rootstocks (Harrington and Edwards 1996), planted-pine BA in the presence of site preparation (77 square feet per acre) was about 2.7 times that found in the absence of site preparation (28 square feet per acre). Diameter distributions reveal that, in the absence of site preparation, a relatively low density of large, residual hardwoods (31 stems per acre of d.b.h. 6 inches and greater) appear to have limited planted-pine BA (figs. 1 B-l C).

Manual Cutting versus Mechanical Site Preparation

Volunteer-pine BA following manual cutting (96 square feet per acre) was over three times the mean value observed for mechanical treatments (30 square feet per acre) (fig. 2A). Apparently in response to severe competition from volunteer pines, planted-pine BA following manual cutting (35 square feet per acre) was about 40 percent of that observed for mechanical treatments (87 square feet per acre). We hypothesized that manual cutting released an abundance of volunteer pines that had germinated the year before pine planting (Harrington and Edwards 1996). Because of overstocking, 91 percent of the volunteer pines in the manual-cutting treatment had a d.b.h. less than 6 inches (987 trees per acre) (fig. 2B). As a result of differences in method of site preparation, diameter distributions for planted pines were either positively-skewed (manual cutting) or relatively normal (mechanical site preparation) (figs. 2B-2C).

Absence versus Presence of Hexazinone

The application of hexazinone during site preparation reduced volunteer-pine BA by half, although it did not result

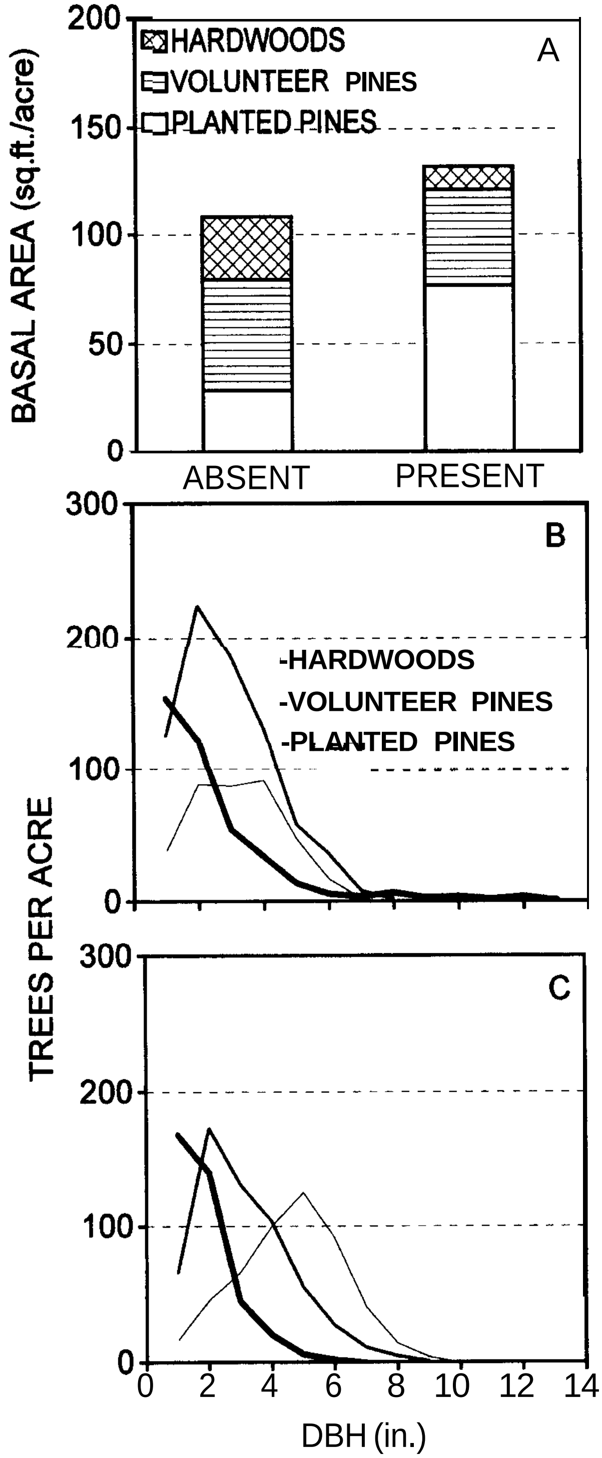

Figure l-Basal area (A) and diameter distributions of pines and hardwoods 12 years following absence (B) versus presence (C) of site preparation.

in statistically significant effects on BA of planted pines or hardwoods (fig. 3A). Stem density of hardwoods in the presence of hexazinone (192 trees per acre) was about 38 percent of that observed in its absence (511 trees per acre) (figs. 3B-3C). Replanting of pines that died from hexazinone may have resulted in a diameter distribution that was relatively flat and positively skewed, because it

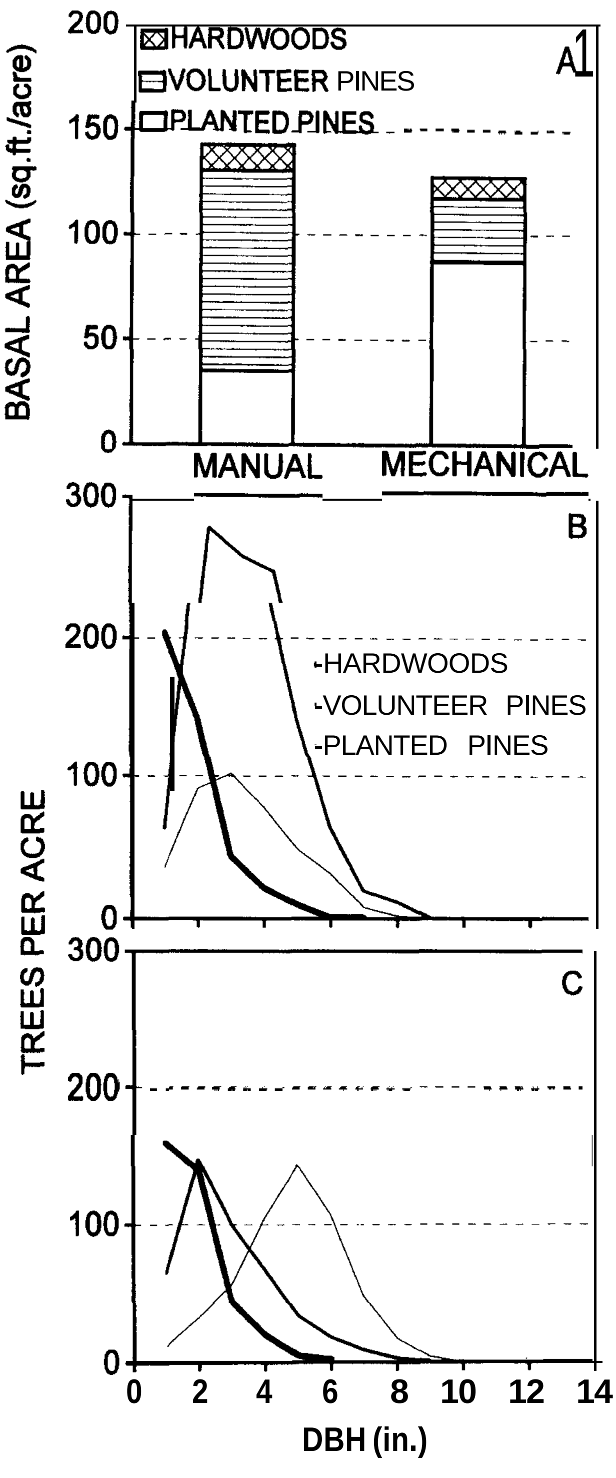

Figure 2-Basal area (A) and diameter distributions of pines and hardwoods 12 years following manual cutting (B) versus mechanical (C) site preparation.

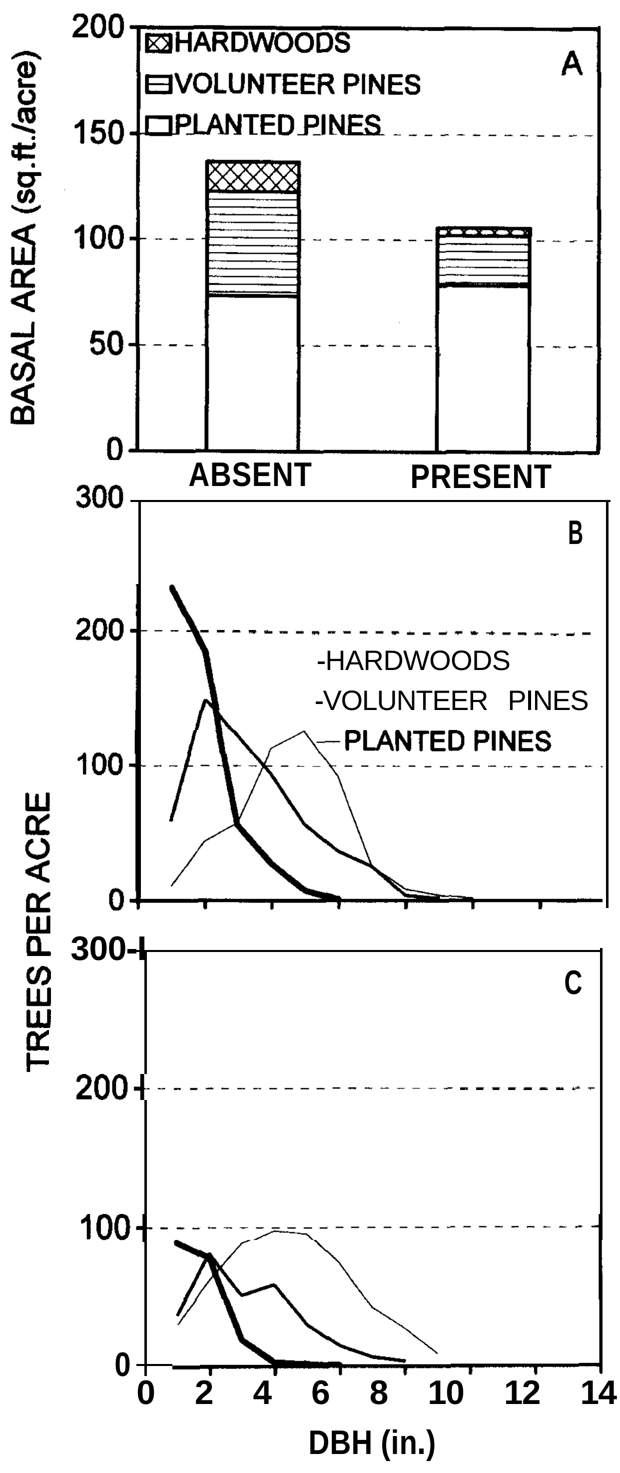

Figure 3-Basal area (A) and diameter distributions of pines and hardwoods 12 years following absence (B) versus presence (C) of hexazinone during site preparation.

introduced a cohort of seedlings that were a year younger than those of the original planting.

Absence versus Presence of Tillage

Planted-pine BA in the presence of tillage (99 square feet per acre) was about 30 percent greater than that observed in its absence (76 square feet per acre) (fig. 4A). However, basal area of volunteer pines and hardwoods did not differ significantly in the absence versus presence of tillage. From these results, we inferred that increases in planted-pine BA from tillage resulted from improvements in soil characteristics, rather than from a reduction in competing vegetation abundance (Harrington and Edwards 1996). In the second year of the study, Miller and Edwards (1985)

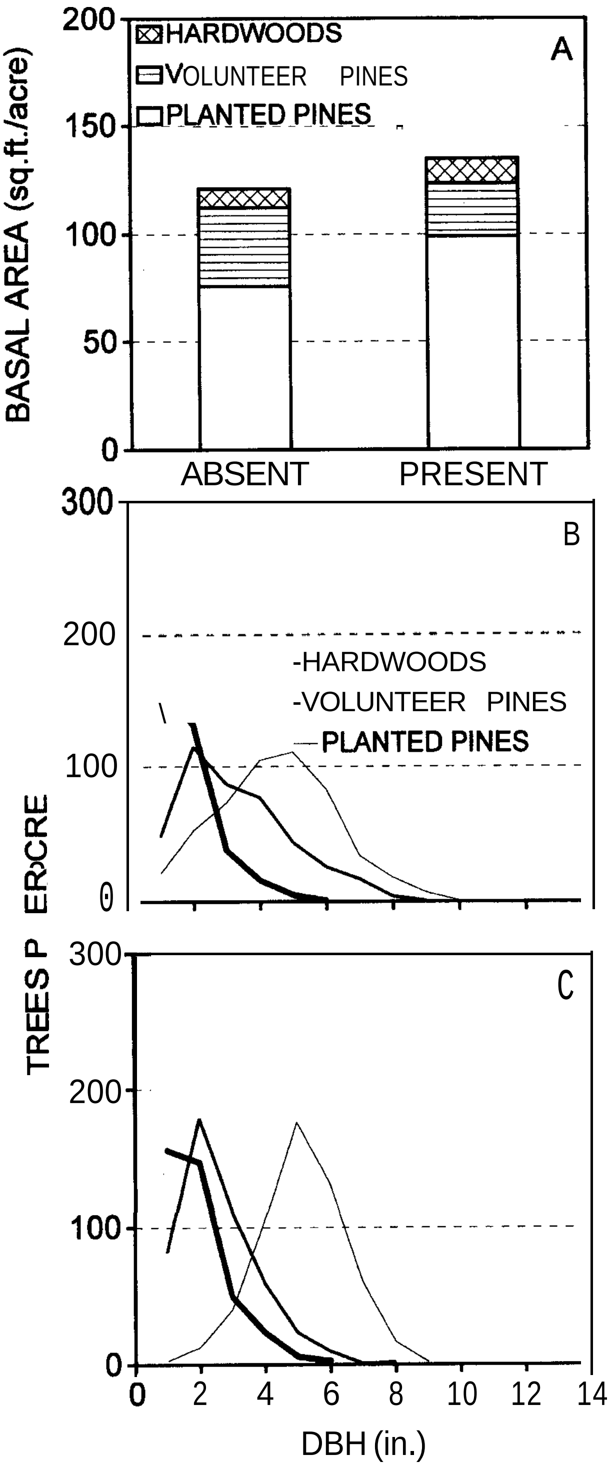

Figure 4-Basal area (A) and diameter distributions of pines and hardwoods 12 years following absence (B) versus presence (C) of tillage during site preparation.

detected reductions in bulk density and increases in pore space following tillage. Presumably because enhanced growing conditions permitted the development of a more uniform stand structure, the normality of the planted-pine diameter distribution was greater in the presence versus absence of tillage (figs. 4B-4C).

CONCLUSIONS

A wide range of stand structures resulted 12 years after various methods and intensities of site preparation. Differences in stand structure resulted because the treatments provided a competitive advantage to either hardwoods, volunteer pines, or planted pines. Absence of site preparation favored residual hardwoods over planted and volunteer pines. Manual cutting released an abundance of volunteer pines from hardwood competition, favoring their dominance over pines planted a year later. Mechanical treatments delayed development of hardwoods and volunteer pines and may have improved soil characteristics-growing conditions that favored the development of productive and uniform stands of planted pine. Results of this research emphasize the importance of understanding how forest disturbances influence subsequent stand development, and how such information can be incorporated into silvicultural systems to better meet stand management objectives.

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STAND DEVELOPMENT 18 YEARS AFTER HARVEST OF A HIGH-QUALITY HARDWOOD SITE ON THE CUMBERLAND PLATEAU IN TENNESSEE

Karen Kuers and Valerie Kuthe[1]

Abstract-Stand composition and development of a 68-acre, high-quality hardwood site in the Cumberland Plateau Region near Sewanee, TN, has been observed since it was regenerated by clearcutting in 1978. Forty-six permanent plots were established and inventoried prior to harvest, annually through age 5, at age 10, and in 1996, 18 years after harvest. After 18 years, the stand has regained its preharvest basal area of 90 square feet per acre. The stem count (all stems > 4.5 feet) increased from a preharvest level of 1,676 stems per acre, to a peak of 5,204 at age 5, before declining to the current level of 1,970. The number of woody species increased from 31 in the preharvest stand, to 38 at age 10, before dropping to 33 species at age 18. Whereas the six most numerous species prior to harvest were hickories (*Carya* spp.), dogwood (*Cornus florida*), chestnut oak (*Quercus prinus*), blackgum (*Nyssa sylvatica*), ash (*Fraxinus* sp.), and yellow-poplar (*Liriodendron tulipifera*), in descending order, the six most numerous species 18 years after harvest are yellow-poplar, hickories, sugar maple (*Acer saccharum*), chestnut oak, redbud (*Cercis canadensis*), and black locust (*Robinia pseudoacacia*). In each case, the six species compose approximately 60 percent of the total stems present. The largest differences in species densities include increases for yellow-poplar, black locust, and maples (red and sugar), and the dramatic decrease in the population of dogwood, presumably due to dogwood anthracnose. The species composition of the regeneration layer has changed more than that of the larger stems. Oaks, predominately white and chestnut, currently represent the same proportion of total stems as in the preharvest stand, approximately 15 percent. Members of the red oak group contributed only 25 and 18 percent of the oak stems present prior to harvest, and in 1996, respectively. Results indicate that species composition on mesic sites may shift to more shade-intolerant, early successional species after clearcutting, even when all stems > 2 inches d.b.h. are felled and undesirable stems are poisoned. The stand currently has 296 stems per acre judged free-to-grow; 28 percent black locust, 26 percent yellow-poplar, and 15 percent chestnut oak. Yellow-poplar, which was on average 10 feet taller and 1.7 inches larger in diameter than the other two major free-to-grow species, will likely continue to dominate much of the site.

INTRODUCTION

The current study is derived from work initiated in 1978 by the USDA Forest Service in cooperation with the University of the South. Its original purpose was to investigate the potential to predict the future stand composition of a high-quality hardwood site on the Cumberland Plateau from preharvest inventory data.

The species composition of the preharvest overstory and midstory influences later species composition by providing potential stump sprouts and a seed source. The latter is especially true for those species such as yellow-poplar (*Liriodendron tulipifera*) whose seeds remain viable on the forest floor. The preharvest woody seedlings provide advanced regeneration that may grow into the next canopy.

The relationship between post-harvest and preharvest stand composition is dependent upon the degree to which external factors influence species establishment after harvest, as well as the degree to which site conditions are similar to those that gave rise to the original stand. Species in adjacent stands may reduce the influence of the preharvest overstory by contributing seed representing species either not present in the preharvest stand, or present only in small numbers. For example, a model was used to predict stand composition based upon preharvest inventory data, and the predicted composition was compared to the actual composition of the stand 1 year after the harvest. The model greatly underestimated the number of seedlings of pioneer species such as black locust (*Robinia pseudoacacia)* and yellow-poplar, which were present in moderate to low numbers in the preharvest stand (Waldrop and others 1986). Comparison to other stands indicated that predictions for older stands were frequently better, largely due to the decline in numbers of the pioneer species as the stands aged.

The current objectives of the study are to (1) compare overall stand species composition 18 years after harvest to the preharvest stand composition for woody stems > 4.5 feet tall and woody stems £ 4.5 feet tall, (2) identify species for which there have been major increases or decreases relative to the preharvest stand, and (3) observe changes in stand density through time to trace the pattern of stand development following the silvicultural clearcut of a high-quality hardwood site. Since the site used in this study was not matched with a control site, these data provide a case study for the development of high-quality hardwood sites in the Cumberland Plateau Region of Middle Tennessee.

METHODS

Study Area

The 68-acre study area is located in a south-facing cove of the Cumberland Plateau near Sewanee, TN. The cove is bisected by a small stream, Kirby-Smith Branch. The study area consists primarily of north- and south-facing plateau escarpments and upper sandstone slopes and benches, representing landtypes 16 and 17 in Smalley's (1982) land classification of the Mid-Cumberland Plateau. With

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elevations from 1600 to 1600 feet, slopes range from gentle to very steep (>100 percent slope). Much of the area is covered with rocky colluvium. The major soils include Grimsly, Bouldin, and Jefferson and site index estimates (base age 50) for yellow-poplar average 101.

The preharvest stand was two-layered. The older, upper layer consisted of trees ranging from 65 to 140 years in age. The average diameter of the 1675 merchantable trees (³ 12 inches d.b.h.) that were marked for harvest was 16.5 inches. The trees were 90 percent chestnut oak, hickory, white oak, northern red oak, and yellow-poplar, in descending order. The same five species composed 90 percent of the 1,149 nonmerchantable trees (8 to 12 inches, and a few large culls) on the site. The major difference in the smaller trees was that the hickories and yellow-poplar each moved up 1 in the relative ranking. A large component of the smaller yellow-poplar were poles that originated from a partial harvest 25 years earlier. Stand basal area was approximately 90 square feet per acre. Reproduction of desirable species was generally sparse (fig. 3B), and the stand had closed to the extent that very few plots contained yellow-poplar seedlings less than 4.5 feet.

Experimental Design

In 1978, prior to harvest, 46 permanent plots were established across the study area. The plots were spaced 200 feet apart along a north-south, east-west grid. Each plot consisted of nested 0.01- and 0.001 -acre circular plots.

The plots were inventoried prior to harvest, at l-year intervals through age 5, in 1988 at age 10, and in 1996 at age 18. Data for all measurements prior to 1996 were obtained from the USDA Forest Service, which initiated the study in cooperation with the University of the South.

At each measurement period all stems > 4.5 feet tall within the 0.01 -acre plots were tallied by species and classified as free-to-grow (FTG) or overtopped. Stems were judged FTG if they were in the codominant or dominant canopy layer. All stems £ 4.5 feet tall within the 0.001 -acre plots were tallied by species. In addition, the d.b.h. and height were measured for the dominant tree in each of the four cardinal quadrants of the 0.01 -acre plots.

In 1996, the O.Ol-acre plots were expanded to 0.02 acres to accommodate the larger tree sizes. D.b.h. was measured on all stems > 4.5 feet tall tallied within the 0.02-acre plots. To facilitate comparison to past data, trees belonging in the original 0.01 -acre plot were identified on the tally sheet.

Pre- and Post-Harvest Treatments

Prior to logging, grapevines were severed near groundline and the stumps were treated with Tordon™ 101. Small stems (2 to 8 inches d.b.h.) of undesirable species [dogwood, sourwood *(Oxydendrum arboreum)*, red maple (*Acer rubrum*), blackgum, and a portion of the hickories] were also injected.

All stems > 8 inches d.b.h. were harvested by conventional logging methods in the spring and summer of 1978.

Approximately 4,700 merchantable board feet per acre (International Rule) were removed in a total of 1,676 stems. An additional 1 ,149 nonmerchantable stems > 8 inches d.b.h. were cut by the loggers.

