Silviculture for Multiple Objectives in the Douglas-Fir Region

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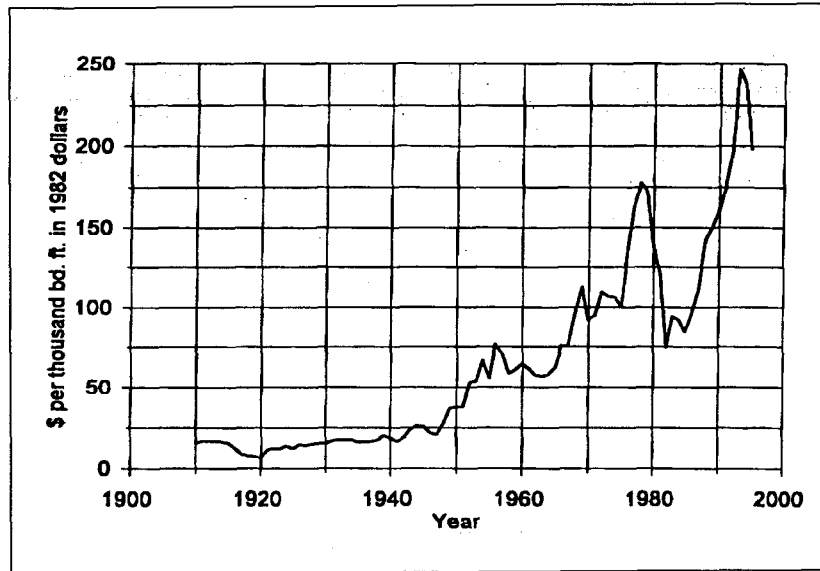Denis P. Lavender, J. Bradley St. Clair, John C. Tappeiner,
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Errata

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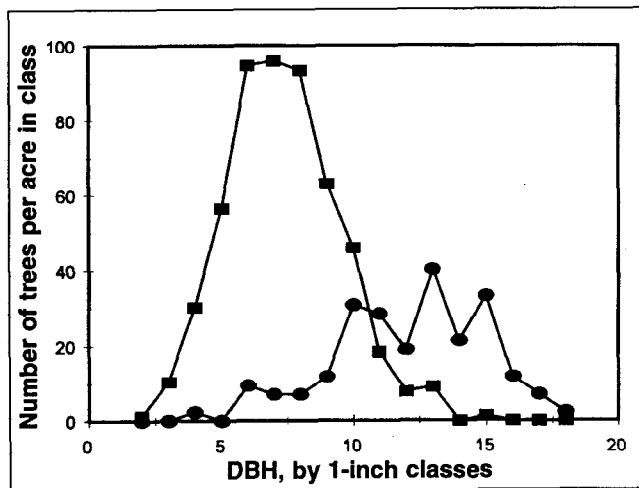
We apologize for any inconvenience this may have caused you.

Abstract

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Silvicultural knowledge and practice have been evolving in the Pacific Northwest for nearly a century. Most research and management activities to date have focused on two major topics: (1) methods to regenerate older, naturally established forests after fire or timber harvest; and (2) growth and management of young stands. Today forest managers can reliably regenerate the major conifer and hardwood species under most conditions by using combinations of natural and artificial regeneration. They also can control stand density and species composition and growth of individual trees, thereby influencing stand structure. Available growth models can reasonably predict the outcome of growing conifer stands under a range of densities, species composition, and management scenarios, providing tree numbers by size class as well as crown characteristics and wood yields.

Most silvicultural efforts have been financed through and directed toward production of wood. Although some other values have been produced or improved in conjunction with such activities, public interest and emphasis on nontimber values have increased. It has become apparent that some values are not benefitted by silvicultural practices aimed solely at wood production. In most situations, however, desired nontimber values can be enhanced by silvicultural measures implemented for their direct benefit or by some modifications of practices applied primarily to produce wood. We discuss the historical development of silviculture in the Pacific Northwest and review the silvicultural practices currently available to forest managers. We then point out how these practices can be modified and used to maintain and produce wildlife habitat, diverse stand structures (including those usually associated with old forests) and pleasing scenery, while also producing wood products. Most of the silvicultural knowledge needed to design and implement regimes for integrated production of these multiple values already exists.

Keywords: Ecosystem management, multiple use, silvicultural systems, wildlife habitat, thinning, landscape management, forest ecology, Douglas-fir.

Contents

Introduction

When biologists took their investigations of the relation of plants to the environment from the laboratory to the field, they found the silviculturist already there with the accumulated facts of a century of field work.

James W. Tourney of Yale University, 1928

The above quotation, from the preface to the first edition of Foundations *of Silviculture Upon an* Ecological Basis (Tourney 1928), emphasizes the fact that silvicultural practice and the research in silviculture and the ecological relations that underpin it antedate the settlement of much of North America. The early foresters in the Pacific Northwest (and elsewhere in the United States) began with forest management concepts imported from Europe. These concepts were in part unsuited to the economic and social conditions existing in the United States at that time (ca. 1900), and to species and climatic conditions that differed somewhat from those of Europe. But this introduction of forestry concepts began a continuing process of adaptation and evolution. In reading the early reports and research publications on forestry in the Pacific Northwest, one is struck by the keen observations and foresight and the tremendous accomplishments of a small group of pioneer workers.

Changing social and economic conditions have led to many changes in forest management practices and policies since the early 1900s. In recent years, the interested general public and specialists trained in disciplines other than traditional forestry have played increasing roles. New ideas have been introduced and outlook has broadened. But differences in background and experience often give rise to communication difficulties, misconceptions, and misunderstandings that are not always recognized. New concepts can be conceived, evaluated, and implemented most effectively when all participants have a shared knowledge about how current practices were developed and why they were adopted. Such understanding also will help to retain past gains, prevent old problems from reappearing, and avoid new problems as new ideas and practices are incorporated in forest management regimes.

Several years ago, the authors prepared a number of short papers for the symposium *Creating a Forestry for the 21st Century,* held in Portland, Oregon, August 24-26, 1993. These were subsequently published as chapters 8 to 10 in a book of the same title (Kohm and Franklin 1997). The symposium framework necessarily imposed constraints on length and scope of discussion, and we subsequently felt that an expanded discussion of the entire subject of silviculture for multiple objectives in the Douglas-fir region was needed. This publication is the result.

Historically, silviculture developed in response to society's need to grow wood to replace declining supplies from unmanaged natural forests, a need that arises sooner or later in all parts of the world. Much of the existing silvicultural literature and silvicultural terminology is therefore phrased in terms of wood production. But the utility of silviculture extends far beyond this. Silviculture consists of a body of knowledge and techniques that can be applied to shape development of forests to meet whatever objectives are selected-whether the emphasis be on watershed protection, scenic values, ecological restoration, development of wildlife habitat, or wood production. Most of our Northwestern forest lands have wood production as a major objective, and some

lands have been dedicated to specific nontimber uses. It is now apparent that needs for wood and for other values can never be adequately met by setting aside major portions of the forest land base for single uses of any kind. Rather, there is a great need for management regimes that can produce multiple values. Such multipurpose management does not mean that all values must receive equal emphasis on all lands. We believe that a variety of regimes must be developed and applied in harmony with land capabilities and management objectives. These regimes may range from intensive wood production on a semiagricultural basis with some incidental production of other values, through management for joint production of wood and nontimber values, to management primarily for wildlife, aesthetic, and recreational uses with some associated production of wood (Curtis and Carey 1996).

In this report, we review the history of silviculture in the Douglas-fir region and the available silvicultural options and techniques. We provide some literature references for those interested in further information. We do not seek to duplicate the excellent discussion of regional silviculture given by Tesch (1995). Rather, our aim is to point out the wide range of possibilities for controlling stand establishment and development to meet a variety of possible objectives, with a focus primarily on the multiple objectives commonly involved in management of forest ecosystems on both public and private lands. And, we will point out some related policy questions and offer some opinions.

Foundations

The science and practice of silviculture provide the means for managing vegetation in forests and thereby influencing forest health, soil and stand productivity, habitats of diverse plant and animal populations, and the welfare of forest-dependent communities and of society in general. In this initial section, we provide general background and trace the development of silviculture in the Douglas-fir region of the Pacific Northwest as it has evolved in the 20th century with changes in knowledge, economics, and philosophies of forest land management. The next section discusses forest and stand development, changing social expectations and management goals, and opportunities to meet them through silvicultural practices. Subsequent sections discuss (1) regeneration systems, (2) silvicultural practices as means of shaping development of young stands to meet desired objectives, (3) harvesting options and rotations, (4) providing diverse structures and habitats, (5) maintenance of site productivity, (6) damaging agents and forest health, and (7) some conclusions and implications. Discussion is primarily in terms of coast Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco var. menziesil) in the Pacific Northwest west of the Cascade summit, although the associated western hemlock (Tsuga heterophylla (Raf.) Sarg.), red alder *(Alms rubra* Bong.), western redcedar *(Thuja phcata* Donn ex. D. Don.), and true firs *(Abies* spp.) also are considered. Many of the concepts involved have much wider applicability.

Some Definitions

Some silvicultural terms used in this report may not be familiar to or completely understood by all readers. Although most terms will be explained when first used, there is also a glossary at the back for easy reference. A few terms that are fundamental to the discussion are defined below.

Silviculture consists of the techniques used to manipulate vegetation and direct stand and tree development to create or maintain desired conditions. Silviculture substitutes small-scale controlled disturbances for large-scale haphazard natural events, such as wildfires and windstorms. It applies ecological knowledge to attainment of human ends. Silvicultural practices influence rates of tree growth and stand development, stand composition, stand structure, and biodiversity.

An **ecosystem** is a complex of plants and animals and the associated physical factors of their environment that functions as a unit. It has the attributes of structure, function (exchange of matter and energy), complexity, interaction and interdependency among its components, and dynamic change in structure and function over time. Spatial dimensions are not an inherent attribute. **Ecosystem** is therefore best regarded as a concept rather than a specific physical entity (Kimmins 1987, p. 26). Silviculture is (or should be) based on ecological knowledge, and the **ecosystem concept** is important in that it emphasizes the need to evaluate the many environmental and biotic factors influencing the choice and outcome of silvicultural treatments and their sequence over time, and the long-term consequences and sustainability of management regimes. **Ecosystem** is often loosely used as a synonym for such terms as stand, forest, and landscape. In this report, however, we elect to use the older, long-established, and more specific terminology.

Ecosystem management is a currently popular term that, again, represents a useful concept but lacks specificity. It is useful in that it emphasizes the need to take a holistic view-on a scale larger than the individual stand-of management possibilities and consequences of management actions on productivity and sustainability of the many values that humans obtain from forests. But it is loosely defined and is often given somewhat different interpretations by different people. And, it seems to be acquiring ideological and political connotations (e.g., Chase 1995). We have consciously avoided the term in this report, in favor of the more specific terms of stand, forest, and land-scape management.

The words **tree, stand,** and **forest** are often used to describe various portions of the forest environment. A **stand** is a group of **trees** and associated vegetation sufficiently similar in composition, structure, and condition to be distinguished from other groups of trees within a forest, and large enough to be considered an entity for management purposes. A **forest** is composed of stands.

A **regeneration system** consists of the procedures by which a new stand or group of trees is intentionally established, after removal of the former stand or part thereof by harvest, fire, or other disturbance. It includes the harvest method used and subsequent operations to establish a new age class or classes.

Thinning is the removal of a portion of the trees from a stand to promote development of the remaining trees (and sometimes understory vegetation) and often to secure intermediate income prior to final harvest. A thinning is **precommercial** if the cut trees are too small for economic use. A thinning is **commercial** if trees are removed and sold.

A **silvicultural system** is a planned program of silvicultural treatments covering the entire life of a stand (in even-aged management), extending from regeneration through any intermediate operations to final removal and regeneration. In uneven-aged man-agement, the silvicultural system encompasses methods of tending and removal and replacement of individual trees or small groups of trees within the stand in perpetuity. Although unforeseen events such as fire or blowdown often require modification of a previously planned system, this does not negate the need for a long-term plan of silvicultural activities.
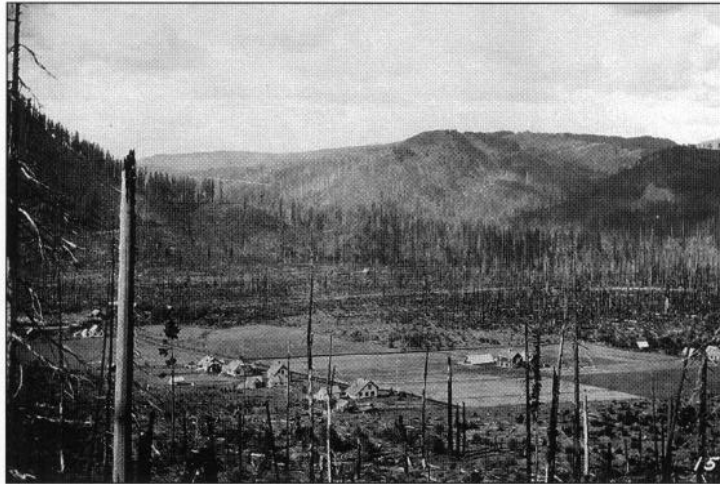
Figure 1-Return of the forest in the Wind River Valley. The Wind River nursery and surrounding area in (A) 1914, after extensive early logging and wildfire; (B) 1935; and (C) 1954.

Silvicultural systems are conventionally discussed under a few broad class designations, but there is, in fact, an almost infinite variety of possible systems. Most of the possible systems have been tried, somewhere, sometime. Silviculture and silvicultural systems are far from new. Their origins in western society extend back to the late Middle Ages; some simple systems were in use in parts of western Europe by the 17th century, and by the mid-19th century silviculture had become an organized and scientifically based discipline with more or less its present terminology (Fernow 1911). European silvicultural concepts and methods were introduced to North America around 1900 and have subsequently gone through a continuing process of modification and adaptation to North American species and changing North American social and economic conditions.

Harvest cuts consciously designed to secure regeneration and provide continued production of timber and other forest values are referred to by the name of the associated silvicultural systems. The wide variety of these are conveniently grouped for discussion purposes into the conventional categories of (1) clearcutting, (2) seed-tree, (3) shelterwood, (4) selection, and (5) accessory systems (Matthews 1989). Excellent discussions are also given by Daniel and others (1979), Nyland (1996), Smith (1986), and Smith and others (1997). In any of these systems, regeneration may be by natural seeding, planting, or a combination of the two. Direct seeding has been used occasionally.

Historical Development of Silviculture in the Douglas-Fir Region

Forest management practices in the Pacific Northwest evolved from beginnings in the mid-19th century. Until the early 19OOs, the forests were viewed as a static resource to be mined, and the usual objective was to harvest high-value timber at minimum direct cost, with little consideration given to reforestation, protection of soil or water, or provision for wildlife habitat. Because of the physical and economic limitations of railroad logging, cutting frequently began at the bottom of a watershed and continued to the uplands until an entire basin was logged. Unmerchantable trees were left standing, and logged areas often were accidentally or intentionally burned. Wildfires were frequent and largely uncontrolled. Some, such as the Yacolt fire of 1902 in southwest Washington, burned huge areas and caused major losses of property and sometimes of human life.

This pattern of large cut areas frequently followed by fire may have more closely mimicked natural disturbance by large fires than the staggered setting, dispersed clearcutting approach that followed. Natural regeneration of trees and shrubs often occurred following early logging or intense fire because mineral soil was exposed and seed was often available from residual trees or from adjoining stands. The results ranged from well-stocked, vigorous young conifer stands (fig. 1), to stands of red alder or sprouting hardwoods, to covers of shrubs or nonwoody plants of various densities with only occasional conifer or hardwood trees.

Change began with the establishment of the National Forests at the end of the 19th century. Establishment of the Wind River nursery in southern Washington (1909) and planting programs for rehabilitation of extensive burns followed. Forest research in the region began ca. 1910. Organized fire suppression was introduced after the disastrous turn-of-the-century fires and became increasingly effective through the 1920s and 1930s. Research leading to early yield tables showed the enormous growth capacity of Northwestern forests (McArdle and Meyer 1930). Methods for consistently regenerating

forests after fire or timber harvest became a high priority for early research. Experimentation with harvest cutting and regeneration techniques began early and continues to the present.

The first permanent research plots (still extant) to study growth and yield of young stands were established in 1910 (fig. 2). Seed crops and seed dispersal were studied. Experiments with plantation spacing and thinning followed. Two pioneering studies begun in 1912 by the United States Forest Service, Wind River Experiment Station (later to become the Pacific Northwest Research Station), compared seed sources and species for plantations. One of the earliest forest genetics studies in the United States (and in the world) compared results of using Douglas-fir seed from different locations and from different parent trees within stands (Munger and Morris 1936). A second study compared 152 forest tree species planted at the Wind River Aboretum over a quarter century (Munger and Kolbe 1932, Silen and Olson 1992); this showed that Pacific Northwest species were inherently superior to any of the exotics tried. Both studies demonstrated the importance of long-term research and the facts that (1) a long time span may be required to evaluate suitability of a species or seed source to the local environment, (2) occasional or rare extreme weather events or seasons may be particularly important in determining adaptation, and (3) maladaptation may be expressed quickly or may occur as a slow decline over many years.

The combination of effective fire control, high productive potential of Northwestern forests, and development of successful regeneration methods made forest management on a permanent basis possible. Very early, Allen (1911) stated the policy and information needs for planned forest management and permanence of the timber industries and forest-dependent communities. The basic silvicultural knowledge needed to regenerate stands after harvest was available by the late 1920s (Munger 1927), although many refinements remained to be worked out. Industrial and private owners and public agencies made substantial forestry investments (Greeley 1948, Hagenstein

Figure 2-Willamette no. 1 in 1997: this and two adjacent study plots, established in 1910, were probably the first long-term research plots in the Northwest and provide an 87-year record of the development of a naturally established untreated Douglas-fir stand.

1986), and these accelerated rapidly in the changed economic climate that followed the end of the Great Depression and World War II. The marked and generally consistent trend of rising timber prices that began shortly after World War II (fig. 3; Haynes and Sohngen 1994) provided a powerful incentive to industrial and other owners to undertake long-term programs of active forest management, including both forest protection and large investments in stand regeneration and management. Along with increased emphasis on planting, tree improvement efforts began in the 1950s with selection of "plus trees" in native stands and establishment of the first seed orchards (Duffield 1955, Isaac 1955a). Tree improvement programs greatly expanded in the 1960s and 1970s (Campbell 1964, Silen 1966, Silen and Wheat 1979, Stonecypher and others 1996), as did the application of cultural treatments such as early respacing and fertilization. The Pacific Northwest became the first region in North America, and perhaps the world, where the people and organizations that came to harvest the original forests stayed and invested in succeeding ones-and made those investments while much of the original old-growth forest remained.

Early efforts to adapt silvicultural systems to the Pacific Northwest included the seed tree method and "selective" cutting, as well as clearcutting.

Though widely applied, the seed tree system did not consistently provide uniform and timely regeneration. Many seed trees were soon lost to wind and other causes (Isaac 1940a, 1943) and seed supply was often insufficient, although for some areas and circumstances it was adequate (Garman 1951).

The advent of the tractor and motor truck about 1930 as alternatives to the donkey engine and railroad logging introduced a new flexibility that made alternative harvest methods possible. On gentle terrain, tractors could skid logs around obstacles and residual trees, and expanding road systems allowed truck access to timberlands. A form of partial cutting popularly called selective logging developed on private lands as a
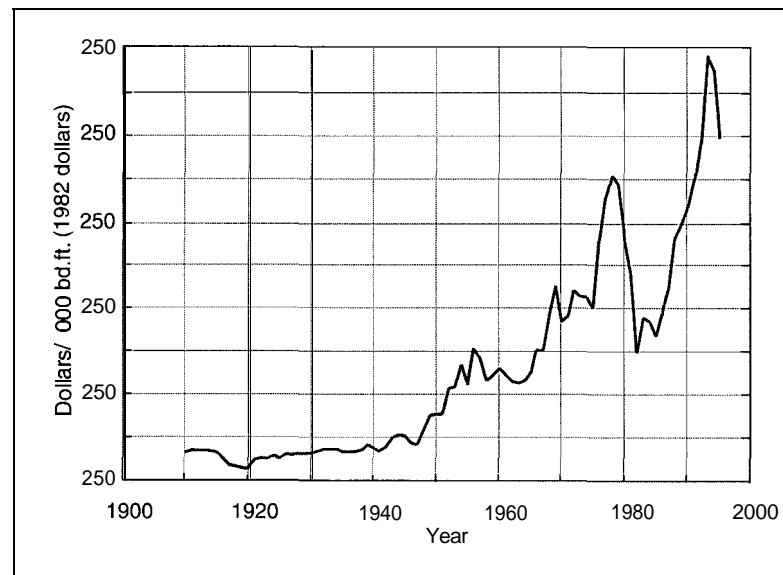
Figure 3-Price trend for National Forest timber sales, 1910 to present, in constant 1982 dollars. The steady rise since World War II provided a powerful incentive for owners to adopt management measures to enhance future wood production.
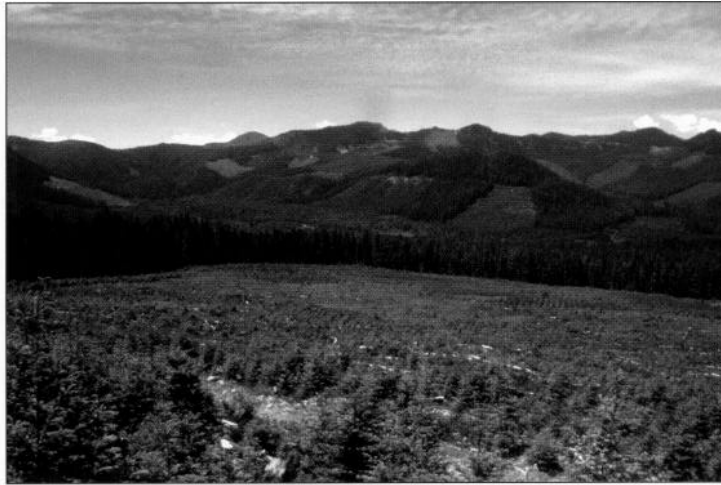
Figure 4-The "staggered setting" pattern of dispersed clearcuts was the most common harvesting practice on National Forests in the period 1950-90.

Figure 5-Clearcut unit with natural seeding from adjacent uncut timber, 1954.

Figure 6-It has been common practice of many owners to use large clearcut harvest units, which are then planted with genetically selected stock.

response to the economic pressures of the depression. Only the more valuable trees were cut and removed. Selective logging might better have been called high-grading or "logger's choice."

Kirkland and Brandstrom (1936) proposed an elaborate scheme for "selective timber management" in Douglas-fir and hemlock stands in the National Forests. This proposal was likewise stimulated by the economic problems of the depression era and was implemented on the public lands on a fairly extensive scale from the mid-1930s to the late 1940s. The proposed system called for detailed economic and stand analyses and frequent entries. It was thought that a number of light partial cuts, each removing mostly large overmature trees, could pay for roading and show favorable financial returns under the existing economic conditions. They envisioned eventual regeneration in group or small patch cuts on the order of 1 to 10 acres, to be introduced gradually over several cutting cycles after the initial entry.

Debate over selective cutting in Douglas-fir was quite lively (Munger 1950, Smith 1970), and its use apparently ended in the late 1940s. Munger (1950) reported that all new Bureau of Land Management and Forest Service sales called for clearcutting, except for some uneven-aged stands of mixed species in southwestern Oregon and certain other thrifty mature stands. Isaac's evaluation of partial cutting (Isaac 1956) and his studies of natural regeneration (Isaac 1943) discredited "selective cutting." Five to ten years of observation by Isaac on permanent plots within selectively cut areas of old-growth forest showed extensive residual tree damage and mortality, substantial windthrow, bark beetle attack, change in species composition from shade intolerant to shade tolerant species, and a lack of Douglas-fir regeneration. Isaac recommended abandoning general use of the system. He did suggest that some form of partial cutting or uneven-aged management might be appropriate for drier sites in southwest Oregon, gravel soils of the Puget Sound region, and severe southerly exposures elsewhere in the region where moisture and shade were critical factors.

In retrospect, Kirkland and Brandstrom's ideas were never thoroughly evaluated, because the unsatisfactory early results caused their abandonment before the stands reached the point of planned group or patch regeneration (Curtis 1998). The primary reasons for failure (Smith 1970) were that (1) the system was applied in old, previously unmanaged, and highly defective stands that were unstable when opened up; and (2) only the largest and best trees could be removed at a profit under the economic conditions of the period. Contributing factors were (1) limitations of existing logging technology, (2) inadequate attention to creating suitable openings for regeneration and to site preparation, (3) total reliance on natural regeneration, and (4) attempted imple-mentation of a single policy despite differences in local site and stand conditions.

The poor results from "selective cutting" in these old stands, the observation that many of the old liquidation cuts had regenerated well when seed was available from nearby uncut timber and fire protection was provided, and accumulating information on repro-ductive requirements of Douglas-fir led to general adoption of the clearcutting system throughout the region. The clearcutting system evolved over the next half century from one of dispersed small (i.e., 40 acres or less; fig. 4) harvest units with natural seeding (fig. 5) from surrounding uncut timber ("staggered settings"), to large harvest units that commonly receive some form of site preparation and are planted with genetically selected stock (fig. 6). Clearcutting had biological, operational, and economic

advantages. It favored Douglas-fir over its more tolerant and less valuable associates and enabled Douglas-fir to grow rapidly after establishment. It simplified slash disposal and brush control measures. It was well adapted to cable logging in steep terrain where other methods were inefficient or inapplicable. Because harvest was concentrated on limited areas, it required less road construction than partial cutting systems. But, it was also highly visible and it became controversial with many segments of the public.

Although clearcutting became the dominant system throughout the Douglas-fir region, there was some limited use of uniform shelterwood on severe sites (Williamson 1973) and some work on shelterwood in western hemlock (Williamson and Ruth 1976). Long-continued experimental trials of other forms of partial cutting and attempts at uneven-aged management do not exist in the region, although there are a few trials in early stages. This lack is unfortunate, for such trials could have provided information useful in designing and evaluating a range of silvicultural systems to meet current needs. Reviews of the underlying science and experience related to application of the various silvicultural systems in the Pacific Northwest are available in Burns (1983, 1989), Fiske and DeBell (1989) Franklin and others (1983), Harris and Johnson (1983), Tesch (1995), and Williamson and Twombly (1983).

The early foresters in the Pacific Northwest recognized that thinning was a beneficial practice that would someday become important. But with huge amounts of large timber available and a rudimentary transportation system, thinning did not become economically feasible until after World War II. In the 1950s many foresters saw commercial thinning as the wave of the future (Worthington and Staebler 1961a), and thinning experiments and some operational thinnings were begun. Subsequent decades saw a shift to shortened rotations-to as little as 40 to 50 years in some ownerships. A concomitant shift took place in attitudes toward thinning. As rotations became shorter, many owners invested heavily in precommercial thinning but most private and industrial owners lost interest in commercial thinning in favor of early harvest of the entire stand.

Until the mid-1970s, there was general agreement that timber production was the primary objective in management of most forest land. Basic assumptions, accepted by nearly all at the time, were that wood production in old-growth stands was essentially static (no net growth), and that insects and disease were diminishing the amount of usable wood in such stands. It therefore seemed desirable to replace old-growth forests with young, rapidly growing stands. The biological, political, and economic environments combined to favor investments in management of young-growth forests by both public and private owners. Much of the forest land in the Douglas-fir region, particularly that in non-Federal ownership, was converted from slow-growing natural mature and old-growth stands to rapidly growing younger managed stands. Although standing timber volume in Pacific Coast forests declined (about 19 percent) from 1952 to 1986 as old-growth forests were harvested, annual net growth in the region increased and came to exceed harvest (MacLean and others 1992, Waddell and others 1989); this is true for the United States as a whole, although differences exist among regions and ownership classes (MacCleery 1992, Powell and others 1993).