After the harvest, small stems (2 to 8 inches d.b.h.) of desirable species were felled but were not poisoned. A small clump of pole size yellow-poplar were left standing near the creek. These stems were identified as residuals in later inventories and were excluded from plot measurements.

RESULTS

The stand currently contains 18 percent more stems per acre > 4.5 feet and 56 percent less stems per acre f 4.5 feet than did the preharvest stand. After harvest the number of stems > 4.5 feet increased from a preharvest level of 1,676 stems per acre to a peak of 5,226 in 1983 (5 years after harvest) before declining to the current level of 1,970 stems per acre (fig. 1A). The number of stems f 4.5 feet increased from a preharvest level of 6,000 stems per acre to a peak of 23,670 in 1980 (2 years after harvest) before declining to the current density of 2,644 stems per acre (fig. 1 B). Stand basal area has regained its the preharvest level of 90 square feet per acre.

Stand closure occurred within 5-10 years of harvest. Densities for individual species generally peaked within 5 years of harvest. Only four species present 10 years after harvest (representing 17 stems per acre) had not become established within 5 years of harvest.

Two different development patterns are apparent among the four most common species in the stand 18 years after harvest (fig. 2). Black locust and yellow-poplar each proliferated and grew rapidly into the canopy, peaked within

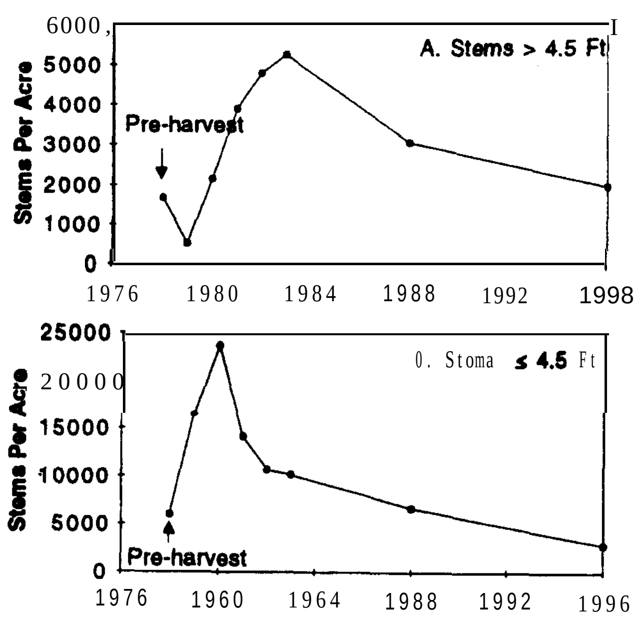

Figure l-Stand density changes 18 years following harvest. (A) All stems > 4.5 feet tall. (B) All stems f 4.5 feet tall.

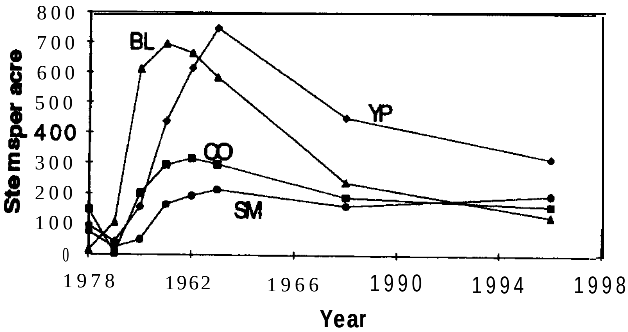

Figure 2-Species density changes for the four most numerous species 18 years after harvest (stems > 4.5 feet). YP = yellow-poplar, BL = black locust, CO = chestnut oak, SM = sugar maple.

3 years, and then began a rapid decline in stems as competition increased and the stand entered the stem exclusion stage of stand development (Oliver and Larson 1996). Eighty-two percent of the young black locust (570 SPA) and 58 percent of the yellow-poplar (433 SPA) died by age 18. Sugar maple produced fewer total stems than either black locust or yellow-poplar, but also exhibited lower mortality (8 percent or 17 SPA). The pattern in chestnut oak was somewhat intermediate (49 percent, or 154 SPA died). The difference in mortality closely mirrors the shade tolerance of the species, with black locust very intolerant, yellow-poplar intolerant, chestnut oak intermediate, and sugar maple tolerant.

The species composition of stems > 4.5 feet is generally similar to that of the preharvest stand. Six of the nine most common species prior to harvest are also among the most common species 18 years later (fig. 3A). Species composing 5 or more percent of the stand prior to harvest

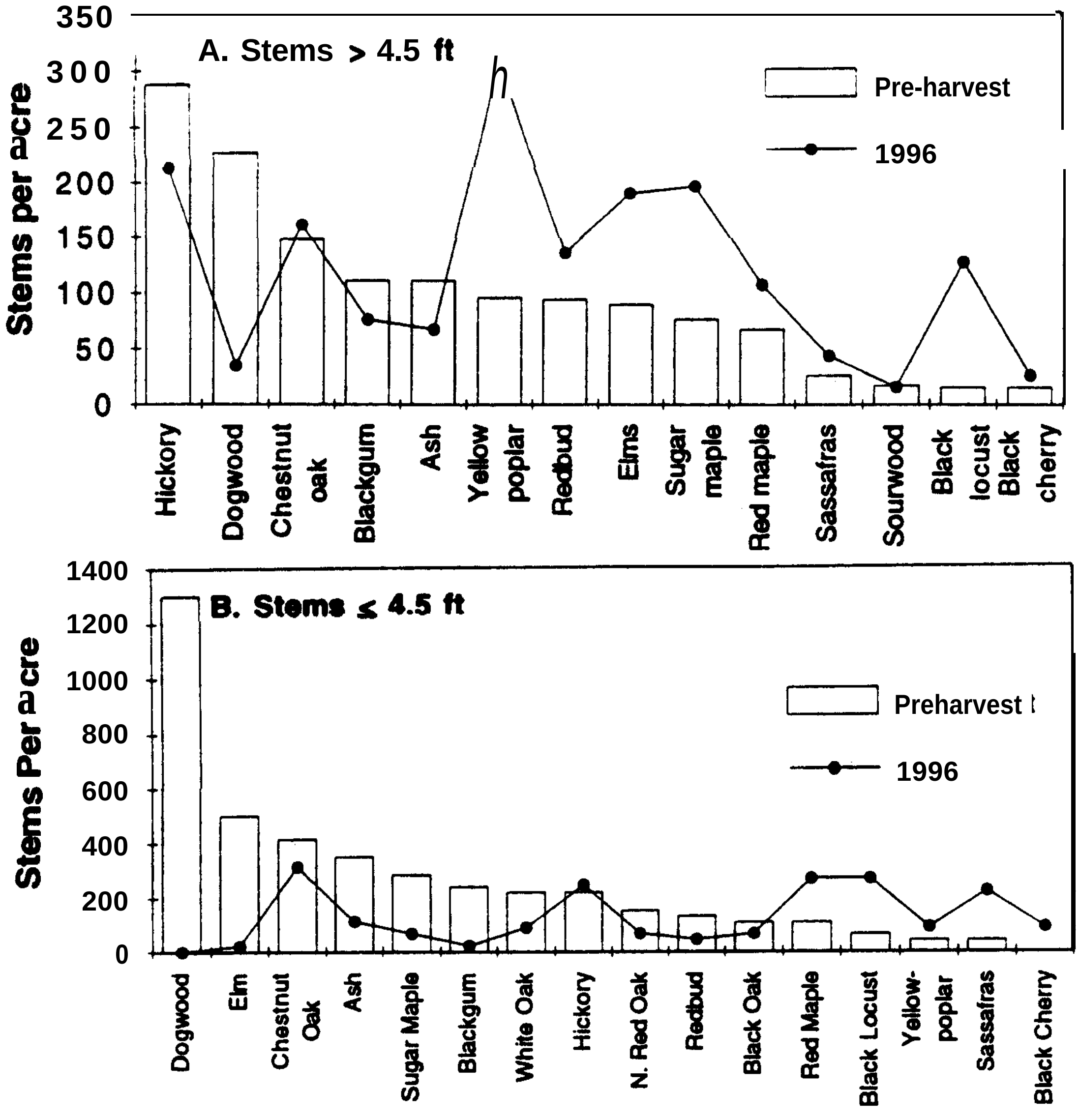

Figure 3-Comparison of pre- and post-harvest density by species. (A) All stems > 4.5 feet tall. (B) All stems £ 4.5 feet tall.

were, in descending order, hickories, dogwood, chestnut oak, blackgum, ash, yellow-poplar, redbud, slippery elm (*Ulmus rubra*), and sugar maple. Together these species composed 75 percent of the total stems > 4.5 feet tall. Species composing 5 or more percent of the current stand are yellow-poplar, hickories, sugar maple, chestnut oak, redbud, black locust, red maple, and slippery elm. Together these species compose 70 percent of the total stems.

Species composition of the smaller stems has changed more than that of the larger stems (fig. 3B). The five most common understory species prior to harvest were dogwood (31 percent of stems f 4.5 feet), slippery elm, chestnut oak, ash, and sugar maple. Combined, these species made up 68 percent of the small stems. Only one of the five most common species in 1996, chestnut oak, was a significant component of the preharvest regeneration layer. Hickory, red maple, black locust, and sassafras (*Sassafras albidum*), which currently constitute 50 percent of the stems f 4.5 feet, only contributed 10 percent of the preharvest small stems.

Five species have changed more than 5 percent as a proportion of total stems (> 4.5 feet) per acre. The three species that increased more than 5 percent include yellow-poplar, with a 10 percent increase (6 to 16 percent of all stems), and black locust (1 to 6 percent) and sugar maple (5 to 10 percent), each with a 5 percent increase. The two species groups that exhibited substantial decreases include dogwood with a decrease of 12 percent (14 to 2 percent of all stems), and hickories (*Carya* spp.) with a decrease of 6 percent (17 to 11 percent). With the exception of those species that were only present in 1978 or 1996, all other species are within 5 percent of their preharvest percentages of total number of stems per acre.

The current number of woody species is slightly higher than its preharvest level. Thirty-one woody species were distributed across the 46 plots in the preharvest stand, while 34 species were identified 18 years after harvest. The largest number of species (38) was found 10 years after harvest. Twenty-four species were common to both the pre- and post-harvest stand, while seven species were found in 1978 but not in 1996, and 9 were found in 1996 but not in 1978 (table 1).

Managers of eastern hardwood forests are greatly interested in maintaining or increasing the number of oaks present after a harvest. At the Kirby-Smith site, oaks make up the same percentage of total stems in 1996 that they did prior to harvest (15 percent). Since there are a greater number of total SPA, the actual number of oak stems increased slightly from 256 to 300 SPA. The majority of the oaks (73 percent), are in the white oak group (fig. 4). This represents a slight decline from the 82 percent present prior to harvest. Chestnut oak is the most common oak.

Seventy percent of the current free-to-grow (FTG) basal area is made up of three species: yellow-poplar (45 percent). black locust (16 percent), and chestnut oak (11 percent). This represents 76, 83, and 43 SPA, respectively (fig. 5). All oaks combined represent 20 percent of all FTG stems, primarily due to chestnut oak, with 15 percent. Seventy-six percent of the 0.01 -acre plots (35 of 46) contained an FTG stem of a desirable species (yellow-poplar, oak, black cherry, ash). Only 35 percent of the plots had an FTG oak stem. FTG yellow-poplar stems are on average 12 feet taller and 2 inches larger in diameter than the other FTG species in the study area (fig. 6).

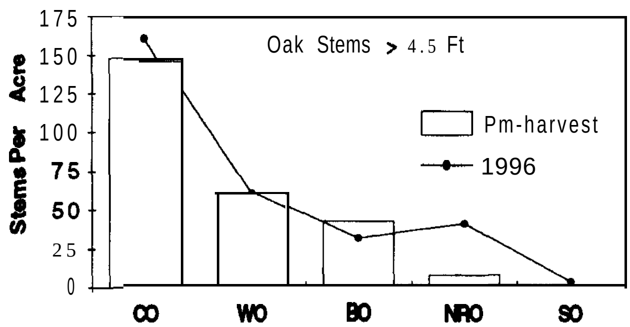

Figure 4-Comparison of pre- and post-harvest oak density by species. CO = chestnut oak, WO = white oak, BO = black oak, NRO = northern red oak, SO = scarlet

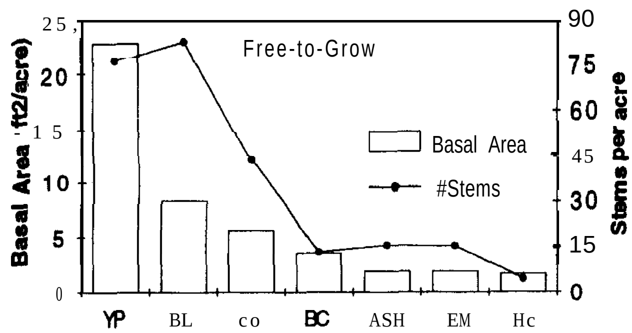

Figure 5—Basal area and density of the stems judged free-to-grow 18 years after harvest. YP = yellow-poplar, BL = black locust, CO = chestnut oak, BC = black cherry, HIC = hickory.

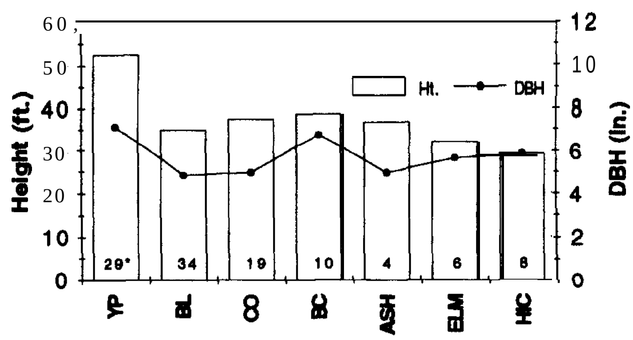

Figure 6-Height and diameter of the stems judged free-to-grow 18 years after harvest (* = number of stems used in the height average; abbreviations are the same as in figure 5).

Table I-Differences in woody species composition between the preharvest inventory and 10 and 18 years after a silvicultural clearcut

Common name	Scientific name	1978 (Preharvest)	1988	1996
American chestnut	*Castanea dentata*	*	*	
Ash	*Fraxinus* (spp)	X	X	X
Azalea	*Rhododendron* (spp)	X	X	X
Blackhaw	*Viburnum rufidulum*	X	X	*
Black cherry	*Prunus serotina*	X	X	X
Blackgum	*Nyssa sylvatica*	X	X	X
Black locust	*Robinia pseudoacacia*	X	X	X
Black Walnut	*Juglans nigra*	*		
Bladdernut	*Staphylea trifolia*	X	*	*
Blueberry	*Vaccinium* (spp)	*	X	*
Carolina buckthorn	*Rhamnus caroliniana*	X		
Dogwood	*Cornus florida*	X	X	X
Eastern redcedar	*Juniperus virginiana*	*	*	
Elm, slippery	*Ulmus rubra*	X	X	X
Elm, winged	*U. alata*		X	X
Hackberry	*Celtis occidentalis*		*	•
Hawthorn	*Crataegus* (spp)	*		
Hickory	*Carya* (spp)	X	X	X
Hophornbeam	*Ostrya virginiana*			*
Hydrangea	*Hydrangea arborescens*	*	X	
Magnolia, cucumber	*Magnolia acuminata*	*	•	⌧
Maple, red	*Acer rubrum*	X	✠	✠
Maple, sugar	*A. saccharum*	X	✠	✠
Mountain laurel	*Kalmia latifolia*	X	✠	✠
Mulberry, red	*Morus rubra*		⌧	
Oak, black	*Quercus velutina*	X	✠	✠
Oak, chestnut	*Q. prinus*	X	✠	✠
Oak, chinquapin	*Q. muehlenbergii*		*	⌧
Oak, northern red	*Q. rubra*	*	✠	✠
Oak, scarlet	Q. coccinea		⌧	⌧
Oak, white	*Q. alba*	X	✠	✠
Persimmon	*Diospyros virginiana*	X	✠	
Plum	*Prunus* (spp)		✠	⌧
Rose, multiflora	*Rosa multiflora*			⌧
Sassafras	*Sassafras albidum*	X	✠	✠
Serviceberry	*Amelanchiar arborea*	*	⌧	⌧
Sourwood	*Oxydendrum arboreum*	X	✠	✠
Spicebush	*Lindera benzoin*	X	✠	✠
Sumac, winged	*Rhus copallina*		✠	
Witch hazel	*Hammamelis virginiana*		⌧	⌧
Yellow-poplar	*Liriodendron tulipifera*	X	✠	✠

* = species represented by fewer than 10 stems per acre.

CONCLUSIONS

The Kirby-Smith site progressed rapidly though the stand initiation stage and is now exhibiting the intense competition characteristics of the stem exclusion stage of stand development. Crown closure occurred between 5 and 10 years after harvest. The number of stems per acre peaked 2 years after harvest, and the greatest mortality occurred both in large and small stems between ages 5 and 10 (figs. 1A and 1 B). The rapid rate of crown closure is characteristic of high-quality sites such as the one in this study. Rapid crown closure will tend to shift species composition of the next stand to species that can become established quickly after disturbance (fast growing, light-seeded species and species with seed in place) and species with a good complement of advanced regeneration and potential stump sprouts present at the time of harvest.

Although the species composition 18 years after harvest is generally similar to that of the preharvest stand, some differences are apparent. The most significant differences are the large increase in yellow-poplar, black locust, and sugar maple, the reduction in hickory, and the dramatic decreases in dogwood. The increases in yellow-poplar and black locust are not surprising given that both are rapid growing, shade-intolerant species with seeds that are easily dispersed from surrounding stands. In addition, black locust produces prolific root sprouts and yellow-poplar sprouts easily from stumps. Yellow-poplar has the added advantage of developing from seed stored 4 to 7 years in the forest floor (Burns and Honkala 1990). The increases in sugar maple are best explained by the combined release of the advanced regeneration and sprouts arising from small stems cut at harvest. (Sugar maple was the fifth most common species in the regeneration layer prior to harvest.) Declines in hickory are likely due both to their slow growth rate and the poisoning of some stems prior to harvest. While the number of hickories > 4.5 feet has declined, the number of hickory stems f 4.5 feet is slightly higher than it was prior to harvest, and it is likely that the number of stems > 4.5 feet will continue to increase as the relatively shade tolerant hickories [mostly shagbark (*Carya ovata*) and pignut (*Carya glabra*)] slowly grow upward toward the canopy.

Dogwood has been virtually eliminated in the stand, and across much of the Cumberland Plateau in the vicinity of Sewanee, as a result of dogwood anthracnose. Whereas 31 percent of the preharvest stems f 4.5 feet were dogwood, no dogwood reproduction was present on any plot in 1996. (In the 1988 inventory, 14 percent of the 6,674 stems/acre f 4.5 feet were dogwoods.) It is possible that part of the explanation for the increase in red and sugar maple is due to the decline in dogwood, but it is unlikely to be the major factor as the decline has primarily occurred within the past 5-8 years.

The best indicator of the future development of the stand is the composition of the FTG stems. Yellow-poplar, which occupies the greatest basal area and is generally taller than the other FTG stems, will likely retain its dominance over much of the site. Black locust is classified as very intolerant of shade and seldom remains in a closed stand unless it is a dominant tree (Burns and Honkala 1990). Within 10 years after clearcutting a high-quality hardwood site in the Southern Appalachians, black locust numbers had begun to decline, even though it remained the most abundant species on the site (McGee and Hooper 1975). Black locust was the most common species in this study for the first 4 years of the study, but by age 5 it had already begun to decline (fig. 2). Yellow-poplar continued to increase through age 5, and it remains the most common species on the site after 18 years. It can be expected that the black locust will continue to decline with time due to yellow-poplar's current height advantage.

The oak component of the future stand is still in question. The Kirby-Smith site is in a south-facing cove, and much of it is covered with rocky colluvium. Since chestnut oak is favored by the somewhat drier conditions characteristic of a south- rather than north-facing slope, and appears to thrive on very rocky slopes (Foley 1903), it may retain its current level in the stand. While it may grow into positions occupied by declining black locust, it is not likely to replace the taller yellow-poplar in the near future. In a study of mixed upland stands, O'Hara (1986) found that yellow-poplar was able to maintain its dominance over oak and hickory for at least 80 years on sites with a yellow-poplar site index of at least 65 feet (base age 50). Since this study site has a yellow-poplar site index of 101, it is likely that yellow-poplar can maintain its dominance even longer. The red oaks, which only constitute 18 percent of the oak stems present, and 3 percent of all FTG stems, are not likely to contribute much to this stand for a very long time, if at all.

It should be pointed out that the nature of the harvest, in which all stems greater than 2 inches d.b.h. were felled, and the preharvest treatment that poisoned vines and a portion of the undesirable species, also contributed to the current stand composition. The partial harvest 25 years before the study began also played a role. The earlier harvest had resulted in a layer of smaller stems beneath the main canopy. The sprouts from those stems would have contributed to the regeneration after the 1978 harvest. With the tendency for smaller stems to sprout more consistently than larger stems for oaks and many other species (Johnson 1993), the smaller stems may have had a greater influence on the current stand than did the dominant canopy. From the current encroachment of vines, it is also likely that much of the regeneration would have been suppressed if the vines had not been controlled.

The results of this study support the findings of others (e.g., Smith and Ashton 1993; McGee and Hooper 1975) that clearcutting on mesic sites leads to an increase in early successional species such as yellow-poplar and black locust. Regeneration of the later successional species on these sites is dependent upon the presence of advanced regeneration at the time of harvest. Shelterwood cuts that retain enough shade to prevent the establishment of shade intolerant seedlings while allowing advanced regeneration of oaks and later successional species to develop, may be necessary to prevent the domination of mesic sites by species such as yellow-poplar and black locust (Loftis 1990a). Evidence indicates that red oak success on high-quality sites is especially dependent upon advanced regeneration (Loftis 1990b). The partial cut 25 years prior to the 1978 harvest in this study may have provided an environment somewhat similar to that of a shelterwood cut, allowing the development of small chestnut oak seedlings. Ten percent of the regeneration present prior to the 1978 harvest was chestnut oak, and that likely contributed to the current success of chestnut oak on the site.

It is unfortunate that there is not a true control stand to which these data can be compared. Nonetheless, this study site, along with other regional permanent plots, can provide valuable information concerning long-term stand dynamics in response to harvest. The site has already been used in the validation of the early predictions of FORCAT, a single tree model of stand dynamics (Waidrop and others 1986), and has the potential to serve as a similar test for later stages of stand development.

ACKNOWLEDGMENT

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STAND DENSITY INDEX FOR SHORTLEAF PINE (*Pinus echinata* Mill.) NATURAL STANDS

Robert F. Wittwer, Thomas B. Lynch, and Michael M. Huebschmann[1]

Abstract-Plots located in dense, unthinned, naturally occurring shortleaf pine stands were used to estimate parameters in Reineke's formulation of the maximum size-density relationship between the logarithm (base IO) of number of trees per acre and the logarithm of quadratic mean tree diameter. A first-difference form of the equation was fitted to the remeasured plot data due to autocorrelation in the ordinary least squares residuals arising from repeated annual measurements of plots. Twice the root mean square error was added to the intercept term in the equation since the maximum size-density relationship should lie above the mean relationship for the plot data. The estimated maximum size-density relationship was: log(N) = 4.3772 - 1.6863(log(D)), where N is the number of trees per acre and D is the quadratic mean diameter (inches). The maximum stand density index implied by this relationship is 491 trees per acre for a stand having a quadratic mean diameter of 10 inches. From this relationship, equations relating maximum basal area per acre to both quadratic mean diameter and number of trees per acre were derived. The maximum basal area per acre relationship implied by the maximum size-density relationship was plotted on the stocking chart of Rogers (1983) together with lines representing 60 percent and 35 percent of the maximum. The curvature of these lines was flatter than the curvature of lines representing equivalent stand density in the Rogers stocking chart.

INTRODUCTION

Management of growing stock levels and manipulation of stand density is a concern of forest managers attempting to satisfy specific management objectives. Determining appropriate levels of growing stock at the stand level is complex because it involves biological, technological, and economic factors specific to each stand (Davis and Johnson 1987). Ideally, individual trees are allocated enough growing space to grow well while not adversely affecting total stand yield.

It is important to distinguish between density and stocking. Density is a measure of the amount of tree vegetation per unit area, while stocking is the relation of any such measure of density to a desired density for a particular objective expressed in the same units (Smith 1986). Forest managers typically measure density of a stand and then are faced with the question: What does the measured density represent relative to an appropriate stocking level in view of management objectives?

Reineke (1933) found the relationship of quadratic mean diameter to number of trees per acre to be very predictable in dense stands experiencing mortality due to competition. This relationship is as follows:

$$\log(N) = b_o + b_1 \log(D) \qquad (1)$$

when

N is the number of trees per acre,

D is the quadratic mean diameter (diameter at breast height of a tree with the average basal area),

log(X) is the base 10 logarithm of X, and

b_o and b_1 are coefficients to be estimated.

Reineke (1933) found b_1, the slope of the line representing the log of number of trees plotted over log of quadratic mean diameter, to be -1.605 for several coniferous species. This relationship, usually using mass as the measure of plant size, has been termed the "self-thinning rule" in the ecological literature (Yoda and others 1963). Reineke used this relationship to develop a stand density index (SDI) by converting stand density to an equivalent value with a standardized average diameter of 10 inches, i.e., SDI is the number of trees per acre if the average stand diameter were 10 inches or:

$$SDI = \log(N) = b_o + b_1 \log(10). \qquad (2)$$

Although Reineke's (1933) concept was first reported over 50 years ago, it appears to have received the most attention in recent years. Stand density management guides for a number of species based on SDI have been developed (Dean and Baldwin 1993, Long 1985, Williams 1994). The general approach defines various key stand density conditions, such as crown closure, the lower limit of self thinning, and full site occupancy as a percentage of the maximum SDI for the species. Thus, it is necessary to have a reliable estimate of the maximum SDI if one wishes to use this approach to develop density management guidelines (Daniel and others 1979).

Comparison of the maximum SDI for various species is also of interest from an ecophysiological viewpoint-pure stands of shade tolerant species experiencing competition-induced mortality might be expected to exhibit higher maximum SDI values than stands composed of intolerants. California-red fir (*Abies magnifica* A. Murr.) and redwood [*Sequoia Sempervirens* (D. Don) Endl.] stands with stand density indexes of 1000 have been found; Douglas fir [*Psuedotsuga menziesii* (Mirb. Franco)] had an SDI of 595; loblolly pine (*Pinus taeda* L.) 450, and longleaf pine (*P.*

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palustris Mill.) 400 (Reineke 1933). Recently, Williams (1996) reported a maximum SDI of 400 for loblolly pine.

The objective of this study was to estimate the maximum SDI for shortleaf pine. The slope of the "self-thinning" line for this species is also of particular interest; Reineke (1933) reported the slope to be steeper than the -1.605 found for several other conifers. Additionally, Zeide (1987) examined data for four *Pinus* and *Picea* species and disputed the assumption of a straight line relationship or constant rate of self thinning. Zeide suggested the line depicting tree size, measured as volume, over tree numbers on a log-log scale is a curve as the rate changes with tree age, species, site quality, and other factors.

METHODS

Study Area

The two study sites are located on industrial forest lands in the Ouachita Mountains of Pushmataha County, OK. Site One is located about 35 miles northwest of Site Two and is within about 25 miles of the western limit of the natural range of shortleaf pine (Lawson 1990). The USDA SCS Soil Survey (Bain and Watterson 1979) includes this site in the Carnasaw-Pirum-Clebit soils association. Measured site index at base age 50 averages 57 ft according to the polymorphic site index curves prepared by Graney and Burkhart (1973). Site Two soil is mapped in the Sherwood-Zafra association (Bain and Watterson 1979). Measured site index at 50 years averaged 73 ft at this site.

Dominant soils at both sites formed in materials weathered from shale and sandstone and are deep and well-drained. The underlying bedrock at Site One is tilted and slope gradients range from 8 to 20 percent, while at Site Two slopes range from 3 to 8 percent (Bain and Watterson 1979). The tilted rock formations result in variable solum thickness within short linear distances, consequently, average soil depth is probably greater at Site Two.

Stand Treatments

A thinning study was installed at Site One in the dormant season prior to the 1989 growing season-stands were 25 to 30 years old at the time (Wittwer and others 1996). Similar thinning treatments were implemented at Site Two 1 year later-these stands were 30 to 37 years old at the time. Three unthinned control plots at each site provide the data for the study reported here. At Site One, measurement plots were 0.10 ac, surrounded by a 33-ft-wide isolation strip. At Site Two, measurement plots were 0.2 ac surrounded by a 33-ft isolation strip. Diameter at breast height of all living trees was measured annually for 8 years at Site One and 7 years at Site TWO.

Data Analysis

Data were summarized on an area basis and quadratic mean diameter computed from the observations Of number of surviving trees and basal area. Statistical procedures based on linear regression analysis were used to estimate the slope parameter for the relationship between the logarithm of number of trees per acre and the logarithm of quadratic mean diameter per acre. Results of this analysis were used to estimate a maximum stand (SDI) for shortleaf pine.

RESULTS AND DISCUSSION

The number of trees was greater and quadratic mean diameter and stand basal area less on Site One compared with Site Two (table 1). During the 8-year observation period on Site One, the total number of trees decreased approximately 46 percent, while on Site Two tree numbers decreased about 28 percent during the 7-year observation period. Total basal area was in the range of 200 ft^2/ac at the last observation. The steady decrease in the number of trees and very slow increase in stand basal area suggest these data should provide a good estimate of the maximum SDI to be attained by shortleaf pine.

A preliminary estimate of the maximum SDI for shortleaf Pine was made, using the slope value of -1.605 found by Reineke (1933) to represent several conifer species (table 1). Estimates did not exhibit an increasing trend, but varied due to random variation in annual mortality rates around a mean of 457 on Site One and 421 on Site Two. Lack of an increasing trend in these annual estimates over several years further suggests these plots are near the maximum SDI for shortleaf pine.

Preliminary estimates of parameters for a linear equation relating the logarithm of number of trees per acre to the logarithm of quadratic mean diameter were made by ordinary least squares (OLS), resulting in an estimate of $b_1 = -1.7686$ for the slope parameter. Annual measurements of trees per acre and quadratic mean diameter were made on each of the plots, so that there were eight measurements at Site One and seven measurements at Site Two. It is well known that autocorrelation from a series of measurements taken in time can result in a violation of the assumption of independent error terms. A standard procedure used to test for autocorrelated error terms is the Durbin-Watson (DW) test (Neter and others 1989). The DW test was performed using the AUTOREG procedure in SAS/ETS (SAS Institute 1993). A DW statistic of 0.2431 with a p-value of 0.0001 resulted, indicating significant autocorrelation. A remedial measure that is frequently used when autocorrelation is present in the OLS residuals is to estimate the slope parameter using the first-difference model. This model is developed as follows:

$$\log(N_t) - \log(N_{t-1}) = b_1\{\log(D_t) - \log(D_{t-1})\} \qquad (3)$$

where

N_t is number of trees per acre in year t,

N_{t-1} is number of trees per acre in year $t-1$,

D_t is quadratic mean diameter in year t, and

D_{t-1} is quadratic mean diameter in Year $t-1$.

The intercept parameter is estimated by requiring the average value of log(N) to satisfy the equation when evaluated at the average value of log(D). Estimating the

Table l-Summary statistics for trees per acre, quadratic mean diameter at breast height, basal area, mortality rate, and Stand Density Index (SDI)[a]

Site /yr.	Trees per acre Min.	Mean	Max.	Quad. mean d.b.h. Min.	Mean	Max.	Basal area Min.	Mean	Max.	Mortality rate	SDI
				----------- Inches ----------			---------- Ft²/acre ----------			Percent	
Site One:											
1	2476	2872	3267	3.0	3.2	3.3	140	158	172		455
										13.3	
2	2291	2489	2886	3.3	3.4	3.5	143	163	177		458
										10.5	
3	2059	2227	2580	3.5	3.6	3.8	146	167	180		455
										10.9	
4	1825	1985	2324	3.8	3.9	4.1	148	169	182		450
										5.0	
5	1748	1885	2181	4.0	4.1	4.4	154	176	187		457
										6.6	
6	1553	1760	2124	4.1	4.4	4.7	157	181	195		460
										5.5	
7	1417	1669	2076	4.2	4.5	4.9	160	184	198		462
										7.3	
8	1340	1547	1914	4.4	4.7	5.1	161	185	200		457
Site Two:											
1	893	1070	1248	5.4	5.7	6.0	175	186	196		427
										3.4	
2	863	1033	1196	5.5	5.8	6.2	178	189	199		430
										10.3	
3	758	927	1062	5.9	6.1	6.5	176	189	199		421
										7.0	
4	689	862	1006	6.0	6.4	6.8	175	189	200		415
										2.9	
5	689	837	949	6.2	6.5	6.9	180	193	202		419
										2.4	
6	674	817	933	6.4	6.7	7.1	183	196	206		422
										6.5	
7	654	764	872	6.5	6.9	7.2	185	195	203		414

[a] $SDI = (\text{trees} / \text{acre}) \times \left(\frac{\text{quadratic mean dbh}}{10}\right)^{1.605}$

slope parameter by using the first difference model gives $b_1 = -1.6863$ with standard error of 0.05.

The DW statistic for the residuals from the first difference model was 2.1 with a p-value of 0.64, indicating failure to reject the null hypothesis of no autocorrelation. However, the power of the DW test is very low for models that do not contain an intercept (Judge and others 1988). Neter and others (1989) suggest fitting the first difference model with an intercept solely for the purpose of testing for autocorrelated errors. This procedure resulted in a DW statistic of 2.0 with a p-value of 0.48, indicating failure to reject the null hypothesis of no autocorrelation. Thus the first-difference model appears to have greatly reduced autocorrelation among error terms.

When the prediction equation for log(N) is required to pass through the means of the data the following model is obtained:

$$\log(N) = 4.3031 - 1.6863(\log(D)). \qquad (4)$$

Fit index = 0.968, Root Mean Square Error (RMSE)=0.03706.

The fit index and RMSE for residuals are based on predictions for log(N). This slope value is not quite as steep as that obtained by OLS but is still steeper than the Reineke value of -1.605. Reineke (1933) also found that his shortleaf data required a slope steeper than -1.605. Although he did not report the numerical value of the slope for shortleaf, figure 7 in Reineke's 1933 publication implies a slope of approximately -1.85. Thus, the value obtained from the Oklahoma data reported in this study lies between Reineke's general value of -1.605 and the value implied by his shortleaf data.

The maximum size density line should be located "above" the average for fully stocked plots. Thus, the intercept for the equation above was increased by adding twice the RMSE of the residuals (4.3031 + 2(0.03706)). The following maximum size-density relationship results:

$$\log(N) = 4.3772 - 1.6863(\log(D)). \qquad (5)$$

The maximum size-density line reported above is plotted with the data used for estimation of the slope coefficient in figure 1. From this, an estimate of maximum SDI can be obtained by using this equation to estimate the maximum number of trees per acre associated with a d.b.h. of D=10:

$$\text{maximum SDI} = 10^{4.3772-1.6863} = 491. \qquad (6)$$

The maximum size-density relationship can be used to establish a relationship between maximum basal area per acre and quadratic mean diameter. Consider the

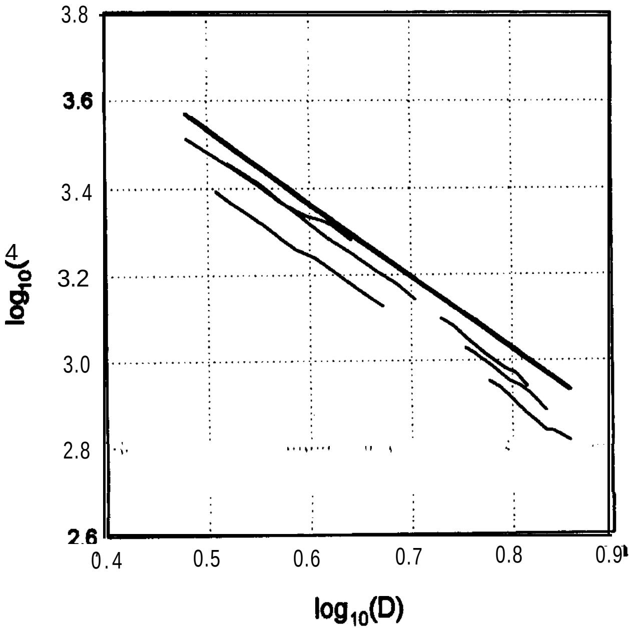

Figure l-Maximum size-density line of base 10 logarithm of number of trees per acre (N) vs. base 10 logarithm of quadratic mean diameter (D), in inches, for shortleaf pine with even-aged natural stand data used for parameter estimation. Line segments below maximum indicate annual measurements for individual plots.

antilogarithm of both sides of the maximum size density equation:

$$N = aD^b \qquad (7)$$

where

$a = 10^{4.3772}$, and

$b = -1.6863$.

To obtain an equation for maximum basal area, multiply both sides of the equation by $0.005454D^2$:

$$0.005454D^2(N) = 0.005454aD^{2+b}. \qquad (8)$$

This results in the following equation relating maximum basal area per acre to quadratic mean diameter:

$$B_{max} = aD^{2+b} \qquad (9)$$

where

B_{max} is maximum basal area per acre.

For the parameter estimates obtained in this study:

$$B_{max} = 129.9952D^{0.3137}. \qquad (10)$$

Note that this implies an increase in maximum basal area per acre with increasing quadratic mean diameter. This trend will occur whenever the absolute value of the slope parameter in the maximum size-density relationship is less than 2. A value of b = -2 would imply that maximum basal area per acre is the same for all values of quadratic mean diameter. Figure 2 indicates the relationship between maximum basal area per acre and number of trees per acre.

The maximum size-density relationship can also be used to obtain a relationship between maximum basal area per acre and number of trees per acre. Solving for quadratic mean diameter and squaring both sides gives the following results:

$$(N/a)^{**} = D^2$$

$$0.005454N(N/a)^{2/b} = 0.005454ND^2 = B_{max}. \qquad (11)$$

Thus, with algebraic simplification, the following relationship between maximum basal area and number Of trees per acre is obtained:

$$B_{max} = 0.005454(1/a)^{2/b} N^{1+2/b}. \qquad (12)$$

For the parameter estimates obtained in this study:

$$B_{max} = 0\ 005454(10^{-4.3772})^{-2/1.6863} N^{1-2/1.6863} = 847.6405N^{-0.1860}. \qquad (13)$$

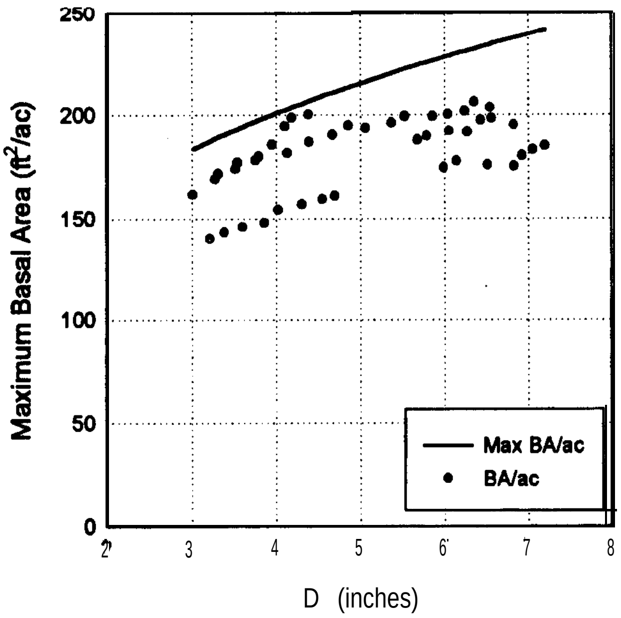

Figure 2--Relationship between maximum basal area per acre and quadratic mean diameter (D) for shortleaf pine with data from even-aged natural shortleaf pine stands.

This indicates that maximum basal area per acre is inversely related to maximum number of trees per acre, and this would be true for all values of $b < -2$. Such a relationship is consistent with the idea that stands having larger quadratic mean diameters have larger basal area per acre, since number of trees per acre is inversely related to tree size. Figure 3 shows the relationship between maximum basal area per acre and number of trees per acre.

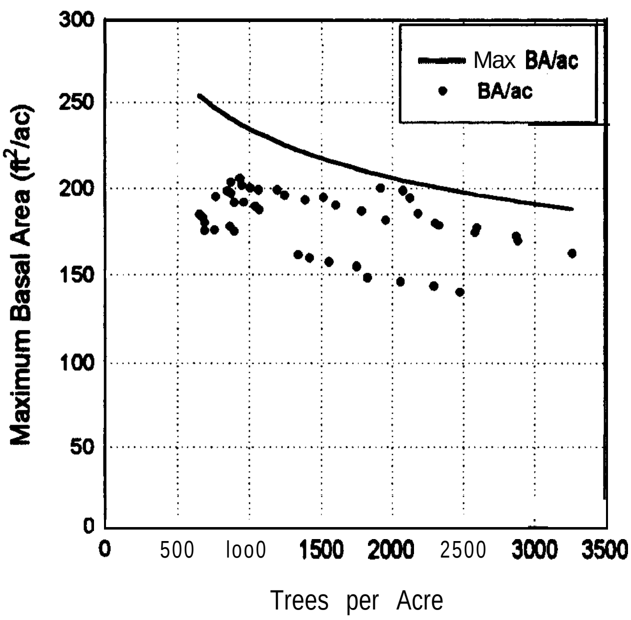

Figure 3--Relationship between maximum basal area per acre and number of trees per acre with data from even-aged natural shortleaf pine stands.

Several authors have used the maximum size-density relationship to develop forest stand density management diagrams (e.g., Williams 1994; Long 1985). Generally, important features of these diagrams include lines drawn parallel to the maximum stand density line which represent stocking levels of significance. Rogers (1983) has developed a stocking chart for shortleaf pine based on the crown competition factor concept (fig. 4). Like the Gingrich (1967) stocking chart for upland central hardwoods, the Rogers (1983) chart is based on basal area per acre (y axis) vs. number of trees per acre (x axis). Kershaw and Fischer (1991) developed a stand density management diagram for upland central hardwoods based on a maximum size-density line relating mean tree volume to maximum number of trees per acre. They commented on the relationship between their diagram and the Gingrich (1967) stocking chart.

Stand density management diagrams based on the Reineke (1933) concept usually indicate regions parallel to the maximum line, which are proportions of maximum density: $pN = (pa)D^b$ where p is proportion of maximum stocking according to the maximum size density relationship between number of trees per acre and quadratic mean diameter per acre. In order to compare Rogers' stocking chart with the density management concept, the following equation was used:

$$B_p = 0.005454(1/(pa))^{2/b} N^{1+2/b}. \qquad (14)$$

This is based on the equation discussed above, which was derived from the maximum size density relationship. For the parameter estimates obtained in this study, this equation is:

$$B_p = 0.005454(1/(p10^{4.3772}))^{-1.1860} N^{-0.1860}. \qquad (15)$$

In figure 4, the Rogers chart is presented together with the maximum stocking curve implied by the maximum size-density relationship above (p=1). Also included are the 60 percent (p = 0.6) and 35 percent (p = 0.35) stocking levels based on the maximum size-density relationship. The 60 percent level of maximum size-density is at or near the level often considered to be the "lower limit of self-thinning" in many density management diagrams, while the 35 percent of maximum size-density level is often considered the "lower limit of full-site occupancy" (Long 1985).