Many changes have occurred in the Douglas-fir region since the mid-197Os, and management issues on both public and private land have become much more complex. Human populations have increased and spread into rural, forested areas. Laws and

regulations-some of which conflict with each other and with older legislation-have been enacted in response to concerns about environmental quality. Forest products markets have changed; they have expanded in size and location, and tree species that previously had limited value are in demand. And, nontimber values as well as wood production have become prominent management considerations.

Forest Conditions, Stand Development, and Management Goals

Forest Conditions

Although the early settlers of the region encountered many large tracts of old-growth forests with trees of impressive size, the common conception of the presettlement Northwestern forest as an unbroken sea of giant old-growth trees existing in perpetuity is false. The proportion of forest that was what we now term "old growth" cannot be determined with any precision, but several estimates suggest it was no more than 40 to 50 percent (Ripple 1994) and perhaps less, and that it fluctuated markedly over time. Old-growth forests currently occupy about 18 percent of the productive forest land in California, Oregon, and Washington (Bolsinger and Waddell 1993), of which more than 80 percent is on Federal land, primarily National Forests. Many sites in the region are, however, incapable of producing "cathedral-like" old-growth stands. Considerable lowland areas now in conifer forest were open prairie and oak woodland prior to settlement (Franklin and Dyrness 1973); at higher elevations extensive grass balds, shrub fields, and huckleberry fields were common. All were maintained by natural fires and by native burning. Presettlement forests were dynamic and were periodically disrupted or destroyed by fire (both lightning and human caused) and windstorms, which created a patchwork of ages and developmental stages over areas both large and small (Agee 1991, 1993; Henderson and others 1989; Kay 1995; Walstad and others 1990).

Most of our present Northwestern forests owe their origin to catastrophic events, principally fire, logging, or a combination of the two. Although all trees may not have been killed or removed and regeneration often took place over an extended period (Spies and Franklin 1991, Tappeiner and others 1997), most stands were more or less even-aged in youth. As they grow older, they gradually develop a more irregular age composition and canopy structure as tolerant understory species capture openings arising from death of individual overstory trees or groups of trees or small-scale disturbance. Because of their fire (or logging plus fire) origin, the forests over much of the region were and are dominated by the relatively intolerant and fire-adapted Douglas-fir, even without conscious human effort to maintain the species.

Plantations dominate the forest landscape on industrial lands, and scattered plantations of smaller extent are a major feature of public lands. Most were planted as pure Douglas-fir, but there are some plantations of other species, including mixed species plantings. Many plantations have acquired a considerable admixture of other conifers, hardwoods, and shrubs through natural seeding, sprouting, or advance reproduction carried over from the previous stand. These plantations do, however, differ considerably from naturally established old forests, as will be discussed in subsequent sections.

Stand Development

Stands and their boundaries are influenced by both natural processes and management activities. Stands are dynamic, changing with time and progressing through successive developmental stages as trees are established, grow, and die. Resource values provided by or occurring within stands change similarly. Changes occur rapidly
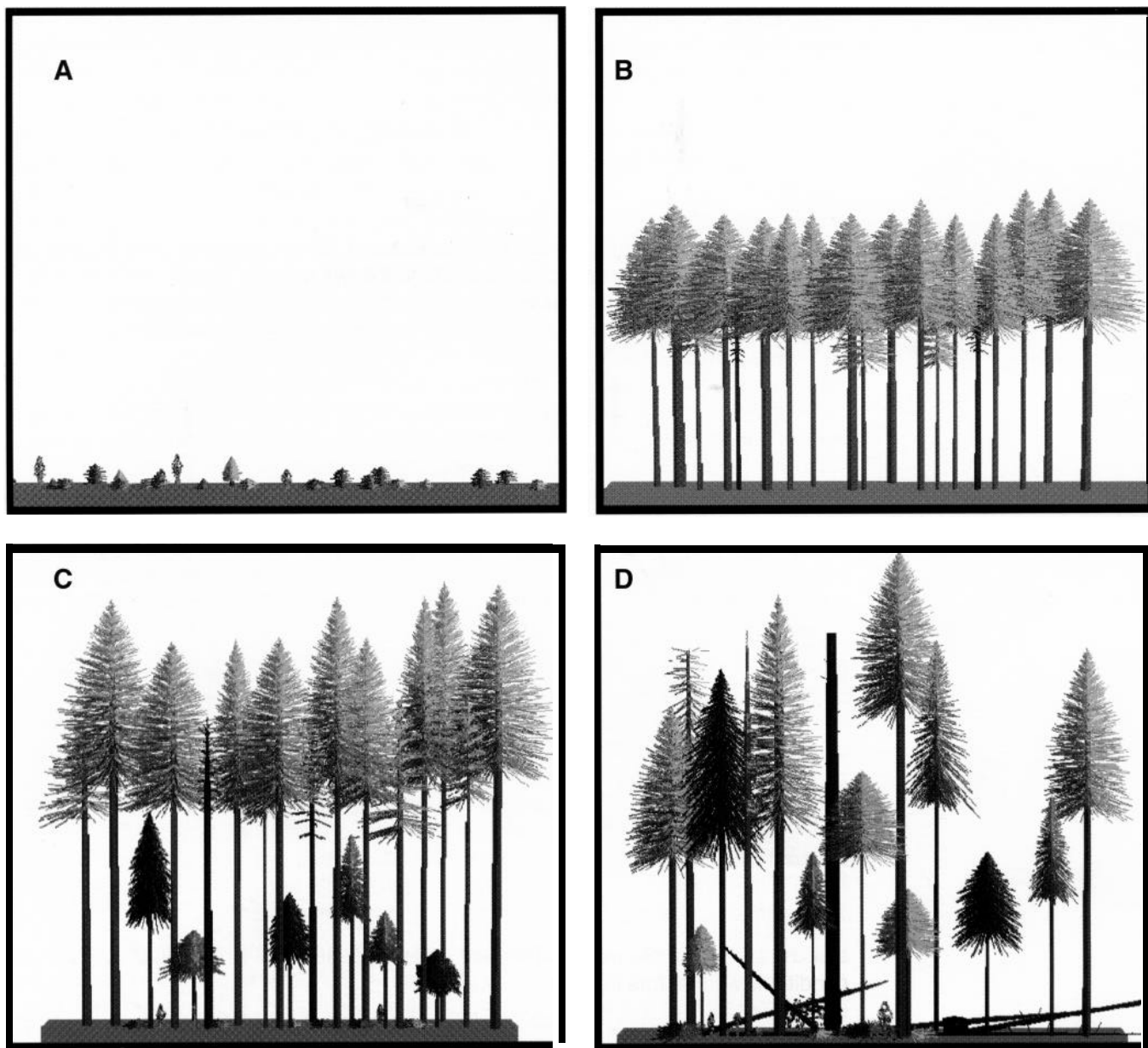
Figure 7-Development stages of natural stands can be characterized as (A) stand initiation, (B) stem exclusion, (C) understory reinitiation, and (D) old growth. Similar stages occur in managed stands but their duration is markedly modified.

and are readily apparent in young stands, but may be nearly imperceptible to casual observation in older stands. Conditions in unmanaged stands may sometimes correspond to the needs and desires of human society or some part thereof; in such cases, natural disturbance events, seed crops, and stand development processes have coincided to provide desired features at the time and place they are wanted. In other cases, natural events and processes have produced forest stands much less suited to human needs and desires.

Development stages of natural stands can be usefully characterized (Oliver and Larson 1996) as (1) **stand initiation, (2) stem exclusion, (3) understory reinitiation,** and (4) **old growth** (fig. 7). The stand initiation stage follows a major disturbance (e.g., fire, windstorm, logging) when new individuals and many species become established. The stem exclusion stage occurs after canopy closure, as the stand begins to differentiate into size classes and shading and competition for nutrients and water by larger trees lead to death of smaller trees and much or all of the understory vegetation. The understory reinitiation stage follows as crowns recede and scattered overstory trees begin to die, and herbs, shrubs, and tree regeneration (usually of tolerant species such as western hemlock, western redcedar, and true firs) appear on the forest floor. The old-growth stage occurs when overstory trees die sporadically and understory trees begin growing into the overstory, creating multiple canopy layers and a gradual shift toward a stand dominated by tolerant species. Subdivisions of these stages also may be recognized. Thus, Carey and others (1996a) add four additional stages between understory reinitiation and old-growth in their description of stages of forest ecosystem development.

The developmental stages described for natural stands also may occur in managed stands (including planted stands). The transition from stand initiation to stem exclusion, however, is generally accelerated, and the progression is often truncated by harvest near the end of the stem exclusion stage. Silvicultural practices strongly influence the rate of progression from stage to stage, the proportions of the forest in different stages, and the specific stand characteristics and values provided.

Observations on the ecology and development of forest stands, and in particular those of the Coast Range of Oregon, lead to the hypothesis that many young stands in these forests may not develop naturally into stands with traits considered typical of old-growth. This suspicion arises from the fact that forest conditions and other environmental factors differ from those prevailing during the formative years of existing old-growth stands, and these are likely to produce different patterns of stand development. These conditions and factors include:

1. Dense initial stocking. Stands established after logging are often more heavily and uniformly stocked with Douglas-fir than were preceding stands. The rapid diameter growth seen in increment cores and stump cross-sections of old-growth trees and differences in tree ages within some old-growth stands provide evidence of long regeneration periods and low stand densities during the first century of life of these old-growth stands (Tappeiner and others 1997).

2. Large populations of browsing ungulates. Current deer and elk populations are far larger than those in the late 19th and early 20th centuries, and possibly larger than those of the presettlement period (Kay 1995). Further, the large wildfires that resulted in

establishment of existing older stands undoubtedly caused a temporary reduction in browsing pressure, because an initially reduced animal population was spread over a very large area of regeneration. Today, selective browsing by deer and elk often retard or eliminate preferred forage species (such as western redcedar and bigleaf maple [Acer *macrophyllum* Pursh]) in the absence of special protective measures. An extreme example of this effect is the massive impact in the Queen Charlotte Islands of an introduced deer population with no predators.

3. Changing climate and weather patterns. Quite aside from the current concern over human-caused global warming, it is well established that there have been substantial variations in climate over periods of decades to several centuries (Layser 1980). Many of our present older stands were established under considerably different and more severe conditions than those prevailing in recent years (Henderson and Brubaker 1986).

4. Existing dense shrub understories. Stands in some areas and sites, particularly in southern and coastal Oregon, have well-developed understories of shrubs (salal [Gaultheria shallon] and vine maple *[A.* circinatum Pursh], as examples) and little conifer regeneration in the understory. In some situations-particularly in southern Oregon-this condition can be attributed to fire exclusion over the past 75 or more years. A similar situation exists on northern Vancouver Island. Work on natural regeneration suggests that these shrub layers often will continue to prevent establishment of conifers. Similarly, alder stands that were established in many areas after logging often have well-developed understories of salmonberry (Rubus spectabilis), swordfern *(Polysfichum munitum),* and elderberry *(Sambucus racemosa)* (Carlton 1988). As the short-lived alder dies, it is likely that many of these stands will be dominated by a dense cover of salmonberry and swordfern that may persist and prevent establishment of conifers for many years (Henderson 1978, Tappeiner and others 1991).

5. In some areas, exotic competing species have become established that have a considerable effect on regeneration, at least locally (e.g., scats broom *[Cytisus* scoparius], gorse *[Eulex europaeus],* Himalayan blackberry [Rubus discolor], certain introduced grasses).

Consequently, we believe that on many sites some management or treatment to obtain understory conifer establishment, to reduce shrub density, and to reduce overstory density in heavily stocked conifer stands will be needed if we wish to promote development of characteristics commonly associated with mature and old-growth forests. Desired characteristics are more likely to be attained by deliberate action than by neglect or passive management.

Changing Goals in Forest Management

Recent years have seen the steadily rising influence of an increasingly urbanized public, concerned about environmental issues and with greater interest in recreational and aesthetic features than in utilitarian forest values. Many people have raised questions about possible effects of current forest management regimes on wildlife, fisheries, and watershed values; on long-term productivity; and on biodiversity in general. There is great interest in and need for silvicultural practices and management regimes that will reduce conflicts among user groups while providing concurrent production of the many values associated with forest lands, on a biologically and economically sustainable basis.

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These concerns are not confined to the Pacific Northwest or to the United States. Foresters and interested publics elsewhere also are giving increased attention to multiple values and are departing from past timber management regimes on significant amounts of forest land. Silvicultural systems other than clearcutting that have been applied on some ownerships in Great Britain are described in a recent Forestry Commission Bulletin (Hart 1995). The Swedish National Board of Forestry produced a well-illustrated book of practical advice to owners on how to manage forests to produce high-quality timber while maintaining their beauty and their value as habitat for plants and animals (National Board of Forestry 1990). Similar interests and major changes in management practices have occurred in Germany (Plochman 1992).

Many approaches have been or are being developed to meet these needs in the United States; they range from short-rotation fiber plantations involving intensive culture of genetically selected hardwood clones, to late-successional reserves, to habitat conservation areas and wilderness areas with little or no active management. Although many of these approaches may play significant roles in future forest management, we will focus in this report on silvicultural practices that may be appropriate for forests managed for multiple objectives, including both wood production and those values commonly associated with natural mature and old-growth forests. Many of these practices or modifications in practices have been suggested in recent years under several banners: "restoration forestry" (Maser 1988); "ecological forestry" (Minckler 1989); "new forestry" (Franklin 1989); "new perspectives" (Brooks and Grant 1992a, 1992b); "high quality forestry" (Kuehne 1993); "ecosystem management" (Galindo-Leal and Bunnell 1995, Loftus and Aune 1995, Overbay 1992, Stewart 1995); "landscape forestry" (Boyce 1995); and "biodiversity pathways" (Carey and others 1996a; Carey and Curtis 1996).

The ideas represented by these terms differ in many respects; goals of some practices or systems may not be clearly defined; and some measures advocated in connection with these ideas seem based on undemonstrated hypotheses rather than on concrete knowledge and experience. But they all advocate some change in conventional practices on portions of the forest land base to provide one or more of the features generally associated with older natural forests; they all recognize the desirability of intentionally managing forests for more than wood production; and thus all involve some degree of multipurpose management.

To sustain diverse, multiple values in specific forest landscapes, we need to systematically foster a balanced distribution in time and space of many stand conditions and stages of stand development (DeBell and Curtis 1993). Forests are dynamic entities, and no condition can be maintained indefinitely. If we wish to have stands with mature and old-growth (late-seral) characteristics in the future, we must provide for development of some stands with these characteristics as future replacements for existing stands. Some ideas on how a desirable balance might be attained are discussed by Carey and others (1996a), McComb and others (1993), and Oliver (1992). Unfortunately, the past history and ownership patterns of the region have created an unbalanced distribution of age classes, both in the region as a whole and within subregions and watersheds. Private ownerships consist predominantly of young age classes, (<65 years) with little mature and negligible old-growth forest; whereas Federal ownership

consists predominantly of much older stands (including considerable amounts of old-growth forest) and young stands (<40 years), with more limited areas (differing considerably among individual National Forests) in intermediate age classes (Adams and others 1992, Sessions and others 1990). Many real and perceived forest management problems are direct consequences of this imbalance, which has grown more striking in recent years with the combination of drastic harvest reductions on Federal lands and accelerated cutting of immature stands on private lands. The latter is in part a consequence of reduction in public timber supplies, current business management practices, and landowner fears of possible future regulations and constraints on management and harvests.

Complete knowledge and absolute certainty are unattainable, and the limitations of existing knowledge often are emphasized by those seeking research funding and by those questioning or advocating some specific action or policy. But in fact, the research and experience of nearly a century in the Northwest (and longer in some other countries) have produced a huge body of information on tree biology, stand development, and forest ecology (Burns and Honkala 1990, Kimmins 1987, Perry 1994, Tourney and Korstian 1947) and on the application of this knowledge through silviculture. Given agreement on objectives for which forests are to be managed (which are primarily determined by social and economic forces) and the conditions needed to achieve them, much of the silvicultural information needed for designing feasible pathways and management techniques is currently available.

Regeneration Methods In this section, we briefly review the research and experience that underpin current methods for establishing stands of forest trees. We consider natural regeneration (including advance reproduction), direct seeding, and planting. Additional modifications in harvest cutting used at the time that regeneration is desired are discussed in a later chapter.

Natural Regeneration Although some of the earliest work on reproduction of western conifers was with planted seedlings (Munger 1911), most early work focused on natural regeneration, in both undisturbed forests and clearcuts. Because conifer regeneration was often found far from any existing seed source, it was hypothesized that Douglas-fir seed was stored in the forest floor (Hofmann 1917, 1924). However, Isaac (1935) showed experimentally that nearly all Douglas-fir seed germinate by the spring following seedfall. He also found that conifer seed could be dispersed over great distances (Isaac 1930). Although most seed falls within 100 to 200 feet of its source, thousands of seeds per acre were found at distances of 500 to 1,000 feet from seed trees. Thus Douglas-fir regeneration can occur at considerable distances from the seed source, without seed storage in the forest floor. This is also true of western hemlock.

Cone and seed crops are highly irregular, with an average of one heavy and one medium crop in seven years (Hermann and Lavender 1990). Extensive damage by cone and seed insects in some years contributes to this variability.

The two seed trees per acre specified in many early National Forest harvests were often quite inadequate to secure satisfactory natural regeneration (Isaac 1943), although results were satisfactory in some instances (Garman 1951). Williamson (1973) showed that good natural regeneration could be obtained in the Oregon Cascades in

shelterwoods that retained 20 to 50 percent of the original basal area. Satisfactory natural regeneration of Douglas-fir was obtained with 10 to 12 large trees per acre in a recent study at Oregon State University's (OSU) McDonald Research Forest (Ketchum 1994), with the combination of a good seed year and some soil disturbance from logging. Some site preparation and supplemental planting usually would be needed, however, to ensure satisfactory regeneration.

Natural seedlings are small and susceptible to mortality from a number of factors during their first several years. Lavender (1958) as well as Garman (1955) and Hermann and Chilcote (1965) found that natural Douglas-fir seedling establishment is enhanced by partial shade that reduces soil temperature and soil moisture evaporation. Disturbance of the forest floor that provides a mineral soil seedbed-and consequently less herbaceous competition, reduced effects of root and stem pathogens, and pests-is also a key to successful natural regeneration (Haig 1936; Haig and others 1941; Isaac 1938, 1940b, 1943, 1955b). Gashwiler (1967, 1970) and Hooven (1958) studied the effects of rodents and other predators on seed supply. Seed predation rates of both conifers and hardwoods are often high both on the tree and on the forest floor (Schubert and Adams 1971, West 1992).

Studies on hardwood regeneration show that protection from high temperatures and frost are also important for small-seeded hardwoods like red alder (Haeusler and Tappeiner 1993, Haeusler and others 1995) and Pacific madrone *(Arbutus menziesii* Pursh) (Tappeiner and others 1986). Species with large seed such as bigleaf maple, tanoak *(Lithocarpus densiflorus* (Hook. & Arn.) Rehd.), and vine maple have less particular requirements for mineral soil seedbeds and shade, although they certainly are susceptible to predation by rodents and birds (Fried and others 1988, O'Dea and others 1995, Tappeiner and Zasada 1993, Tappeiner and others 1986).

Similar studies were carried out elsewhere in the West (e.g., Haig [1936] and Haig and others [1941] in western white pine *[Pinus monticola* Dougl. ex D. Don]; Dunning [1923] and Pearson [1923] in ponderosa pine *[P. ponderosa* Dougl. ex Laws.]; and McDonald [1976a] in Sierra Nevada mixed conifers).

Regeneration of shrubs and conifers in the understory of conifer stands is a relatively new area of investigation. Establishment of salal (Huffman and others 1994) and other shrubs, as well as western hemlock and western redcedar seedlings (Christie and Mack 1984, Harmon and Franklin 1989), is favored by decomposing stumps, snags, and logs on the forest floor although their establishment is not restricted to these substrates. Shrub and hardwood seedling establishment is greater in thinned stands than in unthinned stands (O'Dea and others 1995, Tappeiner and Zasada 1993), as is the vegetative spread by rhizomes and the density of aerial stems produced by developing clones. Clonal shrubs such as salal and salmonberry can apparently persist in the understory for many years, because they can replace dead aerial stems with new sprouts from the bud bank on the rhizomes (Huffman and others 1994, Tappeiner and others 1991).

These and similar studies provide information on biology, ecology, and regeneration of forest plants, define species regeneration niches (Grubb 1977, Haeussler and others 1990), and provide a basis for understanding responses to silvicultural processes.

Site preparation-Conditions on the specific area to be regenerated strongly influence establishment and early development of regeneration. These include surface soil conditions; slash accumulations; overhead shade, if any; aspect, slope, and geographical location as they affect moisture relations and surface temperatures; and existing and prospective vegetative competition and propensity to harbor animals, such as rabbits and mountain beaver *(Aplodontia rufa),* that damage regeneration. Failure to secure prompt and adequate regeneration may result in capture of the site by undesired vegetation, leading to prolonged delays in regeneration, animal damage to seedlings, and inadequate stocking when regeneration of tree species ultimately does occur (figs. 8, 9, and 10).

Figure 8-A 6-year-old Douglas-fir plantation developing without significant brush problems.

Figure 9--Conifer regeneration overwhelmed by unwanted red alder. Treatment is needed if conifers are to be a major stand component.

Figure IO-Dense salmonberry thicket developed after failed conifer regeneration. Treatment will be necessary if tree species are to be restored within a reasonable time.

Site preparation is a collective term for various measures that can be taken to alleviate conditions unfavorable to prompt and adequate regeneration, given an adequate seed supply. These conditions differ widely among physical locations, and the manager must select types and intensities of site preparation appropriate to the local conditions and the requirements of the desired species.

Douglas-fir, and many other tree species, regenerate best on exposed mineral soil. Therefore, some removal or at least some disturbance of the surface organic matter is indicated. This may be partially accomplished through the mechanical action of machinery used in harvesting operations, but additional measures may be needed.

Removal or temporary suppression of competing vegetation is commonly also necessary, and additional competing vegetation control may be needed after initial establishment of tree species. This is particularly true for sites where soil moisture and sunlight may be limiting. On sites characterized by highly aggressive shrub, grass and forb competition, as in much of coastal Oregon and southwest Oregon, thorough treatment to accomplish this is essential to successful regeneration.

Several site preparation methods, including fire, machine scarification, herbicides, hand slashing, and combinations of these methods, are employed in Northwest forests. Each method is effective when it solves the problem and does not conflict with other objectives, and ineffective where it fails to solve the set of problems that are preventing satisfactory regeneration or where it generates major conflicts with societal values. The choice of method depends on evaluation of local conditions and problems and the relative costs and effectiveness of alternatives.

In general terms the attributes of each method may be summarized as follows:

1. **Fire** exposes mineral soil and may control many species of competing vegetation for several years. Soil temperature, chemistry, and physical structure may be adversely affected, however, and certain competing vegetation, such as members of the *Ericaceae,* may be favored. In the past, fire has been widely used for the dual purposes of

site preparation and reduction of fire hazards posed by large slash accumulations (fig. 11). In recent years, air pollution concerns have increasingly restricted its use, while closer utilization and changes in harvesting practices have reduced slash accumulations and the need to burn slash for hazard reduction.

2. Mechanical site preparation with tractor-mounted equipment can prepare mineral soil seedbeds and remove some of the existing vegetation (fig. 12). However, this method also can stimulate establishment of a range of competing vegetation. Excessive removal of the nutrient-rich litter and upper soil horizons can be damaging, as can compaction by heavy machinery on some soils and in some seasons.

3. Herbicides combine the potential to selectively eliminate unwanted competing vegetation with minimal effects on soil productivity and low cost (figs. 13 and 14). They are not appropriate where the main obstacles to seedling establishment are slash or other materials that physically impede seedling establishment. Herbicides are viewed by segments of the public as health hazards, and therefore often cannot be used on sensitive areas (streams or wetlands) or near population centers. Great care must be taken in their use to adhere to regulatory constraints and label precautions.

4. Hand-slashing provides extreme selectivity and is the method least likely to arouse objections from the general public. It is, however, generally slow and expensive, must in many cases be repeated after 2 or 3 years, and is a hazardous activity for workers.
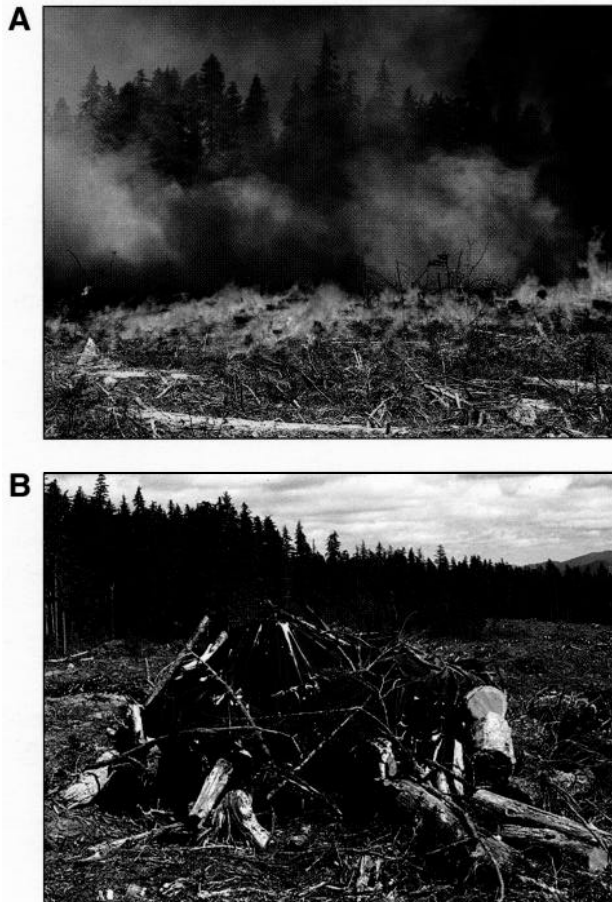

Figure 11-Broadcast burning of slash (A) was usual in the past, but with reduced slash accumulations resulting from closer utilization and other changes in harvest practices, partial disposal (B) or even no disposal often suffices.

Figure 12-Mechanical site preparation can be used to crush and pile slash, reduce existing vegetative competition, and expose mineral soil in preparation for either natural regeneration or planting.
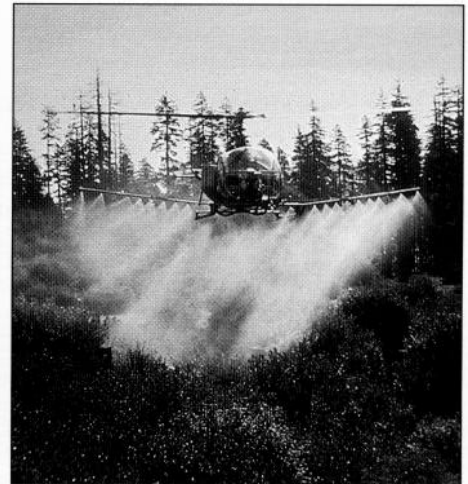

Figure 13-Broadcast spraying of herbicides provides inexpensive control of undesired vegetation that competes with tree regeneration on extensive areas.

Figure 14-Hand application of herbicides provides selective control of scattered clumps of undesired vegetation.

Evaluation of natural regeneration systems-Designed experiments on natural regeneration have been integrated with evaluation of reforestation projects. These evaluations have identified problem sites, determined success of applied regeneration practices, and identified alternatives.

Lavender and others (1956) examined natural regeneration on staggered settings, and Franklin (1963) assessed natural regeneration on strip cuts, small patch cuts (l/4 to 4 acres), and staggered cuttings. These and other studies have shown that partial shade, aspect, reduction of competing plant cover, intensity of burn used to prepare a seed bed, and proximity to seed source all contribute to seedling establishment.