Since Rogers' chart is based on the crown competition factor concept of Krajicek and others (1961), it is not necessarily expected to be equivalent to a density management diagram based on the Reineke maximum size-density relationship. Nevertheless, it is of interest to see how the two concepts compare. The Rogers "B: minimum full-stocking" is based on full site occupancy with trees having maximum crown width. Figure 4 helps evaluate these comparisons. The "A: maximum full-stocking" line is maximum stocking based on a minimum growing space requirement allocating individual trees 60 percent of maximum growing space (Rogers 1983). Clearly, the density management diagram lines have a curvature

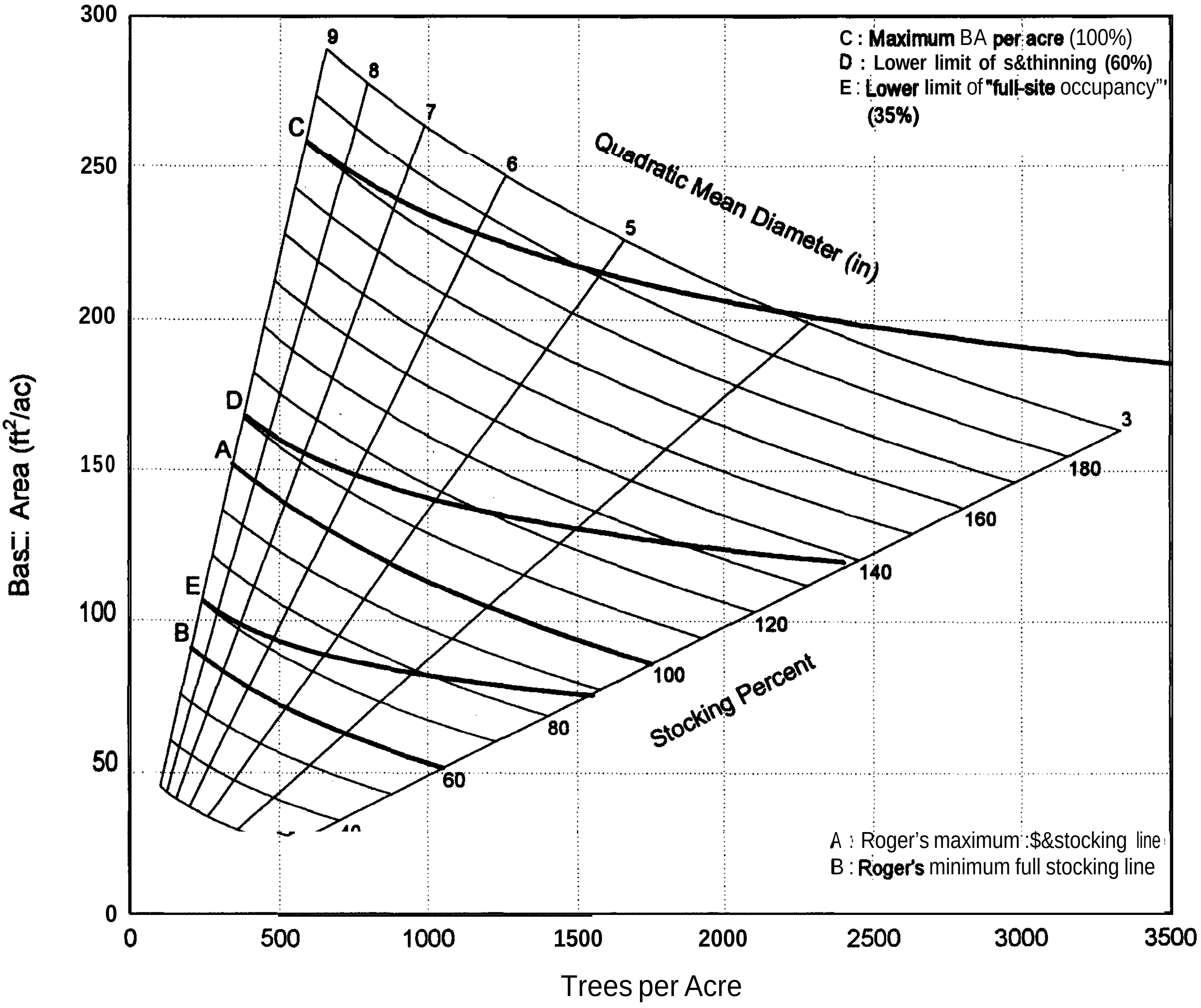

Figure 4—Rogers' (1983) shortleaf pine stocking chart with lines indicating maximum, 60 percent of maximum, and 35 percent of maximum basal area implied by the maximum size-density relationship.

that is different than that on the Rogers stocking chart. Furthermore, "A" on the Rogers maximum full-stocking line is uniformly lower than the 60 percent maximum size-density line. In a similar way, the Rogers "B" line is lower than the 35 percent maximum size-density line.

The curvature of the lines based on the maximum-size density principle is flatter than lines of constant stocking on the Rogers chart. This means that according to the maximum size-density principle, stands of the same basal area but differing in average diameter are more similar with respect to stocking than they would be according to the Rogers stocking chart. This is not necessarily unexpected because the curvature of the basic equation derived from crown competition factor for the Rogers chart is different than the curvature of the relationship between number of trees per acre and basal area per acre derived from the maximum size-density relationship.

SUMMARY AND CONCLUSIONS

Dense, unthinned plots which were established and remeasured over a 7- to 8-year period in naturally occurring, even-aged shortleaf pine stands were used to estimate the parameters of a maximum size-density relationship of the type used by Reineke (1933) between the logarithm of trees per acre and the logarithm of quadratic mean diameter. Since the plots were measured annually, a Durbin-Watson test was used to test for autocorrelation in the ordinary least squares residuals. Autocorrelation in these residuals was significant, therefore the first-difference equation method was used to estimate the parameters of a size-density relationship for these plots. Finally, a maximum line was estimated by adding twice the root mean square error to the intercept in the size-density relationship obtained for these plots. A slope parameter of -1.6863 was obtained for the relationship between the logarithm of number of trees per acre (dependent variable) and the logarithm of quadratic mean diameter (independent variable. This value is steeper than the value -1.605 recommended by Reineke for a wide range of species, but not quite as steep as the value Reineke obtained for his shortleaf data.

Evaluation of stand density based on lines parallel to the maximum size-density line was compared to the Rogers (1983) stocking chart for shortleaf pine. The lines representing percentages of the maximum size-density had flatter curvature than lines of equivalent stocking percentages on the Rogers chart. Lines representing the lower limit of self-thinning and the lower limit of full site occupancy according to the maximum size density concept were located at higher levels than the Rogers "A: maximum full-stocking" and Rogers "B: minimum full-stocking" lines, respectively.

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Measurement and Research Methods

Moderator:

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Southern Research Station

ANALYSIS OF TREE DAMAGE FROM HURRICANE HUGO IN THE CARIBBEAN NATIONAL FOREST, PUERTO RICO

Bernard R. Parresol and Salvador Alemañy[1]

Abstract-Hurricanes strongly influence the structure, composition, and successional processes of many forests. In September of 1989, Hurricane Hugo struck the eastern part of Puerto Rico causing considerable disturbance within the subtropical wet forests. Four areas in the Caribbean National Forest were surveyed: Cubuy, Rio Grande, Sabana 4, and Sabana 8. Individual trees were rated for damage and tree and plot characteristics such as d.b.h., crown class, ground slope, and topography were recorded. Tree damage was rated as: (1) none, (2) loss of small branches, (3) loss of large branches, (4) trunk snapped, and (5) uprooted. Two-way contingency tables of damage type against crown class, d.b.h. class, plot topography, tree topography, and slope class were constructed. Chi-square tests and Spearman correlations were computed. The general results are that proportions in each damage type are not the same among crown class and d.b.h. class, but chi-square tests were not significant with plot topography, tree topography, and slope class. There was moderate correlation of damage type with crown class and d.b.h.. Discriminant analyses were conducted with data from the four areas. Using d.b.h., crown class, and species importance values (relative species frequency, density, and basal area), trees were correctly classified into damage categories with an error rate of 48 percent for Cubuy, 43 percent for Riogrande, 39 percent for Sabana 4, and 44 percent for Sabana 8. Understanding hurricane disturbance helps in assessing the volume of hurricane-related mortality and damage, and in assigning trees and species into damage/risk classes.

INTRODUCTION

We report on individual tree damage from a large-scale disturbance (Hurricane Hugo) in the Caribbean National Forest (CNF) in northeastern Puerto Rico. Hurricanes strongly influence the structure, composition, and successional processes of many forests (Boucher 1990, Lugo and others 1983). Hurricanes have regularly traversed the Caribbean Basin and are recognized as one of the major natural disturbance factors shaping the forest ecology of all the islands of the Antilles (Salivia 1972, Weaver 1989). Wind damage serves as an important source of landscape-level patterning in forests and in initiating vegetation dynamics (Boose and others 1994).

Hurricane Disturbance

Puerto Rico has experienced more than 70 hurricanes since 1700 with an estimated 14 severe storms (category 3 or higher) (fig. 1) during this time period (Salivia 1972, Weaver 1987). The most recent severe storm, Hurricane Hugo, passed over the CNF on September 18, 1989 with winds exceeding 200 kilometers per hour at the wall of the hurricane eye, which had a diameter of 25 kilometers. The strength of the winds declined as the storm passed over land (Zimmerman and others 1995) and, as will be seen, there was a decreasing gradient of damage with westward distance from the hurricane track.

WIND RESEARCH

Before quantifying the damage we want to briefly review some recent work on factors that affect both the type and amount of wind damage sustained by trees. Both Mitchell (1995) and Ruel (1995) report that wind damage depends on a number of factors interacting with each other. Gross tree variables that affect the critical wind speed needed to

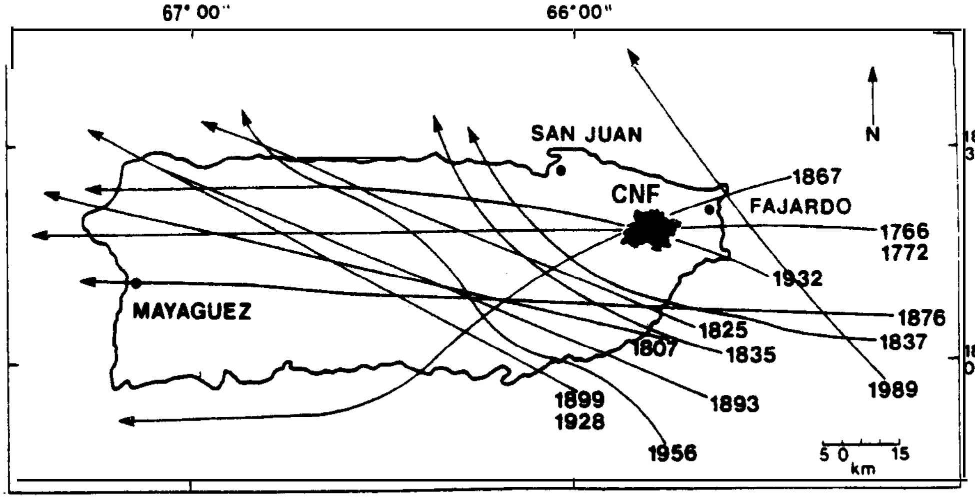

Figure l-Tracks of the 14 most severe hurricanes striking Puerto Rico since 1700. CNF = Caribbean National Forest. 1989 = Hurricane Hugo.

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either remove branches, snap a trunk, or uproot a tree include: tree height, crown size and density, stem thickness, wood strength, wood elasticity, root-soil mass, root strength, and soil shear strength. Gross stand factors that affect the probability of a wind of critical speed acting on a tree include: topographic exposure, canopy structure, canopy density, and position in canopy. Francis and Gillespie (1993) related gust speed to tree damage in Hurricane Hugo from 18 sites in the Antilles. The results of their logistic regression indicated that the probability of a tree suffering some form of damage increased with both increasing gust speed and increasing tree diameter at breast height (d.b.h.). They found that damage was nil below gust speeds of about 80 kilometers per hour, damage increased rapidly as gust speed increased from 60 to 130 kilometers per hour, and beyond 130 kilometers per hour damage was highly variable, depending upon the gross tree and stand variables previously listed. They also confirmed what many tropical ecologists have reported upon, and that is that some tree species have the ability to quickly reduce crown surface area (i.e., wind resistance) by easily shedding leaves and twigs and thus avoiding severe forms of damage.

THE STUDY AREAS

The Caribbean National Forest is located in a mountainous area of northeastern Puerto Rico known as the Luquillo Cordillera. We studied four areas located between 300 and 600 meters elevation and at increasing distances from the path of Hurricane Hugo. The locations in the CNF are shown in figure 2. Sabana 4 and Sabana 8 are near the eastern boundary of the forest and are physically close to one another. Sabana 8 is an area that had been farmed prior to 1947, when it was acquired. Sabana 4 appears to be an older, less disturbed site. Rio Grande has no record of cultivation, but a 1934 map showed cutover forest at intermediate elevation and sierra palm (*Prestoea montana*) forest on slopes and at higher elevations. The forest site at Cubuy is located in original Spanish crown lands. The presence of bamboo, a few coffee plants, and ornamental trees at the Cubuy site indicates the area was not entirely free of human disturbance. There were probably illegal homesteads in this crown land abandoned prior to 1936, when the area was surveyed.

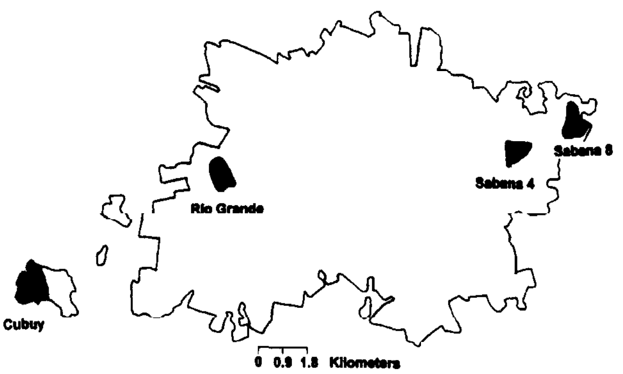

Figure 2-Locations of the four study areas within the Caribbean National Forest.

DATA COLLECTION

In 1991, a little over a year after the storm, a systematic sampling design of plots was established in each of the four study areas. Cubuy had 116 plots, Rio Grande had 104 plots, Sabana 4 had 106 plots, and Sabana 8 had 108 plots. Each plot consisted of two areas (fig. 3). The inner area (area A) was a 1/10-acre circular subplot with a radius of 11.35 meters. All trees with a d.b.h. > 9.1 centimeters were measurement trees. The outer area (area B) was a 1/5-acre circular subplot with a radius of 16.05 meters. All trees with a d.b.h. >= 24.2 centimeters were measurement trees. Each measurement tree was visually rated for damage type as: (1) none, (2) loss of small branches, (3) loss of large branches, (4) trunk snapped (50 percent or more of tree trunk down), and (5) uprooted. Tree variables taken were crown class (dominanat, codominant, intermediate, suppressed), ground slope (percentage from horizontal), d.b.h., and topography (convex, bottom, terrace, ridge, slope, concave). Overall plot topography was recorded as ridge, slope, upland valley, or riparian valley.

ANALYSIS AND RESULTS

There were 3 types of analyses performed: (1) descriptive (charts and graphs), (2) two-way contingency tables (chi-square tests) of damage type versus tree and plot variables, and (3) discriminant analysis whereby we tried to correctly assign trees into their damage class based on tree and plot variables. All sample trees were weighted to express their contribution on a per-hectare basis for the entire sample area. Thus, if d.b.h. < 24.2 centimeters then plot area = π (11.35 meters)* = 404.71 square meters or .0405 hectares. So each of these trees was weighted by 1/.0405/n or 24.71/n, where n=number of plots. For trees with d.b.h. $\geq$ 24.2 centimeters plot area = π (16.05 meters)^2 = 809.28 square meters or .0809 hectares. So each of these trees was weighted by 1/.0809/n or 12.36/n.

Descriptive Analyses

The two areas closest to the hurricane track, not surprisingly, suffered the greatest amount of damage. The

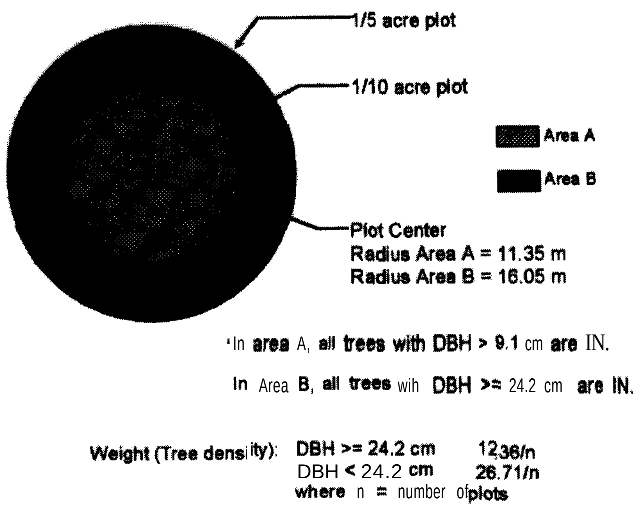

Figure 3-Plot layout in the hurricane tree damage study, Caribbean National Forest.

Cabana 8 study area had 86.35 percent of the trees sustain damage. The breakdown by damage type is: None-l 3.65 percent, loss of small branches-32.4 percent, loss of large branches-29.62 percent, trunk snap-8.87 percent, and uprooted-15.47 percent (fig. 4). For Sabana 4, 79.37 percent of the trees sustained damage. The breakdown by damage type is: None-20.63 percent, loss of small branches-23.92 percent, loss of large branches-27.61 percent, trunk snap-7.88 percent, and uprooted-19.96 percent (fig. 4). For Rio Grande, 61.06 percent of the trees sustained damage. The breakdown by damage type is: None-38.94 percent, loss of small branches-34.95 percent, loss of large branches—19.68 percent, trunk snap-2.26 percent, and uprooted—4.17 percent (fig. 4). The least hit area, Cubuy, had 50.6 percent of the trees sustain damage. The breakdown by damage type is: None49.4 percent, loss of small branches-31.81 percent, loss of large branches-l 2.83 percent, trunk snap-3.09 percent, and uprooted-2.87 percent (fig. 4).

In figure 5 we see a breakdown of damage type by diameter class for Sabana 8. All trees larger than the 37.5 centimeter d.b.h. class were damaged. Ten percent or more of the trees in all size classes (except 72.5 centimeters) were uprooted. A large proportion of the trees in all size classes, especially the two largest, suffered loss of large branches. In figure 6 we see results for Sabana 4. Nearly all trees above the 17.5 centimeter class were damaged. Similar to Sabana 8, 10 to 15 percent or more of the trees in each size class were uprooted. It appears in areas heavily impacted by the hurricane, there is a somewhat uniform distribution of uprooting across all diameters of trees. The same seems to be true for trunk-snapped trees. There seems to be a fairly uniform 5- to 10-percent proportion across all diameter classes in Sabana 4 and Sabana 8. In Rio Grande, an area about 10 kilometers west of Sabana 4 (fig. 2), we still see uprooting and trunk snapping basically across all d.b.h. classes, but the percentage of trees in these classes has dropped off to about 5 percent for uprooting and about 2 to 3 percent for trunk snap (fig. 7). Though Cubuy, an area about 8 kilometers southwest of Rio Grande, was the least hit area, still a significant proportion (50 percent) of the trees sustained damage. In figure 8 we see many of the smaller trees have escaped being damaged. There appears to be a reverse J shape to the no damage class. In the two largest d.b.h. classes every tree was damaged. The three largest d.b.h. classes had no uprooting and the five largest d.b.h. classes had no trunk-snapped trees. In the remaining d.b.h. classes there still appears to be a reasonably uniform distribution of uprooted and trunk-snapped trees.

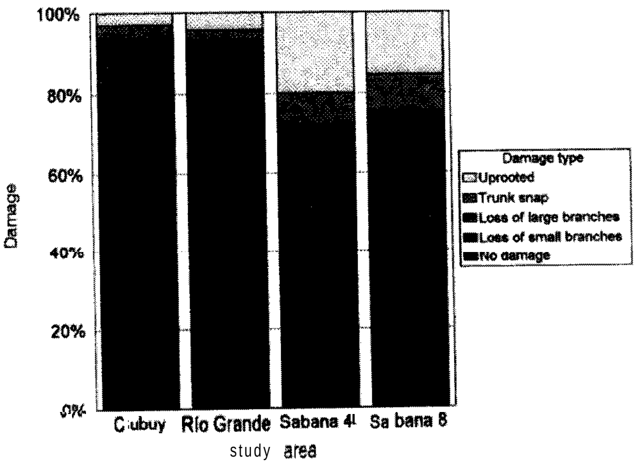

Figure 4-Five damage type classes and their tree damage percent for each study area.

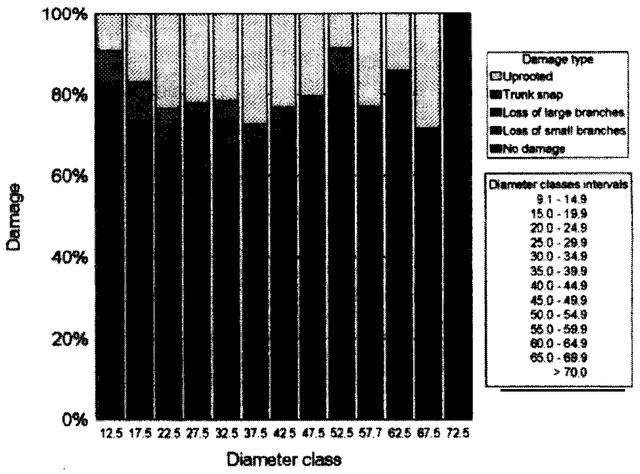

Figure 5-Diameter classes (in centimeters) and percent of damage type for all trees in Sabana 8.

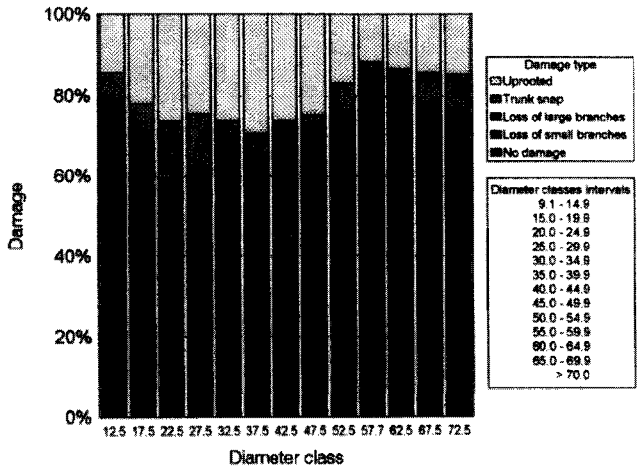

Figure 6-Diameter classes (in centimeters) and percent of damage type for all trees in Sabana 4.

Contingency Table Analyses and Correlations

We constructed two-way tables of damage type against crown class, d.b.h. class, tree topography, slope class (eight degree classes, i.e., 0 to 8, 9 to 16, etc.), and plot topography. Chi-square tests and Spearman correlations were computed. The outcomes are listed in table 1. The general results are that proportions in each damage type

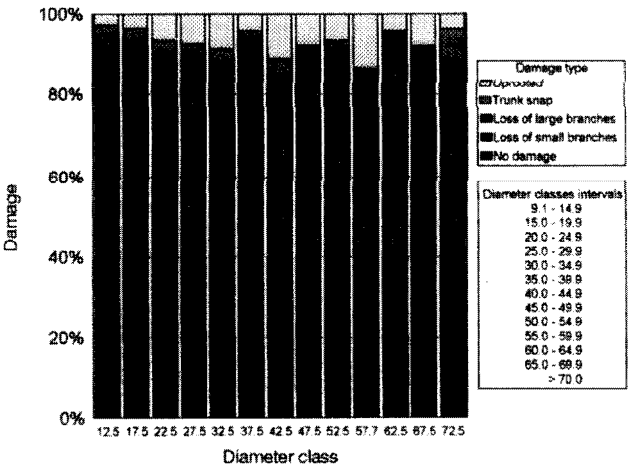

Figure 7-Diameter classes (in centimeters) and percent of damage type for all trees in Rio Grande.

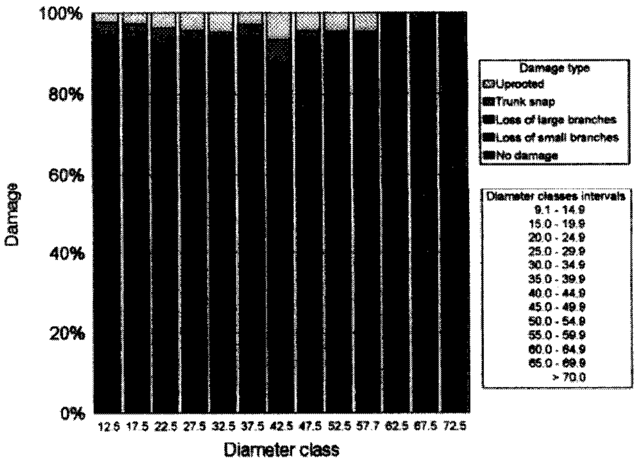

Figure 8-Diameter classes (in centimeters) and percent of damage type for all trees in Cubuy.

are not the same among crown class and d.b.h. class. Chi-square tests were not significant with tree topography, slope class, and plot topography. There appears to be moderate correlation in some of the data, that is, with crown class and d.b.h. class, and low correlation in the rest of the data.

Discriminant Analyses

A discriminant procedure computes various discriminant functions for classifying observations into two or more groups on the basis of one or more quantitative variables. The idea behind discriminant analysis is to see if you can correctly place an individual into its proper group based on certain measurable characteristics of the individual. If you can correctly place most individuals into their respective groups, then you should be able to place future individuals into their proper groups based on the same characteristics, with a known error rate. Based on the contingency table analyses, it is reasonable to conclude that d.b.h. and crown class are good candidate variables for the discriminant analyses, because they have differing patterns across the damage types and there is a moderate degree of correlation between these variables and damage type. In addition, to bring in the effect of species differences, we computed the importance value (IV) for each species for use in the discriminant analyses. The IV is computed as:

$$IV = (Rel\ BA + Rel\ DEN + Rel\ FRQ)/3$$

where

Rel BA is relative basal area (species BA/total BA x 100),

Rel DEN is relative density (number of trees for species/total number of trees x 100), and

Rel FRQ is relative frequency (number of plots where species occurs/total number of plots x 100).

For the discriminant analyses we reassigned the damage types into three classes. For the two hardest hit areas, Sabana 4 and Sabana 8, we had: (1) none + loss of small branches, (2) loss of large branches, and (3) trunk snapped + uprooted. For Cubuy and Rio Grande we had: (1) none, (2) loss of small branches, and (3) loss of large branches + trunk snapped + uprooted. Table 2 gives the error rate by damage class and the overall error rate for each of the four study areas. As is obvious from table 2, there was a high

Table I--Results of two-way contingency table analyses and correlation analyses of damage type against other variables

Location	Variable[a]	X^2 [b]	P-value	Spearman r
Sabana 8	Crown class	234.1	.001	.226
	D.b.h. class	69.8	.022	.252
	Tree topo	25.7	.175	-.043
	Slope class	—	—	—
	Plot topo	10.3	.592	.020
Sabana 4	Crown class	208.7	.001	.173
	D.b.h. class	129.0	.001	.332
	Tree topo	16.8	.669	.004
	Slope class	4.0	.999	-.021
	Plot topo	9.1	.691	-.058
Rio Grande	Crown class	155.2	.001	-.217
	D.b.h. class	158.4	.001	.321
	Tree topo	14.1	.823	.081
	Slope class	7.0	.997	-.011
	Plot topo	13.8	.314	-.011
Cubuy	Crown class	202.4	.001	.073
	D.b.h. class	73.4	.011	.216
	Tree topo	7.5	.995	.020
	Slope class	15.5	.745	.028
	Plot topo	7.5	.822	.013

[a] Topo = topography.
[b] Degrees of freedom: crown class-12, d.b.h. class-48, tree topography-20, slope class-20, plot topography-12.

Table 2—Discriminant analysis error classification summaries for the four study areas in the Caribbean National Forest

Location	Class error rate[a]			Overall error rate
	1	2	3	
	Percent			
Sabana 8	12.8	16.8	14.1	43.7
Sabana 4	14.1	15.3	9.7	39.1
Rio Grande	14.8	16.1	12.4	43.3
Cubuy	6.4	27.2	14.2	47.8

[a] Class 1 represents trees with none to slight damage, class 2 represents tree with moderate damage, and class 3 represents trees with severe damage.

rate of error in correctly classifying trees into their proper damage class. Still, about 57 percent of the time we were able to place an individual tree into its correct class out of the three damage classes defined for the analyses.

DISCUSSION

Several trends are readily apparent. As Francis and Gillespie (1993) observed, if you are a large tree you will sustain damage. In areas close to the hurricane track (Sabana 4 and 8), which experienced heavy gusts, winds were such that all trees experienced some damage, save a few of the very smallest. In areas farther from the hurricane track (Rio Grande and Cubuy), the greater the d.b.h. the greater the probability of being damaged. It was interesting to discover a somewhat uniform distribution of trunk-snapped and uprooted trees over diameter class at each site. Why this is probably relates to the gross tree and plot factors affecting the type and amount of wind damage sustained by trees. These factors were expounded by Mitchell (1995) and Ruel (1995) and reviewed in the section on **WIND RESEARCH.**

Not all trees are created equal with respect to hurricane resistance. The main adaptation to survival in hurricanes is quick reduction of wind resistance through defoliation. As examples, let us consider balsa (*Ochroma lagopus*) and yagrumo (*Cecropia schreberiana*). Both species have relatively weak wood, but quickly lost all of their few, large leaves, and consequently experienced very little damage. Large, strong trees of the forest like *Buchenavia tetraphyla* and tabonuco (*Dacroydes excelsa*), suffered extensive branch breakage because they have large spreading crowns which do not readily defoliate.

The forests of Puerto Rico have amazing resiliency. Many species, like *Shefflera morototonii*, readily sprout new branches. Gaps created by uprooted and trunk-snapped trees fill in quickly. Damage can be highly variable and is determined by many interacting factors such as species characteristics, soil properties, stand structure, and topography. Trying to predict individual tree outcomes at each area with discriminant functions was only moderately successful. Still, it gives us a tool for assessing potential damage and mortality from future storms.

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PREDICTING THE MOVEMENT OF IMIDACLOPRID IN A COASTAL PLAIN SETTING USING VSPDT

Bryan K. Burkingstock, Parshall B. Bush, Yvette C. Berisford, John F. Dowd, James B. Feild, West W. Johnson, Todd C. Rasmussen, and John W. Taylor'

Abstract-Imidacloprid has been shown to control pine tip moths (*Rhyacionia* spp.) in loblolly pine seedlings (*Pinus taeda* L.). Field data for an imidacloprid dissipation study were used to calibrate the computer model VSPDT (Variably Saturated 2-Dimensional Transport). VS2DT uses a finite-difference approximation of the advection-dispersion equation to simulate contaminant transport through variably saturated porous media. The site was simulated in a vertical cross section (X-Z plane) of a treated watershed from the soil surface to the water table (approximately 60 ft) spanning 260 ft horizontally. The cross section was centered on an ephemeral stream which drains the watershed, but for symmetry reasons, only half (130 ft horizontal distance) of the cross section was modeled. Modeling results showed that imidacloprid moved more rapidly through sandy soils than sandy clay loam soil material. No imidacloprid concentrations above the detection limit of 0.6 ppb were predicted in groundwater or in lysimeters in the unsaturated zone through 6 months post-application.

INTRODUCTION

Infestation by pine tip moths (*Rhyacionia* spp.) is one of the limiting factors in early growth and development of pine stands in the Southeastern United States. Imidacloprid (1-[(6-chloro-3-pyridinyl)-methyl]-4,5-dihydro-*N*-nitro-1H-imidazol-e-amine) is a systemic insecticide which has shown efficacy in controlling sucking insects, some beetles, and leafminers on various crops. Applied in a Florida field study, imidacloprid controlled tip moths on loblolly pine seedlings (*Pinus taeda* L.) for 1 to 3 years.'

An imidacloprid soil dissipation study was initiated in January, 1996 on a coastal plain site near Downs, GA. Imidacloprid residues in runoff-water, soil solution, and groundwater were monitored after significant rainfall events. These residue data were used to assess the VS2DT hydrologic model.

The fate and transport of pesticides depend, in part, on the flow path within the soil. There are three major flow paths: overland flow, subsurface lateral flow, and vertical percolation through the unsaturated zone to the water table. Overland flow rarely occurs within forested watersheds. Solute transport through the subsurface is controlled by various mechanisms including advective transport (Solutes move with the flowing water.), hydrodynamic dispersion (variability of fluid velocity causes a spreading of solutes toward the average direction of water flow.), and solute sorption. Solute transport is also dependent on the soil structure because interconnected macropores induce preferential flow paths which accelerate the movement of solutes.

Computer models were developed to simulate the fate of pesticides because environmental fate studies are expensive and time consuming. Hydrologic computer models for water and solute movement within variably saturated porous media are useful tools for gaining insight into processes that occur within the unsaturated zone. A hydrologic environmental model, VS2DT (Variably Saturated 2-Dimensional Transport) was developed by the U.S. Geological Survey. This model uses a finite-difference approximation to the advection-dispersion equation to simulate water movement through variably saturated porous media. VS2DT can simulate problems in one-dimensional columns, two-dimensional vertical cross sections (X-Z plane), or three-dimensional, axially symmetric cylinders (Healy 1990, Healy and others 1993). Boundary conditions used for flow include fixed pressure heads, infiltration with ponding, evaporation from the soil surface, plant transpiration, or seepage faces.

OBJECTIVES

The objectives of this study were to:

(1) Evaluate VS2DT's simulation of imidacloprid movement in a coastal plain watershed by comparing field data to the predicted values from VS2DT.

(2) Determine VS2DT limitations in predicting pesticide movement.

MATERIALS AND METHODS

Study Site

The imidacloprid study area is located in the Georgia Coastal Plain near the town of Downs, GA, in Washington County, approximately 90 miles south of Athens, GA. Historically, the area was a natural forest and pesticides have not been applied to the study area for at least 40 years. The imidacloprid site is surrounded by mature, mixed hardwood and loblolly pine forests. A stream borders the site on the southwestern side. The stream flows from

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the northwest to the southeast and has a width of approximately 15 ft and depth of 2 to 4 ft. An ephemeral stream forms and drains the bottom of the watershed during large rainfall events. Within this study area, a 5.4-acre watershed was chosen to monitor the movement of imidacloprid.

The soil is predominately Orangeburg series with small areas of Ochlocknee series in the draws. Coastal plain soils of the Orangeburg series are generally well drained, permeable soils of sedimentary origin. The upland flats are characterized by three distinct soil layers based on split spoon samples taken during well installation onsite. The upper layer is an approximate 3- to 4-ft sand to loamy sand. The middle layer is clay-enriched and consists of red, dense, sandy clay to sandy clay loam that is approximately 15 to 17 ft thick. Visual observations of a nearby road cut showed rainfall-related saturation on top of the sandy clay loam layer. The final layer extends from the bottom of the red clay-enriched layer to the water table and has the same characteristics as the first horizon with a distinct bedding of sand. The watershed was created by massive erosion that exposed the red clay-enriched layer at certain areas within the site. Three-dimensional pictures of the red layer within the watershed were constructed using observations taken during the installation of lysimeters. The Clay layers slope toward the center of the watershed and have erosional features hidden by overlying sand. These irregularities could aid in concentrating the insecticide within the site.

Site Preparation

Trees onsite were harvested during August 1994. Site and regeneration activities included spot raking (June 2, 1995), chopping using a drum roller (June 30, 1995), burning (July 14, 1995) and harrowing (September 12, 1995). On November 7, 1995, loblolly pine seedlings were planted with a mechanical planter along the contour of the watershed in a 6 ft- by 12 ft-spacing (600 trees/acre).

Instrumentation of the Treated Watershed

The watershed was instrumented with the following (fig. 1):

(1) a weather station equipped with a pyranometer, ananemometer, weather vane, relative humidity gauge, internal and external temperature gauges, barometer, tipping rain gauge, standard rain gauge, and an evaporation pan;

(2) 42 porous cup lysimeters for sampling soil water in the unsaturated zone;

(3) five 2-in diameter PVC wells for monitoring and sampling groundwater; and

(4) a 1.5-ft H-flume equipped with an FW-1 stage-height recorder for determining runoff volume and duration.

Pesticide Application

On February 26, 1996, approximately 1 gram of active ingredient imidacloprid was applied in a dibble hole at a point that was approximately 4 in deep and 4 to 6 in from the base of each pine seedling. As part of the vegetation management program for the pine plantation, herbicides were applied on April 1, 1996 (hexazinone and sulfometuron methyl) and September 24, 1996 (imazapyr).

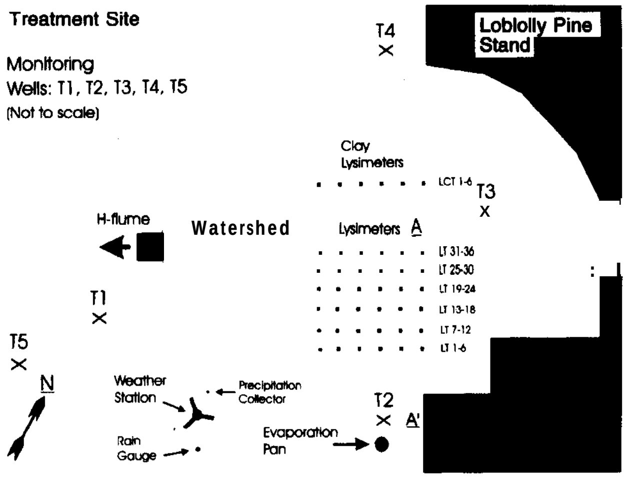

Figure 1-X-Y view of the treated watershed and the position of the monitoring devices.

FIELD DATA

Field data collection began prior to the imidacloprid application and will continue through 3 years post-application. Rainfall input-runoff ratios were calculated from rainfall data and data from surface flow duration and runoff volume through H-flumes that were measured from March 1996 through September 1996. These data showed that an average of 3 percent of the total rainfall volume on the watershed flows through the H-flumes. Based on these results, the major pathway that imidacloprid travels is through the vadose zone to the water table. This assumes that the insecticide does not biodegrade, adsorb strongly to organic matter or clay, or is totally absorbed systemically by vegetation.

Lysimeters and monitoring wells were used to collect water as it traveled through the unsaturated zone to the water table. Water in the lysimeters accounted for horizontal movement and preferential flow paths above the clay-enriched layer. Thirty-six lysimeters were installed approximately 24 ft apart in a 6 x 6 array in the treatment watershed. Water samples were collected from lysimeters after each significant rainfall event (>0.5 in rainfall) and analyzed for imidacloprid residues. The five monitoring wells were sampled monthly to detect groundwater contamination. Imidacloprid was not detected (method detection limit of 0.6 ppb) in groundwater.

CONCENTRATION CALCULATIONS

Imidacloprid concentrations in the application scoop (71 cm^3) and in the top 15 cm of soil (304 cm^3) were calculated to calibrate the model output. The total concentration in the soil is the aqueous phase concentration plus the concentration adsorbed to the soil. The imidacloprid concentration (active ingredient) in the formulation material is 25,000 ppm. The theoretical concentration in the top 15-

cm soil core is 1,890 ppm (assuming the whole application area is sampled). The initial total imidacloprid concentration in the 0 to15 cm range from the model should be consistent with the value calculated for the total concentration in a 15-cm core.

MODEL DESCRIPTION

VS2DT was used to simulate the movement of imidacloprid in the treated watershed. This model is governed by the advection-dispersion and conservation of mass equations. The values for the model are approximated by a two-dimensional, block-centered, finite-difference scheme.

VS2DT utilizes rainfall events to introduce water into the problem. Rainfall events are considered recharge events, and the times between them are considered evaporation events. Data from a tipping-bucket rain gauge were used to calculate the duration and intensity of the precipitation periods. The concentrations of imidacloprid during the rainfall events were introduced into the model.

VS2DT uses aqueous phase concentrations. In this study, only the initial total application concentration was known. The initial aqueous phase concentration was adjusted to meet the calculated initial total concentration in a 15-cm core. Site specific parameters such as meteorological data, soil parameters, and imidacloprid characteristics were used in the model. VS2DT simulated 191 days using meteorological data from the treated watershed starting on February 19, 1996 and ending on August 28, 1996.

As with any model, VS2DT has problems which must be considered:

(1) Aqueous phase concentrations are used as inputs for the model.

(2) The evaporation boundary condition is treated differently from other boundaries where water leaves the domain; evaporating water is assumed to be solute free (no solute leaves the domain through evaporation.). Therefore, evaporation nodes may become concentrated as evaporation proceeds (Healy 1990).

(3) VS2DT does not account for losses due to uptake by plants (transpiration).

(4) Preferential flow can not be simulated in VS2DT. Systems which exhibit preferential flow characteristics can not be accurately modeled.

(5) VS2DT can only use a domain (grid) which has ≤ 36,000 nodes.

(6) VS2DT assumes homogeneous and isotropic conditions within the defined soil textures.

(7) Large nodal models with small discretization require fast computers with ample hard drive space and a great deal of memory.

Two conceptual models of different scales were used to simulate flow through the vadose zone. VS2DT has a tilt factor built into the code (Healy 1990). At the top of the grid, the left side is A, while the right side is A'. When the tilt is used, A' is raised to create a downward slope from A' to A (A is the pivot point). Models 1 and 2 have a 6 percent tilt.

Model 1

Model 1 was used to simulate the movement of imidacloprid from a single imidacloprid application through the top 15 cm and down to a single lysimeter (fig. 2). This model is a fragment of Model 2 and used a finer grid (112 rows by 132 columns). The rows had a vertical height of 1 cm and the columns were 2.54 cm wide. The total height was 122 cm (4 ft) and the total horizontal distance was 335.3 cm (11 ft). Only two soil textures were used: loamy sand and sandy clay loam.

The imidacloprid aqueous concentration inputs occurred in three nodes representing a total volume of 45.7 cm^3 (6 cm x 7.62 cm x 1 cm). The observation nodes in Model 1 were used to record the initial concentrations in order to compare these results with the calculated values, and the lysimeter nodes were compared with the field data. To calibrate the model, the concentration of the observation nodes in the top 15 cm will be averaged and compared to the calculated total concentration in the upper 15 cm.

Model 2

Model 2 was used to simulate the movement of imidacloprid from the ground surface to the water table (fig. 2). The nodal grid used in the model was 220 rows by 132 columns. The nodes for the first 111 rows had a vertical height of 1 cm. The next 68 rows had a vertical height of 7.62 cm (3 in), and the remaining 40 rows had a vertical height of 30.48 cm (1 ft). Horizontally, the 132 columns had a length of 30.48 cm (1 ft) per block. The total vertical distance was 60 ft to the water table and the total horizontal distance was 132 ft.

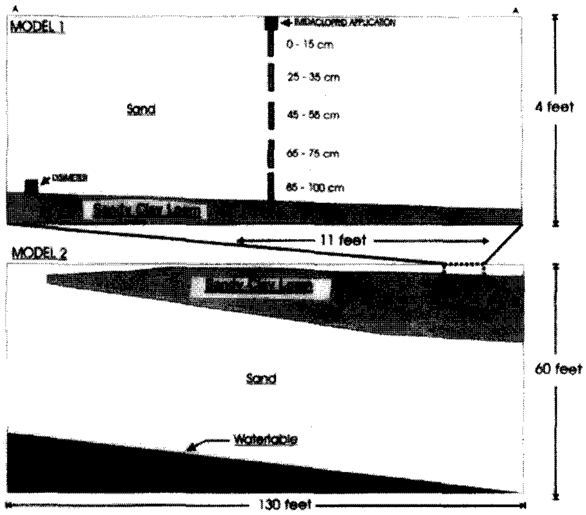

Figure 2-Conceptual Models 1 and 2 used in VS2DT to simulate the movement of imidacloprid in a coastal plain setting. Both models are tilted 6 percent in VS2DT (A is raised 6 degrees.).

Three soil layers simulated were: loamy sand, sandy clay loam, and sand. At A', the loamy sand is 4 ft thick, the sandy clay loam layer is 17 ft thick, and the sand is 40 ft thick. At A, the loamy sand is 4 ft thick, and the sand is 57 ft thick.

Eight observation nodes were used to track the concentration of imidacloprid over time. The nodes were positioned in two columns: nodes consisting of all sand and nodes of sand-clay-sand down to the water table. This strategy allowed the comparison of how imidacloprid behaves in the sand and in the sandy clay loam layers. The nodes closest to the water table for each column were used to estimate the concentration entering the groundwater.

Model 1 and 2 Correlation

Model 1 was used to calibrate the predictions of VS2DT to the field data (both groundwater and lysimeter data) and the top 15-cm calculation. Once they agreed, Model 2 was run using the same parameters as Model 1. However, Model 2 had an initial concentration six times higher than Model 1 due to the difference in height of the application nodes.

VS2DT RESULTS

Calibration with Calculated Concentration

To accurately predict the movement of imidacloprid through the two models, the models must be calibrated to the calculated total concentration. The concentration that both models predicted was 2020 ppm in the top 15 cm. This value is consistent with the range from the calculations. After these calculations were verified for both models, the simulation was run for 191 days (approximately 6 months), and the observation points at the lysimeter, water table, and various points between were analyzed.

Lysimeters

The lysimeter concentrations predicted by VS2DT were below the detection limit (c 0.6 ppb). Based on these predictions, no imidacloprid reaches the lysimeters, and the concentration by day 191 averaged 10^{-28} ppb.

In the field, however, lysimeter row LT1 3-18 was the only row of lysimeters to show measurable concentrations of imidacloprid. The lysimeters in this row are located in a distinctively different area from the other lysimeters. Lysimeters LT13-18 are positioned between large remnant stumps with extensive root systems which could cause preferential flow and aid in the movement of solutes. The inputs for VS2DT do not account for this type of movement.

Discounting the model's predictions for row LT13-18, due to its inability to account for preferential flow, the model fits the field data by predicting that levels of imidacloprid in the lysimeters are far below detection limits.

Movement in a Sand Column versus Sand-Clay-Sand Column

tmidacloprid moved more quickly through the sand column than the sand-clay-sand (S-C-S) column. Detectable concentrations were predicted down to 220 cm (7.2 ft) in the sand column on the 191st day, but concentrations were below detection limits below that point. The S-C-S column shows that the concentration of the solute was severely retarded by the clay-enriched layer. Measurable concentrations were predicted within the upper 7.2 ft, but the nodes within the clay-enriched layer and below showed concentrations far below detection limits. The solute traveled approximately twice as fast and as far vertically in the sand column as in the S-C-S column.