Considerable work has been done on regeneration by using the shelterwood method (Gordon 1970, 1979; Laacke and Fiddler 1986; Laacke and Tomascheski 1986; McDonald 1976b, 1983; Seidel 1983; Tesch and Mann 1991; Williamson 1973; Williamson and Ruth 1976). This work has shown that seedling density is generally satisfactory if sufficient seed producing and windfirm trees are left in the overwood and if there is adequate site preparation to prepare a seed bed and reduce competition.

Minore (1978) and Stein (1981, 1986) examined regeneration results following harvesting on sites considered difficult to regenerate in southwestern Oregon. Minore (1978) found that shelter prevented frost damage to seedlings and saplings on the Dead Indian Plateau in southwestern Oregon. Holbo and Childs (1987), Minore (1978) Stein (1981), and Williamson and Minore (1978) point out the value of advance regeneration, and of natural regeneration among planted seedlings, on sites with extreme variation in temperatures and on rocky soils that are difficult to plant.

Advance regeneration-Use of advance regeneration, established naturally before logging in some stands and after thinning in many others, can be a very effective way to regenerate forest stands. It should be a common practice on sites difficult to regenerate and in unevenaged systems (Minore 1978, Stein 1981) and may be especially desirable for preferred browse species, such as western redcedar. In dense stands, advance reproduction will be comprised almost entirely of shade tolerant species such as western hemlock, western redcedar, and some true firs; but in open stands and stands subjected to heavy thinning regimes (particularly on dry and warm sites), less tolerant species such as Douglas-fir may become established (fig. 15). Gordon (1973), Helms and Sandiford (1985) Oliver (1986), and Tesch and Korpela (1993) developed methods for assessing potential vigor of advance regeneration following logging. Logging damage to advance regeneration increases with seedling size. Tesch and others (1993) found that damaged seedlings often recovered within 3 to 6 years. Growth of advance regeneration was similar to that of planted seedlings (Korpela and Tesch 1992).

Genetic considerations in natural regeneration-Opportunities for genetic improvement are available through choice of seed trees for natural regeneration, and through selection among trees within a stand during intermediate treatments (Zobel and Talbert 1984). Genetic degradation can occur from dysgenic selection when the best trees are taken, leaving poor-quality, slow-growing trees to produce the next generation. Traits under strong genetic control, such as stem form and disease resistance, are the most responsive to genetic manipulation. Rate of stem growth is only moderately heritable

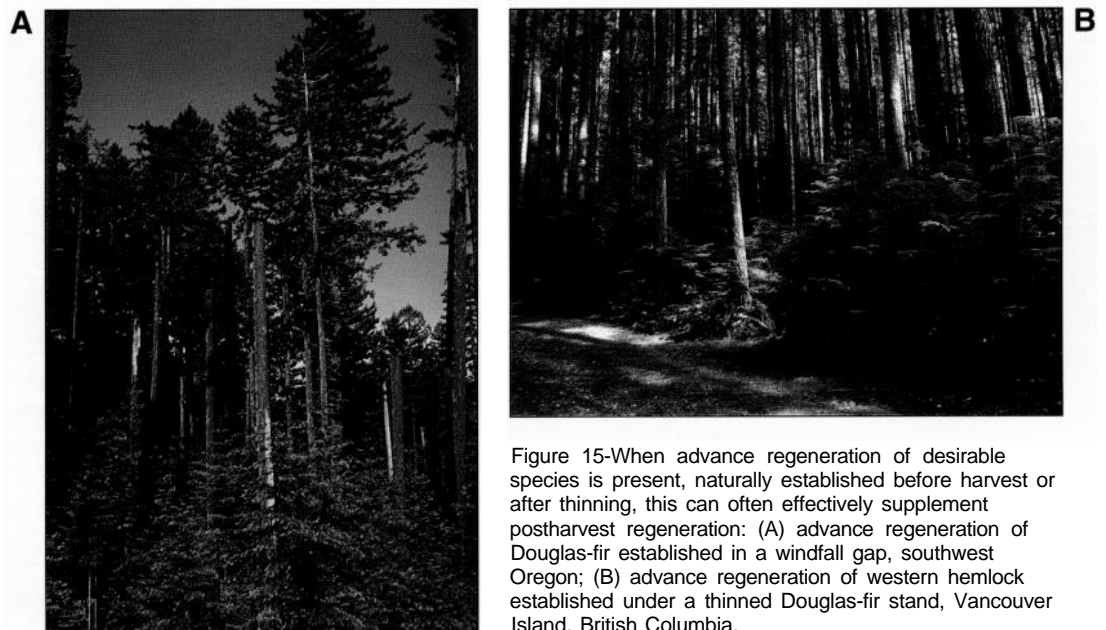Figure 15-When advance regeneration of desirable species is present, naturally established before harvest or after thinning, this can often effectively supplement postharvest regeneration: (A) advance regeneration of Douglas-fir established in a windfall gap, southwest Oregon; (B) advance regeneration of western hemlock established under a thinned Douglas-fir stand, Vancouver Island, British Columbia.

and thus less responsive to selection. Nevertheless, comparisons between select and nonselect Douglas-fir in genetic tests in Oregon and Washington indicate that phenotypic selection in natural stands gives an average 5-percent improvement in juvenile height growth (Stonecypher and others 1996). Although selection may be less effective with typical silvicultural manipulations, these results indicate that over several generations selection for stem size and other traits will likely lead to large genetic gains. Conversely, removal of the better trees will produce losses from dysgenic selection.

Natural regeneration can be important for genetic conservation. Genetic conservation efforts usually involve both ex situ germ plasm collections and in situ habitat preservation. The objective of *in* situ management is to protect and perpetuate both samples of genes and genotypes representative of a species and the evolutionary processes and relationships between a species and its biotic and abiotic environment. Lands that specifically include this management objective have been termed gene resource management units (GRMUs) (Krugman 1984, Ledig 1988, Millar and Libby 1991). These may include both lands excluded from timber harvest and lands in which wood production is a major objective. In either case, natural regeneration can both perpetuate existing gene pools and allow evolutionary processes to proceed.

Summary-The following generalizations emerge from studies of seedling establishment and natural regeneration methods:

- Seed production is variable, with 6- to 8-year intervals between adequate seed crops frequent for some species, especially Douglas-fir. Cone and seed insects can cause partial failure of seed crops and accentuate this variability.

- Most seed falls within 100 to 200 feet of the source, although windborne conifer seeds can spread up to 1,000 feet.

- Seed predation rates of Douglas-fir, ponderosa pine, and large-seeded hardwoods, such as bigleaf maple and tanoak, are high both on the tree and on the forest floor.

- Mortality rates during the first 2 to 3 years after germination are high. Causes are high soil temperatures, pathogens and insects in the forest floor, competition for light and soil water, litter-fall, and frost.

- Seedling survival of Douglas-fir, red alder, ponderosa pine, and true firs is usually highest on bare mineral soil; Sitka spruce *(Picea sitchensis* (Bong.) Carr.), western hemlock, and large-seeded hardwoods survive well on both mineral soil and organic seed beds.

- Partial canopy cover often aids initial seedling survival-even for intolerant species-because it reduces soil temperature, air temperature, and evaporative capacity of air near the ground in summer. It also reduces the chance of frost damage in winter and early spring.

- Shade conditions that foster early seedling survival in the understory of forest stands generally do not favor subsequent growth. Seedlings of most species tend to be shade tolerant when very young but become less so after the initial establishment stage.

- Intense competition from established grasses, forbs, shrubs, and trees may cause high seedling mortality.

- Advance regeneration, when present, can provide successful regeneration after logging and may be especially useful on hard-to-regenerate sites. It often will be of different species than the former overstory. Augmentation by seeding or planting may be needed to attain desired species composition and stocking.

- The small openings created by group selection and single-tree selection methods generally favor shade-tolerant species such as true firs, western hemlock, western redcedar, tanoak, and bigleaf maple over the less tolerant Douglas-fir in most of the region. Small openings do, however, favor Douglas-fir and Pacific madrone, chinkapin *(Castonopsis chrysophylla* (Dougl.) A. DC.), and other sclerophyllous species over the less tolerant pines on dry, warm sites in southern Oregon and northern California.

- Shelterwood methods and small openings or small clearcuts (< 10 acres) appear to be most suitable for the regeneration of true firs at higher elevations (Gordon 1970, 1973, 1979; Gratkowski 1958), although they will work for other species, including Douglas-fir (Williamson 1973, Worthington 1953).

- Choice of leave trees during silvicultural manipulations may provide opportunities to achieve genetic gain, or conversely, may lead to dysgenic selection and genetic degradation. Response to selection may be minimal in one or two generations but could be significant after several generations.

- Natural regeneration can be a valuable tool on forest lands for which genetic conservation is an important objective.

- Natural reproduction may maintain a forest cover, but does not ensure desired species composition, stocking and distribution, or timely stand reestablishment (Lavender and others 1990).

Good overviews of the subject are the series of articles in Hobbs and others (1992) and Lavender and others (1990).

Direct Seeding and Planting

Conifers-Studies on planting western conifers began in the early 1900s (Munger 1911, Show 1930). The need for reforestation of the great Yacolt (1902) and other burns in southwestern Washington led to establishment of the Wind River nursery and initial planting programs. Also, the decision to use clearcutting on Federal lands (Munger 1950) and the Tillamook burns (a series of fires in 1933, 1939, 1945, and 1951 that burned over 360,000 acres in northwestern Oregon and created the area once known as the Tillamook Burn and now known as the Tillamook Forest) further stimulated both direct seeding and planting in the Pacific Northwest. The major blowdown and subsequent salvage operation resulting from the Columbus Day storm of 1962 was an additional catalyst for large-scale planting.

Prior to the Yacolt, Cispus, and Tillamook fires, most cutover lands were reforested by natural regeneration. Although seed trees were frequently retained, insufficient numbers of well-distributed seed-producing trees following intense fire and seed predation by small mammals (Hooven 1958, 1970; Schubert and Adams 1971) strongly limited

the usefulness of the method. Direct seeding was used in early reforestation of the Tillamook Burn. Annual projects of 10,000 to 15,000 acres were seeded with Douglas-fir seed treated with rodenticides. Seed treatments were only partially successful in preventing seed predation. Also, direct seeding was limited by inadequate seed supplies and the fact that large, contiguous areas were needed for efficient application of aerial seeding. Although direct seeding accounted for reforestation of about 50 percent of the Burn, emphasis on planting increased as reforestation progressed.

State forest practices acts also affected reforestation practices. Thus, the Oregon State Forest Practices Act (1941), which required either leaving seed trees or planting, was changed in 1971 and subsequent years to require that reforestation efforts on clearcuts begin within 12 months, planting must be completed within two planting seasons, and at least 200 trees per acre must be "free-to-grow" within five growing seasons of planting. Current Forest Practices Board regulations for western Washington require at least 190 established and well-distributed seedlings per acre within 3 years after clearcut harvest.

Tree spacing in early plantations was often close (6 feet or so) but was later increased substantially on most lands (to 10 or 15 feet or more) in the hope that planting costs could be reduced and the need for precommercial thinning avoided. Early plantation spacing trials also showed poor development at close spacings. At the opposite extreme, most owners concluded that problems with very wide spacing, such as large branches, lack of opportunity to select trees during juvenile respacing, and unstacked areas resulting from early mortality, more than offset the decreased costs of planting stock and labor. And, there is some recent evidence indicating that early tree development is slower at very wide spacings than at intermediate spacings (Scott and others 1998). The most commonly used spacings at present are 10 to 12 feet, differing somewhat with species and ownership.

Most spacings have been nominally square, but with hand planting on areas that typically have numerous large stumps, down logs, and slash accumulations, there is usually considerable irregularity in spacing and geometrical arrangement, although less than exists in most natural stands.

Tree mortality was often high in the early plantations, and research sought to increase seedling survival and growth. This research had two major facets: (1) studies of seedling size and morphology (Hermann 1967, Iverson 1984, Jenkinson 1980, Newton and others 1993); and (2) studies of seedling physiology with particular emphasis upon the effects on seedling vigor of nursery practices such as lifting date, storage, and fertilization (Hermann 1967; Hermann and others 1972; Lavender 1964, 1984, 1985, 1988, 1990a, 1990b; Lavender and Hermann 1970; Lavender and Waring 1972; Lavender and others 1968; Ritchie 1984; van den Driessche 1984; Winjum 1963).

This research produced methods for growing high-quality seedlings of the major commercial conifer species (Duryea and Dougherty 1991, Margolis and Brand 1990). This work also provided a physiological basis for understanding seedling growth potential and stress from planting or planting site conditions. Foresters have developed guidelines to select stock types best suited to various microsites on harvested areas and improved methods for handling and planting of seedlings (Rose and others 1990). As a consequence, average survival of seedlings has increased to 85 percent or better.

Competition from other vegetation also affects regeneration success. Consequently, extensive research (Stein 1995, Stewart 1978, Stewart and others 1984, Walstad and Kuch 1987) has addressed effects of such competition and methods for controlling it when needed. Control of grasses, forbs, and shrubs often is used to ensure favorable light conditions and adequate soil moisture for seedling survival and growth. The degree and nature of competition is strongly related to site and plant association. Competition for moisture is most severe on dry sites in southwestern Oregon. On good sites in the high rainfall areas along the Pacific coast, shading by tall shrubs and hardwoods is generally of more concern.

The small openings created in the group shelterwood or group selection methods (Smith 1986) are similar to those created by small-scale disturbances by wind, insects, or root disease. Experience in regenerating small openings (0.5 acre) on OSU's McDonald Research Forest indicates that the reforestation methods used in larger clearcuts can be applied. After 4 years, growth and survival of planted seedlings in the openings were not different from that in clearcuts (Ketchum 1994). This similarity in seedling development will probably not continue unless openings are widened. As with clearcuts, animal browsing and shrub competition affect seedling survival and growth in these small openings. There is a great deal of variability among openings: some with high light intensity developed covers of grass or low shrubs; others with low light levels became dominated by tall shrubs. Grand fir *(Abies* amabilis Dougl. ex Forbes) appears better suited to regeneration in small openings than Douglas-fir, because the former is browsed much less and is more shade tolerant. Natural Douglas-fir regeneration was not plentiful in these small openings, although it was abundant in adjoining stands where 10 to 12 trees per acre have been left.

Although 0.5-acre openings were used in the study described above (McComb and others 1994), larger openings or a variety of opening sizes might be more appropriate. Size of opening, aspect, and height of surrounding trees will all affect seedling development. Thinning the stand between the openings or widening openings may be needed to increase light and growing space for the young conifers in openings, especially when on north aspects or surrounded by tall trees. Twenty-seven years of observation of openings of similar size in the Challenge Experimental Forest in northern California showed substantially reduced establishment and growth of natural regeneration, compared to larger openings (Aune 1996, McDonald 1976a). Isaac (1943) recommended openings of 1 acre or larger. Openings of 2 to 5 acres should both facilitate stand treatments and assure satisfactory development of regeneration (Curtis and Carey 1996).

Hardwoods-The ecological and economic roles of hardwoods, particularly red alder and black cottonwood *(Populus trichocarpa* Torr. & Gray) and Populus hybrids, have received increasing recognition during the past 20 years (Comeau and others 1996, Heilman and others 1991, Hibbs and others 1994). Both genera are rapid-growing, shade-intolerant pioneer trees that require bare or new soil to regenerate naturally. Thus, natural stands commonly occur along streams and other areas where soil has been exposed and moisture conditions are favorable.

Several industrial firms have recently begun to plant and intensively manage both alder and cottonwood. The primary objective of pure red alder plantings is raw material for solid wood products or fine papers. Mixed species plantings of hardwoods and conifers are less common and occur primarily on public lands; they are established mostly to enhance site productivity (through nitrogen fixation by alder), riparian habitat, and forest biodiversity. Plantations in the Wind River Experimental Forest (Miller and Murray 1978, 1979) and the OSU McDonald Forest demonstrate the gains possible with mixtures of alder and Douglas-fir. Also, red alder is immune to the common root rots that affect conifers and is thus a suitable species for planting in areas severely infected with *Phellinus weiri* (Thies and Sturrock 1995). Although competing vegetation may need to be controlled, trees can be planted successfully without the extensive exposure of bare soil needed for natural seeding.

Hybrid cottonwood plantations for fiber production have been established on marginal agricultural land along the lower Columbia River, in northwest Washington and British Columbia, and on irrigated sagebrush-steppe land in the Columbia basin of eastern Washington and Oregon. Rectangular spacings are sometimes used to facilitate cultivation between rows. These plantations are grown as agricultural crops and are harvested 6 to 8 years after planting (fig. 16). Such very intensive short-rotation re-gimes imply a likely future need for agricultural type soil amendments if they are to be sustainable.

With superior hybrid clones, optimal spacing, suitable soils, effective weed control, and in some cases irrigation and fertilization, poplars planted in the Pacific Northwest may average 60 feet in height and 6 to 7 inches in diameter at 6 years. Stemwood produc-tion rates may reach three times average production of Douglas-fir under conventional management regimes (Curtis and others 1981, DeBell and others 1996). One acre devoted to such management can produce as much wood as 3 acres under conven-tional forest management or even more devoted to extensive multipurpose manage-ment. Thus, in a mix of approaches, clonal poplar culture can reduce pressures on other lands and create additional opportunities to emphasize other uses on these other lands.

Figure 16--Hybrid cottonwood plantation, 4 years after planting. On suitable soils, such planta-tions can be grown as agricul-tural crops giving high fiber yields on very short rotations.
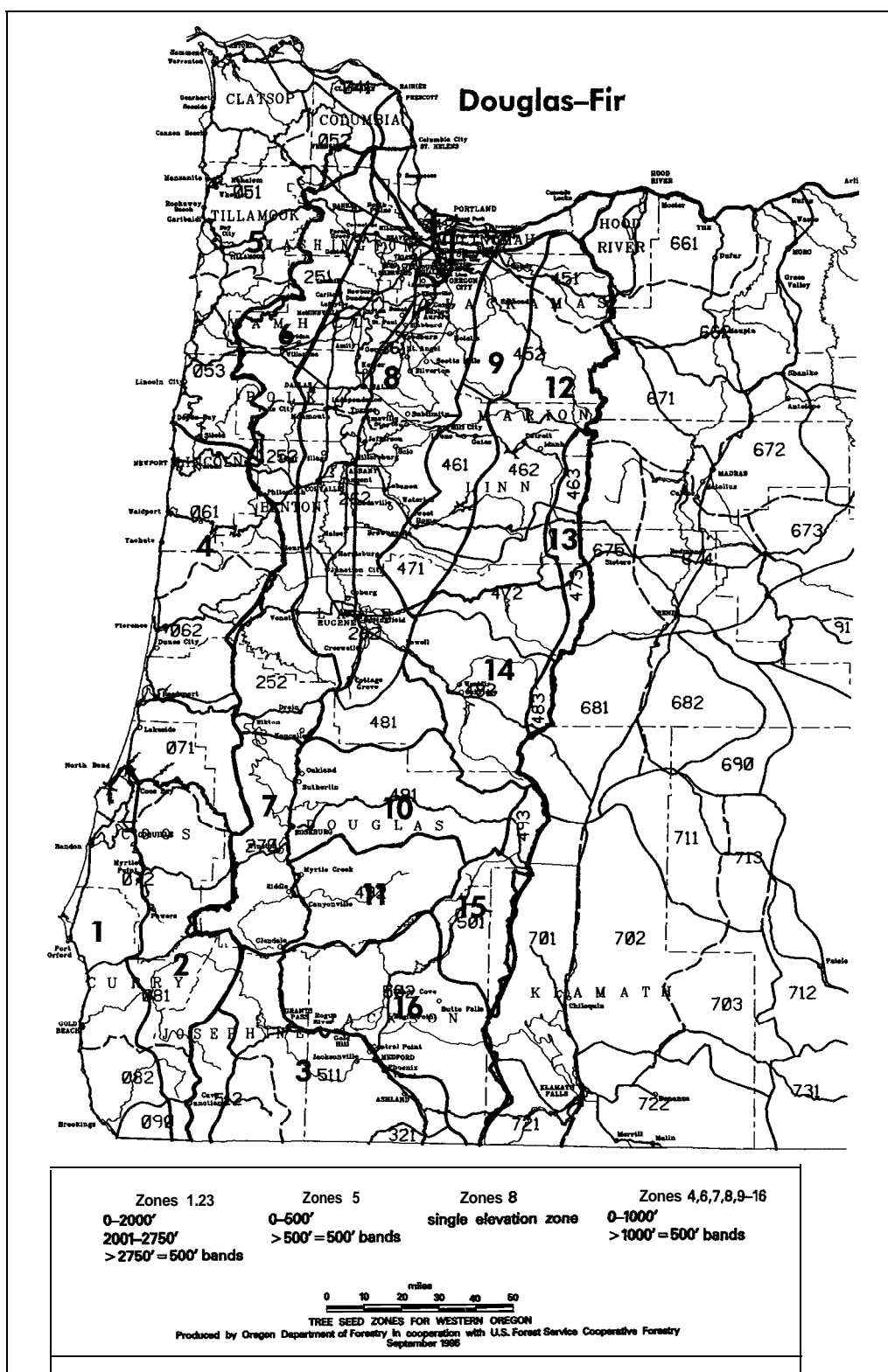
Figure 17-Seed collection zones have been established to ensure that planting stock is adapted to local climatic conditions.

Genetic considerations in planting-Basic and applied research in forest tree genetics has contributed to planting programs for several decades. Proper seed source selection and deployment is important to ensure high productivity and long-term stability of planted forests. Two general sources of seed are (1) seed collected from parents in commercial forests or forest reserves, and (2) seed from tree improvement programs, usually produced in seed orchards. Both assume that seed originating from parents near the planting site is best adapted to that site. Seed zones and seed transfer rules are used to ensure adapted seed sources from commercial forests or reserves. Restrictions in mating of parents from different locations ("breeding zones") are used to ensure adapted progeny from tree improvement programs.

The degree of local adaptation depends on the genetic structure of the species; that is, whether genetic variation is predominately among individuals or among populations of different geographic origin. Thus, western white pine has considerable genetic variation within stands but little variation among populations (Campbell and Sugano 1989, Rehfeldt 1979). Western white pine seed therefore may be safely moved over large geographic and elevational distances, and breeding populations in tree improvement programs may encompass parents from a large area. Douglas-fir typifies species with considerable genetic differences among populations and strong geographic patterning (Campbell 1979, 1986; Campbell and Sugano 1993; Hermann and Lavender 1968; Rehfeldt 1989; Silen, 1982; Sorensen 1983). Thus, a considerable number of seed zones and breeding zones are recognized for Douglas-fir.

Seed zones and seed transfer rules were first developed in the Pacific Northwest in the 1960s as a consequence of early observations of poor growth and survival of plantations established with seed from distant, apparently poorly adapted sources. Seed zone maps (first published in 1966, revised in 1973) were based on local knowledge of topography, climate, and tree growth. These maps have since been extensively used to certify origin of forest tree seed. Later, knowledge of geographic genetic variation for individual species led to the development of mathematical models to more effectively determine safe limits for seed movement (Campbell 1979,1986; Campbell and Sugano 1987, 1989, 1993). In general, the greater the environmental difference between the planting location and the seed origin, the greater the risk of maladaptation. Recently, new seed transfer guidelines and maps have been developed for individual species in western Oregon based on current knowledge of geographic genetic variation (Randall 1996; fig. 17). The new guidelines are less restrictive, particularly for north-south movements.

Seed orchards in the Pacific Northwest are beginning to produce a considerable amount of seed, and genetically improved planting stock is being used increasingly for reforestation. Tree improvement programs in the region constitute a considerable investment in enhancing productivity on commercial forest lands. Progeny from more than 42,000 parent trees are being tested in over 1,300 test plantations covering over 10,000 acres with an investment estimated at approximately a quarter-billion dollars (Adams and others 1990). Data from these tests are used to rogue (see "Glossary") seed orchards and select parents for the next generation of improvement. More than 10 species are included in tree improvement programs, but most effort is focused on

Douglas-fir. The primary trait of interest is increased stem volume growth. Wood quality, tree form, disease resistance, and adaptation to environmental extremes are given varying emphases in different programs and species.

Adaptation is maintained in improved populations by working with many small, localized breeding populations, particularly for programs in western Oregon and Washington (Adams and others 1992, Silen and Wheat 1979). The small breeding zones may be overly conservative, and opportunities exist in future generations to extend the geographic range of parents in a breeding program (Lester 1986, Stonecypher and others 1996). Genetic sources should be tested over a large geographic area to define the limits of adaptation, and these tests also should include screening for important adaptive traits such as drought tolerance and cold hardiness (Aitken and Adams 1996, Zhang and others 1994). Compared to agricultural crops, trees are long-lived and subject to greater risk from weather extremes. Early results should be interpreted cautiously, in view of failures of some seed sources in long-term studies and plantations after many years of previously good growth (Silen and Olson 1992). Risk of maladaptation is minimized by including many parent trees in a program, both within the initial base population (usually more than 200 selections originating from throughout the breeding zone) and within the population that is deployed (seed orchards usually include more than 50 unrelated clones or families). Deployment of mixtures of seed of parents from different environments may provide another opportunity to create stands with a broad base of genetic diversity, particularly given the uncertainty of future climates.

Figure 18-Western white pine (A) is a fine species that has been nearly eliminated from Northwestern forests by blister rust, a disease accidentally introduced in the early 1900s. (B) Selection for blister rust resistance has provided resistant planting stock that promises restoration of this species in Northwestern forests. Pruning provides additional protection against infection (spores are most abundant near the ground) as well as improved wood quality.

Results from genetic tests indicate heritable differences that support tree improvement investments, although empirical evidence of realized genetic gains in stand (as opposed to individual tree) productivity is lacking. The gains to be achieved from tree improvement appear substantial, particularly because even small gains add up quickly when spread over a large land base. Estimates of genetic gains, however, depend on many factors. Some factors differ among programs and landowners (e.g., selection intensities in seed orchards), some are difficult to measure annually (e.g., unequal contributions of parents and pollen contamination in seed orchards), and some involve untested assumptions (e.g., the effects of selection at young ages and before appreciable competition). Much forest genetics research is aimed at addressing these factors, and stand-level plots are being established in the region with the goal of providing estimates of realized genetic gains to be incorporated into growth and yield models (St. Clair 1993).

Multipurpose silviculture and ecosystem restoration stand to benefit greatly from regional tree improvement programs. The rapid juvenile growth of improved planting stock may help alleviate stand establishment problems associated with reduced site preparation, increased competition from grass and shrubs, and animal browsing. Rapid growth also may promote stand development, allowing us to achieve desired tree sizes and stand structures more quickly. Restoration efforts may benefit from an assured supply of seed from seed orchards, particularly from species and populations with infrequent seed years. The development of disease-resistant planting stock allows continued planting of species such as western white pine and sugar pine *(Pinus lambertiana* Dougl.) that might otherwise be extirpated from large areas (fig. 18).

Genetic diversity is a key component of biodiversity, and continued care in the management of genetic diversity is essential to long-term ecosystem health. Components of genetic resource management include adherence to guidelines for the movement of seed, avoidance of disgenic selection practices, proper design of advanced generation breeding programs to maintain adapted and diverse populations, proper deployment of genetically improved planting stock, and an active genetic conservation program. Resource managers and restoration specialists are beginning to plant and transfer seed of many species for which we have no guidelines for seed movement. Development of seed transfer guidelines is badly needed for these noncommercial tree, herbaceous, and grass species. Until guidelines are established, seed from local populations should be used as much as possible. Genecological studies are critical to the development of seed transfer guidelines, as well as to the design of genetic conservation and breeding programs.

Site preparation-Considerations and methods similar to those previously discussed under natural regeneration also apply to establishment of stands through planting. There are some differences, however. Normally, planting immediately follows (or should follow) harvest, and planted seedlings commonly make more rapid early height growth than do natural seedlings. Consequently, the period during which control of competing vegetation must be continued is often considerably shorter with planting than with natural regeneration. Exposure of mineral soil often may be unnecessary or can be limited to the actual planting spot. But, an additional objective of removing or reducing heavy slash and shrubs or undesired tree species is to remove physical obstacles to planting crews.