Groundwater

The nodes at a depth of 57.1 ft (just above the water table) for both the sand and S-C-S columns, showed concentrations of imidacloprid below detection limits. This prediction agreed with the field data that showed that concentrations of imidacloprid in the groundwater were below detection limits.

CONCLUSIONS

Infiltration is the main agent of transport for imidacloprid. During rainfall events, imidacloprid desorbs from the application clay and increases the aqueous concentration in the soil-pore water. This relationship depends on the soil water content and amount of rainfall.

After rainfall events, evaporation dominates and the upper soil horizon dries. The aqueous concentration within the loamy sand nodes decreases during this period as the imidacloprid adsorbs to the soil.

Imidacloprid transport is different within the loamy sand and sandy clay loam layers. The insecticide travels more slowly through the clay-enriched layer than in the sandy layers. Computer simulations predicted that imidacloprid will not reach the water table or lysimeters within 191 days following application.

ACKNOWLEDGMENT

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INITIAL INVESTIGATION OF HEIGHT-DIAMETER RELATIONSHIPS OF DOMINANT TREES IN THE MIXED HARDWOOD BOTTOMLAND FORESTS OF EAST TEXAS

Brian P. Oswald, Gordon Holley, Leslie Dale, and Gary D. Kronrad[1]

Abstract-Three to five dominant trees from each of 445 ten-factor variable radius inventory points were utilized to evaluate the height- diameter relationships of 13 species or genera found on bottomland hardwood sites throughout east Texas. Regression analysis was performed using the linear model such that height $= \beta_0 + \beta_1$ x (d.b.h.). The species were placed into six groups: (1) pines (*Pinus taeda* and *P. enchinata*); (2) water oak/willow oak/white oak/swamp chestnut oak (*Quercus nigra*)/(*Q. phellos*)/(*Q. alba*)/(*Q. michauxii*); (3) blackgum/laurel oak/overcup oak (*Nyssa sylvatica*)/(*Q. laurifolia*)/(*Q. lyrata*); (4) ash/maple (*Fraxinus* spp.)/(*Acer* spp.); (5) hickories (*Carya* spp.), and (6) elms (*Ulmus* spp.), or were analyzed as individual species: (7) cherrybark oak (Q. *pagoda)* and (8) sweetgum (*Liquidambar styraciflua*) based on similar intercepts and slopes of the regression lines. The coefficients of the model were estimated and residual analysis conducted for each species group.

INTRODUCTION

There are about 180 million acres of commercial forest land in the Southern United States, 50 percent of which can be classified as being composed of hardwoods. Bottomland hardwood forests, growing on the flood plains of rivers and streams, comprise 14 percent (1.6 million acres) of the total commercial forest land in east Texas. These forests provide quality timber along with wildlife habitat. In east Texas, the area classified as bottomland hardwood has decreased by about 12 percent in the last 15 years, due primarily to the logging of accessible mature stands, shifts to croplands, and the development of man-made lakes (McWilliams and Lord 1988).

The demand for hardwood products, both within the United States and for export, is increasing (McWilliams 1988, Hair 1980). The pulp and paper industry is utilizing more hardwoods in an effort to increase the quality of their product. In addition, the demand for high-quality logs for lumber, plywood, and veneer is increasing. Since 1975, the world demand for US. hardwood logs, veneer, and lumber has quadrupled (Araman 1989). Hardwood harvesting rates are increasing while the supply is decreasing (Tansey 1988, Birdsey 1983).

Adequate information on bottomland hardwood growth and management has not kept pace with the knowledge we have on southern pines. (Porterfied 1972). Most of the research performed on bottomland hardwoods in the South to determine growth and yield information and management strategies of these species (Barrett 1995, Burns and Honkala 1990, Baker and Broadfoot 1979) often did not involve stands located in east Texas. The best management practices for the species found in these ecosystems in east Texas have not been determined, and growth equations, volume and yield tables, and site index curves for many southern hardwood species are lacking. This information gap is of such high priority to the National Hardwood Lumber Association, that resolution of this gap is one of their priorities for 1996. Since many of these questions can not be resolved in a single year, there will be a priority over the next decade to obtain the necessary information from which proper management decisions can be made.

There is a need to obtain information on what species are found in the bottomlands of east Texas as well as the stand structure of these bottomlands. Basic height and diameter relationship information on the dominant trees in these stands will provide some of this information. The objective of this study was to evaluate the dominant tree height-diameter relationships of the major species in the mixed bottomland hardwood forests of east Texas.

METHODS

The study areas were chosen to represent bottomland hardwood stands common to the region and data was collected from numerous sites within Angelina, Nacogdoches, Newton, Sabine, San Augustine, and Shelby Counties in the summers of 1993, 1994, and 1995. Sample points were systematically located within the study areas. Distance between points was three chains, and distance between transect lines was five chains. Initially the tallest five trees sampled with a lo-factor prism were utilized in this study, and the species, total height (to nearest foot) breast height (d.b.h. to nearest tenth of a foot) were recorded for each of these sampled trees. Species included cherrybark oak (Quercus pagoda), willow oak (Q. *phellos*), water oak (Q. *nigra*), laurel oak (Q. *laurifolia*), white oak (*Q. alba*), overcup oak (*Q. lyrata*), swamp chestnut oak (Q. *michauxii*), sweetgum (*Liquidambar styraciflua*), blackgum (*Nyssa sylvatica*), and pines (*Pinus taeda* and *P. enchinata*). A variety of hickories (*Carya* spp.), elms (*Ulmus* spp.), ash (*Fraxinus* spp.), and maples (*Acer* spp.) were also recorded. Additional species were initially included in the sample, but since they each totaled less than 10 individuals across all of the sample points, they were excluded from the analysis.

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Statistical analysis followed Oswald and others (1994). Preliminary analysis indicated that the relationship between tree height and d.b.h. of the dominant trees was linear. Therefore, the following equation was used for each of the above species:

$$\text{Height} = \beta_o + \beta_1 \times (\text{d.b.h.}). \qquad (1)$$

Based on the similarity of the intercepts and slopes of the regression lines for each species, some of the species were placed into species groups. The equation (1) was then fitted to each species group. Otherwise, the species were evaluated individually. Residual analysis was also conducted for each model.

RESULTS AND DISCUSSION

Among the 2,165 dominant trees sampled, 73.7 percent were oaks (*Q.* spp.) with willow oak (26.1 percent), cherrybark oak (15.5 percent), and water oak (14.0 percent) being the dominant species (table 1). Only sweetgum (15.2 percent) approached these oaks in frequency. The tallest species tended to be cherrybark, white, willow and water oaks, while those with the largest d.b.h. were swamp chestnut oak and cherrybark oak. As is usually found on these sites, the maples, ash, and blackgum had the smallest mean diameters, while maple was the shortest in mean height.

The equation (1) was fitted to each species with more than 10 individuals over all of the plots. Based on similarity of the intercepts and slopes of the regression lines for each species, the species were placed into six species groups : Pines, water oak/willow oak/white oak/swamp chestnut , blackgum/laurel oak/overcup oak, ash/maple, hickories, and elms, or were analyzed as individual species: cherrybark oak and sweetgum. Then the equation (1) was refitted to the groups and the resulting models obtained:

(1) Ash/maple: HT = 54.40 + 1.82(d.b.h.) with N = 42, R^2 = 0.39, and C.V. = 18.1 percent
(2) Blackgum/laurel oak/overcup oak: HT = 63.05 + 1.30(d.b.h.) with N = 327, R^2 = 0.35, and C.V. = 13.7 percent
(3) White oak/swamp chestnut oak/willow oak/water oak: HT = 76.27 + 1.10(d.b.h.) with N = 990, R^2 = 0.26, and C.V. = 12.1 percent
(4) Cherrybark oak: HT = 82.59 + 1.08(d.b.h.) with N = 334 , R^2 = 0.26, and C.V. = 13.7 percent
(5) Pine spp: HT = 67.46 + 1.45(d.b.h.) with N = 81, R^2 = 0.39, and C.V. = 9.7 percent
(6) Sweetgum: HT = 60.02 + 1.95(d.b.h.) with N = 328, R^2 = 0.47, and C.V. = 12.6 percent
(7) Hickory spp.: HT = 69.87 + 1.23(d.b.h.) with N = 43, R^2 = 0.16, and C.V. = 16.5 percent
(8) Elm: HT = 19.50 + 3.07(d.b.h.) with N = 12, R^2 = 0.57, and C.V. = 18.9 percent

Equation (1) was also fitted to the total number of trees (2,165) to provide an overall equation for the relationship between height and diameter of all of the dominant trees:

HT = 69.78 + 1.36(d.b.h.) with R^2 = 0.33, and C.V. = 13.67

Table I-Total number of trees, averages, and ranges of tree diameter and height of the dominant trees

Species	No. trees	Mean d.b.h.	Range	Mean height	Range
			Inches		*Feet*
Fraxinus spp.	33	18.9	7.1-35.4	92.9	45-150
Nyssa sylvatica	59	18.1	6.6-39.1	85.8	58-135
Ulmus spp.	13	20.7	11.8-28.3	83.2	45-125
Carya spp.	44	21.7	9.3-38.8	95.7	53-127
Pinus spp.	82	22.1	9.6-34.4	99.5	76-133
Acer spp.	10	18.8	12.4-26.7	75	55-92
Liquidambar styraciflua	329	19.7	4.0-40.2	98.6	16-141
Quercus pagoda	335	25.2	2.5-70.5	109.9	20-163
Q. lyrata	116	22.9	10.4-38.9	93.5	60-124
Q. michauxii	70	25.9	12.5-55.3	98.3	67-128
Q. nigra	303	22.4	7.7-43.4	101.4	46-153
Q. alba	52	22.4	10.9-37.3	101	70-130
Q. phellos	566	22.9	7.5-60.0	102	51-144
Q. laurifolia	153	19.8	4.8-48.6	88.7	58-136
Total	2165	21.6	2.5-70.5	94.7	20-163

Although the R^2's of the models appear low, the primary purpose of the study was to evaluate the relationship between height and diameter of the dominant trees, not for prediction. The simulations using the above models for the groups are illustrated in figure 1.

The dominant oak species (cherrybark, willow, and water) all have good-to-excellent growth rates, are intolerant to shade, and are intermediate to very intolerant to periodic flooding. Cherrybark is the best of the red oaks in the region, while water and willow oaks can be favored through management on the flats (Barrett 1995). The other highly frequent species, sweetgum, needs release for best growth and form, but shows medium growth rates when compared to the above oaks. Some of the other species found in this study, specifically the hickories and ashes, can be managed for, as they can provide good-quality products for a variety of uses when found on better sites. The two pine species will most likely become even less of a component of these stands with harvesting and succession. Even-aged management in the form of clearcuts or modified shelterwood (Loftis 1990), or with uneven management through group-selection, are common management tools used in other bottomland hardwoods in the South (Barrett 1995), and should be effective in producing a high-quality product while maintaining the stand structure found on these sites.

CONCLUSIONS

Stands similar to those utilized in this study are found throughout east Texas. Many of these stands have been mis-managed, poorly managed, or not managed for a number of years. These same stands had been high-graded in the past, and are now made up of a variety of species,

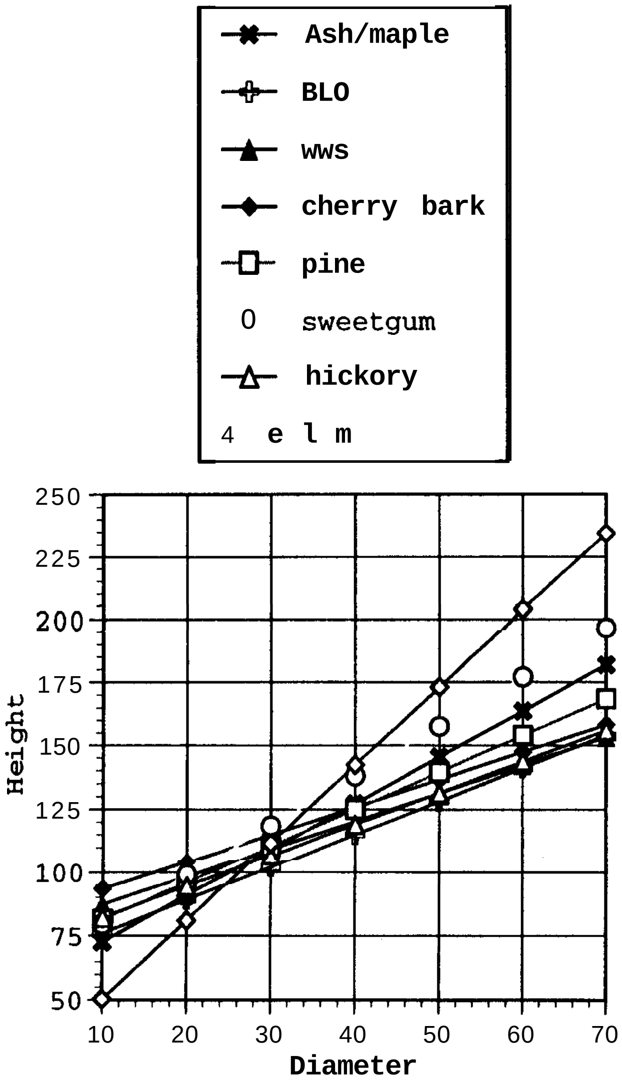

Figure l-Simulation models of eight species groups.

many of which do not have traditional market value. With the increase in demand for hardwood by the pulp and paper industry, these species-traditionally an impediment to harvesting, regeneration, and management-make these stands more attractive for management. As can be seen from this study, these stands can and do produce good individual stems of high-quality species such as cherrybark and some of the other oaks, as well as sweetgum and occasionally loblolly pine. More information is needed on stand structure, age/height/diameter relationships and site productivity before the necessary management guidelines can be developed.

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COMPARISON OF OPTICAL DENDROMETERS FOR PREDICTION OF STANDING TREE VOLUME

Robert C. Parker and Thomas G. Matney[1]

Abstract-Enhanced sets of compatible stem profile equations were used with data collected from felled and standing pine trees to calculate tree volumes to various top merchantability limits. Standing trees were measured with the Criterion 400 Laser, Tele-Relaskop, and Wheeler Penta prism. These measurements were used to compare accuracies of the optical dendrometers for the measurement of tree d.b.h. and height and the prediction of tree volume from stem profile equations. The Criterion 400 Laser was more accurate for d.b.h. and total height measurement than was the Tele-Relaskop or the Wheeler Penta prism. Mean percent differences in d.b.h. measurement translated, in absolute units, to -0.05, +0.20, and • 0.34 inches of the mean tree d.b.h. for the Criterion 400, Tele-Relaskop, and Wheeler Penta prism instruments, respectively. Mean percent differences in total height measurement translated, in absolute units, to 0.5, 1.6, and 1.7 ft, respectively, of the average tree height. The combined measurement data for d.b.h. and dob_{16}, indicated the Tele-Relaskop would produce more reliable volume results than the other instruments if the dendrometer measurements were used with form class volumes. Profile equations developed with felled-tree data produced the most consistent estimates of merchantable height and cubic foot volume to specified merchantable top limits. In general, the Criterion 400 produced the smallest mean differences in standing-tree measurements and profile equation predictions of merchantable height and cubic foot volume. However, the Tele-Relaskop produced the most consistent tree measurement and profile prediction trends. The Wheeler Penta prism was the least accurate of the three dendrometers.

INTRODUCTION

The prediction of standing tree volume has traditionally involved destructive measurement methods, but these methods cannot be used in fragile forest ecosystems. Recent developments in telescopic and laser dendrometer instruments make it feasible to obtain upper-stem measurements of standing trees in a nondestructive manner. However, the measurement accuracy and application technology of these instruments have not been evaluated.

The Tele-Relaskop (Bitterlich 1978) is a precision, telescopic dendrometer that has been used, in limited industrial and research applications, to develop taper and volume functions for standing trees (Parker 1996, Bitterlich 1984, Heske and Parker 1983, Parker 1983). Parker (1983, 1995) expanded the theoretical conoid concepts for tree volume computations proposed by Bitterlich with polynomial taper functions, developed application software for the microcomputer, and compared volume and taper applications with conventional inventory procedures.

Laser dendrometers and distance measuring instruments are being developed and some have been tested by the USDA Forest Service (Jasumback and Carr 1991). According to Carr (1992), laser technology of the Criterion model 400, manufactured by Laser Technology, Inc. (1992), has advanced to a point where accurate short- and long-range measurements are possible on nonreflective objects such as trees. In forestry applications, the Criterion 400 has been used for measuring tree heights and diameters, locating a specific height or diameter, selecting sample trees in variable plot inventories, measuring horizontal and slope distances, and determining coordinate azimuths and distances to defined targets (LaBau 1991, Liu and others 1995).

The Wheeler Penta prism (Wheeler 1962) has been used in forestry applications for obtaining upper stem diameters for many years. Although it does not have the telescopic optics of the Tele-Relaskop or sophisticated electronic circuitry of the Criterion 400, it can provide consistent estimates of upper stem diameters at heights determined by an attached clinometer.

Stem profile equations provide the most flexible methods of calculating tree volumes to specified merchantable top diameters from standing tree measurements. The technology of stem profile systems used by Burkhart (1977), Clutter (1980), Matney and Sullivan (1982), and Van Deusen and others (1982) did not allow the use of upper stem diameters. Newer technology has produced compatible sets of stem profile equations (Matney and Parker 1992) that allow the prediction of tree volume to user-defined top merchantability limits.

This paper compares d.b.h. and height measurements taken on standing trees with the Criterion 400 Laser, Tele-Relaskop, and Wheeler Penta prism with direct measurements after felling. It also compares predicted volumes and heights from an enhanced set of compatible stem profile equations using the optical measurements on standing trees and the direct measurements on felled trees.

DATA COLLECTION

One hundred sample trees (*Pinus taeda* L.) were selected from a stand on the John Starr Memorial Forest that had been previously thinned from below to remove intermediate and suppressed trees. The sample trees ranged in size from 5.7 to 24.2 inches in d.b.h. and 53 to 109 ft in height. On each sample tree, breast height (4.5 ft above average

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ground level) and the top of the first 16.04 log (16.5 ft, assuming a 0.5ft stump) were marked with a horizontal orange line and measured with a caliper.

Since operational inventories in fragile ecosystems would preclude the use of destructive measurement of felled trees (at 4.0-ft intervals) and would possibly be limited by time and/or economics, stem measurement data obtained with optical or laser dendrometers would most likely be taken at stem intervals exceeding 4.0 ft. Therefore, dendrometer measurements of stem diameter [outside bark (o.b.)] and height were taken at breast height, at the top of the first 16.0-ft log, at two intermediate points spaced approximately equal between the top of the first 16.0-ft log and an estimated 3.0 inch top (o.b.), at an estimated 3.0 inch top (o.b.), and at total tree height. These stem measurement locations correspond to the d.b.h., four intermediate, and total height points described by Parker (1995) in previous applications of the Tele-Relaskop.

Sample trees were felled with a 0.5-ft stump. Diameters (o.b.) and bark thickness measurements were taken at the stump, 3.0 ft (2.5 ft above stump height), breast height (4.0 ft above stump height), and 4.0-ft intervals along the stem to the terminal bud. Diameters were measured to the nearest 0.1 in. with a steel caliper, and two bark thicknesses were obtained (one under each caliper arm) with a bark gauge to the nearest 0.1 in. Total tree height was computed as the sum of the measurement intervals and the distance from the last diameter measurement to the tip.

DATA ANALYSIS

Although the primary objective of this study was to compare volume prediction accuracy of stem profile equations developed from optical dendrometer and felled-tree data, estimates of "point" measurement accuracy could be obtained for common measurements taken at breast height, 16.5 ft, and total height. The data sets were reduced to 96 trees because 4 trees in the felled-tree data set had at least one missing (inaccessible) measurement at or below breast height caused during the felling operation. Mean percent difference and standard error of the mean percent difference between the dendrometer measurements and felled-tree values were computed (table 1). The observed differences between felled-tree values and dendrometer measurements are expressed as a percentage of felled-tree value. Felled tree diameters at breast height and 16.5 ft were measured with a caliper in the same plane as viewed with the optical dendrometers.

To simulate measurement practices during operational forest inventories and to obtain sample tree volumes to variable top diameters, a compatible set of stem profile equations was developed to allow the prediction of outside- and inside-bark stem diameters at desired merchantability points from standing tree measurements of d.b.h. and total tree height. The profile prediction system models used in this study are enhanced versions of the nonsegmented, third-degree polynomial conditioned through the top (i.e. at $h_i=h_{total}$ or $X=h_i/h_{total}=1$, $dob_{hi}=0$) used by Parker (1983, 1996) and the fifth-order polynomial constrained through d.b.h. and the top merchantability limit (i.e., $dob_{hi}/d.b.h.=1$ when $h_i=4.5$ ft and dob_{hi} = merchantable top dob when $h_i=h_m$) used by Matney and Parker (1992).