Summary-Successful planting requires careful attention to the details of seed source and nursery and planting practices, as well as a thorough evaluation of environmental conditions (Hobbs and others 1992) and control of competing vegetation, where needed. Microclimate, competition from herbs, shrubs, and hardwoods, and animal browsing (discussed in a later section) often affect seedling survival and growth. The effects on early growth also carry over into later stand development.

Cafferata (1986), Cleary and others (1978), Hobbs and others (1992), and Lavender and others (1990) provide excellent overviews of the application of current reforestation practices. Guidelines for conifers (DeYoe 1986, Schubert and Adams 1971, Strothman and Roy 1984) and hardwoods (Ahrens and others 1992) are available. In summary, measures must be taken at all stages to ensure careful attention to the following:

- Proper selection of seed source and proper seed handling

- Nursery procedures that optimize seedling vigor, and storage and handling procedures in nursery and field that minimize seedling dehydration, respiration, and damage

- Careful planting, including onsite inspection of planting procedures

- Site-specific prescriptions for site preparation and weed control

- Monitoring for 3 or more years to ensure seedling survival and growth

- Early thinning to control stocking and species composition

The ability to consistently regenerate forests with present technology is demonstrated in the annual reforestation report of the Oregon State Board of Forestry for 1992. This shows that of 85,689 acres of private land requiring reforestation by the end of 1992, 82,034 acres or 96 percent were in compliance with the standards of the Oregon State Forest Practices-Act.

Shaping Development of Young Natural Stands and Plantations

The choice of regeneration system and decisions about patterns of cutting, including retention of live and dead trees, influence the nature of a regenerating forest after harvest and affect later growth. Subsequent silvicultural treatments are the tools for shaping development of established stands to meet specific or multiple objectives, which may change over time and over the life of the stand.

During the past half century, silvicultural practices (harvest systems, spacing control, vegetation management, and-to a lesser extent-fertilization and pruning) have been applied throughout the world, wherever soils and climate, social policies, and markets combine to favor long-term forestry enterprises. Research, development, and implementation of these practices were justified primarily by the quantity or quality of wood that could be grown or harvested, although other goals also were served. The basic knowledge and experience acquired, however, can be applied to meet additional objectives. Appropriate further silvicultural investments may be justified to meet expanded social desires and concerns for other forest values and products, provided that goals are specified in terms of desired forest conditions and mechanisms exist for equitable (or acceptable) distribution of associated costs and benefits.

In this section, we first provide some background on changing societal expectations and their influence on silvicultural opportunities. Then, we describe several silvicultural practices, how conventional application influences stand development, and how they might be applied or modified to meet other or additional objectives.

Social Expectations and Silvicultural Opportunities

It has long been recognized that forests provide the multiple benefits of timber production, watershed protection, wildlife habitat, recreational and aesthetic values. Increased attention to nontimber values is now demanded by various segments of society and required by public law. As these values and the stand conditions required to produce them become more clearly defined, their provision and enhancement over time will require silvicultural manipulation of stands, integrated at the landscape level.

Although managed forest landscapes may appear more natural and more diverse than landscapes associated with most human endeavors, extensive areas of young managed plantations do contrast markedly with natural mature and old-growth forests. Many of the features associated with older natural forests (Franklin and others 1981, Ruggiero and others 1991) are reduced or absent in young stands, whether managed or unmanaged (Carey and Johnson 1995); and many are minimized with conventional short-rotation plantation management. Such features may include large trees, snags, down woody debris, "ragged" edges, within-stand structural complexity, and diversity in age, size, shape, and distribution patterns of stands across the landscape (Hansen and others 1991, 1993). Many of these features contribute to habitat for wildlife (Brown 1985, Hunter 1990, Thomas 1979) or are otherwise thought by some groups or individuals to be related to or essential to other forest values and general forest health. Existing young natural stands (or plantations) will not necessarily develop into stands comparable to present old-growth in the absence of human intervention. The desire to retain such features or to produce similar features in managed forests has stimulated interest in various modifications of conventional silvicultural practice (Carey and Curtis 1996, DeBell 1989, DeBell and Curtis 1993, Franklin and others 1986, Kohm and Franklin 1997).

The general nature of silvicultural practices needed to foster structural features similar to those of natural mature and old-growth forests is fairly apparent, but the specifics of implementation are not. It may be obvious, for example, that a given feature (such as a shrub species in the understory) provides important habitat for one or more species. But little is known about the response of the forest ecosystem or of other species to various levels or distribution patterns of that feature. Even less is known about other biological or economic costs and benefits associated with such management. Appropriate practices undoubtedly will differ with forest types, landscapes, specific stand and site conditions, and public preferences. These uncertainties should not be used to justify reluctance or failure to modify conventional practices. But they should foster a skepticism of widespread implementation or legislative requirement of untested, highly specific modifications, particularly in the absence of effective monitoring efforts. And such uncertainties also should stimulate soundly designed experiments to test and compare a range of approaches or options.

Figure 19-(A) An exceptionally uniform plantation in the Mount St. Helens blast area. Aerial photography (B) shows that the unthinned stand is actually much less uniform than it appears from the road. Conventional thinning (C) increases uniformity, but heterogeneity can be enhanced by irregular thinning (D).

Figure 20-The Wind River plantation spacing trial is a striking example of the effects of differences in initial spacing on a relatively poor site, without subsequent thinning: (A) 4-foot spacing, and (B) 12-foot spacing, 71 years after planting.

The greatest near-term opportunity to develop such management knowledge and experience and to provide more diverse habitat lies in the millions of acres of existing plantations, which range in age from 1 year to 40 or 50 years. Plantations are sometimes disparaged as uniform monocultures of minimal or even negative value for purposes other than wood production. This view arises in part from the fact that many plantations in the Pacific Northwest are now in the early stem exclusion stage, in which relatively uniform and dense canopies have eliminated most understory vegetation. Moreover, plantations usually appear much more uniform when viewed from a highway or forest road than they are in fact (fig. 19). Even without further management, this uniformity is gradually modified by natural processes of stand development and by such agents as root diseases and snow breakage, in a manner similar to that occurring in natural stands (Silviculture Interpretations Working Group 1992). Many plantations established 40 or more years ago are now barely recognizable as plantations. With appropriate management, stand differentiation can be accelerated (Curtis and others 1997). Most of these plantations are now in a highly plastic stage of development, and there are major opportunities to mold them-individually and in a landscape context-toward a variety of objectives.

Objectives will differ by ownership, geographic location, condition of surrounding stands and landscapes, and public desires. Rapidly growing uniform stands focused primarily on wood production will be a major or sole management objective for some plantations. Accelerated development of habitat for threatened or endangered species may be the primary objective in some others. Many owners and managers will have multiple objectives, which can be met through use of a variety of silvicultural practices. A number of modifications of conventional silvicultural practices merit consideration and some are now being applied by several landowners and organizations.

Early Density Control

Initial density has a strong influence on subsequent stand development (Dilworth 1980, Omule 1988, Reukema 1979, Reukema and Smith 1987, Smith and Reukema 1986). The effects of initial plantation spacing in the absence of subsequent stand treatment are well illustrated in the Wind River spacing test (figs. 20 and 21). In dense naturally seeded stands and in plantations established at close spacings or having a substantial component of naturally seeded stems (fig. 22), early thinning (=precommercial thinning =respacing) is often needed to keep stand density within acceptable limits.
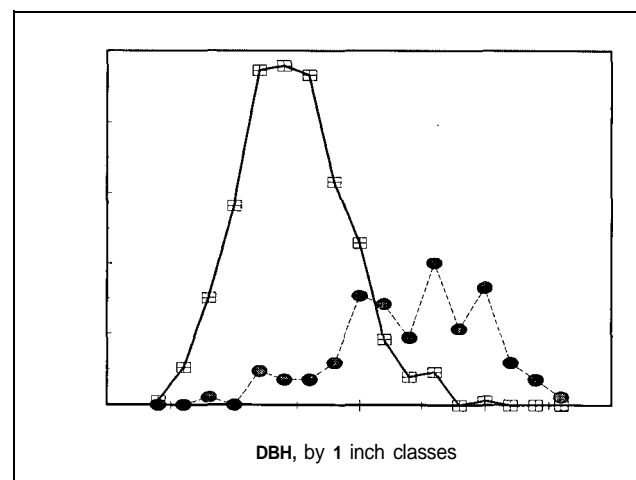

DBH, by **1** inch classes

Figure 21-Differences in initial spacing have produced widely different diameter distributions in the Wind River spacing test. Numbers of trees per acre by diameter classes in the 6- and lo-foot spacings in 1991, 66 years after planting.

Figure 22-Excessive tree numbers without subsequent thinning produce stands with small diameters, slender boles, and small crowns, with little understory vegetation (A). Such stands become very susceptible to breakage from wind, ice, and snow (B).

Figure 23-Precommercial thinning of dense young stands accelerates tree growth, promotes understory development and browse production, and allows selection of the better individual trees. Young noble fir stand (A) before and (B) after precommercial thinning.

Precommercial thinning is commonly applied near the end of the stand initiation stage (10 to 15 years) to enhance survival, growth, and value of future crop trees (fig. 23). Thinnings usually are aimed at leaving the most valuable larger trees at relatively even spacing (Reukema 1975). This treatment increases stand uniformity; but the reduced stand density also accelerates tree growth (Hoyer and Swanzy 1986, Omule 1985) and may promote development of a shrub and herbaceous understory and browse production. It frequently also leads to early establishment of natural regeneration of tolerant tree species, such as western hemlock and western redcedar (Curtis and others 1997).

Past prescriptions sometimes overemphasized current market values or current tree size. Thus, western redcedar often was discriminated against in early respacing of stands on the Washington coast, where long-term growth potential of the species is high and the species has considerable value for wildlife and possibly in nutrient cycling. Hardwoods such as red alder (useful in nitrogen fixation) and bigleaf maple likewise have been singled out for removal.

A number of modifications to promote biodiversity are possible and have been applied to a limited extent on some public lands. These modifications involve selection criteria for residual trees, spacing distances, and intentional creation of small openings. Trees left after thinning can be selected to increase diversity in size and species, thus accelerating stand differentiation and increasing structural complexity. Many spacing prescriptions on public lands now specify that occasional hardwoods, western redcedar, Pacific yew (Taxus *brevifolia* Nutt.), and western white pine shall not be cut during thinning, although they are not actively favored. Wide spacing, either initial or in early thinning, will enhance development of understories and large live crowns and branches. Spacing can be varied in patches throughout the plantations, and some patches may be retained in an undisturbed condition. Small openings or gaps can be created to retain some components of the early stem initiation stage and later develop patches of young trees. Park and McCulloch (1993) give some guidelines for such operations.

Thinning in Older Stands

Thinning in older stands (=commercial thinning) has long been a generally accepted practice in European countries and rests on over a century of experience and research embodied in an enormous literature (Braathe 1957). Commercial thinning was not widely applied in the Pacific Northwest until very recently, because large volumes of old timber were available, markets for smaller and poorer quality material were limited, and equipment then available was not well suited to thinning operations. But the economic, technical, and social context has changed, and thinning is rapidly increasing in importance. It provides opportunities to both produce wood and enhance nontimber objectives. Thinning combined with extended rotations can maintain visually attractive forest cover for long periods while still producing wood products and current income.

A considerable body of thinning research exists in the Pacific Northwest, dating from about 1950 (Curtis and Clendenen 1994; Curtis and Marshall 1986; Hilt and others 1977; King 1986; Marshall and others 1992; O'Hara 1990; Oliver and Murray 1983; Oliver and others 1986; Omule 1985; Reukema 1972; Reukema and Bruce 1977; Reukema and Pienaar 1973; Worthington and Staebler 1961a, 1961b). A number of more or less equivalent density control guides and density measures are available for planning and administering thinning activities (Curtis 1982, Drew and Flewelling 1979, Long and others 1988, Reineke 1933). Several publicly available simulation models and a number of proprietary models exist that provide useful guidance in developing stand management regimes; for example DFSIM (Curtis and others 1981, Fight and others 1984), ORGANON (Hann and others 1995), WinTIPSY (Mitchell and others 1995), STIM (Bonnor and others 1995), SPS (Arney 1988), and FPS (Arney 1995).

The traditional purposes of thinning are to harvest potential mortality, maintain or increase growth rates of remaining trees of desired species, and promote stem quality and tree vigor while producing intermediate income. Thinned stands produce larger trees at any given age than do unthinned stands; thinned stands are more open and sometimes more diverse. One recent study in the Pacific Northwest (Marshall and others 1992) showed that over a 20-year period repeated thinning in a young stand on a good site produced increases of 33 to 56 percent in diameter growth of the largest 40 stems per acre, compared to the unthinned condition (fig. 24). Thinning also provides income and timber flow during the intermediate stages of stand development.
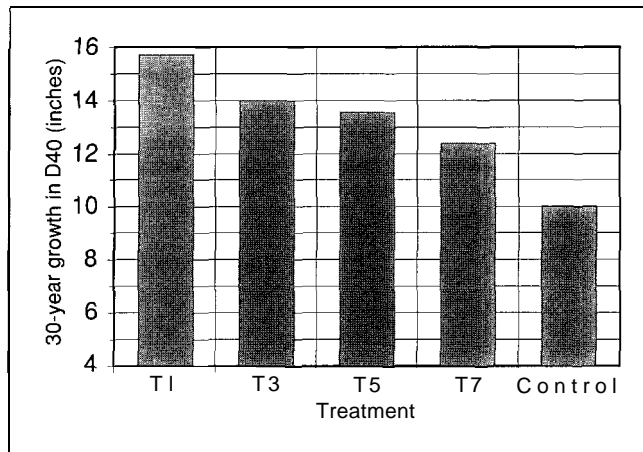
Figure 24-Thirty-year increment (ages 20 to 50) in average
diameter of the largest 40 trees per acre, for four treatments
involving early and repeated thinning and a control. Thinning
treatments range from one with low growing stock retention (TI) to
one with high growing stock retention (T7). Data are from Hoskins
LOGS study (Marshall and others 1992).

Most past thinning studies were oriented to timber production, but thinning also strongly
influences other stand attributes. Thinning, depending on how it is done, may or may
not promote vertical stratification (figs. 25 and 26). It usually accelerates understory
development and succession and movement of the stand into the understory reinitiation
stage. If begun early, changes can be striking over comparatively short periods (fig.
27). Operationally, there can be considerable loss of understory from damage during
thinning. If understory reduction is considered undesirable, such effects can be mini-
mized by training, use of designated skid trails and corridors, proper equipment, and
heavy initial thinning that allows relatively long intervals between subsequent thinnings.

Most thinning research has been done in young and intermediate-aged stands (<60
years). Opportunities to influence tree and stand development through thinning are
greatest if thinning is begun early. A first thinning that is delayed until after stands have
developed high relative densities and shortened crowns involves an increased risk of
windthrow and snowbreakage as well as delayed growth response and therefore must
be lighter (usually) than an early initial thinning. Crown expansion potential slows with
age, and therefore thinnings should generally become lighter and entries less frequent
as stands age; however, even late thinning in vigorous, relatively old stands (>lOO
years) can be effective in capturing some mortality, maintaining stand vigor, and
reducing losses from insects and disease (Williamson 1982, Williamson and Price
1971). The maximum age at which thinning is justified in relatively vigorous stands is
more a matter of owner objectives than biological limitations. Financial returns and
development of specific habitat characteristics may be important considerations.

A less obvious but important effect of repeated thinning is that trees and stands main-
tain rapid growth to older ages than without thinning. Culmination age (age that maxi-
mizes wood production) has yet to be determined for repeatedly thinned Douglas-fir in
the Pacific Northwest, but it is greater than for dense unthinned stands (Curtis 1994,

Figure 25-Thinning on good sites can produce large trees and considerable vertical structure within relatively short periods: (A) Delezenne thinning study (Curtis 1995, O'Hara 1990) at age 73, first thinned at age 36, natural origin; and (B) developing hemlock understory in a thinned stand, Soleduck Ranger District, Olympic National Forest, Washington.

Figure 26-Late thinning in a poor site stand of natural origin, first thinned at age 60, and now 117. Mount Walker thinning study: (A) heavy thinning, and (B) unthinned control.

Figure 27-On good sites, early thinning can greatly accelerate diameter growth and markedly alter stand structures. These photographs from the Iron Creek LOGS study at age 45 (Curtis and Clendenen 1994) show (A) untreated control plot containing planted trees plus much natural regeneration, (B) plot with repeated light thinning, and (C) plot with repeated heavy thinning, showing understory western hemlock, western redcedar, and shrubs and vertical structure developing in response to thinning.

1995; Curtis and Marshall 1993; Worthington and Staebler 196la). Where terrain and harvesting methods permit thinning, large trees can be grown on longer rotations, with no loss and perhaps even an increase in annual wood production per unit area. Stem quality and value per unit of volume may be increased. Repeated thinnings on extended rotations can maintain forest cover for long periods while providing current income and employment (Curtis and Carey 1996, Lippke and others 1996), maintaining tree and stand vigor, promoting stand health and stability, and developing stand structures favorable to certain wildlife species associated with late successional stages (Carey and others 1996a). It also may provide additional opportunities and flexibility to capture benefits from stands composed of mixed species with differing tolerance and growth patterns.

Thinning encourages seedling establishment of shade-tolerant conifers (Del Rio and Berg 1979), hardwoods (Fried and others 1988) and shrubs (Huffman and others 1994, O'Dea and others 1995, Tappeiner and Zasada 1993), but it also results in vegetative expansion of shrubs by rhizomes (Tappeiner and others 1991) and layering. By reducing overstory density and providing a seedbed, thinning results in invasion by new plants not previously in the stand (Carey and others 1996b) and the spread of those already established. This generally produces a dense, diverse understory of shrubs, herbs, and tree seedlings and saplings that may provide enhanced wildlife habitat.

Regeneration of understory conifers after thinning often will enhance the development of stands with structures similar to mature and old-growth stands. On some sites, however, thinning may produce dense shrub layers that inhibit later establishment of desired conifers. Dense understories of salal, Oregon grape (Berberis nervosa Pursh), salmonberry, vine maple and other shrubs may develop and prevent establishment of a second layer of conifers. Conifer seed will germinate under such shrub layers but few seedlings survive. These shrub layers often are quite persistent. They produce new aerial stems annually that replace older stems as they die, thereby maintaining a dense cover for decades (Huffman and others 1994). On some sites (particularly at low elevations and in the Oregon Coast Range), some disturbance of these brush layers and possibly underplanting of conifers may be necessary to establish multilayer conifer stands.

Nutrient Management Nutrient management is an important consideration, particularly in the Douglas-fir region where soils are young and considerable nitrogen is immobilized in organic matter. Inadequate supplies of available nitrogen limit natural productivity and rates of stand development on many sites. Relatively small and infrequent applications of nitrogen fertilizers have been used to increase wood production in conventionally managed forests, and often produce striking responses in tree growth and stand development (fig. 28) (Chappell and others 1992b, Gessel and others 1979). The largest and most long-lasting responses occur when nutrient deficiencies are severe (Miller and Pienaar 1973, Miller and Tarrant 1983, Miller and others 1986) and when fertilizer application is combined with thinning (Brix 1993, Chappell and others 1992a).
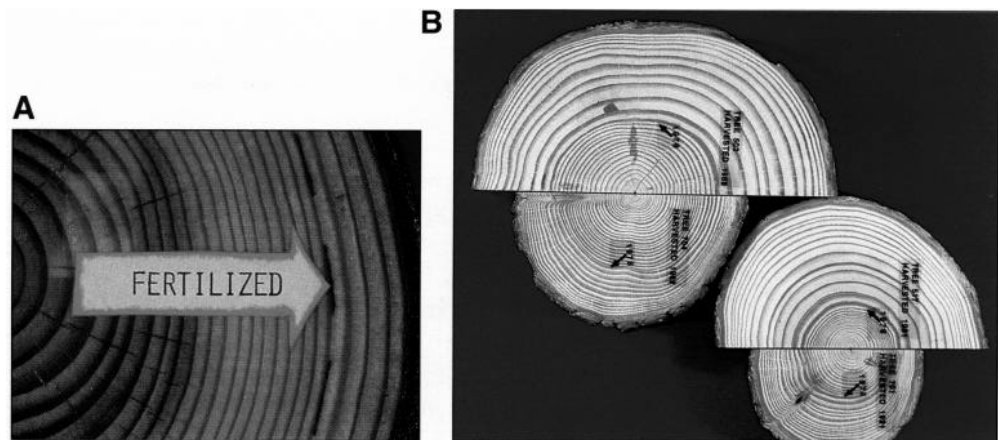
Figure 28--Relatively small and infrequent applications of nitrogen fertilizer often produce striking response in tree vigor and stand development, particularly on poor sites. Typical response in diameter growth (A), shown by wide growth rings commencing in the year following fertilization; and an extreme example of response (B) shown by paired stem sections, cut from trees on adjacent fertilized and unfertilized plots on a very poor site.

In newly established and very young plantations, broadcast applications of fertilizer produce earlier canopy closure and greater stand uniformity (DeBell and others 1986); in older stands where trees have begun to differentiate into crown classes, fertilizer application accelerates the stand development processes of crown differentiation and competition-related mortality (Miller and Pienaar 1973, Miller and Tarrant 1983). Other site resources, such as amount and nutritional quality of wildlife forage (Sullivan and Rochelle 1992), may be increased.

One modification of the conventional practice of broadcast application of fertilizer that could be considered is small-scale individual tree or group application. This could be used to promote development of a layered canopy and differences in understory vegetation, in contrast to broadcast applications that simply increase the overall rate of stand development. It also could be used to enhance growth and nutritional value of forage in openings created for that purpose. Individual tree application was deemed feasible and profitable nearly 20 years ago by scientists of the Washington Department of Natural Resources (Anderson and Hyatt 1979). Coupled with selective thinning and pruning, individual tree applications also could increase production of high-quality wood.

Introduction or favoring of nitrogen-fixing plants also merits consideration. These can provide benefits similar to those of fertilization on some nitrogen-deficient sites (Miller and Murray 1978, Tarrant and others 1983, Trappe and others 1968) and may have additional benefits in economic and ecological diversity. Natural red alder regeneration often is abundant in conifer plantations. Mixed stands could be established by retaining selected alder stems during precommercial thinning. Individual, scattered red alder trees have been favored in early thinnings of young conifer plantations on nitrogen-deficient soils of the Siuslaw National Forest (Turpin 1981). Early height growth is much more rapid in alder than in conifers, so wide spacing of the alder would be necessary to maintain the conifers. Unlike shade tolerant species, alder will not survive beneath a

conifer overstory. After 25 to 30 years on good sites, conifers that have not been suppressed will dominate the alder (Newton and others 1968). Stemwise (tree-by-tree) mixtures thus are difficult to maintain. Planting or retention of naturally established red alder in groups or small blocks within conifer regeneration should reduce the crown competition problems encountered in stemwise mixtures, while still providing nutrient benefits. A pure alder crop grown prior to establishment of a new Douglas-fir stand would have nutritional benefits for the latter and may be particularly appropriate on land heavily infected with Phellinus *weirii* (a serious root disease of conifers) because of alder's immunity (Harrington and others 1994). Other nonleguminous nitrogen-fixing species, such as Sitka alder *(Alnus sinuata* (Regel) Rydb.) (Binkley and others 1984, Harrington and Deal 1982) ceanothus *(Ceanothus* ssp.) (Binkley and Husted 1983), and leguminous species (Miller and Zalunardo 1979) may offer fewer competition problems and add some soil nitrogen and organic matter.

Mixed stands of red alder and conifers are more productive than pure conifer stands on soils with low nitrogen levels (Miller and Murray 1979), provided the conifers are not overtopped by the alder. An interplanting of red alder with Douglas-fir at Wind River Experimental Forest in southern Washington is a classic example of potential opportunities; nearly one-half century after planting, heights of dominant Douglas-fir grown with interplanted red alder were taller than those in an adjoining pure Douglas-fir stand by the equivalent of one full site class (Miller and Murray 1978). Volume of Douglas-fir in the mixed plantation equaled that in the pure stand, but it occurred on fewer and larger stems and hence had greater value. Total volume of Douglas-fir and alder in the mixed stand was double that of the surrounding pure Douglas-fir stand. Soil under the mixed stand contained about 1,000 pounds of nitrogen per acre more than soil under the adjoining pure Douglas-fir stand (Tarrant 1961, Tarrant and Miller 1963).

Such mixed species stands might also benefit some wildlife species (McComb 1994). Mixed plantations of red alder and Douglas-fir also have been established by William Emmingham and Denis Lavender at OSU's McDonald Forest. The purpose was to use alder's nitrogen-fixing ability to increase growth of Douglas-fir while producing greater diversity in both the tree and herbaceous layers than might occur in a pure Douglas-fir stand. Because of alder's rapid juvenile height growth rate, alder in this instance was planted when the Douglas-fir was over 15 feet tall. Early data demonstrate that competition with Douglas-fir improves the form of alder and that the Douglas-fir are 30 percent larger than saplings in pure stands, although spacing also may be a factor in the observed size differences.

Planting different species in small groups rather than as stemwise mixtures should avoid many of the problems in maintaining stemwise mixtures, although some of the possible benefits may be delayed or foregone. Harrington and Deal (1982) examined comparative height growth patterns of Sitka alder and Douglas-fir and provide recommendations for planting mixtures of this less competitive species with Douglas-fir to avoid overtopping the Douglas-fir while providing a source of nitrogen.

Pruning

Pruning (removal of branches from the lower bole) has been advocated primarily to increase the amount of clear wood produced in young stands (Hanley and others 1995). Pruning has been little used until very recently because of uncertainties about economic returns and future markets, but there is now increased interest and operational application by some owners. It has also been recommended as part of a program to control blister rust in western white and sugar pines (Russell 1988). Most pruning for improved wood quality has been in stands in the stem exclusion stage. Current practice is to begin pruning much earlier than was common in the past. Pruning may be done on all trees, but-to reduce costs-often is confined to a subset of trees corresponding to the number expected to be retained after future thinning.

Pruning gives stands an open appearance, which may make them more attractive aesthetically. If begun before stand closure, removal of lower branches could increase the amount of light reaching the forest floor and favor development of the woody and herbaceous understory (which also may somewhat reduce overstory growth). Because some wildlife species use branches as hunting perches or use some trees with long continuous crowns, there may be benefits, in addition to cost savings, to retaining some unpruned trees within pruned stands. In regimes with repeated thinning on relatively long rotations, removal of some pruned trees during thinning might increase financial returns and perhaps offset some costs of other silvicultural activities.

Summary, Shaping Development

There are many opportunities for directing development of young naturally established or planted stands toward desired future conditions. Well-established techniques are presented in standard texts such as Smith and others (1997). Although many were originally developed to promote wood production, these techniques are equally applicable to production of multiple forest benefits. These techniques include:

- Initial planting spacing or early thinning, or both, can be used to control spacing and species composition.

- Thinning can be applied in older stands to:

  -control species composition and stand structure

  -shorten the duration of the stem exclusion stage and enhance understory development

  -produce larger, more valuable, and visually more attractive trees at any given age

  -produce current income while maintaining visually acceptable forest cover for long periods

  -promote forage production

  -promote tree and stand health

  -forestall or harvest mortality

- Nutrient management can improve stand vigor and growth rates through application of fertilizer on nutrient deficient sites, or through use of nitrogen-fixing species (such as red alder) as alternatives to artificial fertilizers.

- Pruning can improve quality and value of wood produced, help control blister rust in white and sugar pines, and give stands a more open appearance.

Harvesting Considerations

Timber harvest and the subsequent site preparation and regeneration are probably the most influential of all operations that can be carried out in multipurpose forests. The methods used and the manner in which they are applied have dramatic and long-lasting effects on forest characteristics. Harvesting is the operation that generates the most conflict between objectives, between people, and between institutions. It also generates most of the revenue that directly or indirectly supports management of forests for multiple objectives.