Table 1 -Comparisons of optical dendrometers for diameter and height measurement of standing trees where is mean percent difference (observed difference as a percentage of felled-tree value) and is the standard error of the mean percentage difference (Basis: 96 trees)

Measurement		Criterion 400	Tele-Relaskop	Wheeler Penta prism
		Percent		
D.b.h.	a	-0.39	+1.41	-2.40
($\overline{dbh}$=14.1 in.)	$s_{\bar{d}}$	+0.53	+0.40	+0.57
Dob_{16}	a	+1.92	+1.54	-4.16
($\overline{dob}_{16}$=12.6 in.)	$s_{\bar{d}}$	+0.60	+0.66	+0.56
Total height	$\bar{d}$	+0.59	+1.68	+1.87
($\bar{H}_t$=92.8 ft)	$s_{\bar{d}}$	+0.45	+0.78	+0.33

The set of profile prediction system models applied to the felled and optical dendrometer tree data where b_i and b'_i are regression coefficients for outside and inside bark, respectively, are:

At stump height of 0.5 feet (i.e. h_i= 0.5 ft)

$$\frac{dob_{0.5}}{dbh_{ob}} = b_1\left(\frac{1}{dbh_{ob}}\right) + b_2 \qquad (1)$$

$$\frac{dib_{0.5}}{dbh_{ob}} = b'_1\left(\frac{1}{dbh_{ob}}\right) + b'_2$$

At d.b.h.: $d.b.h._{ob}$ to $d.b.h._{ib}$ conversions (i.e. h_i = 4.5 ft)

$$\frac{dbh_{ib}}{dbh_{ob}} = b_3\left(\frac{1}{dbh_{ob}}\right) + b_4 \qquad (2)$$

Variables for below/above breast height profile equations:

Dependent: $y_i = \frac{dob_{h_i}}{dbh_{ob}}$, $z_i = \frac{dib_{h_i}}{dbh_{ib}}$

Independent: $x_i = \frac{h_i}{h_t}$, $w_i = \frac{4.5}{h_t}$

Below breast height (i.e. h_i < 4.5 ft)

$$y_i = 1 + b_5(x_i - w_i) + b_6(x_i^2 - w_i^2) \qquad (3)$$

$$z_i = 1 + b'_5(x_i - w_i) + b'_6(x_i^2 - w_i^2)$$

Above breast height (i.e. $h_i > 4.5$ ft)

$$y_i = \frac{x_i - 1}{w_i - 1} + b_7\left[(x_i^2 - 1) - \frac{(w_i^2 - 1)(x_i - 1)}{(w_i - 1)}\right] + b_8\left[(x_i^3 - 1) - \frac{(w_i^3 - 1)(x_i - 1)}{(w_i - 1)}\right]$$
$$z_i = \frac{x_i - 1}{w_i - 1} + b'_7\left[(x_i^2 - 1) - \frac{(w_i^2 - 1)(x_i - 1)}{(w_i - 1)}\right] + b'_8\left[(x_i^3 - 1) - \frac{(w_i^3 - 1)(x_i - 1)}{(w_i - 1)}\right] \qquad (4)$$

Bark relationship above breast height (i.e. $h_i > 4.5$ ft)

$$\left(\frac{dib_{h_i}}{dob_{h_i}}\right) = \left(\frac{dbh_{ib}}{dbh_{ob}}\right) e^{b'_9\left[\frac{dbh_{ob}}{dob_{h_i}} - 1\right]^{0.25}} \qquad (5)$$

Equation (1) predicts stump diameter (o.b. and i.b.) at 0.5 ft aboveground from d.b.h.$_{ob}$. Equation (2) predicts d.b.h.$_{ib}$ from d.b.h.$_{ob}$. Equation (3) is a constrained, second-degree polynomial, profile model to predict stem diameter (o.b. and Lb.) between stump height and breast height. Equation (3) is constrained through breast height such that at h_i=4.5 ft, dob_{hi}/d.b.h.$_{ob}$ =l. Equation (4) is a constrained, third-degree polynomial, profile model to predict stem diameter (o.b. and i.b.) between breast height and total tree height. Equation (4) is constrained through both breast and total height such that at $h_i = h_{total}$, $dob_{hi} = 0$ and $dib_{hi} = 0$. Thus, equation (4) is constrained through ratio estimate points 1 and 0. Equation (5) predicts the dib/dob (i.e. bark) relationship along the upper stem above breast height. The exponent in equation (5) was fixed at 0.25 because attempts to fit that parameter often causes convergence problems with some nonlinear procedures. Equation (5) was developed from the felled-tree data for use with the dendrometer data sets when an inside bark diameter is needed. Computing the bark relationship with equation (5) is more efficient than computing the o.b. and i.b. values in two steps with equation (4).

PROFILE EQUATION RESULTS

The resulting profile equations to predict dob/diob diameters below breast height and the bark relationship above breast height for the felled-tree data set, where $s_{y.x}$ is the standard error of prediction and I^2 is the index of fit for 96 trees. are:

At stump height of 0.5 feet (i.e. $h_i = 0.5$ ft)

$$\frac{dob_{0.5}}{dbh_{ob}} = 0.9364\left(\frac{1}{dbh_{ob}}\right) + 1.1294 \qquad (6)$$

with n=96, $s_{y.x=0.0708}$ and $I^2 = 0.1165$

$$\frac{dib_{0.5}}{dbh_{ob}} - -0.0149\left(\frac{1}{dbh_{ob}}\right) + 1.0342$$

with n=96, $s_{y.x=0.0697}$ and $I^2 = 0.0000$

At d.b.h.: d.b.h.$_{ob}$ to d.b.h.$_{ib}$ conversions (i.e. $h_i = 4.5$ ft)

$$\frac{dbh_{ib}}{dbh_{ob}} - -0.3815\left(\frac{1}{dbh_{ob}}\right) + 0.8896 \qquad (7)$$

with n=96, $s_{y.x=0.0295}$ and $I^2 = 0.1124$

Below breast height (i.e. $h_i < 4.5$ ft)

$$y_i = 1 + -7.1727(x_i - w_i) + 45.3420(x_i^2 - w_i^2) \qquad (8)$$

with n=192, $s_{y.x=0.0567}$ and $I^2 = 0.6691$

$$z_i = 1 + -8.0688(x_i - w_i) + 62.1590(x_i^2 - w_i^2)$$

with n=192, $s_{y.x=0.0572}$ and $I^2 = 0.6778$

Bark relationship above breast height (i.e. $h_i > 4.5$ ft)

$$\left(\frac{dib_{h_i}}{dob_{h_i}}\right) = \left(\frac{dbh_{ib}}{dbh_{ob}}\right) e^{0.0642\left[\frac{dbh_{ob}}{dob_{h_i}} - 1\right]^{0.25}} \qquad (9)$$

with n=1,600, $s_{y.x=0.0368}$ and $I^2 = -0.5791$

The parameter estimates and statistics of fit for equation (4), developed from the felled-tree and dendrometer data taken above breast height, are shown in table 2. Since optical and laser dendrometers are most commonly used to obtain outside bark diameters for above-breast height stem locations because of stump visibility limitations, only the coefficients for equation (4) were obtained for the dendrometers.

Each data set equation was judged significantly different from zero and each data set equation was judged significantly different from other equations at the 0.01 level. Profile equations were fitted to the felled-tree data set and to the three sets of optical dendrometer data. Heights to various diameters and cubic foot volumes were predicted with the profile equations and compared to the computed, felled-tree volumes. Table 3 shows the mean percent differences between heights and volumes computed with the profile system equations and measured felled-tree

Table 2-Tree profile prediction system parameter estimates* and statistics of fit for felled-tree and optical dendrometer (above breast height) data for loblolly pine where O.B. and I.B. are outside and inside bark, n is number of observations, $s_{y.x}$ is the standard error of prediction, and I^2 is the index of fit

Parameter	Felled-tree 0.6.	Felled-tree I.B.	Criterion 400 O.B.	Tele-Relaskop O.B.	Wheeler Penta prism O.B.
b_7	+1.7496	+1.1616	+1.8016	+1.6914	+1.9809
b_8	-1.5837	-1.3391	-1.5607	-1.5266	-1.6567
n	1699	1699	477	476	470
$s_{y.x}$	0.0457	0.0484	0.0642	0.0623	0.0508
I^2	0.9665	0.9651	0.9589	0.9624	0.9737

Table 3-Comparisons of profile equation predictions of tree height and cubic foot volume from felled tree and optical dendrometer data where $\bar{d}$ is mean percent difference (observed difference as a percent of measured felled tree value) and is standard error of the mean percent difference (Basis: 96 trees)

Profile value	Felled-tree		Criterion 400		Tele-Relaskop		Wheeler Penta prism	
(Mean of actual value)	$\bar{d}$	$s_{\bar{d}}$	$\bar{d}$	$s_{\bar{d}}$	$\bar{d}$	$s_{\bar{d}}$	$\bar{d}$	$s_{\bar{d}}$
Height to 0 in. top (92.3 ft)	-0.002	0.002	+0.583	0.456	+ 1.684	0.781	+1.874	0.330
Height to 3 in. top (80.4 ft)	+1.873	0.355	+1.695	0.589	+ 3.401	0.794	+2.484	0.476
Height to 6 in. top (64.7 ft)	+3.400	1.410	-0.385	1.744	+ 5.318	1.463	-3.606	1.725
Height to 8 in. top (49.6 ft)	+4.805	1.800	+2.031	3.678	+ 9.439	2.158	-4.999	2.804
Height to 10 in. top (34.5 ft)	+6.212	2.848	-0.039	3.036	+11.236	3.025	-4.735	3.209
Cu. ft to 0 in. top (49.4 ft^3)	+0.483	0.938	-3.027	1.305	+ 3.658	1.278	-7.031	1.252
Cu. ft to 3 in. top (49.2 ft^3)	+0.496	0.966	-3.117	1.323	+ 3.663	1.295	-7.226	1.273
Cu. ft to 6 in. top (47.3 ft^3)	+1.891	1.552	-3.594	2.101	+ 5.635	1.699	-10.379	1.956
Cu. ft to 8 in. top (43.1 ft^3)	+2.315	1.734	-1.089	3.817	+ 8.728	2.211	-10.549	2.878
Cu. ft to 10 in. top (36.4 ft^3)	+3.277	2.631	-3.217	3.225	+10.085	3.112	-9.782	3.249

values. Cubic foot volumes and merchantable heights of the felled trees were computed to 0, 3, 6, 8, and lo-inch top diameters (o.b.) using Smalian's formula and linear interpolation of intermediate bolt diameters. Percent difference is the arithmetic difference between the computed value from the profile system equation(s) and the measured felled-tree value expressed as a percentage of felled-tree value. Equation (4) coefficients for each of the felled-tree and dendrometer data sets (table 2) were used to compute upper stem diameters at 4.0-ft intervals above breast height. Diameters below breast height (0.5 and 3.0 ft) were computed for all data sets with felled-tree equations (6) and (8). Bolt length to a specified top merchantability limit that was contained within a bolt was obtained by linear interpolation of computed endpoint bolt diameters.

DENDROMETER COMPARISONS

Point Estimates

The Criterion 400 was more accurate for d.b.h. and total height measurement than the Tele-Relaskop or the Wheeler Penta prism. While the mean percent differences in table 1 were significantly different statistically, they were most likely not significantly different in a practical sense. The mean percent differences for the d.b.h. measurement in table 1 translated in absolute units to -0.05, +0.20, and -0.34 inches of the mean tree d.b.h. for the Criterion 400, Tele-Relaskop, and Wheeler Penta prism instruments, respectively. None of these mean differences would result in a change in tree diameter for a l-inch d.b.h. class interval.

The mean percent differences for a quadratic mean dob_{16} of 12.6 inches would translate, in absolute units, to -0.24, +0.19, and -0.52 inches for the Criterion 400, Tele-Relaskop, and Wheeler Penta prism, respectively. While these differences might appear to be insignificant from a practical standpoint, they could translate into significant volume differences if the d.b.h. and dob_{16} dendrometer measurements were used to obtain Mesavage and Girard form class volumes. For example, using the average tree values of dob_{16} = 12.6 in. and $d.b.h._{ob}$ = 14.1, equation (7) for $d.b.h._{ib}$, and equation (9) for dib,,; the computed form class for the "average tree" would be:

$d.b.h._{ib}$ = -0.3815 + 0.8896(14.1 in. $d.b.h._{ob}$)
= 12.16 in from equation (7)

dib,, = 12.6(12.16/14.10)exp[0.0642(14.1/12.6 -1)$^{0.25}$]
= 11.29 in from equation (9)

FC = (11.29/14.10)100%
= 80.04% = 80% from definition of form class

Likewise, using the resulting average dob_{16} values for the dendrometers (i.e. 12.6-0.24, 12.6+0.19, 12.6-0.52), the resulting $d.b.h._{ob}$ values (i.e. 14.1-0.05, 14.1+0.20, 14.1-

0.34), equation (7) for d.b.h.$_{ib}$, and equation (9) for dib,,; the computed form classes for the "average" Criterion 400, Tele-Relskop, and Wheeler Penta prism tree would be 79 Percent, 80 percent, and 79 percent, respectively. If the assumption of 3 percent (board foot) volume change per form Class point is used, the volume differences would be ▪ 3 percent, 0 percent, and -3 percent, respectively. Cubic foot volume changes approximately 2 percent per form class point. Thus, the combined measurement data for d.b.h. and dob_{16} indicate that the Tele-Relaskop would produce more reliable volume results than would the other instruments if the dendrometer measurements were used with form class volumes.

The Criterion 400 was more accurate for total height measurement than was the Tele-Relaskop or the Wheeler Penta prism. Again, the mean percent differences are not different from a practical standpoint because they translate to absolute height differences of 0.5, 1.6, and 1.7 ft from the average tree height of 92.8 ft The height difference associated with the Wheeler Penta prism are attributable to the accuracy of the attached clinometer, not the optics of the dendrometer.

Profile Equation Estimates

All upper-stem profile equations [from equation (4)] were judged to be statistically significant and all possible pair-wise comparisons showed that each equation was significantly different from the others at a significance probability of less than 0.0001.

Since the primary objective of this study was to compare volume prediction accuracy of stem profile equations developed from optical dendrometer and felled-tree data, estimates of merchantable height (i.e., stem length) and cubic foot volume to various top merchantability limits were computed with the profile equations for each data set and compared to the felled-tree values (table 3). The o.b. upper-stem profile equation coefficients for each data set (b_7 and b_8 in table 2) were used to compute estimates of merchantable height and volume above breast height. Cubic foot volume below breast height was computed for all data sets with predicted diameters at 0.5 and 3.0 ft from felled-tree equations (6) and (8), respectively. Profile equations for predicting diameters below breast height were not developed for the dendrometers because in field applications, visibility of the stump and most stem locations below breast height is severely limited by forest Vegetation. This is not a serious limiting factor in dendrometer use because the stem section below breast height can be treated as a cylinder or other appropriate geometric solid.

The accuracy of computed height (stem length) and volume values to a specified merchantability limit from a felled-tree profile equation diminishes as the merchantability limit moves down the stem from the top toward breast height (table 3). This decline in prediction accuracy is attributable in part to changes in taper caused by inflection points of the stem profile. The upper-stem profile equations used in this study are constrained through the top and breast height, but as the rate of stem taper decreases in the midportion of the tree bole above breast height, relatively small changes in predicted diameter result in large changes in stem length (height). For example, the mean measured felled-tree heights in table 3, reflect a taper rate of 0.252 in./ft between the tree top and a 3 in. top dob, 0.191 in./ft between 3 in. and 6 in., 0.132 in./ft between 6 in. and 8 in., 0.132 in./ft between 8 in. and 10 in., and 0.134 in./ft between 10 in. and the average d.b.h. Of 14.1 in. These "average tree" taper rates show that the Stem profile is "relatively flat" (actually, the taper rate is relatively constant) between a 6 in. top and d.b.h. Thus, a +4.8 percent error in height to an 8 in. top translates to +2.4 ft which equates to a error of +0.295 inches in diameter prediction if the taper rate is 0.132 in./ft. From a practical standpoint, a 4 to 6 percent error in merchantable height prediction in the midbole region of a standing tree should have little impact on volume prediction,

The error associated with profile equation prediction of merchantable height (table 3) increases in a consistent manner as the top merchantability limit increases (i.e., moves down the stem toward d.b.h.) for the felled-tree and Tele-Relaskop data sets, appears to be random for the Criterion 400 data, and has a segmented trend for the Wheeler data.

Errors in profile prediction of cubic volume should be attributable to the combined effects of errors in merchantable height and stem diameter prediction. For example in table 3, the average height prediction error (expressed as mean percent difference) for the felled-tree data profile equation is +4.805 percent or 2.38 ft for the 8 in. top. Using the previously established taper rate of 0.132 in./ft, the end diameter of this +2.38 ft "error bolt" would be approximately 8.3 inches and its cubic volume would be approximately +0.86 ft^3. The actual volume difference for the 8 in. top in table 4 is +2.315 percent or 0.99 ft^3.

Overestimation of height and/or stem diameter should result in overestimation of cubic volume. The computed values for felled-tree and Tele-Relaskop equations produced consistent error patterns in diameter, height, and cubic foot volume. The Tele-Relaskop overestimated d.b.h., dob_{16}, and total tree height (table 1) and the resulting profile equations overestimated merchantable height and therefore cubic foot volume (table 3). The Criterion 400 underestimated standing tree diameters, overestimated total height, and had both positive and negative estimation errors in profile height prediction. Yet, the profile equation volume prediction was consistently low. Since cubic foot volume varies with the square of bolt diameter, it must be concluded that the Criterion 400's underestimation of stem diameter has a stronger influence on volume prediction than does its inconsistent estimation of height. Likewise, the Wheeler Penta prism underestimated standing tree diameters and the resulting profile equations consistently underestimated cubic volume by 7.0 - 10.5 percent.

The profile equations developed with felled-tree data produce the most consistent estimates of merchantable height and cubic foot volume to various merchantable top limits. It is difficult, however, to make definitive conclusions about the accuracy ranking of the Criterion 400, Tele-Relaskop, and Wheeler Penta prism. In general, the Criterion 400 produced the smallest mean differences in standing tree measurements and profile equation predictions of merchantable height and cubic foot volume. On the other hand, the Tele-Relaskop produced the most consistent tree measurement and profile prediction trends. There is no doubt that the Wheeler Penta prism was the least accurate of the three dendrometers in a statistical sense, but these inaccuracies may not be relevant in a practical sense.

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BENEFITS OF LONG-TERM SILVICULTURE RESEARCH TO ACCOMPLISHING TOTAL MANAGEMENT OBJECTIVES

M. Boyd Edwards'

Abstract-In 1982, a study on the benefits of six site preparation treatments to survival and growth of loblolly pine was initiated in the Piedmont of Georgia. That original study is still active and a study summary will be presented. However, in addition to research information obtained from the original study about survival and growth of young loblolly pine stands, nine additional studies have resulted on the site that deal with subjects such as wildlife benefits, floristics/succession, economics, stand development, soil relationships, and vegetation/environmental relationships. Highlights from individual studies will be presented that serve to demonstrate the benefits of long-term silviculture research to accomplishing the science needed to sustain and enhance southern pine productivity.

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CANOPY LIGHT TRANSMITTANCE IN NATURAL STANDS ON UPLAND SITES IN ARKANSAS

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Abstract-The relationship between overstory basal areas and understory light intensity was modeled from measurements of photosynthetically active radiation from a series of ongoing research studies, demonstration areas, and operational-level stands that represented a wide range in conditions (age, density, structure, and species composition) and sites (poor and good). Light intensity was sampled with a ceptometer during clear sky conditions at 4.5 ft in height between 1030 and 1330 solar time in the summer. There was a total of 93 observations, representing the following stand compositions: 35 pine, 54 pine-hardwood, and 4 hardwood. The developed model is: $I=100/(1+T\ exp(-5.401+0.01446\ T+7.786\ H/r)$, where I is percent light intensity, and Tand Hare the total stand and hardwood basal areas, respectively (ft^2/acre). All regression coefficients were significant at $P \geq 0.001$, and the fit index was 0.94. Hardwoods appear to intercept more light per unit of basal area than pines. This difference can be attributed to crown size and foliar characteristics. The relationship between overstory basal area and understory light intensity has implications for stand regeneration, competing vegetation, and wildlife habitat.

INTRODUCTION

The transmittance of light through the canopy is an important stand characteristic that has a pronounced effect on the understory environment (Valigura and Messina 1994), and its measurement can be used to estimate the canopy's energy capturing ability and leaf area index (Pierce and Running 1988). Silviculturists manipulate light transmittance by controlling the density, structure, and species composition of the trees making up the canopy. Such manipulations of light transmittance are usually incidental to some other management goal, but they become crucial when stands are being naturally regenerated using either even- or uneven-aged techniques. Because most natural reproduction cutting methods retain some overstory trees on the site during stand regeneration, seedlings developing in natural stands typically grow in the partial shade of overstory trees. For even-aged methods, seed-tree stands of southern pines typically retain 5 to 10 ft^2/acre of overstory pines, while retention in shelterwood stands is 20 to 40 ft^2/acre (Willett and Baker 1993). In contrast, acceptable stocking levels in uneven-aged pine stands range from 45 to 75 ft^2/acre (Baker and others 1996). In addition, some nonindustrial private landowners and public land managers want to retain a component of overstory hardwoods during stand regeneration to enhance the nontimber resources of their stands (Waldrop 1989).

Successful natural regeneration depends on creating an acceptable understory environment for seedling establishment and development. A key feature of the understory environment is light intensity and quality. Regrettably, these overstory-understory relationships are still poorly known for loblolly (*Pinus taeda* L.) and shortleaf (I? *echinata* Mill.) pines and their hardwood associates. To develop a model for canopy light transmittance in natural stands, we compiled data from a number of ongoing research studies where both light intensity and overstory basal areas were measured. These data were supplemented by measurements from several demonstration areas and operational-level stands.

METHODS

Study areas

Sampling utilized an existing series of research areas, demonstration areas, and operational-level stands, which were all natural in origin. These studies and stands are summarized in table 1.

Study 1 is testing the initial application of uneven-aged silviculture using single-tree selection in an irregularly structured shortleaf pine-oak stand (Shelton and Murphy 1991). The study is located in Perry County, AR and consists of 20 square 0.5-acre plots surrounded by a 58-foot isolation strip treated in an identical manner. The study plots were arranged in a randomized complete block design with four replicates. One plot per block was designated as an untreated control that was not harvested. The pine component of the treated plots was reduced to a target basal area of 60 ft^2/acre using uneven-aged marking guidelines, and plots were harvested during the winter of 1988/89. Treatments were three levels of retained hardwoods (0, 15, and 30 ft^2/acre in trees with d.b.h. of 3.6 inches and greater). Hardwoods were uniformly scattered across the plot; in addition, the treatment retaining 15 ft^2/acre of hardwoods was repeated with a clustered distribution of hardwoods. Hardwoods ($\geq$1 inch d.b.h.) that were not designated for retention were controlled with stem-injected herbicide.

Study 2 is testing the shelter-wood reproduction method in a shortleaf pine-oak stand in Perry County, AR (Shelton and Baker 1992). Eight rectangular 3-acre plots were established and surrounded by a 66-foot isolation strip that was treated in an identical manner. Plots were arranged in a randomized complete block design with four replicates.

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Table l-Summary of the stand and site conditions sampled for light intensity

Designation	Management system and intensity[a]	Dominant tree Species[b]	Age	Pine basal area	Hardwood basal area
			Years	*Ft²/acre*	*Ft²/acre*
Study 1	UEA/high	SLP	50-80	57-68	o-35
Study 1[c]	EA/low	SLP	50-80	71-116	18-55
Study 2	SW/high	SLP.	55-75	27-32	O-18
Study 3	EA/high	LOB	36	72-113	o-39
Study 4	None	LOB	50-l 20	61-1 83	21-78
Stand 1	EA/high	LOB	50	62-70	0
Stand 2	UEA/high	LOB/SLP	50-80	56-73	0
Stand 3	UEA/high	LOB/SLP	50-80	44-50	0
Stand 4	ST/high	LOB	50	8-22	0
Stand 5	EA/low	OAKS	60-80	2-6	84-100

[a] Management systems are: UEA=uneven-aged using single-tree selection, EA=established even-aged stands managed with periodic thinnings, SW=shelterwood reproduction cutting method, ST=seedtree reproduction cutting method. High intensity stands are harvested frequently and have some type of understory control imposed. Low intensity stands are infrequently thinned and have no understory control. Study 4 has had no significant disturbance for over 60 years.
[b] LOB=loblolly pine, SLP=shortleaf pine, OAKS=mixed upland oaks, Stands dominated by SLP are on poor sites (50 to 60 ft for shortleaf pine at 50 years): all other stands are on good sites (85 to 95 ft for loblolly pine at 50 years).
[c] Unharvested control plots.