In this section, we discuss primarily harvests that may occur at the end of a rotation (even-aged management) or harvest cycle (uneven-aged management) as part of a planned management regime. Similar considerations apply to harvests that take place as a response to unplanned, perhaps large-scale, natural disturbances such as windstorms, fire, severe insect outbreaks, and volcanic eruptions; or as a component of efforts to restore forests that have been drastically altered or degraded by past natural or human-caused events. We also discuss the question of harvest ages, and conclude with brief discussion of some considerations related to harvest of special forest products.

Regeneration Harvests

A silvicultural system or management regime consists of a regeneration method, intermediate stand treatments (if any), and a harvest method. The choice of harvest method is influenced by both desired future conditions and comparative costs. A method that is perfectly feasible and highly desirable on gentle terrain may be quite impractical on steep topography. Details of application are influenced by present and desired future species composition and by differences in site and expected vegetative competition.

In the appendix, we illustrate a number of possible regimes that appear feasible for lands having both wood production and nontimber values as objectives, and that are included in trials now being established on Washington Department of Natural Resources (DNR) lands (Curtis and others 1996). These regimes are expected to produce widely different stand conditions with differing visual effects and habitat values, while retaining wood production as a major objective. Many variations are possible.

Planned regeneration harvests are conventionally classified into several broad categories or associated silvicultural systems (Matthews 1989, Nyland 1996, Smith 1986, Smith and others 1997). These represent segments of a continuum of possible practices classified by site exposure and sequence of operations, rather than rigid and clearly demarcated alternatives.

The **clearcutting** method removes all trees from relatively large areas at one time, followed by regeneration by either planting or natural seeding from adjacent uncut trees or stands (see figs. 4, 5, and 6). It is highly cost-efficient for wood production with species and sites where large open areas are readily regenerated. It minimizes road costs and direct harvesting costs (especially on steep terrain) and markedly simplifies planning and future administration and management. It is commonly thought, though not fully demonstrated, to give greater wood production per unit area than alternative systems. It was the dominant system throughout the Douglas-fir region for many years and remains important on non-Federal lands. In recent years, it has come under public attack and its use has been greatly diminished on Federal lands. A clearcut is a highly visible treatment that is aesthetically displeasing to many people. There also are perceived or actual unfavorable effects on some wildlife and other environmental values. These problems are exacerbated by short-rotation management on many

ownerships and by unbalanced stand age distributions. Some of the problems in part reflect changes in societal attitudes and effects of past forest planning, harvest scheduling, and other management practices, rather than inherent characteristics of the clearcutting method. But such distinctions are commonly lost in public debate.

The **seed-tree** method leaves widely scattered individual trees or clumps of trees as a seed source. This has long been abandoned as a regeneration method over most of the region because it is usually less effective and less reliable than other methods in regenerating Douglas-fir, though not invariably so (e.g., Garman 1951).

The **shelterwood** method consists of removal of a sufficient portion of the old stand to provide the environmental conditions needed for establishment of Douglas-fir seedlings (either planted or natural), while the remaining overstory (= overwood) provides protection from excessive insolation, temperature, and frost (fig. 29). Once regeneration is established, the remainder of the old stand is removed to allow free growth of the new stand. The shelterwood method can be applied uniformly over large areas, or as a so-called irregular or group shelterwood in which openings are gradually enlarged as regeneration becomes established.

The above methods produce even-aged stands; i.e., stands in which the trees are of similar age. If applied over contiguous stands within a short period, a large forest area may consist of stands with little variation in ages; however, such large-scale uniformity is a result of harvest patterns and scheduling and is not inherent in even-aged methods.

In contrast, **selection** methods aim to develop unevenaged stands, which contain a wide range of tree ages within the individual stand. Differences in age structure and general appearance between adjacent stands will tend to disappear over time. In **single-tree selection,** different age classes are developed in a stemwise mixture through removal of individual trees. This method strongly favors shade-tolerant species because of the small size of openings. It is difficult and expensive to carry out, and damage to remaining trees can be extensive. Single-tree selection is therefore rarely used in the Douglas-fir region. In **group selection,** the aim is to develop a mosaic of small even-aged groups or patches of differing ages within a stand (fig. 30). As the area

Figure 29-Regeneration established under a shelterwood. The overwood is usually removed after a few years, to produce a new even-aged stand. Alternatively, the overwood can be retained for further growth, as a reserve shelterwood or two-aged stand.

Figure 30-Group selection in Douglas-fir, McDonald Forest, Oregon State University.

of the group or patch is increased, conditions within the patch approach those under clearcutting and become suitable for intolerant species and amenable to the same regeneration practices.

Accessory systems (Matthews 1989) include conscious establishment of layered and two-aged stands, potentially important in the Pacific Northwest. These include **two-aged systems** such as clearcutting with reserves (retention of scattered trees or groups of trees from the former stand) and reserve shelterwoods (Nyland 1996), in which a more or less uniformly distributed overwood is retained for much or all of the next rotation. Both two-aged and layered but essentially even-aged stands often arise naturally because of differences in species tolerance and growth rates, and often are thought favorable to wildlife and biodiversity values. Such conditions can be created by planting appropriate species mixtures or by cultural practices designed to favor development of such species mixtures in either natural or planted stands.

It has become common practice, mandated by state regulations and by management guidelines on Federal lands, to leave scattered green trees or groups of trees on harvest units for wildlife and other ecological purposes. Although this may initially produce stand conditions that appear similar to those created by the seed tree method, the retained trees are not left primarily for seed production and are not intended or expected to provide adequate regeneration (fig. 31). Harvest cuts including such features are sometimes referred to as "retention harvests" or "retention harvest systems" (Franklin and others 1997). This is inconsistent with long-established terminology used worldwide. Depending on number, arrangement, and planned retention of leave trees, such harvests are more accurately characterized as "clearcut with reserves," "irregular shelterwood" (Smith 1986), or "reserve shelter-wood" (Nyland 1996). Questions of terminology aside, Franklin and others (1997) provide a good discussion of some of the variations on the basic ideas involved and of the hypothesized value of these measures in promoting wildlife habitat and rapid recolonization of harvested areas by a variety of plants and animals.

Figure 31-It is now common practice to leave scattered green trees or groups of trees and snags on harvest units for wildlife and other purposes. Although such "new forestry" harvest units have a superficial resemblance to the seed tree cuts of the past, the trees are not retained for regeneration purposes.

Timber harvesting after large-scale catastrophic events often does not easily lend itself to overall classification, because many of the critical harvesting considerations are landscape rather than stand-level ones. The scale of disturbance can be orders of magnitude greater than the mean stand size (many thousands of acres vs. less than 100 acres). Thus, recent management plans in Oregon (e.g., following the Silver and Longwood fires in the Siskiyou National Forest and the Warner Creek fire in the Willamette National Forest) have redefined stand boundaries in ways that attempt to mimic natural patterns on the landscape and have reduced the amount of salvage or cutting of green trees in some units in an attempt to recreate natural patterns and accelerate the development of a range of stand structures within the landscape.

Rotations

The progressive reduction in harvest ages (rotations) in recent decades has contributed to current problems. The net result of past harvest practices, reduced harvest ages, and historical harvest patterns is that many landscapes are dominated by recent clearcuts and by stands in the stand initiation and stem exclusion stages (fig. 6). Many people find this aesthetically distasteful and regard it as irresponsible destruction of "nature," creating horrendous public relations and political problems with huge indirect costs to the landowner and the public. The possible effects of frequent drastic disturbance on wildlife, hydrology, biodiversity, site productivity, timber quality, and long-term sustainability also have been questioned. Similarly, people have raised concerns about regimes in which most of the landscape is occupied by relatively uniform young stands.

A shift to extended rotations on some part of the land base (combined with increased commercial thinning and-where feasible-regeneration systems other than extensive clearcuts) can help to reduce the visual impacts of forestry operations. Longer rotations also would help maintain species diversity, wildlife, and other environmental values on lands where continued and sustainable timber production is a major objective.

Douglas-fir, because of the past history of the forests and the relatively intolerant nature of the species, is usually grown in even-aged stands and will probably continue to be so managed for the foreseeable future. This does not necessarily imply the large units of a single age class that are common today. Below, we define and discuss some terms and relations related to even-aged management. Although these are defined in terms of wood production, they remain important in management and policy decisions involving any form of integrated management for production of multiple benefits, including wood production.

Definitions-Rotation is the planned number of years between stand regeneration (or removal of the previous stand) and final harvest. **Yield** is the sum of standing volume + cumulative amount removed in thinnings since stand establishment, at a specified age. **Mean annual increment** (MAI) is volume produced (standing volume + volume removed in thinnings), divided by stand age (i.e., average annual production rate from establishment to the age in question). **Current annual increment** (CAI) is growth rate in volume per year at specified age (which is not directly measurable). **Periodic annual increment** (PAI) is an approximation to CAI, calculated as the difference in stand volume at two successive measurements, divided by the number of years between measurements.
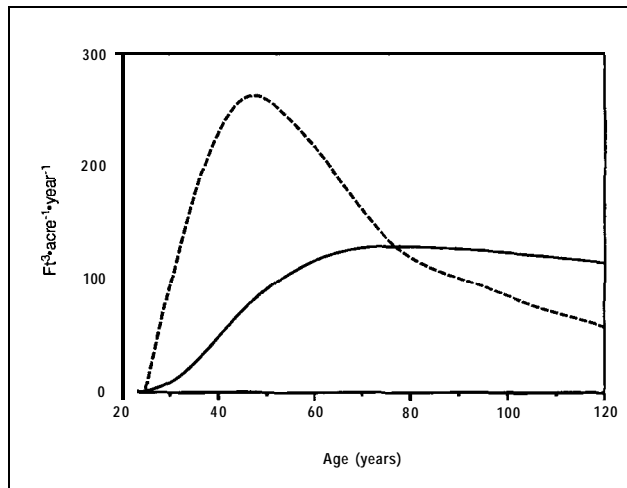
Figure 32-The curves for mean annual increment (solid line) and periodic annual increment (dashed line) intersect at culmination of mean annual increment, at the age which gives maximum average volume production. Values are as shown for site III in McArdle and others (1961) adjusted to volumes to a 6-inch top.

The MAI and PAI trends over time are important expressions of stand and species development patterns. The MAI and PAI curves for a given stand have characteristic patterns, (shown schematically in fig. 32) and intersect at the maximum point ("culmination") of the MAI curve.

Historically, there are three basic theoretical concepts of "optimum" rotation. In traditional presentations, these are based on timber volume or timber value only (Chang 1984, Newman 1988, Pearse 1967):

- The first maximizes **value** of timber produced per year and corresponds to age of culmination of mean annual value increment.

- The second maximizes timber **volume** produced per year and corresponds to age of culmination of mean annual volume increment.

- The third or financial rotation maximizes the **net value** of all costs and returns, **discounted** either to the present or to the year of stand establishment, at some specified interest rate. The value discounted to year zero is known as **soil expectation value** and represents the amount that an investor could pay for bare land to be used for timber production and still earn the specified interest rate, given full knowledge of future costs and returns.

In general, the first is longer than the second; the financial rotation is the shortest of the three-much shorter if the assumed interest rate is high. Foresters have argued about these for a century and a half. Forest economists usually advocate the third, or variations thereof, as the theoretically "correct" answer. In real life, many other considerations enter into the rotation decision. A major factor today is the existence of multiple management goals, not restricted to or necessarily emphasizing timber production or economic return, and often not readily expressible in monetary terms.

Extended rotations-Extended rotations can be a major component of any strategy to reduce conflicts and promote joint production of commodity and ecological values (Curtis and Carey 1996, Curtis and Marshall 1993, Kuehne 1993, Lippke and Fretwell 1997, Newton and Cole 1987, Voelker 1973).

As rotations have become shorter, a greater percentage of forest land is cut annually, and more of the stands and total forest area are in the visually least attractive and least diverse stand initiation and stem exclusion stages. Although short rotations may maximize the discounted present net value of timber, trees are smaller, wood quality and value at harvest are lower, and productivity of both wood and other forest values are reduced in comparison with biological potentials.

Long rotations are biologically feasible in the Pacific Northwest because Douglas-fir and its conifer associates are very long-lived and can maintain rapid growth to advanced ages. The widespread perception in the United States that high yields and intensive management imply short rotations is not necessarily true. On the contrary, long rotations have long been associated with very intensive management regimes in some European countries.

Possible advantages of extended rotations include:

- Reduced land area in regeneration and early development stages, hence:

  -reduced visual impacts

    - reduced frequency of major site disturbance

    - less need for herbicides, slash disposal, etc.

  -lower (less frequent) regeneration and respacing costs

- Larger trees and higher value wood

- Opportunity to adjust present age distributions for better balance and a greater range in ages across landscapes, and to develop multistoried stand structures

- Higher quality wildlife habitat for some species and enhancement of biodiversity

- Hydrological and possible long-term site productivity benefits

- Increased carbon storage associated with larger growing stock

- Preservation of options for future management changes

Maximum long-term volume production is attained when stands are grown to the age of culmination of MAI. The MAI curve is relatively flat in the vicinity of culmination age, systematic thinning will probably delay culmination, and there is a considerable range of possible rotation ages that will produce approximately the same MAI (fig. 33). Moderate extension of rotations over those common at present would not decrease long-term volume production (Curtis 1992, 1994, 1995; Curtis and Marshall 1993), might well increase value production, and would certainly increase aesthetic and some wildlife and biodiversity values.

Age of culmination of MAI is the minimum harvest age specified for National Forest lands under the National Forest Management Act of 1976. (In application, the age corresponding to 95 percent of estimated maximum MAI is usually taken as a minimum.) Subject to this constraint, actual harvest ages are determined by a combination of even-flow constraints on harvests; age class distribution constraints; existing stocking and growth rates; and economic, environmental, and political considerations. One
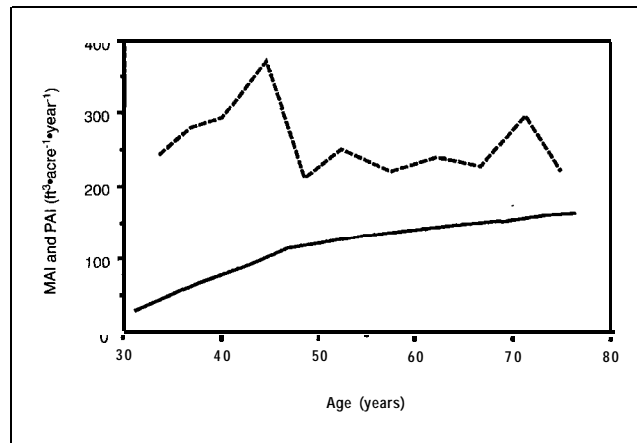
Figure 33-Systematically thinned stands often maintain rapid growth well beyond the culmination age indicated in old normal yield tables, as shown by mean values from four repeatedly thinned plots at Cowichan Lake, British Columbia. Culmination of mean annual increment (solid line) has not been reached at age 76 (Curtis 1995).

difficulty is that culmination age is not a fixed known quantity. It is influenced by management regime, and within regimes, there are substantial differences among available estimates.

The conventional economic argument based on maximizing the discounted monetary value of all future costs and returns gives great weight to near-term income and negligible weight to long-term societal values (Overton and Hunt 1974). The most common and simplistic analyses have major shortcomings. Employment, wildlife, water, fish, biodiversity and amenity values, which usually do not provide revenue to the landowner, often are ignored. Expression of many of these values in monetary terms is imprecise at best, and impossible for some. Yet, public policy considerations demand maintaining productivity of all values and avoiding actions with unacceptable effects on social values. Public desires for nontimber values have become dominant influences on management of Forest Service and some other public lands. And, public perceptions are strongly influenced by the visual impact of management regimes and are a major driving force behind costly and increasing regulatory constraints and pressures for land withdrawals for special uses.

Rotations are strongly influenced by financial and supply considerations and owner objectives as well as by biology, and rotations of maximum MAI in volume or in value are probably not appropriate for many private owners. Unpredictable damage by wind, fire, insects, disease, or current stand conditions will always make early harvest of some stands advisable (Harrington and Knapp 1994). Continuation of the recent trend toward very short rotations on many non-Federal lands, however, likely will lead to sharply reduced productivity compared to potential, restricted future management options, reduced nontimber benefits, and exacerbation of antiforestry attitudes among major segments of the public.

Wood Supply, Cash Flows, and Distribution of Stand Ages and Conditions

A "desirable" or "optimum" rotation represents a long-term goal, rather than a measure that can be immediately implemented everywhere. Change must be gradual because of constraints of existing age class distributions, economic demand and supply, and public and political pressures. Extending rotations could ultimately increase wood supplies as well as the associated nontimber forest values. Unfortunately, both extension of rotations and some recent changes in harvest practices also imply temporary reductions in

harvest volumes and (probably) increased operating costs. An immediate practical problem is the need to maintain some acceptable level of wood supplies and cash flows (which are generated primarily from timber) during any transition period.

This need is critical for private and industrial ownerships, and should not be ignored by public agencies. Legislative bodies may be reluctant to fund large-scale land management programs over extended periods to promote intangible benefits, in the absence of concurrent revenues. Programs based on silvicultural regimes that truly integrate production of timber and nontimber values and produce substantial current revenues along with nonmonetary values seem much more likely to survive and prosper.

Increased thinning can help to maintain wood supply and cash flow during any transition period. Silvicultural regimes might be selected to maximize yields from thinnings even though they may result in some reduction in yields at final harvest. A number of examples (Curtis 1995) suggest that thinning regimes can be designed that combine high intermediate yields and relatively infrequent entries with development of stands acceptable for both timber and nontimber objectives.

Balanced age distributions (i.e., a "regulated forest") have traditionally been a long-term goal of forest management, motivated primarily by the desire for stable wood supplies and cash flows. Balanced stand condition distributions also have an important role in promoting nontimber values (Oliver 1992). Distributions of stand ages and of stand conditions are not the same thing, although obviously related; stand conditions are jointly determined by age, management regime, and site. Stands cannot be maintained in any given condition indefinitely. Given a mix of different silvicultural regimes and differences in objectives among owners, we do not necessarily need equal areas in all age classes. But if we wish to have a given stand condition represented in the future, we must provide for future replacement of the stands now in that condition. Stand condition or stand age distributions that are in some sense balanced on local or landscape scales provide a range of seral stages and stand conditions and a variety of wildlife habitats and are an essential part of long-term sustainability of both commodity and noncommodity values. Landscapes dominated by a single developmental stage (sometimes visually monotonous or unattractive or otherwise undesirable for some values) thereby would be avoided and some impacts related to human and natural disturbances would be lessened.

Existing stand age distributions are quite unbalanced, on both regional and local scales (Adams and others 1992, Sessions and others 1990). Figure 34 shows the regional distribution of age classes for (1) all ownerships combined; and for (2) National Forests and (3) industrial ownerships, which are the two ownership categories with the greatest differences in age distributions. Overall age distributions of nonindustrial private owners and other public agencies (primarily states) appear fairly well balanced to about age 80 but contain few older stands.

On a regional scale, age distributions within National Forest lands appear reasonably well balanced for production of multiple values and preservation of future management flexibility. In contrast, that for industry lands is quite narrow and severely limits options available to owners (Haynes and others 1995). Regional totals such as those for National Forests, however, mask major differences among Forests and among watersheds or other localized areas within Forests, which reflect differences in fire history
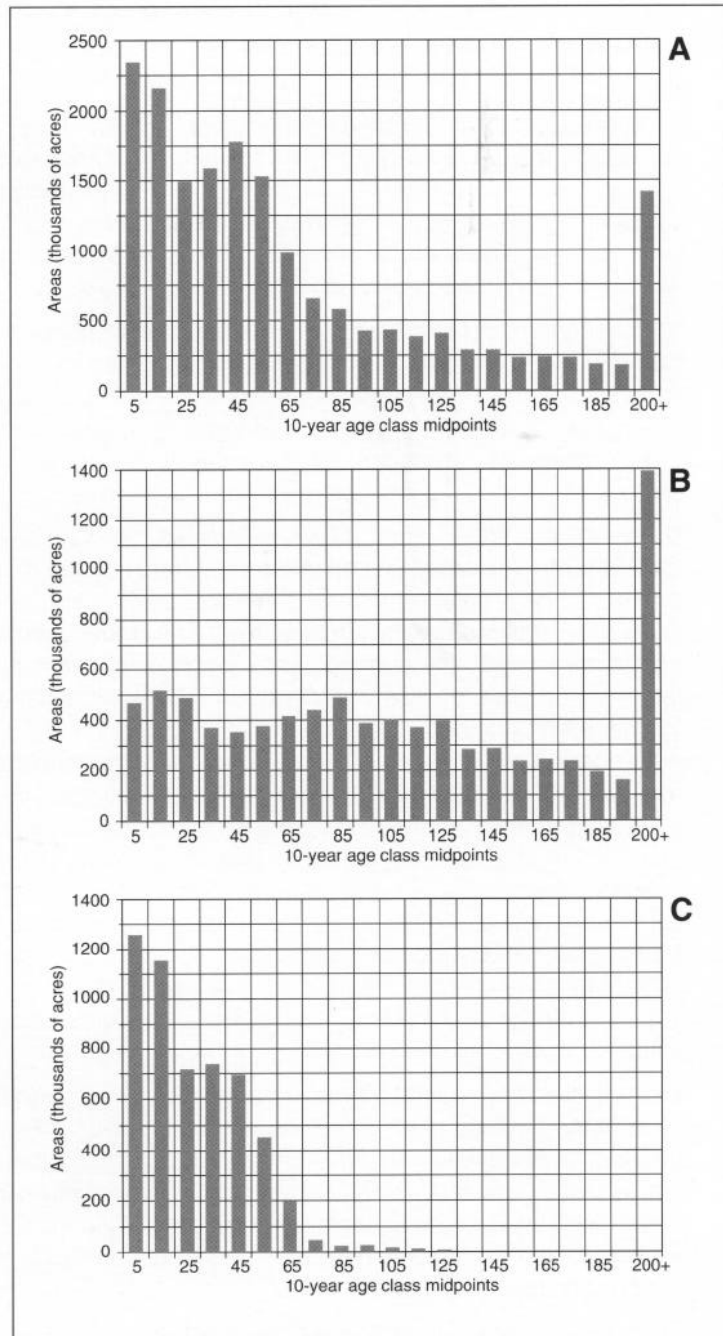
Figure 34—Overall distribution of ages class in western Washington and Oregon for (A) all ownerships, (B) National Forests, and (C) industrial ownerships.

and harvesting history. And, because of the delays involved in the inventory process, the figures shown (derived from Bolsinger and others 1997 and unpublished data') do not include changes arising from accelerated harvesting on industrial lands (and other private, not shown) following the near-cessation of harvests from National Forest lands in 1992. The narrow range in ages on industrial lands and the continuing reduction in harvest ages imply that large blocks of land are and will continue to be devoid of stands older than about 45 to 50 years. Development of stand age or stand condition distributions that are more nearly balanced on watershed or other local scales will require that some stands be carried to advanced ages and some others be harvested at ages substantially less than might otherwise be desirable (which also aids in meeting the short-term timber supply problem). Spatial distributions and total areas involved are both important.

Efforts to create a wider range in ages and stand conditions and more balanced age and spatial distributions are likely to be severely hampered by the current near-elimination of timber harvests from Federal lands. Indeed, current policies are having an effect directly counter to that intended. The scramble for timber supplies following the near-cessation of harvests from Federal lands has produced sharply accelerated and excessive cutting of immature stands on private lands. This cannot be continued for long and will result in decreased future production and degradation of environmental values that will last for decades. Conversely, stable supplies of Federal timber at some reasonable and predictable level would reduce pressures for immediate harvest on private lands and thereby could help in achieving improved management of the region's forests for both commodity and noncommodity values. There is precedent for some form of cooperative harvest planning-though in a different context-in the Sustained Yield Forest Management Act of 1944 (Dana 1956, p. 284).

Special Forest Products

Harvesting of special forest products (floral greens, Christmas trees and boughs, berries, mushrooms, bark for medicinal purposes, moss, shrubs, plants for landscaping) is becoming a substantial revenue source and involves a number of scientific and management questions (Molina and others 1997). Management practices can either promote or degrade productivity of these values. Information on the effects of repeated harvesting of these products and specific measures to promote their production is quite limited, but common sense indicates that harvesting of some of these must be controlled to be sustainable. It has been shown, for example, that repeated harvesting of swordfern fronds reduces frond length and plant survival considerably (Isaac 1945). Anecdotal information suggests that repeated harvesting of mushrooms and some harvesting practices may reduce future crops; studies are underway on this topic (Amaranthus and Pilz 1996). Stand density control has obvious effects on productivity of species such as salal and huckleberry *(Vaccinium* ssp.). Production of Christmas trees and boughs from young true fir stands often enables managers to turn needed spacing and pruning into revenue-producing operations (Murray and Crawford 1981).

Summary, Harvesting Considerations

Harvest operations that take place at the time of removal and regeneration in even-aged management (or in each cutting cycle in uneven-aged management) are the major source of both user conflicts and revenues that support management of most

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'Data for western Oregon provided by Tim Swedberg, Pacific Northwest Research Station, Portland, OR, April 25, 1997; and by John Teply, USDA Forest Service, Pacific Northwest Region, Portland, OR, May 7, 1997. On file with: Forestry Sciences Laboratory, 3625-93d Avenue SW, Olympia, WA 98512.

forest benefits. They have a profound effect on the nature and development of stands and forests. Appropriate methods must be used to attain desired objectives.

- Regeneration harvests are conventionally classified into a number of silvicultural systems or methods, discussed at length in standard texts. These are not rigid procedures, but segments of a continuum of possible actions. Selection and application of harvest methods depend primarily on characteristics of the specific stand and site, tempered with public relations and environmental considerations. No one system should be applied everywhere.

- Rotation length affects forest productivity for all values. Extension of rotations beyond ages now in common use would have important benefits for some values. Reduced frequency and extent of regeneration harvests would benefit aesthetic, fish, and watershed values. The older stands would include stand structures more favorable to some wildlife. Extended rotations would provide more flexibility to respond to future changes. They might also give greater long-term wood production and employment.

- Rotation choices involve important economic and policy considerations. Choices will be different for different owners and owner objectives. The need to maintain some stability in wood supply and cash flows is an important limitation on the rate and magnitude of changes in rotations and management regimes.

- Stand age and stand condition distributions are important in long-term sustainability. No stand condition can be maintained indefinitely. Provision must be made for continuous replacement of stands over whatever range of stand ages, stand conditions, and spatial distribution is considered desirable for owner and societal objectives.

- Special forest products (commodities such as floral greens, boughs, berries, Christmas trees, mushrooms) have become important and in some cases provide substantial revenues. Special forest products create additional opportunities but may require some management modifications.

Providing Diverse Structures and Habitats

Forest management goals are commonly expressed as desired forest conditions. The characteristics of individual stands as well as broad landscapes strongly influence attainment of management goals and the choice of appropriate silvicultural measures. Stands can be described in terms of structure, species composition, and site quality. Stand structure includes the dimensions and vertical and horizontal arrangement of trees, shrubs, herbs, grasses, nonvascular plants, and also snags, down logs, forest floor depth, etc. Species composition describes the variety or relative species richness of plants present within a given stand. Site quality integrates a combination of factors (soil physical characteristics, soil fertility, climatic conditions) that affect potential stand growth. Recent work suggests that increased diversity in structure and composition, within and between stands, will enhance some wildlife habitat, biodiversity and aesthetic goals (Carey and Curtis 1996; Carey and Johnson 1995; Carey and others 1996a, 1996b).

Biological diversity has several aspects. These include the number (richness) and relative abundance (evenness) of species present in a given stand; the variation in

species and their abundance among stands and across landscapes; the variation in presence and structure of canopy layers, within and between stands and across landscapes; and the genetic variation among individuals within a species. Stand structure and composition change over time as stands develop. Different wildlife species tend to be associated with different stand conditions. Thus, landscapes that include substantial areas in early successional stages favor deer, elk, and berries; those with substantial areas in late successional stages favor spotted owls (Strix occidentalis). It follows that to provide and maintain habitat for a wide variety of species, a balanced distribution of stand structures and developmental stages needs to be developed across landscapes (Oliver 1992).