The pine component on all plots was reduced to a target basal area of 30 ft²/acre in trees selected principally for their potential as seed trees. Two levels of overstory hardwoods were retained (0 and 15 ft²/acre in trees 3.6 inches d.b.h. and larger). All merchantable pines were harvested during the winter of 1989190, and merchantable hardwoods not designated for retention were harvested during the spring and summer of 1990. After harvesting was completed in 1989, plots were split into two 0.70-acre measurement plots, and two control methods for submerchantable hardwoods (21 inch d.b.h.) were imposed (chainsaw felling with and without stump-applied herbicides).

Study 3 is a thinning study in a 35-year-old loblolly pine-hardwood stand in Drew County, AR (Tappe and others 1993). Twenty-seven circular 0.2-acre plots were established and surrounded by a 33-foot isolation strip that was treated in an identical manner. Plots were arranged in a completely randomized design with three replicates. The pine component was reduced to three basal areas (70, 85, and 100 ft²/acre). Three levels of hardwoods were retained (0, 15, and 30 ft²/acre in trees 3.6 inches d.b.h. and larger). Merchantable pines and hardwoods that were not designated for retention were harvested during 1988189. Submerchantable hardwoods (≥ 1 inch d.b.h.) were controlled with stem-injected herbicide.

Study 4 is located in the RR. Reynolds Research Natural Area in Ashley County, AR (Cain and Shelton 1995). This 80-acre area is a mature pine-hardwood stand, where many of the dominant trees are more than 100 years old. The stand developed after harvest of the virgin forest in the 1910's, and there have been no significant stand disturbances over the last 60 years. Twelve 0.25-acre plots were located systematically within the stand.

Stand 1 is a 5-acre demonstration area in the Crossett Experimental Forest in Ashley County, AR that was regenerated to loblolly pine using clearcutting with seeding from the adjoining stand in 1942 (Baker and Murphy 1982). The stand has been thinned from below on a 5-year interval. Understory vegetation was periodically controlled by prescribed burning.

Stands 2 and 3 are the Good and Poor Farm Forestry Forties, two 40-acre demonstration areas in the Crossett Experimental Forest. No study treatments were imposed in these stands, which have been under uneven-aged silviculture for more than 50 years (Reynolds and others 1984). Herbicide control of nonpine understory vegetation was applied during the late summer of 1989. The most recent harvest within the stands was during the winter of 1990191.

Stand 4 is an operational-level loblolly pine seed-tree stand located in Ashley County, AR. The stand was about 40 acres and was cut about 2 years earlier. Competing vegetation was controlled with an area-applied herbicide.

Stand 5 is an upland oak stand located in Drew County, AR. There was no recent evidence of cutting or stand treatments.

Measurements and Data Analysis

The d.b.h. of each tree ≥ 3.6 inches d.b.h. in the research plots was obtained from the most recent inventory, which was either annually or biennially. For the other stands, pines and hardwoods ≥ 3.6 inches d.b.h. were tallied using a 10-BAF prism at 10 points in Stand 1 and 20 in the others. Sampling in Stands 2, 3, and 4 was restricted to an area of about 10 acres.

Photosynthetically active radiation (PAR) was determined at 4.5 feet aboveground during clear sky conditions using an 80-sensor Sunfleck Ceptometer (Decagon Devices, Inc., Pullman, WA). Sampling was conducted on the following dates: August 2, 1991 (Study 1); August 1, 1991 (Study 2); July 31, 1991 (Study 3); August 8, 1991 (Study 4); August 20, 1991 (Stands 1, 2, 3, 4); and July 23, 1991 (Stand 5). All measurements were taken between 1030 and 1330 solar time. Measurements were also made several times during each date in full sunlight, which permitted calculating relative light intensity. For Studies 1 and 2, PAR was determined at 10 and 18 permanent 0.001 -acre subplots, respectively, that were used for regeneration inventories in each plot, taking 10 readings across each subplot. For Study 3, a total of 30 readings was systematically taken across each 0.20-acre plot. For Study 4, five temporary 0.001 -acre subplots were located and PAR was determined as described before. For all of the other stands, three temporary 0.001 -acre subplots were located within 10 feet of the prism point, taking 10 readings across each subplot.

For the research studies, PAR was averaged for each plot, and the basal area in pine and hardwood components was calculated. For the other stands, PAR and basal areas were averaged for groupings of five adjacent prism points; we felt that this would provide an observation fairly comparable to those from the research plots. There was a total of 75 observations of basal area and light from the research studies and 18 from the other stands for a total of 93, representing stand compositions of 35 pine, 54 pine-hardwood, and 4 hardwood.

The Beer-Lambert law is generally used to describe the relationship between light transmittance and leaf area index (LAI):

$$I = I_0 \exp(-k \, \mathrm{LAI}) \qquad (1)$$

where

I is the amount of incident PAR penetrating the canopy,

I_0 is the incident PAR, and

k is a coefficient (Kera and others 1969).

By replacing LAI with total basal area and adding a term for hardwood/total basal area ratio in the model, several modified models were tested. After evaluating the potential models, the following one was selected because it had the lowest root mean square error and highest fit index (analogous to R^2 for linear equations):

$$I = 100/(1 + T \exp(b_0 + b_1 T + b_2 H/T)) \qquad (2)$$

where

I is the relative light intensity (PAR at 4.5 ft expressed as a percentage of PAR in full sunlight), and

T and H are the total stand and hardwood basal areas, respectively (ft^2/acre), and the b_i's are the coefficients to be determined by nonlinear least squares regression using the SAS MODEL procedure (SAS Institute 1988).

RESULTS AND DISCUSSION

The developed equation for canopy light transmission is:

$$I = 100/[1 + T \exp(-5.401 + 0.01446\,T + 1.786\,H/T)] \quad (3)$$

All regression coefficients were significantly different from zero ($P \leq 0.001$). The fit index was 0.94, and the root mean square error was 6.7 percent. The equation uses a modification of the logistic function and thus is constrained to yield a value of 100 percent for a total basal area of 0 ft^2/acre. The significance of the regression coefficient for the ratio of hardwood basal area to total basal area [H/T in equation (1)] indicates that pines and hardwoods have different effects on canopy light transmittance.

The equation was solved for a reasonable range of total and hardwood basal areas that were represented in the data and results are shown in figure 1. Predicted light transmittance ranges from 98 percent for a pine-only basal area of 5 ft^2/acre to 6 percent for a total basal area of 180 ft^2/acre, which is made up of 135 ft^2/acre for pines and 45 ft^2/acre for hardwoods.

Hardwoods appear to intercept more light per unit basal area than pines. This is apparent in figure 1 because the light intensity progressively decreases as hardwoods make up a higher proportion of total basal area. The reduction in light intensity from retained hardwood is most evident at

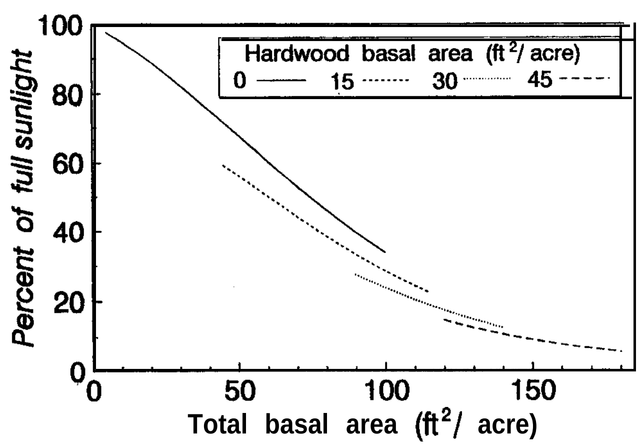

Figure l-Relationship between basal area and light intensity.

the lower values of total basal area. When total basal area is held constant at 45 ft^2/acre, for example, increasing the hardwood component from 0 to 15 ft^2/acre reduces light intensity from 72 to 59 percent, a difference of 13 percentage points. Increasing the hardwood component from 0 to 15 ft^2/acre when the total basal area is 100 ft^2/acre will reduce light intensity from 34 to 29 percent, a difference of 5 percentage points. The greater light interception of hardwoods probably reflects their large crowns, short heights, and broad leaves.

In studying the effect of shottleaf pine basal area on light intensity, Jackson and Harper (1955) reported an inverse relationship between the logarithm of stand basal area and the logarithm of light intensity. This relationship is close to the one found in this study. For instance, with a shortleaf pine basal area of 40 ft^2/acre, the light intensity was about 60 percent of full sunlight, and the light intensity decreased to about 20 percent at a basal area of 120 ft^2/acre. For the same basal areas, the predicted light intensity in this study was 70 and 25 percent, respectively. For a shelterwood stand with 40 ft^2/acre of loblolly pine basal area, Valigura and Messina (1994) reported that the daily total PAR was 64 percent of that in an open area. The minor difference in transmittance of Valigura and Messina's study and ours (64 versus 70 percent) may be due to the difference in the methods of data collection. Our data were collected between 1030 and 1330 hours when shadow length was minimum. In contrast, Valigura and Messina (1994) used daily total PAR. Shade length was found to affect light intensity in the understot-y in a tropical forest (Longman and Jenik 1974).

The light relationships of mixed pine-hardwood stands have not been intensively studied. However, hardwoods have generally been observed to intercept more light than pines. Under temperate hardwoods, light intensities from 1 to 5 percent are common, while the common ranges for even-aged pine stands are from 10 to 15 percent (Spurr and Barnes 1980). In addition, Garrett and others (1977) reported that shortleaf pine stands transmitted more than twice as much light as white oak (*Quercus alba* L.) stands with the same basal area. Species composition also influences light quality with more green light being reflected by hardwoods (Spurr 1960).

Our model for canopy light transmission is limited because it is heavily weighted toward sawtimber-sized pine stands with and without a significant component of midcanopy hardwoods. However, additional sampling is planned in the future to include younger stands and managed hardwood stands.

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A SYSTEM FOR DRAWING SYNTHETIC IMAGES OF FORESTED LANDSCAPES

Timothy P. McDonald'

Abstract-A software package for drawing images of forested landscapes was developed. Programs included in the system convert topographic and stand polygon information output from a GIS into a form that can be read by a general-purpose ray-tracing renderer. Other programs generate definitions for surface features, mainly trees but ground surface textural properties as well. The package can be used to design logging cut unit boundaries that are less visible from a given viewpoint. Images created using the system may also be suitable for showing the public how a given prescription might appear if implemented. The package was used to make images showing the potential for using strip clearcutting as a means of mitigating the visual impact of harvests on steeply sloping ground. An analysis of the package indicated that there was a potential to improve its data handling and user interface components.

INTRODUCTION

Appearance is the most convincing source of information available to the public in evaluating the status of a landscape (Nassauer 1992). Silvicultural treatments on a landscape can leave unintended visual impacts that persist for a number of years. These impacts can often be avoided or reduced by careful planning but it is difficult to incorporate consideration of the visual effects of a prescription into the planning process. This has led to the development of software tools that give feedback to treatment designers on how decisions might affect the appearance of a landscape. Pictures derived from these tools have been found to be useful in both planning prescriptions, and in gauging the public's reaction to a proposed treatment before it is implemented (Bergen and others 1992).

Perhaps the most succesful computer terrain visualization tool developed to date has been Vantage Point (Fridley and others 1991), developed at the University of Washington Cooperative for Forest-Systems Engineering. Vantage Point is a highly integrated environment for creating visual simulations of forested landscapes. It has the capability to incorporate topographic and stand-related information into a rendering system to produce high-quality images showing landform, trees, roads, and cut areas. The software also has domain-specific knowledge of how trees grow and can use this to generate time-sequenced images of a series of treatments.

Although Vantage Point is a powerful design tool, it is currently available only for a specific workstation-class platform. Other tools are more widely available. SmartForest, for example, developed at the University of Illinois Landscape Architecture Department's Imaging Lab, runs on a variety of Unix-based workstations. UVIEW is PC-based and is a geographic analysis software package developed by the USDA Forest Service that includes some landscape rendering capabilities. At present, however, these alternatives are designed primarily for purposes other than landscape visualization and their output quality cannot duplicate that of Vantage Point.

The need exists for a visualization tool that provides output renderings of acceptable quality, and that is available for use on a variety of hardware/operating system platforms. Such a system should be inexpensive, be flexible enough to interface with any number of data sources, particularly GIS, and should be relatively simple to operate. This paper reports on the development of such a system that, although it does not duplicate the full functionality of Vantage Point, it does produce high-quality renderings of forested landscapes.

DESIGN OBJECTIVES

The visualization system was conceived as a means of achieving two related functions: (1) to provide feedback to logging engineers on the visual impacts of cutblock boundary changes when designing treatments, and (2) to create images that could accurately convey to the public the results of the engineer's design decisions. As a design tool, producing images should be fast and simple enough so that a sufficient number of alternatives can be evaluated within a treatment design cycle. The system should also interface smoothly with a GIS to easily access topographic, unit boundary, and stand data. As a tool for informing the public on treatment decisions, output images should be realistic with respect to boundary placement, residual stand density, landform, and other visual cues an observer might use in judging the scenic beauty of a landscape.

The primary development objective for the system was that it should be reasonably simple to use and available for as wide an array of computer platforms as possible. This required designing to a "least common denominator" and development efforts therefore concentrated mainly on functional aspects as opposed to user interface concerns. Although the user interface was not considered a primary feature of the system, the various components were kept fairly consistent in their usage. Finally, because there was a great deal of previously developed software freely available, it was decided to use public domain programs to as great an extent as possible.

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SYSTEM DEVELOPMENT

From a software development standpoint, the most difficult part of creating a landscape viewing system is building the rendering engine, the program that calculates the interaction between "lights" and "objects" in a virtual "world," and creates a depiction of the scene based on its results. Fortunately, several rendering systems have been developed and are in the public domain. Of those available, the POVRAY ray tracer is available for nearly every computer platform that exists, is actively used by thousands worldwide, and is under continuous development by a group of very talented people. POVRAY is a powerful ray tracer that uses a very general scripting language as its input, includes many standard and prebuilt objects and textures, can model a large set of graphics primitives and do constructive solid geometry with most (for example, do intersections or unions between two objects), and can model atmospheric attenuation and particle-induced scattering (haze, smoke, or fog). Because of its flexibility, power, and availability, POVRAY was chosen as the rendering engine of our landscape visualization system. The remaining components of the system were designed to provide the data necessary to drive the rendering engine and included tools for terrain and object (for this application, tree) modeling.

Terrain data is available in many digital forms, most commonly as U.S. Geological Survey Digital Elevation Models (DEM's). A DEM is a matrix of elevations arranged in row echelon, and is sometimes referred to as a heightfield. Heightfields are discrete in nature, but for locating objects on its surface we need a method of interpolating between the grid points. There are, again, multiple means of interpolating heightfields, but we chose the triangulated irregular network (or TIN) as our preferred method. TIN's can significantly reduce the amount of data required to represent smooth surfaces, they are continuous (except along triangle intersection lines) and use planar facets, making it simple to calculate surface object locations. Since most topography data exists as DEM's, however, a method was needed to convert this type of data to a TIN. Again this problem has been solved and the tools placed in the public domain. A package known as scape, developed by Paul Heckbert and Michael Garland at Carnegie Mellon University, was chosen to fulfill this task in our system (Garland and Heckbert 1995).

Rendering trees requires some notion of where on the landscape trees should and should not be, and what they should look like. Our contributions to the visualization package were in developing tools to integrate the various components, and in developing methods for efficiently drawing and placing trees on the landscape. Two assumptions were made concerning tree locations in developing the methods: (1) trees were assumed to be objects uniformly distributed within any given polygon, and (2) locations of individual trees were assumed to be independent of all others regardless of species or age. With this model, only a density and polygon boundary are necessary to generate object locations. Assigning an object type (tree, for example) and object characteristics (species and age) to locations is done separately and can make use of positional information in classifying them. Species may vary with elevation, for example, and methods are provided to assign characteristics based on height above a reference plane.

SYSTEM USAGE

Table 1 lists a sequence of steps necessary to create a rendered image of a landscape, and the programs used in each step. The system is intended to be used in conjunction with a GIS for maintaining stand, DEM, and polygon data. We are currently using the GRASS GIS for data storage, and translation utilities have been developed to convert output data into intermediate formats understood by the system programs. Using another GIS would require development of a similar set of utilities.

DISCUSSION

The visualization package was designed to meet two particular goals: that it provide a design tool for logging engineers to evaluate prescriptions for their visual impacts; and that it produce images that accurately convey a sense of how a given prescription would look if implemented. Testing of the system by outside users has not been

Table I-Steps and tools used in creating a rendered landscape image

Step	Software	Input requirements	output
1. Data assembly	GIS		DEM, view points, stand polygons, tree species and age info
2. Create TIN	scape	raster DEM	List of triangle vertices
3. Add vertex normals	normcalc	TIN	TIN with vertex normals, in intermediate format
4. Add trees	lt cutpoly	TIN, stand polygons, # of trees	List of x, y, z coordinates tree locations
5. Convert TIN to POV-Ray	gs2pov	TIN, surface texture Info	POV-Ray object with textures assigned to triangles
6. Assign species, age to trees	trees2pov	Tree types, sizes	A list of "tree" objects for inclusion in POV-RAY
7. Render	POV-Ray	Control script, tree definitions	24-bit color image of landscape

conducted so it is difficult to draw conclusions on how well the system meets these goals. Some preliminary observations based on a trial study by our research unit, however, indicate that it can potentially do both given that the user is aware of specific problems.

Data from a study on alternative silvicultural prescriptions in upland hardwood management were used as a test case. An objective of the study was to measure the difference in visual impact due to prescription based on viewer preferences. Because of space constraints, the prescriptions could not be implemented on a large scale. It was felt that viewer response to the actual treatment plots would not accurately reflect their feelings about large-scale implementation of the prescriptions, so the visualization system was used to produce images showing the treatments applied across a large hillside.

The study site was in northern Alabama near the Bankhead National Forest. A sequence of images was created to duplicate the view from an observation point across a narrow valley looking toward the hillslope where the treatments were installed. Figures 1 through 3 are a series of images created using the visualization system and show the hillslope in an uncut state, with a 72-acre clearcut, and with 43 acres removed as three 150 ft-wide strips following the terrain contour.

Suitability as a Design Tool

Based on experience in developing the images in figures 1 through 3, problem areas were identified that might limit the utility of the visualization system. One was the lack of true integration between the system components. Although this was not generally a problem, lack of integration forces the user to be familiar with the workings of several independent programs and the data formats, and idiosyncracies, of each. An example of this type of problem was the inconsistency in how scaling of data was handled by the various system programs. For example, the TIN generation tool takes as input a DEM that is a form of raster. A raster format is assumed to be on a uniform grid and, therefore, no x,y coordinate data are included. This means, however, that scaling information is lost-the output TIN covers an mXn grid, where m and n are the number of rows and columns of the input DEM. This shortcoming is easily fixed by simply multiplying the output TIN x and y coordinates by the DEM scale. It does illustrate, however, the degree of familiarity with the system that is required, and the need for the user to direct the flow of correct information between the system components.

Generating images using the system was a data-intensive process. For the 4 alternatives evaluated in our study, a total of 11 data files were needed: a control script to drive the renderer (~0.6K bytes in size), a file defining how trees were to be drawn (1.2K), plus images of trees (in our case, 6, each about 12K), the topography TIN (600K plus foreground and cut area texture image files, each about 15K), and lists of tree locations (unique to each image, ranging from 3970K to 4540K in size—49,759 to 56,850 trees). Although the system required about 5000K of data

Figure l-Example application of the visualization system. Rendered view of a hillside in an uncut state.

Figure 2—Identical view as in figure 1, but with a 72-acre clearcut imposed.

Figure 3-Identical view as in figure 1, but with a 43-acre strip clearcut imposed.

to create a single image, no integrated tools were provided to manage it. Again, this was not a limiting problem, but required methodical documentation of the steps taken to keep track of file locations.

The use of a general-purpose rendering engine meant that there was a significant amount of time spent in learning to use it. A degree of familiarity with the syntax and capabilities of POVRAY is needed to create the script file defining viewpoints, camera direction, lighting, and other object characteristics. This can only be gained from reading the large amount of documentation supplied with POVRAY, and by actually using it.

Creating realistic trees was the most difficult part of using POVRAY. Trees themselves are complex 3D objects, and it was difficult to capture that complexity in such a way that enough trees could be included in the scenes without exceeding the memory constraints of the computer system. Initially, trees were modeled as cylindrical trunks with a 3D polygonal canopy. It was found, however, that only about 3,000 of these trees could be placed in the scene before the virtual memory capacity of our workstation was exceeded. The circumstances in our test case required about 50,000 trees be included, so another type of tree had to be used. Our solution to this problem was a transparent, zero-thickness box with a picture of a tree painted on it. POVRAY had no problem handling 57,000 of these "flat" trees (-47M bytes virtual memory peak usage), and they appeared as visually complex as a real tree as long as they were viewed from an adequate distance. Images with trees in the foreground, however, might require a different approach.

As a design tool, application of the visualization system was constrained primarily by the familiarity of the user with POVRAY. Once the details of the rendering process were worked out, time on the part of the user to create an image was on the order of a few hours from start to finish. If the design goal is selecting among alternative cut unit boundaries, the image creation process is greatly simplified after the first, and the time per picture is reduced to essentially the time to render. Rendering times for an image like those in the figures averaged a little over 60 minutes on a SUN workstation at 600 x 400 resolution. Increasing resolution had the most dramatic effect on rendering times-a 2048 x 1536 image took 9 hours 36 minutes to complete. Adding atmospheric scattering effects increased rendering times by a factor of 3.

Quality of the Images

Bergen and others (1993) compared observer response to computer-generated and photographic images of a particular viewshed. Their results indicated that, as long as elements that are important in forming an opinion about a scene are preserved, computer-generated images are suitable as a basis for gauging public opinion about a silvicultural treatment. The most important visual cue in these images was topography. Examination of the rendered images and several photos taken from observation points showed that there were some small differences between the generated terrain and the actual. The differences were mainly visible along the ridge top, with the rendered scene showing more relief than was truly present. This was likely due to inaccuracies in the input DEM, but this has not been verified. Accuracy of the trees in the rendered images could also be improved. As stated before, trees were "painted" on transparent boxes to create the scenes. The tree images used in the process were more like clip-art, and greater realism in the final renderings would be possible if scanned photos of canopy-grown hardwoods were used.

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