Because forests are dynamic entities, this implies active management to produce desired structures and regenerate stands as needed to maintain the desired age and stand condition distributions. The biggest current imbalance is the general lack of mature and old-growth stands on non-Federal lands. The recent establishment of large late-successional reserves will, if long continued, produce a similar shortage of early successional stages on Federal lands in the future. These imbalances will not be mutually compensating because of wide geographic separation.

Much recent discussion of biodiversity has focused on old-growth stands and on efforts to shape younger stands toward similar conditions, although this represents only one segment of the needed range in stand conditions. This emphasis on old growth probably arises from the perception that this is the condition in most limited supply and most difficult to replace if lost.

Forest characteristics important for some wildlife and aesthetic values do include some characteristics commonly associated with mature and old-growth stands: (1) large trees; (2) layered structure including some understory trees and shrubs; (3) mixed species composition; (4) presence of large snags and live trees with cavities or other attributes needed for nesting, roosting, and foraging; (5) presence of large woody debris on the forest floor; and (6) within-stand variation in overstory density and corresponding variation in density of the understory. Although these characteristics commonly develop at advanced ages in unmanaged stands, there is abundant evidence that their development can be markedly accelerated in much younger stands by appropriate silvicultural measures (e.g., table 1; Curtis and Carey 1996). Currently heavily stocked young stands may not develop these characteristics without silvicultural treatment (Tappeiner and others 1997). Many of these measures also can produce direct economic benefits through the concomitant production of wood.

Composition and structure of forest stands can be markedly altered by silvicultural practices applied at appropriate stages in stand development. Some examples of such practices have been mentioned previously. Below, we further discuss (at risk of some repetition) practices that can be used to increase the range and diversity of stand structures and to promote wildlife and other nontimber values. Practices must be evaluated for each site, in relation to management objectives, stand characteristics, cost, and safety considerations. If practices are properly applied, inherent site quality can be maintained indefinitely.

Table I-Measures for producing diverse structures and habitats

At harvest	At stand establishment	Young to mid-age stands
Use long rotations	Plant with mixed species, irregular spacing	Thin to produce large trees with deep crowns and to promote understory development
Use advance regeneration, group selection, group shelterwood, strip shelterwood small patch cuts (1-10 acres)	Thin to variable densities within same stand	Thin to variable densities within stand
Save advance regeneration	Encourage natural seedlings within plantations	Release advance tree and shrub regeneration
Retain snags and down logs	Save patches of hardwoods and shrubs to increase future stand variability	Retain existing snags and down logs when thinning
Retain green trees, groups or singly	Leave portions of stand undisturbed by site preparation or slash disposal	Make additional snags and down logs where needed
Work toward balanced age distribution on landscape level		Underplant where natural understory regeneration is lacking

Species Mixtures

Mixed species planting with suitable density control can produce multilayered stands because of differential species growth patterns and differential browsing by herbivores. For example, Douglas-fir and western redcedar planted together may form stands with multiple layers, because the redcedar generally grows slower than Douglas-fir, is more susceptible to browsing, and its shade tolerance allows survival in the understory. Subsequent thinning may be needed to maintain the slower growing species in the understory. Natural regeneration of hemlock and other tolerant species often is abundant in young Douglas-fir plantations, and retention of some stems of these species during precommercial thinning will favor development of mixed stands and layered structures. Differences in species susceptibility also may make such mixed species stands less susceptible to damage from root rots.

Douglas-fir plantations often quickly develop a considerable component of other conifers and hardwoods. Good stems of species such as western hemlock and western redcedar, and occasional hardwoods such as bigleaf maple, can be retained in precommercial and later thinnings to enhance species and structural diversity of the future stand.

Stand Management for Structural Diversity

Modifications of conventional thinning practice (table 1) might include favoring trees of diverse species and sizes to foster crown stratification and understory development for improved wildlife habitat (Hagar and others 1996). Small openings or gaps can be created, which ultimately will be occupied by younger trees. Root rots, bark beetles, and windthrow often do this independent of human intervention. As stands grow older, dead trees can be retained to provide snags needed for some wildlife species; if needed, additional snags can be created. Tolerant tree species such as western redcedar, grand fir, Pacific yew, western hemlock, and bigleaf maple can be introduced through underplanting, if seed sources of these species are lacking. Most species are more tolerant when young, and conditions suitable at establishment may have to be altered as plants age. Regeneration in riparian areas can be especially challenging; these sites often have substantial existing understory vegetation, and animal damage to young trees may be severe.

Modifications such as irregular thinning and underplanting are being evaluated in the forest ecosystem study recently installed at Fort Lewis, WA (Carey 1993, Carey and others 1996b), the Olympic habitat development study (Harrington and Carey 1994), and the COPE (Coastal Oregon Productivity Enhancement) program (Emmingham 1996). Thinning prescriptions in these studies are designed to increase within-stand variation in crown lengths, tree size, species composition, and understory distribution. Although large-diameter trees are a desired component of these stands, the thinnings are designed to promote increases in spatial heterogeneity and in the other structural attributes found in natural stands. This contrasts with conventional uniform thinning prescriptions, which produce more evenly spaced, large-diameter trees with more even understory distribution. As stands grow older, some trees will die and provide snags needed for some wildlife species. Other cavity trees will form as a result of damage from wind, snow and ice breakage, and thinning injuries. If needed, managers can provide additional cavity trees by killing, wounding, or topping some trees.

There are many well-stocked young stands (10 to 50+ years) in the Douglas-fir region that have been established after fire or timber harvest. About 30 to 60 percent of many watersheds on Federal land, and a majority of private lands, are stocked with these young stands. For the most part, they have been regenerated and managed at high densities to produce high yields of wood, and not to develop diverse structure. In contrast, old-growth stands often have only 10 to 30 trees per acre in the upper canopy (Spies and Franklin 1991). Thus, if we wish to develop future old-growth-like character-istics in some portion of these young stands, considerable reduction in stocking over time is needed to produce large trees with deep crowns and provide a more open environment for understory development. Seedlings of tolerant species can be estab-lished after thinning in young conifer stands, but subsequent reduction in canopy density will be needed to ensure their future development.

Thinning and regulation of overstory density can be used to produce large trees quickly, develop stand structure, and generally aid the development of mature forest and old-growth-like characteristics (Curtis and Marshall 1993, Newton and Cole 1987, Hayes et al. 1997). Advance regeneration can be released to produce multiple layers. There often are numerous hardwood seedlings and conifers (Fried and others 1988, Tappeiner and McDonald 1984) in the understory that will respond to a reduction in

overstory density. In dense stands with no tree understory, the increased light and limited soil disturbance from thinning favor establishment of both conifer seedlings (Del Rio and Berg 1979) and hardwood seedlings (Fried and others 1988, Tappeiner and others 1986). In a western Oregon study that compared understory characteristics in thinned and unthinned Douglas-fir stands, one of the most striking differences between the stands was the stocking of natural conifer seedlings in the understory of the thinned stand (Bailey 1996). Additional thinning to mimic natural stand development could release conifers and hardwoods and leave the overstory at variable densities to encourage "patchy" understory development, but this also would cause considerable damage to the existing understory.

Shade-tolerant conifers can be planted in the understory after thinning to develop multilayered stands, with some of the characteristics that are found in naturally developed stands of much greater age and that are considered favorable to some wildlife species. Thus, Alan Berg of Oregon State University thinned a 40-year-old Douglas-fir stand to 50 trees per acre and planted western hemlock in the understory. About 40 years later, this is a well-developed two-storied stand (Curtis and Marshall 1993). At 80 years of age, the overstory of 50 trees per acre is probably too dense for continued understory growth, although the overstory trees are still growing rapidly. Average diameter of the Douglas-fir overstory is about 30 inches. In the nearby unthinned stand, average diameter is only 15 inches with practically no understory.

Pure red alder stands are common in riparian areas, especially in coastal forests. But, some conifer component is often desirable in these areas to provide large logs for stream channnel structure and to produce a more diverse forest for wildlife. Emmingham and others (1989) successfully planted western hemlock under thinned red alder stands. Both overstory density reduction and long-term salmonberry control were needed to establish hemlock. Elk (Cervus elaphus) and beaver *(Castor canadensis)* have caused major damage to planted seedlings on similar sites. Chance of seedling establishment is increased by using large planting stock and planting large areas at a time, to reduce animal damage (discussed in a later section). Where advance conifer regeneration is present under red alder, it can be released to grow large conifers. Newton and others (1996) discuss problems and applicable techniques.

Use of Advance Reproduction

Current methods of planting and tending young stands can be altered to produce stands of diverse structures and species composition after fire, clearcutting, or other disturbance. Retaining poles, saplings, and seedlings of acceptable vigor and form from the previous stand will accelerate the regeneration of the next stand and tend to encourage development of more "patchy" stands and a variety of tree sizes and species (Tesch and Korpela 1993). Such use of advance reproduction is most promising on the drier sites and in the mixed species stands common in southwestern Oregon. On the better sites and in the northern part of the region, advance regeneration is likely to be of tolerant species (hemlock, true firs) that are highly susceptible to rot entering through logging wounds, and early removal of damaged trees may be needed.

Shrub and Hardwood Management

Managing competition of shrubs, herbs and hardwoods at the time of regeneration will affect species composition, structure, and subsequent development of the future stand. The models developed by Harrington and others (1991 a, 1991 b) for tanoak and Pacific

madrone and by Knowe and others (1995) for bigleaf maple estimate the amount of cover produced by sprouting hardwoods, the effects on conifer survival and growth rates, and effects on stocking of understory shrubs and herbs. Use of such models will help forest managers forecast the development and influence of hardwoods during early stages of stand establishment.

Shade-tolerant hardwoods such as bigleaf maple and tanoak will provide a layered stand as they are overtopped by conifers at about 40 to 50 years of age. Large over-topped hardwoods provide cavities as large branches die and decay. California black oak *(Quercus kelloggii* Newb.) and Pacific madrone are more likely to be shaded out by overtopping conifers. They can be maintained in well-stocked older conifer stands by growing them in groups and thinning adjacent conifers. Hardwoods provide important structural diversity and diverse food sources (seeds and nuts) for wildlife.

Thinning favors regeneration of shrub understories under established stands. These understories can be beneficial from a wildlife standpoint but also can be a major obstacle to future regeneration of tree species. Salal (Huffman and others 1994) and salmonberry (Tappeiner and others 1991) commonly increase with reduction of over-story density through rhizome extension and other means of vegetative expansion. Vine maple clones are spread by "layering" as a result of thinning. Slash from natural disturbance of the overstory or from commercial thinning may pin the vine maple crowns to the forest floor where the branches often root and form a dense understory of new sprouts (O'Dea and others 1995). Establishment of salal, vine maple, and salmon-berry seedlings is also favored by thinning, but their expansion and development of a dense cover is mainly by vegetative clonal expansion. (Huffman and others 1994, Tappeiner and Zasada 1993, Tappeiner and others 1991). Thus, dense, continuous understories of these and other shrub species can develop after heavy thinning or partial removal of the overstory. Because of the potential for rapid vegetative expansion of shrubs, there may be a relatively "narrow" window for establishment of new conifer plants by natural seeding or by planting, and vegetation control measures also may be necessary. Composition and severity of shrub competition are strongly influenced by differences in site and canopy density (Klinka and others 1996) and by stand history.

Providing Cavities, Snags, and Coarse Woody Debris

In stands managed for wood production, decadent, dying, and dead trees have been viewed as problems to be avoided or at least minimized by harvesting before they deteriorate or contribute to spread of insect pests and disease. Thus, spacing guide-lines are based on the number of trees that can be grown to some desired size before significant competition-induced mortality occurs. Trees killed by insects, diseases, and fire usually have been salvaged immediately where economics and accessibility permit. Until recently, existing snags were commonly felled for fire hazard reduction and worker safety. Debris from harvesting operations often was burned to reduce fire hazard, facilitate planting, and control shrub competition. Yet dying, dead, and down trees are important components of forest ecosystems, and a variety of organisms are associated with them. These organisms range from cavity-dwellers like squirrels and other small mammals and many birds, to amphibians and invertebrates, to diverse vascular **and** nonvascular plants and microorganisms. Provision therefore should be made for dead wood management in multipurpose forests, particularly those where conservation of biodiversity is a primary management objective. Low-value tops, defective logs, and

coarse slash can be left onsite. Stumps (and the attached root systems) represent a substantial fraction of the biomass. We know of no quantitative evaluation of the role of stumps after harvest of young-growth Douglas-fir; but it is obvious that, if trees are grown to large sizes, stumps will serve some of the same functions attributed to large down logs.

Retaining large trees, snags, and down logs in some ways mimics the results of natural disturbance by fire or wind (Spies and Franklin 1991). Natural disturbances often do not kill all trees, and trees that die contribute large pieces of wood to the forest floor. Retention of some large trees after harvest-especially those with large limbs and cavities-as well as large snags and logs will help ensure later development of a stand with diverse structure (fig. 35). Leaving undisturbed groups of trees may aid carryover of some plants and other organisms, so-called biological legacies, from one stand to the next. Leaving groups of large trees (small patches) rather than scattered individuals also may facilitate logging and reforestation. Although partial overhead shade is often beneficial to initial establishment of tree seedlings, even a few retained overstory trees markedly reduce subsequent growth of established regeneration (Acker 1995, Hoyer 1993, Wampler 1993, Zenner 1995); a cost that may or may not be partially offset by growth of the reserve trees.

Surveys of plant communities in clearcut and burned areas indicate that most herbaceous plants growing in old forests are adapted to disturbance (Dyrness 1973, Franklin and Dyrness 1971, Halpern 1988, Halpern and Spies 1995), and that changes in understory diversity after disturbance are usually fairly short-lived. Therefore, use of different silvicultural systems or thinning regimes is not likely to have a great long-term effect on the herbaceous component of forest stands.
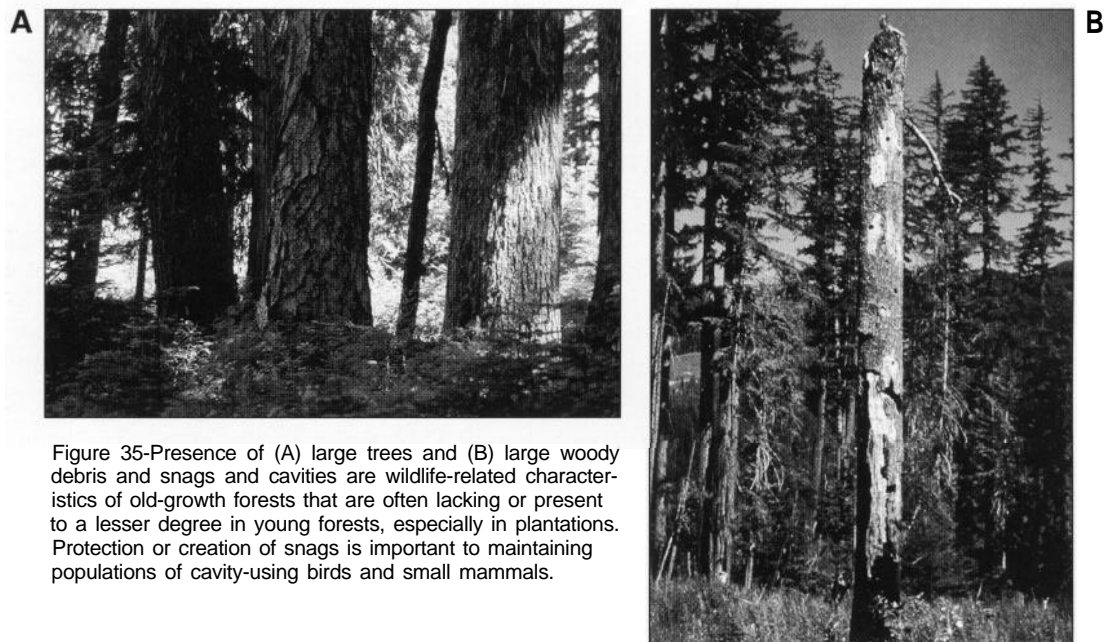
Figure 35-Presence of (A) large trees and (B) large woody debris and snags and cavities are wildlife-related characteristics of old-growth forests that are often lacking or present to a lesser degree in young forests, especially in plantations. Protection or creation of snags is important to maintaining populations of cavity-using birds and small mammals.

Plans for management of snags, live trees with cavities, and down wood must consider numbers, sizes, species, spatial distribution, and dynamics of decay and persistence. Many questions on desirable amount, distribution, condition and expected longevity of dead and down material are currently unanswered. Because of the importance of snags to wildlife (Carey and Johnson 1995, Carey and others 1996b) and the high economic cost of protecting or creating them, it is critical that uncertainties be resolved and methods for snag creation be developed that are both biologically effective and economically acceptable. In the absence of definitive information, forest managers and wildlife biologists from nearly every region have recommended snag densities that are remarkably consistent, with an average of 2 to 4 snags per acre suggested as a reasonable target (Hunter 1990). Snag dynamics have been studied in the Pacific Northwest (Neitro and others 1985), and computer programs exist that estimate desirable numbers for various bird species and snag persistence over decades (Marcot 1992). A minimum size (diameter and height) usually is suitable for each species, and in general large snags are better than small snags because they will last longer and more species will be able to use the snag. Carey and others (1991) report that all species of cavity-using birds in natural forests preferentially selected moderately decayed snags over 30 inches in diameter at breast height. Similar results were reported by Lundquist and Mariani (1991). In managed forests where residual snags may be rare (and cavity-using bird populations low), birds will use well-decayed hard-wood snags. A range of sizes may be needed, however, because some cavity users "defend" the snag from use by other species (Gibbons and Lindenmayer 1996). Slowly decaying species are usually most desirable because they will persist longer, but both "hard" and "soft" snags are needed. New snags of suitable characteristics must be recruited periodically to replace those that have fallen and are providing values associated with down wood.

Five matters specific to management of cavities and dead wood should be considered in silvicultural efforts to shape stand development and vegetative habitat:

1. Protection or retention of standing dead (snags) and down trees. Some and perhaps all of the largest of these should be retained during silvicultural operations, where feasible. Unfortunately, retention of existing snags often conflicts with fire prevention needs and current logging safety requirements, which differ among states and regions. Operational and safety considerations may make it preferable to create and preserve snags within small uncut groups of trees, rather than distributed over an area. Existing snags, however, are good sources of coarse woody debris for the forest floor.

2. Protection of live trees with cavities. Although snags are a recognized element of wildlife habitat for many animals, the importance of live trees with cavities is some-times overlooked or underrated. Thus, Carey and others (1997) report that over 50 percent of flying squirrel *(Glaucomys sabrinus)* nests are in live trees. Cavity trees can be equally or more important than snags for several reasons: living trees with cavities may persist much longer than dead trees, and the presence of live foliage can increase cavity security and modify microclimate in ways beneficial to cavity dwellers.

3. Creation of snags and down trees in stands where they are scarce or absent due to past stand history. Trees in existing stands can be killed by girdling or injection with herbicides, but there is uncertainty about the biological effectiveness of such methods because of differing decay development patterns. Some biologists and managers have tried other techniques, including blowing off tops with explosives, cutting off tops with saws, inoculating with fungi, and attracting beetles with sex pheromones (Baker and others 1996, Bull and Partridge 1986, Conner and others 1983). The existence of some low-quality trees in most stands (that otherwise would be removed in thinning) provides a low-cost opportunity to create snags. In some instances in British Columbia, snags have been "planted" in clearcuts by using material of little merchantable value, although their long-term value has not been demonstrated.

4. Creation of cavities. In general, retention of existing snags, perhaps supplemented with snag creation, will provide cavities sufficient to meet wildlife objectives. In specific instances, however, installation of nest boxes or creation of cavities by den-routing (Carey and Sanderson 1981) or by cutting a hole with a chainsaw and covering it with a faceplate (Carey and Gill 1983) may be appropriate. These approaches are being evaluated for effects on flying squirrel populations in young-growth Douglas-fir forests (Carey 1993); 2 years after installation, nestboxes were used more heavily than artificial cavities, and both nestboxers and cavities had greater usage in previously thinned than in unthinned stands (Carey and others 1996b).

5. It may be possible to accelerate development of snags and cavities in live trees by indirect and less costly treatments. Thinning and fertilization could be applied in ways that increase variation in tree growth (e.g., release or fertilization of individual trees). Favored trees would become superdominants, with crowns extending above the general canopy. Such superdominant trees would be expected to have large branches in the upper canopy, and some would develop the crook or umbrella tops that favor nesting or roosting by animals using such structures. The types of stands (age, stocking) and site conditions most responsive to such activities can be identified, but the details of such treatment have not been worked out or their effectiveness evaluated.

In summary, many standard silvicultural practices (such as thinning, fertilizing, and pruning) can be applied to favor the growth and development of trees of desired characteristics (size, species, form, age) in specific locations. With appropriate rotation lengths and better understanding of the dynamics of snag populations, it should be relatively easy to provide standing dead and down wood in amounts and locations consistent with forest management objectives and without major effects on other objectives and costs. The possible benefits of clumping versus scattering of coarse woody debris in conjunction with thinning operations is being evaluated in a long-term study in the Olympic National Forest (Harrington and Carey 1994).

Other Considerations

Several aspects of extended rotations and associated thinning and regeneration options will generally favor biodiversity and production of wildlife (Curtis and Carey 1996) and will help maintain plant species diversity (Halpern and Spies 1995):

- Extended rotations allow development of a wide range of age classes, tree sizes, and structures and provide the opportunity to develop late successional characteristics within stand management programs.

- Thinning and alternative regeneration systems, combined with extended rotations, will minimize the influence of the stem exclusion stage and of harvests on dispersal and colonization processes. They will promote development of structural diversity and, with suitable placement and sizes of harvest units, should reduce or eliminate the unfavorable effects often thought to be associated with forest fragmentation into spatially disconnected units of radically different characteristics.

- Thinning entries usually will be infrequent during the latter part of a rotation, and there will therefore be some unsalvaged mortality that will provide snags and coarse woody debris, additional to stumps and tops, from thinning. If these are insufficient, additional trees can be killed or treated to provide snags, cavities, and coarse woody debris.

- Thinning provides flexibility in control of stand density and structure that can be consciously used to promote habitat for late-successional species through development of understory and creation of small openings and within-stand density variation. Systematic thinning begun at a relatively early age can produce large trees and markedly alter stand structures within relatively short periods.

The emphasis given to these options obviously will be strongly influenced by existing land ownership and owner objectives.

Summary, Diverse Structures

Stand characteristics favorable to some biodiversity, wildlife, and aesthetic goals can be actively enhanced by a number of modifications to conventional silvicultural practices and additional measures. These include:

- Modified thinning practices to develop mixed species stands, muliple canopy layers, and more diverse understories. Irregular thinning and underplanting of openings with tolerant species can be used to promote vertical and horizontal heterogeneity.

- Thinning, especially if begun early, to produce large trees with deep crowns (more nearly comparable to those in existing older stands) and a more open environment for understory development. Early thinning minimizes the duration of the least diverse and least productive (for wildlife) stem exclusion stage of stand development.

- Retention of some hardwoods and minor species in thinning can enhance species and structural diversity.

- Release of existing conifers and underplanting of tolerant species in riparian hardwood stands can provide a more diverse riparian forest and eventually produce the large conifer logs needed to enhance stream channel structure.

- Protection or retention of standing dead and down trees, where feasible, for nest sites and coarse woody debris.

- Protection of live trees with cavities as nest sites.

- Creation of snags, cavity trees, and down trees in stands where they are scarce or absent.

- Retention of scattered trees or (probably preferable) groups of trees at harvest, for future production of snags and coarse woody debris.

- Use of extended rotations (in combination with thinning) and alternative regeneration systems to develop a wide range of stand ages, tree sizes, and structures.

Maintaining Site Productivity

Productivity as a general concept, as opposed to productivity for a specific product, is not easily defined or measured. Forest or ecosystem productivity can be discussed or quantified in various ways. One could seek to determine the productivity of forest landscapes for spotted owls, for deer, for harvestable crops of mushrooms, or for cubic feet of wood. Or, overall productivity can be expressed as the rate of production of organic matter in a system that is in some more or less stable (if such exists) or average condition. Forest ecosystems can be described in terms of basic functions (biomass accumulation and nutrient cycling) and structure (species diversity and complexity) (see Bradshaw 1987; Harrington, in press; Magnuson and others 1980). In ecological terminology, forest ecosystems that exhibit increases in biomass accumulation and nutrient cycling rates or in complexity of species composition are considered to be aggrading, and systems that exhibit losses in these factors are degrading. Thus, ecosystem degradation can occur through simplification of the system (reduction in species or structural complexity) without necessarily reducing the inherent productivity potential of a site or its potential to aggrade in the future.

In a forestry context, productivity is commonly defined in terms of biomass production per unit of time, net primary productivity (Grier and others 1989). But measurement of biomass production rates is difficult and imprecise, and they are markedly influenced by stand age and condition. Forest productivity and soil productivity are related but somewhat different concepts. Forest productivity refers to the entire forest system composed of soil, climate, and the associated vegetation and other organisms. Forest productivity is influenced by species composition, genetic composition, stand structure, and age structure, all of which can be readily modified by management over relatively short periods.

In contrast, soil productive capacity (or site productivity) refers specifically to inherent potential as determined by local climate and soil conditions. Gross climate is not subject to human control, but some management actions can influence soil characteristics and hence soil productivity. Some actions can improve soil productivity, whereas others can be harmful. Sustainable forestry obviously requires that soil productivity shall not be materially reduced and, if possible, increased by management activities.

Soil or site productivity is usually discussed in terms of the basic ability of the site to produce biomass, or more commonly, surrogates such as bolewood volume or site index (height at a specified reference age), which are much more easily measured and for which considerable data are available. Much information is available about soil characteristics that are related to fertility (Heilman and others 1979). The general direction of effects that specific management practices may have on these is known,

whether or not these effects are large enough to produce measurable or important effects on soil productivity. The magnitude of effects will be markedly affected by conditions existing on the specific site.

The effect of plant species composition on site productivity is not well known, with some exceptions. If a site is nitrogen limited, then nitrogen-fixing plants can enhance productivity. There are substantial differences in nutrient cycling among plant species, related to nutrient uptake, leaching, or chemical composition of leaf and other plant part litter. For example, western redcedar takes up calcium from deep soil layers and transports it to the surface via litter fall; this may be an important mechanism to maintain productivity on some sites (Weetman and others 1987). Many deciduous tree and shrub species also serve specialized roles in cation cycling. Presence of some species has been associated with acidification (e.g., red alder and spruce-hemlock; see Bormann and others 1994). Most of these effects have been documented but their effects on long-term productivity are unclear.

Soil porosity and soil organic matter are generally recognized as important factors in fertility. Porosity is reduced by compaction by heavy machinery. Porosity (and nitrogen content) also is strongly related to organic matter content. Organic matter in the surface layers (and ultimately, in the lower horizons) is reduced by very close utilization and by severe or repeated burning.

Nutrient content is important. Nitrogen is the only nutrient currently recognized as widely growth limiting in the Douglas-fir region, a deficiency probably resulting from the relatively young age of soils developed on glacial or volcanic parent materials as well as more recent fire history. Other nutrients, however, are also necessary. Long-term nutrient status depends on both the initial supply and the balance between nutrient withdrawals and nutrient inputs-which are usually from natural sources, although fertilizer applications also can supply them. Nutrient withdrawals occur through removal of biomass from the site, through leaching and erosion, and through volatilization during burning (principally nitrogen). Nutrient inputs occur through decomposition of minerals; nitrogen and sulphur deposition in rainfall; biological nitrogen fixation; and (sometimes) fertilizer application. Rainfall deposition is in part human-caused, and biological nitrogen fixation can be promoted through management and control of species composition.

Concerns sometimes are raised about the possible effects of forest management practices on long-term soil productivity. Possible changes attributable to management are not clearly separable from changes attributable to factors such as climatic variations, air pollution, pathogens, and changes in stand composition and structure that may be associated with either natural events or management practices. Thus, the widely cited spruce decline in Germany in the early 1900s was the result of misguided attempts to convert sites that formerly supported hardwood or mixed species stands to pure spruce (Aune and others 1990, Lutz and Chandler 1946, Stone 1973, Troup 1952); more recent problems are associated primarily with air pollution rather than stand management. Similar problems can arise from use of unsuitable seed sources. Although excessive soil disturbance in harvesting and site preparation can cause reductions in growth of unknown duration (Lavender and Newton 1985, Miller and

others 1989), there is little or no concrete evidence in the Douglas-fir region that forest management practices similar to those now in use have caused substantial long-term site degradation (Morris and Miller 1994), and few instances in moist temperate climates elsewhere in the world (Worrell and Hampson 1997). They can have the opposite effect, as shown by superior growth observed in some second and third generation stands. Thus, recent European data (IUFRO 1995) seem to show a general increase in site index and growth rates in managed stands over the last half of the 20th century. A rare instance of accurate yield records extending over three successive rotations is given by Evans (1996), who found no evidence of decline in productivity in *Pinus pafula* plantations in Swaziland.

Nutrient budget calculations seem to indicate that on most sites there is little likelihood of substantial degradation through loss of nutrients in stands conservatively managed for conventional saw-log and pulpwood material. Substantial reduction in nutrient capital and site productivity does appear possible with very short rotations and complete tree utilization (Kimmins 1987, Morris and Miller 1994, Proe and others 1996). Continued production under very intensive short-rotation agricultural-type regimes, as with *Populus* hybrids, implies a need for intensive nutrient management similar to that in agriculture.

In general, the nutrient content per unit of weight or volume of tree crowns is greater than that of sapwood, which in turn is greater than that of heartwood. Consequently, nutrient removals are greater with complete tree utilization vs. bolewood utilization only; greater with complete bole utilization vs. utilization to a diameter limit; and greater for vigorous small trees vs. large mature trees. Hot slash burns and frequently repeated burns cause substantial losses of organic matter and nutrients, particularly nitrogen. Soil disturbance in logging, road building, and site preparation can cause measurable erosion losses and soil compaction.

Because sites differ in initial nutrient capital, in erodibility, in susceptibility to compaction, and in rates of biological soil development processes (including nitrogen fixation), positive and negative effects of specific practices differ among sites. In general, any detrimental effects that may exist will be more serious on poor sites than on good sites. Thus, current data from the generally good sites of the Tillamook Forest seem to indicate greater productivity of young stands established after severe fire and intense salvage logging than was exhibited by the previous stands. One would not expect such results from stands on adverse sites and shallow rocky soils.

One can easily imagine a worst case regime that could not fail to cause site degradation. But this would be far outside the range of regimes currently in use. We do not know whether or not current practices may have long-term negative (or positive) effects on soil productivity. We can indicate, however, some choices associated with greater or less likelihood of such effects. Likelihood of site degradation will generally be less if (see the series of articles in Perry and others 1989):

- Harvest is with cable systems; or if by ground systems, skidding is confined to designated skid trails.

- Slash burning is avoided or limited to the minimum necessary for acceptable hazard reduction and regeneration establishment.

- Branchwood and tops are left on site; very intensive utilization is avoided.

- Provision is made for restoring nitrogen on nitrogen-deficient sites, through use of either nitrogen-fixing vegetation or artificial fertilization.

- Mechanical soil disturbance during site preparation is minimal.

- Intervals between thinning entries are relatively long.

- Rotations are relatively long, hence

    -a high proportion of wood removed is heartwood.

    -need for site preparation and regeneration (i.e., site disturbance) arises only at long intervals.

Beuter and Johnson (1989) point out that conventional economic analyses, based on discounted timber values, provide little justification for expenditures to maintain long-term productivity beyond the current rotation even if declines are real and substantial. This would seem to conflict with the long-term interests of society and with the widely accepted goal of sustainability, unless lost productivity can be restored in the future at reasonable cost; it is perhaps indicative of the limitations of conventional economic analyses. The question is perhaps moot in the absence of evidence of declining productivity, but prudence suggests that severe site disturbance, complete tree utilization, unnecessary use of fire, and very short rotations should be avoided.

Summary, Site Productivity There is little or no evidence in the Northwest, or in moist temperate climates elsewhere, that forest management measures similar to those now in use in the Pacific Northwest have reduced site productivity, and some have increased it. Possible unfavorable effects are difficult to detect over short time spans, however, and are probably related to characteristics of the individual site. Existing knowledge and prudence suggest that in general:

- Soil disturbance and slash burning should be restricted to the minimum necessary to secure adequate regeneration.

- Whole-tree utilization should be avoided.

- Very short rotations should be avoided.

Damaging Agents and Forest Health Trees and forests are subject to various forms of injury from fire, weather, insects, mammals, and disease. These agents can at times materially alter the development and composition of stands and forests, prevent attainment of desired goals, place limitations on the use of otherwise desirable management measures, and reduce productivity. They may require specific management actions to avoid unacceptable losses. Thus, they can be important considerations in selection of silvicultural regimes to meet various objectives.

The major causes of tree damage and death in coastal Douglas-fir and its associates (aside from normal competition) are fire, weather, bark beetles, mammals, various root and foliage diseases, and bole rots. With the exception of fire, these are more or less

endemic factors in stand development and of little concern so long as they involve only occasional trees. Indeed, death of occasional scattered trees can be beneficial in that it provides snags and down wood for wildlife and tends to promote development of diversity in species composition and stand structure. However, these agents also can cause major economic losses, drastically disrupt stand management, and preclude attainment of desired forest conditions and management goals. Management practices can reduce the probability and magnitude of such events.

Fire

Most of the Northwest forest found by the early European settlers originated as a result of wildfire. But uncontrolled fire is incompatible with any form of planned management or even human occupancy, and establishment of effective fire prevention and control was one of the great early achievements of forestry. We have not had a really big fire (on the scale of the Yacolt and Tillamook fires) in the Douglas-fir region since the 1940s. Although modern fire prevention and control measures greatly reduce the probability of large fires, they do not eliminate the possibility, given sufficiently extreme weather conditions (fig. 36). Some changes in land use may reduce risks (e.g., highways, agriculture, urbanization), but others, such as residential expansion into forest areas, increase both the risks and the potential magnitude of damage. Some measures currently advocated and used to favor wildlife and biodiversity also increase the risks and difficulty of controlling fire: notably, retention of standing dead trees, large accumulations of dead wood on the ground, and development of layered stand structures that can readily carry fire from ground to tree crowns.

Weather

Wind-Douglas-fir is a relatively windfirm species. But windfirmness differs with soils, soil moisture content, topography, previous stand history, and location with respect to adjacent recent harvest areas, and must be taken into account in management. Sporadic windfall must be expected. Heavy thinning in previously unthinned stands can result in increased windfall in the first few years after treatment. Losses can be high in shelterwood or other partial cuts in dense stands that have developed without thinning and along edges of clearcut units, particularly in exposed situations. Extremely high stand density also can lead to major losses from wind and snow breakage in unthinned stands. Systematic thinning begun early reduces windfall losses through development of strong root systems, large bole diameters in relation to height, and increased live crown ratios, which lower the center of crown mass (Stathers and others 1994).

Catastrophic windfall events occur somewhere in the region at intervals of 10 to 30 years. Examples are the great 1921 blowdown on the western Olympic Peninsula, the 1950-51 blowdown in the Oregon Coast Range, and the 1962 Columbus Day and 1993 Inauguration Day storms that caused widespread blowdown in both Washington and Oregon.

Minor scattered windfall and breakage from wind and snow are frequent, are a part of normal stand development, and provide a source of snags and down wood of value for wildlife. Major windfalls are not only an economic loss and a disruption of stand management but also create serious fire hazards and potential for bark beetle outbreaks (fig. 37).

Figure 36-Wildfires can destroy large areas of forest and drastically alter species composition. This large burn in the northern Sierra Nevada was salvage logged and planted, producing a new forest rather than the unproductive brushfield that otherwise would occupy the site for many years.

Figure 37-Minor scattered windfalls are a part of normal stand development and provide snags and down wood of value to wildlife. Major windfalls can destroy entire stands, are an economic loss, and create serious fire and insect hazards.

Ice, snow, and freeze damage-These occur sporadically at fairly long intervals, and resulting losses can be severe. Thus the 1955 freeze caused extensive defoliation and top dieback of conifers in western Washington, and the 1996 ice storm caused extensive bole and branch breakage of red alder and top breakage in Douglas-fir. Management can do little to avoid such damage, other than using appropriate seed sources and avoiding development of very dense stands with high height-to-diameter ratios.

Bark Beetles

Compared with the interior form of Douglas-fir (and with most other conifers), coast Douglas-fir is relatively free from serious insect pests. The major pest is the Douglas-fir bark beetle *(Dendroctonus pseudotsugae* Hopkins). Sporadic outbreaks of this insect have caused major losses in the past. A notable example is the large outbreak in western Oregon and southwestern Washington triggered by the combination of extensive blowdown in 1950 and 1951 and two successive drought years. An estimated 10 billion board feet of timber was blown down and an additional 3 billion board feet was killed by the Douglas-fir beetle (Greeley and others 1953). Small localized and less spectacular outbreaks are common in mature and old-growth stands.

Damage by the Douglas-fir bark beetle has declined markedly with the decreasing acreage in old and highly susceptible stands and improved access for salvaging windthrown and fire-damaged timber. As with other bark beetles, the primary control is through silviculture. Practices promoting tree and stand vigor also reduce susceptibility to bark beetle attack. Major outbreaks are usually triggered by windfall or fire events (Mitchell and Sartwell 1974). Drought and root disease also predispose trees to attack. The beetles are attracted to and breed in green damaged or down trees and spread from these to nearby healthy trees. Maintenance of stand vigor and prompt salvage of dead, dying, and infested trees after windfall or fire therefore are the best means of prevention and control (Furniss and Carolin 1977). Failure to conduct prompt salvage operations when they are appropriate may lead to greatly increased damage.

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Mammals

A considerable number of mammal species cause significant damage and can seriously interfere with and modify stand establishment and development. The extent and severity of damage are highly variable and often localized. The most important mammal species damaging forests in the coast Douglas-fir region are:

- Mountain beaver, a rodent peculiar to the Pacific Northwest (unrelated to the true beaver). These rodents cut seedlings up to 1 inch in diameter and strip branches and bark from considerably larger trees. They can seriously impede establishment of regeneration. The shrub and herbaceous understory common in low-density stands and thinned stands provides the food supply for an endemic population. Harvest or natural disturbance may briefly reduce the food supply and is usually followed by prolific development of shrub and herbaceous vegetation within the next several years. A corresponding increase in the mountain beaver population (and associated damage) reflects in part an increase in the resident population and in part in-migration from immediately surrounding areas.

- Deer *(Odocoileus hemeonus)* and elk. These species browse the leaders on conifer seedlings and small saplings, and foliage and twigs on western redcedar and hardwoods. Severe browsing can cause regeneration failure. Although Douglas-fir is not a highly preferred browse species, damage often is severe locally (fig. 38). Preferred browse species such as redcedar and bigleaf maple may be eliminated. Most hardwoods (other than tanoak) are browsed whenever leaves are present, although red alder is not commonly browsed until late summer or fall (Dobkowski and others 1994, McComb 1994).

- Black bear *(Ursus americanus).* Bear strip bark from pole- and small-sawtimber-size trees, often killing the tree or creating wounds that are entrance points for bole rots (fig. 39).

Figure 38-Deer and elk browsing at times causes severe damage to regeneration and may eliminate species such as western redcedar. This western redcedar seedling is only a foot in height after 15 years of repeated browsing.

Figure 39-Bark stripping by black bear often kills trees or provides entrance points for rots. Damage can be extensive.

Although some damage from these causes is unavoidable and part of natural stand development, severe damage is incompatible with any form of planned management and can change the course of stand development. Methods for limiting such damage at the stand level include:

- Use of vigorous planting stock and vegetation management to promote rapid early growth, thereby reducing the time during which regeneration is exposed to significant clipping and browsing damage.

- Use of repellents and plastic tubes to protect seedlings.

- Local reduction in populations through trapping (mountain beaver) or hunting (deer, elk, bear).

- Removal of individual problem animals or supplemental feeding (bear).

- Fostering alternative and preferred forage (Campbell and Evans 1978).

The severity of animal damage problems and methods for limiting damage differ with size of animal populations, current stand conditions, and conditions in neighboring stands. Existing information is summarized in Black (1992), and possible control measures are further discussed by Nolte and Otto (1996).

Diseases

Root rots-The major problem diseases in coastal Douglas-fir affect tree roots. These are (1) laminated root rot, caused by *Phellinus weirii,* (2) armillaria root disease *(Armillaria obscura);* (3) annosus root disease *(Heterobasidion annosum);* and (4) black stain root disease *(Ceratocystis wageneri)* (Hadfield and others 1986). Of these, the most serious is *P. weirii.* This is endemic throughout the Douglas-fir region, with impacts ranging from minor to severe. Minor infections can be considered part of the natural process of stand development and may benefit some objectives. Snags resulting from root rots meet some habitat needs but often fall relatively quickly. The resulting down wood and openings have a long-term influence on canopy structure and species diversity. Major infections cause severe economic losses and may seriously interfere with attainment of other stand management objectives.

Control can be achieved by removal of infected stumps (Thies and Sturrock 1995). This is economically feasible only in the case of severe infections on highly productive land and gentle terrain. Losses from light infections can be minimized by salvage of dead and dying trees during thinning. For more severe infections, the most generally feasible approach is to cut trees of susceptible species on and adjacent to root rot pockets and replace them with resistant or nonsusceptible species, such as western redcedar, hardwoods, or pines. (Red alder is not only immune and fast growing in youth but also adds substantial amounts of soil nitrogen.)

Bole rots-In the past the largest economic loss from disease has probably been the loss of merchantable wood caused by heart rotting fungi in old stands, particularly *Phellinus* (formerly Fames) pini (Boyce and others 1953). These are primarily diseases of old, unmanaged stands and become comparatively minor in second-growth stands, even when these are managed on long rotations. Stem rots in young stands occur principally in western hemlock and true fir damaged during harvesting operations. Bear damage is also a common source of entry. The principal control measure is careful

planning and close control to minimize mechanical damage during thinning and partial harvest operations. Some rot will always be present and, in minor amounts, has value in that it facilitates cavity excavation by some wildlife species.

Foliage diseases-There is considerable concern over recent damage by Swiss needle cast *(Phaeocryptopus gaeumanni)* to Douglas-fir, which in the past was not regarded as a serious pest (Kanaskie and others 1996). Extent and future importance of the damage and possible control measures have not been well evaluated, but the problem seems confined at present to Douglas-fir plantations in the *Picea sitchensis* zone along the Oregon coast.

Dwarf Mistletoes

Dwarf mistletoes are parasitic seed plants. Two species occur in the Douglas-fir region, *Arceuthobium douglasii* on Douglas-fir and *A. tsugense* on western hemlock, mountain hemlock *(Tsuga mertensiana* (Bong.) Carr.), and Pacific silver fir *(Abies amabilis* Dougl. ex Forbes) (Bega 1978). Dwarf mistletoes spread by seed released from dwarf mistletoe plants growing on infested, principally overstory, trees. The released seed falls on the foliage of other trees below the infested tree and is washed onto young stem tissue, where it germinates and infects the new host and causes stem and branch deformities and reductions in vigor and growth rate. The potential radius of spread from the host tree therefore is limited.

Although Douglas-fir dwarf mistletoe is a serious pest in the interior West, it is absent or of minor importance on most coast Douglas-fir. It does cause considerable damage in southwest Oregon and northern California and along the east slope of the Cascade Range. In contrast, hemlock dwarf mistletoe is present on western hemlock, mountain hemlock, and Pacific silver fir throughout the region and can cause substantial damage and considerable reductions in growth (Ruth and Harris 1979).

Control consists of removing all infested trees at time of harvest. The clearcutting widely practiced in the region is also an effective means of dwarf mistletoe control, particularly when followed by slash burning, which eradicates infested advance reproduction. Removal of any residual stems and visibly infested advance regeneration in early precommercial thinning also can be effective (Russell 1976).

A concern that has not been satisfactorily evaluated is that the partial cutting systems and green tree retention requirements recently adopted by some agencies and organizations may lead to a greatly intensified dwarf mistletoe problem in western hemlock and true fir forests, through spread from infested residual trees to regeneration. This problem was totally ignored in the management plan developed for the Clayoquot Sound area on Vancouver Island, BC.

A recent comprehensive monograph provides much information on biology, pathology, and control of dwarf mistletoes (Hawskworth and Wiens 1996).

Summary, Forest Health

Sporadic minor damage from various weather events, insects, animals, and diseases is a normal part of stand development. Severe damage can cause unacceptable losses and disruption and is to be avoided to the extent feasible. Some applicable management measures include:

- Systematic thinning to develop trees with high vigor and low height-to-diameter ratios that are resistant to windfall, snow breakage, and insect attack.

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- Planting stock and site preparation methods that provide rapid juvenile height growth, thereby reducing the period of exposure to animal browsing.

- Prompt salvage of major windfalls as a precaution against bark beetle outbreaks.

- Planting or favoring resistant species in and around existing root disease centers.

In Conclusion

Silviculture consists of the techniques for manipulating the establishment, composition, structure, and rates of development of forest stands, including both trees and associated other vegetation. These techniques are the product of a long history of accumulated research and experience. Although many of these techniques were originally developed to enhance wood production, they can easily be extended to the broader problems of developing forests, stands, and trees with the characteristics desired for multiple forest objectives. In young stands particularly, stand characteristics can be markedly modified and development rates sharply accelerated within relatively short periods. Details of application must of course be worked out for any specific set of conditions and objectives.

Future stand management will probably involve a range of silvicultural regimes and objectives (Curtis and Carey 1996), from (1) some stands managed with the primary objective of producing high wood yields, through (2) others under multipurpose management designed for joint production of wood and nontimber values, to (3) others managed primarily to promote wildlife, biodiversity, recreational and mature-forest values along with some incidental wood production. We believe that considerable wildlife habitat and other values can be provided while producing relatively high yields of wood in production forests; and that significant amounts of wood can be produced in multipurpose forests while meeting the other needs and desires of society. The knowledge and skills are available to pursue diverse objectives effectively in both kinds of forests. Many owners will likely manage stands within their forests under a combination of both approaches.

Management Choices

The selection and application of appropriate regimes requires well-defined objectives. Unfortunately, the lack of clear definition and acceptance of objectives today hinders effective management of many forests, particularly those in public ownership. Objectives also change over time in response to changes in economic and social factors. Some obstacles to establishment of objectives include:

- Lack of agreement on the desired balance of forest conditions, forest products, uses, and values

- Inadequate knowledge and understanding of the relations between stand conditions and nontimber values

- Inadequate knowledge and understanding of the associated costs and benefits

- Lack of agreement on distribution of costs and benefits among segments of our present and future society

- Uncertain political environments and regulatory controls

What *is* the desired future stand condition for a specific tract or ownership? What *are* the relative values to the landowner and to society of the several forest outputs involved-wood, special forest products (boughs, mushrooms, berries, etc.), wildlife (what kinds of wildlife?), water, aesthetics? And, what are the associated costs of producing these? Objectives must be defined in terms allowing measurement of progress or success.

The wide variety of possible management regimes and of objectives in stand management are in part a landowner's choice, but major constraints also are imposed by differences in stand conditions and sites. Management regimes begun at stand establishment or early in the life of the stand offer far more opportunity to shape stand composition and development than is available when efforts are begun relatively late in the life of the stand. Responses to specific silvicultural measures differ markedly among sites. No one management regime can be applied uniformly to a species or forest type with satisfactory results. (Some of our present problems stem from past attempts to do just that!) Rather, treatments must be tailored to stand and site conditions as well as to management objectives, and they must be chosen in the context of the surrounding landscape, rather than stand by stand. Will landscape productivity for any desired values be markedly influenced by treatment of the stand? Can a particular treatment regime enhance or provide conditions that are needed and now lacking in the larger unit? Applicable measures and reasonable objectives will differ among stands.

There is necessarily much uncertainty in objectives, in current judgments of the value of specific stand characteristics for different objectives, and in the effects of specific treatments (including no treatment) on those values. Management objectives of a few years ago were markedly different from those of today, and those of a few years hence will probably differ from today's. Thus, it is generally recognized that snags and some down wood are important, but we do not know how much is necessary or how it should be distributed to meet selected objectives in different forest landscapes: and we will not know without long-term experimentation and monitoring. Incomplete knowledge and uncertainty about the future are facts of life. Yet, a manager must make decisions involving long-term goals and programs while attempting to retain flexibility to respond to future goal changes.

We can make reasonably solid predictions (at least qualitatively) of the likely course of stand development, given a present condition, a specified treatment regime, and freedom from major stand damage or catastrophe. But it is clear from the known history and prehistory of Pacific Northwest forests that major stand damage and catastrophes are abundant on time scales approaching the biological life span of forest trees. And, management objectives change over time. Attempts to delineate specific physical areas for preservation or development of a target condition over periods of one to several centuries are unlikely to succeed. Rather, objectives should be specified in terms of a desired mix of future stand conditions and rotations, and stand management regimes adopted that will preserve future flexibility.

Despite the uncertainties, we have a large body of research and experience showing that stand characteristics and rates of stand development can be markedly altered within relatively short periods through appropriate silvicultural treatments to meet whatever future objectives may be selected.

Information Needs

Additional information and experience needed to successfully implement the regeneration and stand management treatments that have been suggested include:

- Quantitative evaluation of effectiveness and costs of measures such as green tree retention, snag retention and snag creation, retention of large woody debris. How much is needed? How should it be distributed? What use is made of different stand structures and stand components (snags, down wood, understory vegetation layers) by wildlife species? What are the actual gains in value of wildlife habitat and in biodiversity from different amounts of these structural features? What are the tradeoffs among these benefits and costs? What are the most cost-effective means of providing these benefits?

- Quantitative comparisons of a range of silvicultural systems and stand treatments and of their arrangement in space and time. What are the effects on wildlife populations, on timber outputs, and on aesthetic, watershed, and other environmental values? What are the comparative costs and economic returns of feasible alternatives?

- Development of cost-efficient methods for accelerating development of mature- and old-forest characteristics in selected young stands.

- Quantitative information on growth and development patterns of mixed species stands and mature stands (100+ years) and their response to stand treatments.

- Quantitative information on the effects of stand density and harvesting methods on reproduction and growth of hardwoods, conifers, and shrubs in the understory of conifer stands, and effects of understory and overstory density on other components of the ecosystem and on incidence and severity of damage from wind, pathogens, insects, etc.

- Development of improved simulation models that allow reliable prediction of regeneration and stand and forest development for a wide range of initial stand structures and silvicultural regimes and to stand ages of 200 years or more.

- Information on the biology and management of previously neglected tree and shrub species.

- Adequate techniques for evaluating the economic **and social consequences of** management actions, in benefits produced and benefits foregone. The techniques traditionally used in forest economics are clearly inadequate, but we do not have satisfactory and generally accepted alternatives.

Discussion has been primarily in terms of Douglas-fir, which is the most important species in the region and the one most extensively studied, as evidenced by numerous citations above and the summary papers in Oliver and others (1986). However, its associates-western hemlock, red alder, grand fir, Pacific silver fir, noble fir *(Abies procera* Rehd.), and western redcedar-also are ecologically and economically important. There is a considerable body of research and experience on the biology and management of western hemlock (e.g. Atkinson and Zasoski 1976, Hoyer and Swanzy 1986, Ruth and Harris 1979) and red alder (Briggs and others 1978, Hibbs and others 1994). Existing information on all aspects of the biology and management of the true

firs and of western redcedar is much more limited (Franklin and others 1983, Oliver and Kenady 1981, Smith 1987) and should be a fertile field for research, particularly with the current interest in mixed species management and biodiversity.

Some Policy Questions

Resolution of current conflicts and improvement of future forest land management involves some fundamental social, political, and economic questions. United States industrial wood use is at an all-time high and is projected to increase by nearly 40 percent in the next half century (Haynes 1991, Haynes and others 1995; Kaiser 1997) (fig. 40). World population is projected to double (Keyfitz 1989), and wood consumption is expected to increase worldwide in response to the combination of population growth and economic growth (Brooks 1997). The United States is already one of the largest importers of wood and wood products in the world and has the largest per capita use of wood products. The present primary limitations on U.S. wood production involve questions of social objectives, attitudes, and policies rather than of biological or economic productivity or technical knowledge (Beuter 1995, Frederick and Sedjo 1991).

Will we in the United States produce our own wood supplies? Or will we seek our wood supplies elsewhere in the world from much less productive lands where long-term sustainable management is less likely (Dekker-Robertson and Libby 1998)? How much land can or should we retain in forest? What is the desired balance of products, uses, and values for whatever forest land is available? There are many possible combinations and they can be greatly affected by management.

Some considerations are:

- The population of the United States has doubled within the lifetime of the authors and is still increasing

- United States industrial wood use is at an all-time high and increasing

- Wood is one of the most environmentally "friendly" materials used by human societies (Koch 1991)
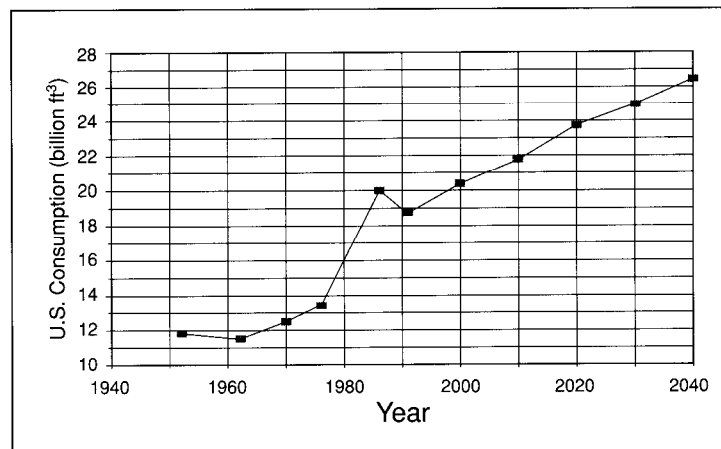

Figure 40—United States historical roundwood consumption 1952-91 and projections to 2040. (Haynes and others 1995).
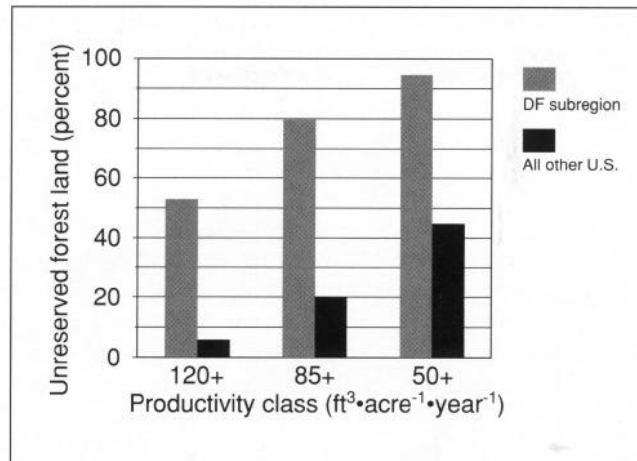
Figure 41—Productivity of forest land in the Douglas-fir region far exceeds that of most other regions of the United States (graph derived from Waddell and others 1989).

- The Pacific Northwest is one of the most productive forest regions of the world (fig. 41)

- The Pacific Northwest is one of the few places in the developed world where substantial areas of intact, original forest remain, with unique challenges and opportunities for management of forest landscapes and biological diversity

- Our actions cannot for long be isolated from trends and consequences in the rest of the world (Brooks 1993, Schallau and Goetzl 1992, Sedjo 1993)

It does seem clear that although multipurpose forestry and ecosystem management give increased weight to forest values other than timber, timber values will remain important on most forest lands. Sustainability of forests and human society requires active management (Berlyn and Ashton 1996), although the specifics will necessarily differ by sites, with existing stand and forest conditions (Kimmins 1997), with the prevailing economic and social climate, and with owner objectives. No one silvicultural system or management regime exists that can or should be applied to all areas. And, the need to develop a balanced distribution of stand structures and developmental stages should not be forgotten in the current preoccupation with old-growth values.

Most silvicultural activities in the past have been driven by the objective of maximizing landowner revenues, which arise primarily from wood production. Most other forest values are benefits that accrue to society at large rather than to the landowner. Some measures that can be taken to enhance these values involve little or no increase in costs or decrease in revenue to the landowner. But others are quite costly. It would seem justifiable for society to provide incentives to private landowners to offset increased costs and reduced revenues associated with measures to promote societal values on individual ownerships (Bourland and Stroup 1996, Boyce 1995, Lippke and Fretwell 1997, Lippke and Oliver 1993, Framstad 1996) and to promote cooperative planning across land ownerships (Johnson 1995). Such measures would probably be less expensive, less disruptive, and socially more acceptable than attempts to force

change through regulation (Lippke and others 1996). Indeed, some current regulatory approaches are counterproductive in that they penalize socially desirable behavior by the landowner. Thus, uncertainties and fears about future constraints (e.g., of a regulatory "taking" as endangered species habitat) have undoubtedly motivated some owners to cut stands now rather than holding them for higher yields and improved environmental values in the future.

On public lands, some part of the additional costs and decreased revenues associated with recent changes and conflicts has been offset from general tax revenues. But historically, revenues from commodity production have directly or indirectly supported most other activities on public lands. It seems unlikely that society can or will indefinitely subsidize on a huge scale measures to promote intangible and nonmonetary values in the absence of concurrent revenues. We therefore believe that regimes that include commodity production at reasonable and sustainable levels will be a necessary component of future programs for management of public lands, particularly in the West where the public lands represent such a large portion of the forest landscape.

A considerable part of our perceived problems stems from the unbalanced distribution of age classes, both regionally and-even more-within local areas. This arises from past and recent harvesting history and from reluctance to manage stands for longer rotations and differing stand structures. Management should strive to reduce the imbalance. This implies that some lands should be managed under extended rotations and for a variety of stand and landscape structures and characteristics. Major questions and opportunities are involved in future management of the huge area of plantations, and these will become major research and policy questions of the near future.

The art and science of silviculture continues to evolve. There is a huge and often unappreciated body of silvicultural research and practical experience, both in the Pacific Northwest and elsewhere, that provides guidance on how to attain chosen objectives **in ways that are both biologically and economically feasible. Successful use** of the various possible silvicultural systems and regeneration methods will depend to a large extent on public perceptions and acceptance. There is no one universally applicable system or management regime. Management regimes must be tailored to site characteristics and management objectives.

Increasingly, societal pressures are exerted to influence objectives by constraining the use of practices that could yield positive results in terms of habitat, biodiversity and other environmental values along with wood production. Forest managers and researchers therefore need to involve the public in developing clearly defined forest and stand management objectives and selecting appropriate practices to achieve them. Given Societal agreement and acceptance, much of the silvicultural knowledge needed to achieve most objectives (whether single or multiple) is currently available, although there is a continuing need for both monitoring and designed experiments to work out the details of application to specific situations and changing objectives.

Acknowledgments

Metric Equivalents

1 inch = 2.54 centimeters

1 foot = 0.3048 meter

1 square foot = 0.09290 square meter

1 cubic foot = 0.028 cubic meter

1 acre = 0.4047 hectare

1 square foot per acre = 0.2296 square meter per hectare

1 cubic foot per acre = 0.06997 cubic meter per hectare

1 mile = 1.609 kilometers

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Appendix: Some
Possible Management
Scenarios

The regimes listed below represent some alternatives for combined timber production and habitat development objectives, which we believe to be feasible on the basis of existing knowledge, although they are not equally desirable for all purposes. Examples of several of these exist in the region, but long-continued designed experiments are lacking for evaluation of regimes other than clearcutting, and little or no information is available on comparative costs and outputs. The regimes listed do not by any means represent all possibilities.

The regimes listed are taken from an ongoing cooperative management experiment.[1] Specifications are written in the context of an ownership (Washington Department of Natural Resources) that has wood production as a major objective but also has major concerns about wildlife values and aesthetic values in visually sensitive locations. The starting condition is even-aged stands that are predominantly Douglas-fir and in the age range of 50 to 70 years. These are preferably, but not necessarily, stands that have had prior thinning. Sites are quite productive, in an area (Capitol State Forest) where shrub competition with regeneration is considerably less severe than on many coastal sites. The species composition desired in future is Douglas-fir with a secondary component of western hemlock, western redcedar, and occasional hardwoods. In those regimes involving repeated entries, we use a 15-year cycle as the basis for planning, although either a shorter or a longer cycle may ultimately prove preferable. In all regimes, residual trees will be left along streams and in small uncut groups elsewhere within the stand to provide stream protection, wildlife trees, and a future source of snags and large down logs.

The regimes considered are outlined in figure 42 and described below. The illustrations of expected stand development are projections made with the west-side variant of the forest vegetation simulator (FVS, formerly called PROGNOSIS; Wykoff and others 1982), depicted with the stand visualization system (McGaughey, in prep.).

1. Clearcut

This system is well understood and is included primarily to provide a direct quantitative comparison of costs and outputs with the other systems discussed.

Initial cut-Cut all merchantable and unmerchantable trees on the area, except for streamside strips and scattered groups of leave trees to meet Forest Practice Act and Habitat Conservation Plan requirements. Mark root rot pockets so they can be identified later.

Regeneration-Plant according to current Washington Department of Natural Resources (DNR) practice (400 Douglas-fir per acre), except plant root rot areas with some combination of western redcedar, white pine, or hardwoods; or (less desirable) favor hemlock regeneration if present.

Subsequent operations-

Brush control-If and when needed, according to current DNR practice.

Precommercial thinning (PCT)-Decision at around 10 years, to depend on stocking achieved and feasibility of very early commercial thinning as an alternative. Retain some naturally established stems of species other than Douglas-fir, when present.

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[1] Curtis, R.O.; Clendenen, G.W.; DeBell, D.D.; DeBell, J.; Shumway, J.; T. Poch, T. 1996. Silvicultural options for harvesting young-growth production forests. Part I: The stand-level silvicultural experiment. Unpublished study plan. On file with: Forestry Sciences Laboratory, 3625-93d Avenue SW, Olympia, WA 98512.
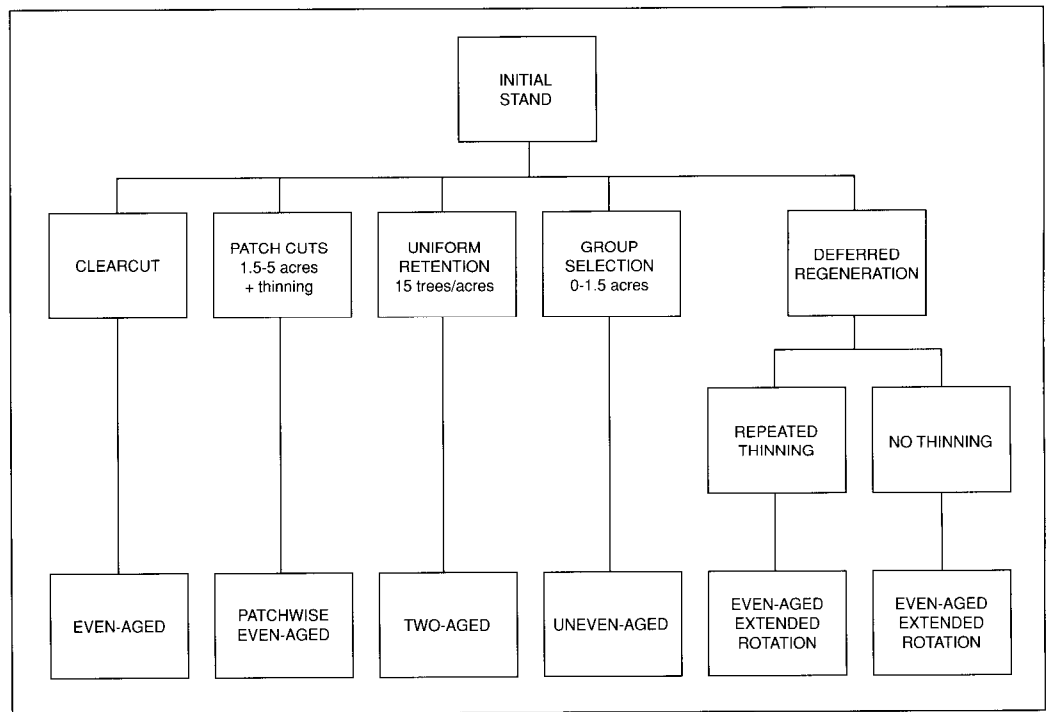
Figure 42—Some alternative management regimes that are expected to produce markedly different stand conditions.

Commercial thinning (CT)—Repeated thinnings, to reduce RD (relative density, Curtis 1982) to about RD35 in the first thinning and thereafter maintain density in the range of RD40 to RD60.

Harvest—At a rotation age to be determined, probably in the range of 60 to 80 years.

Characteristics—Well-understood regime, simple management, will probably maximize yield and minimize administrative and harvest costs. Appearance objectionable to much of public, may not be politically possible in future.

Figure 43 illustrates expected stand conditions at 1, 30, and 75 years after initial cut.

2. Two-Aged Stand Management (=Reserve Shelterwood)

This initially resembles a conventional shelterwood but with the overwood or a portion of it carried through the second rotation to provide large sizes and high-quality material. On many areas, the younger age class will probably contain an increased proportion of western hemlock. A hemlock-cedar understory will probably develop reasonably well under overstory densities that restrict establishment and growth of Douglas-fir.

Initial cut—This will remove a high percentage of the initial basal area. Residual basal area stocking will be <20 percent of "full" stocking. Leave trees would be principally well-distributed Douglas-fir selected for vigor and stem quality, plus some vigorous and well-formed redcedar and hemlock. Redcedar and hemlock will be preferred within or immediately adjacent to root rot pockets.

Figure 43-Projected appearance of the clearcut regime at time from initial cut of (A) 1 year, (B) 30 years, and (C) 75 years.

Regeneration-Supplement existing and prospective natural regeneration by underplanting Douglas-fir. Aim is a mixed species stand, but including at least 50 percent Douglas-fir.

Subsequent operations-

Brush control-If needed.

PCT-This probably will be needed some years after initial cut, to control spacing and remove advance regeneration damaged in harvesting.

CT-As needed to maintain reasonable growth rates in the younger cohort.

At some point a need will arise to remove additional stems from the overstory, both to salvage dead and dying trees and to keep density low enough to allow satisfactory growth of the understory. We have no present basis for estimating timing, but this will certainly be needed by the time basal area reaches 50 percent of "full" stocking based on current QMD (quadratic mean diameter) of residuals, and maybe sooner.

Harvest-At a rotation age to be determined, perhaps 60 years after the initial cut. This would correspond to stand ages of about 60 years for the understory and 120 years for the Douglas-fir overstory.

Characteristics-Maintains at least partial forest cover over two conventional rotations, sharply reducing the area in the highly visible freshly harvested condition. Potential for high value production in the retained overstory. Layered structure favorable to some wildlife. Probable increase in hemlock component. Possibility of major windfall losses.

Figure 44 illustrates expected stand condition at 1, 30, and 75 years after initial cut.

3. Patch-Wise Even-Aged Management

Small patch cuts on the order of 1.5 to 5 acres can be regenerated either naturally or by planting and can be treated by conventional even-aged management techniques emphasizing Douglas-fir. Over time, a unit can be converted to an uneven-aged mosaic of such even-aged patches that would be predominantly Douglas-fir (with lesser proportions of western hemlock and western redcedar) while lacking large and visually obtrusive harvest areas. The visual effects will be strongly influenced by cutting cycle and rotation age (which determine the proportion of the area in the early regeneration stage) and by patch size.

A possible sequence of operations follows.

First entry-Cut all stems on patches of 1.5 to 5 acres in size, dispersed over the unit and amounting to 20 percent of the available area. Patches to be somewhat irregular and differing in shape, but length-to-width ratio should not exceed 2:l. Concurrently, do a light thinning in the intervening areas, aimed to reduce RD in the thinned area to perhaps RD45 (except, do not remove more than one-third of prethinning basal area in the first cut in previously thinned stands, or one-fourth in unthinned stands). Plant patches to Douglas-fir or a mix of Douglas-fir and other species, but use western redcedar, white pine, or hardwoods in and around former root rot pockets where feasible. Do any brush control needed to obtain reasonable survival and early growth.
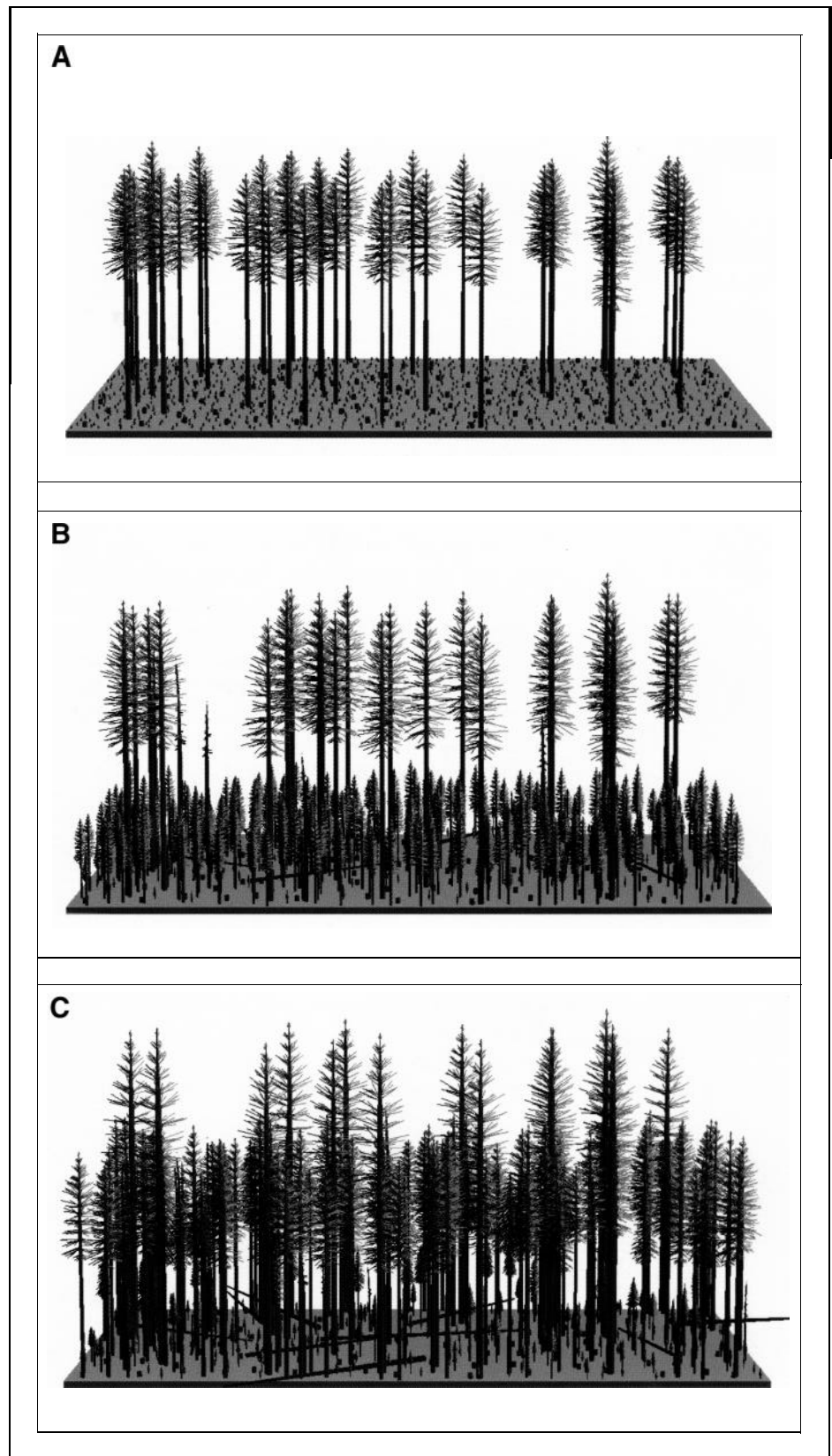
Figure 44-Projected appearance of the two-aged (reserve shelterwood) regime at time from initial cut of (A) 1 year, (B) 30 years, and (C) 75 years.

Subsequent entries (15-year cycle)-Do patch cuts and secure regeneration on another 20 percent of area. Precommercially thin previously regenerated areas as needed. Commercially thin intervening areas as appropriate, to maintain in the range of RD40 to RD60 in the older cohort and somewhat lower levels (RD35 to RD55) in younger cohorts established in cut patches. This will in time produce a stand consisting of five age classes with a 75-year rotation; a condition that could be maintained indefinitely.

The minimum patch size of about 1.5 acres is determined by the needs for (1) direct light for satisfactory development of Douglas-fir, and (2) avoidance of future need to fell trees into existing regeneration. The latter requirement leads to a minimum patch size of about two mature tree heights in diameter. Because of the extended conversion period involved, the first cut might ideally be made at a somewhat younger age than in the case of the other systems listed and later cuts will be at ages considerably greater than 75 years.

Characteristics-This regime avoids large and highly visible harvest areas, provides near-constant landscapes, and will probably maintain the Douglas-fir component and provide long-term yields near those under clearcutting. It uses well-known even-aged management techniques in treatment of patches. It provides higher yields in early years than regime (5) below, while automatically working toward a balanced age distribution. Compared with regimes (1) and (2) above, harvest and road costs will be higher, and there will be increased costs and complexity in maintaining control over operations on many small areas. The mix of habitat conditions should be favorable for many wildlife species. The intimate mixture of age classes should obviate the possible problems associated with fragmentation and species recolonization.

Figure 45 illustrates expected stand conditions at 1, 30, and 75 years after the initial cut.

4. Group Selection   This will resemble regime (3) above, except that removals will **cover** a range from individual trees to groups not exceeding 1.5 acre in size.

Because of the small size of groups it will not be feasible to control the cut in terms of area. But residual basal area over the area as a whole will be comparable to that in regime 3 of the same replication. In early entries, cuts will not differ much from conventional thinning, except that they will include conscious creation of scattered small openings intended to secure or release regeneration.
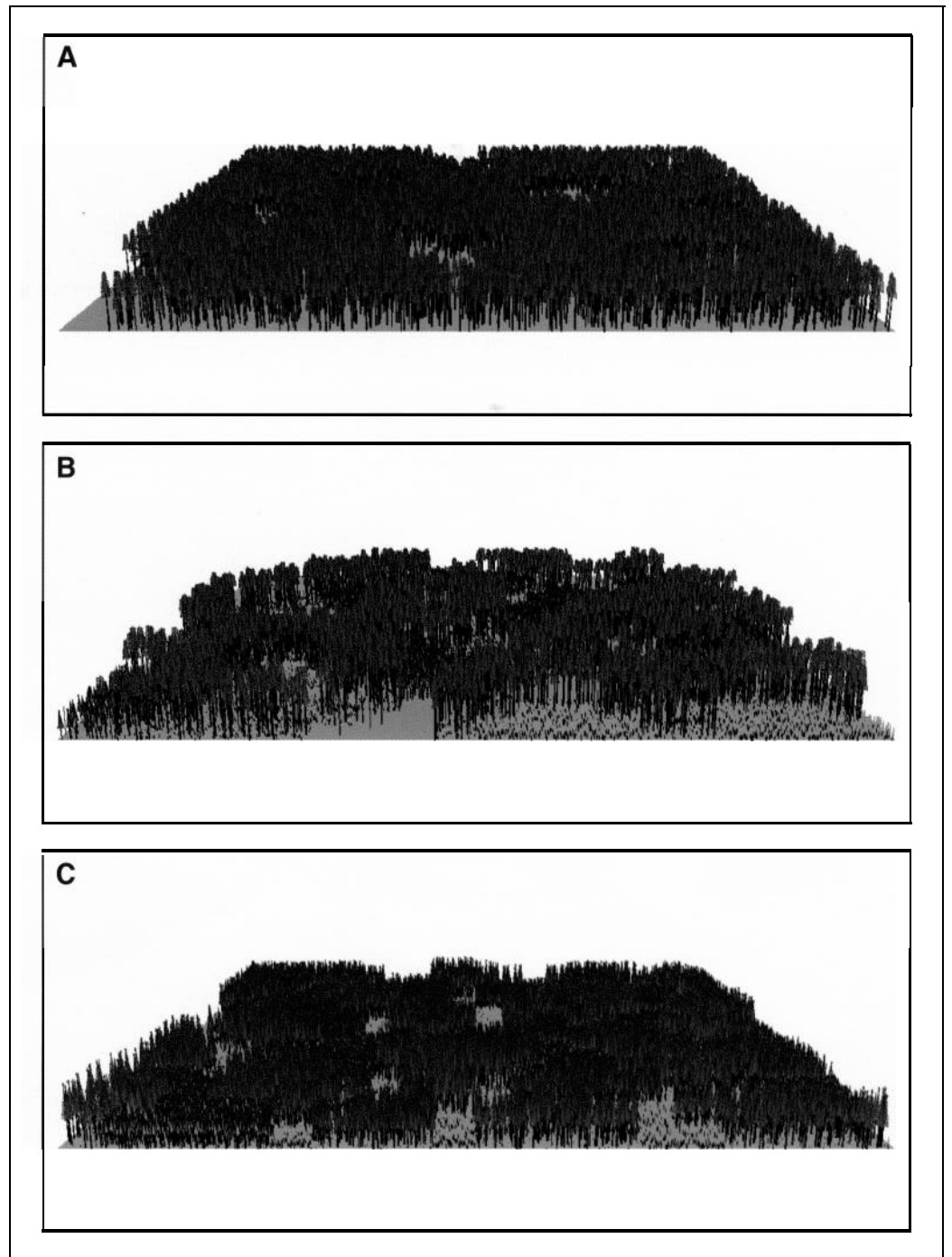
Figure 45-Projected appearance of the patchwise even-aged management regime at time from initial cut of (A) 1 year, (B) 30 years, and (C) 75 years.
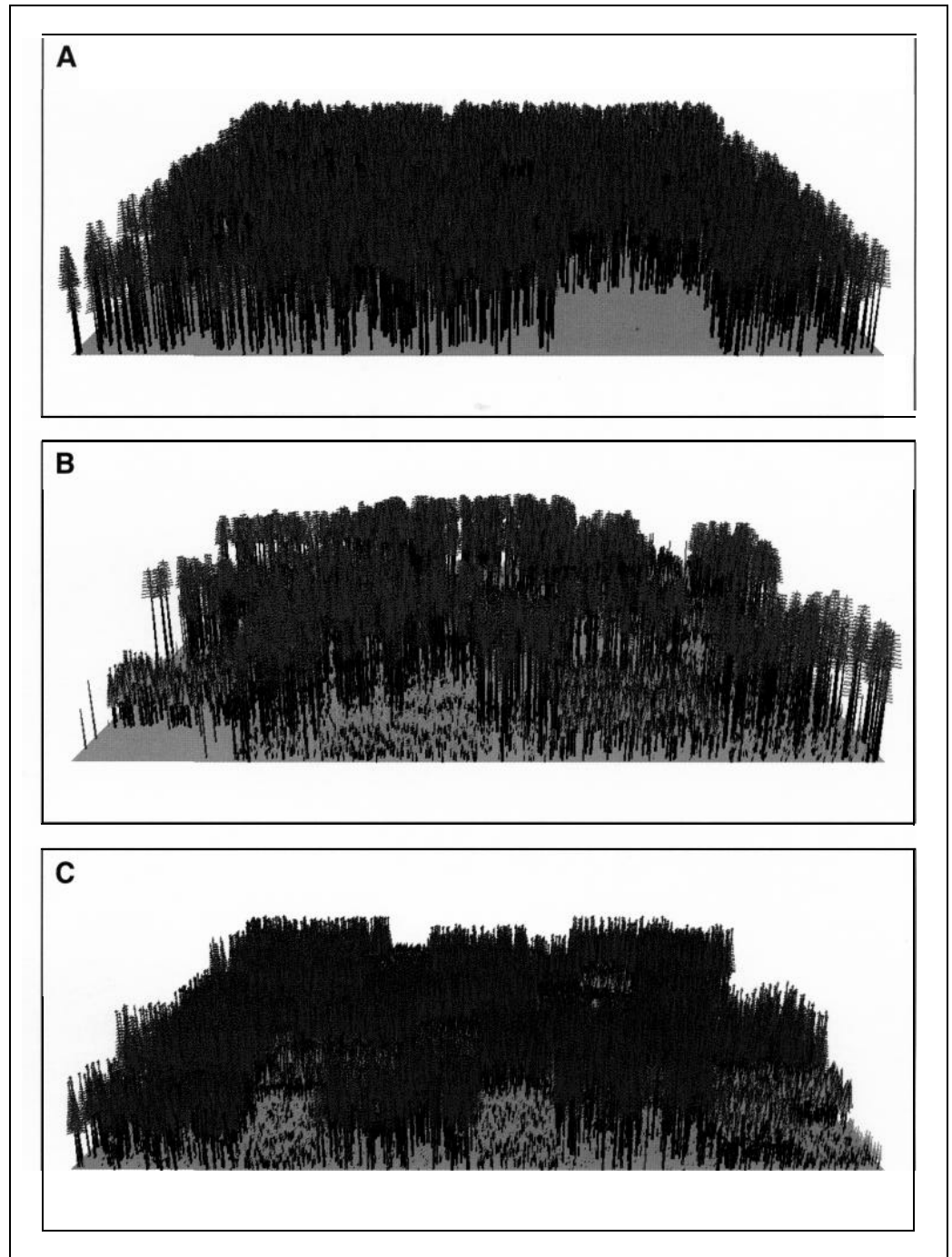
Figure 46-Projected appearance of the group selection regime at time from initial cut of (A) 1 year, (B) 30 years, and (C) 75 years. [Note that this is a considerably larger scale than the patch cut in figure 45.]

Characteristics-Compared to regime (3), the smaller group size would mean (a) reduced visual impacts, (b) increased difficulty of managing intermediate treatments, and (c) increased harvesting costs and damage. The small size of openings will likely mean reduced representation of Douglas-fir in regeneration and possibly reduced growth of all species.

Figure 46 illustrates expected stand conditions at 1, 30, and 75 years after initial cut.

5. Continued Commercial Thinning on Extended Rotation

Available information suggests that systematic thinning of vigorous Douglas-fir stands can maintain high growth rates in volume and value for extended periods, to ages of 100 years or more. Culmination has not been observed within the range of ages included in existing commercial thinning trials. Continued commercial thinning can prolong the period of high production and produce current income, while producing aesthetically desirable large trees and reducing the area of land in the highly visible regeneration stage at any point in time. This is therefore one of the options to be considered for reducing visual impacts.

Repeated commercial thinning is expected to produce an understory of tolerant species. The stand would ultimately be reproduced by clearcutting, shelterwood, or patch cuts, at some rotation age now unspecified but possibly of the order of 120 years. The regime will produce large and high-value trees.

Figure 47 illustrates expected stand conditions at years 1, 30, and 75 years after the initial cut.

6. Extended Rotation Without Commercial Thinning

This provides a basis for comparison with gains obtainable by commercial thinning (regime 5) when stands are held on an extended rotation. It also constitutes a management option for reducing the proportion of the forest in highly visible harvest operations while adjusting currently unbalanced age distributions. Figure 48 illustrates expected stand conditions at establishment of the experiment and 75 years later.
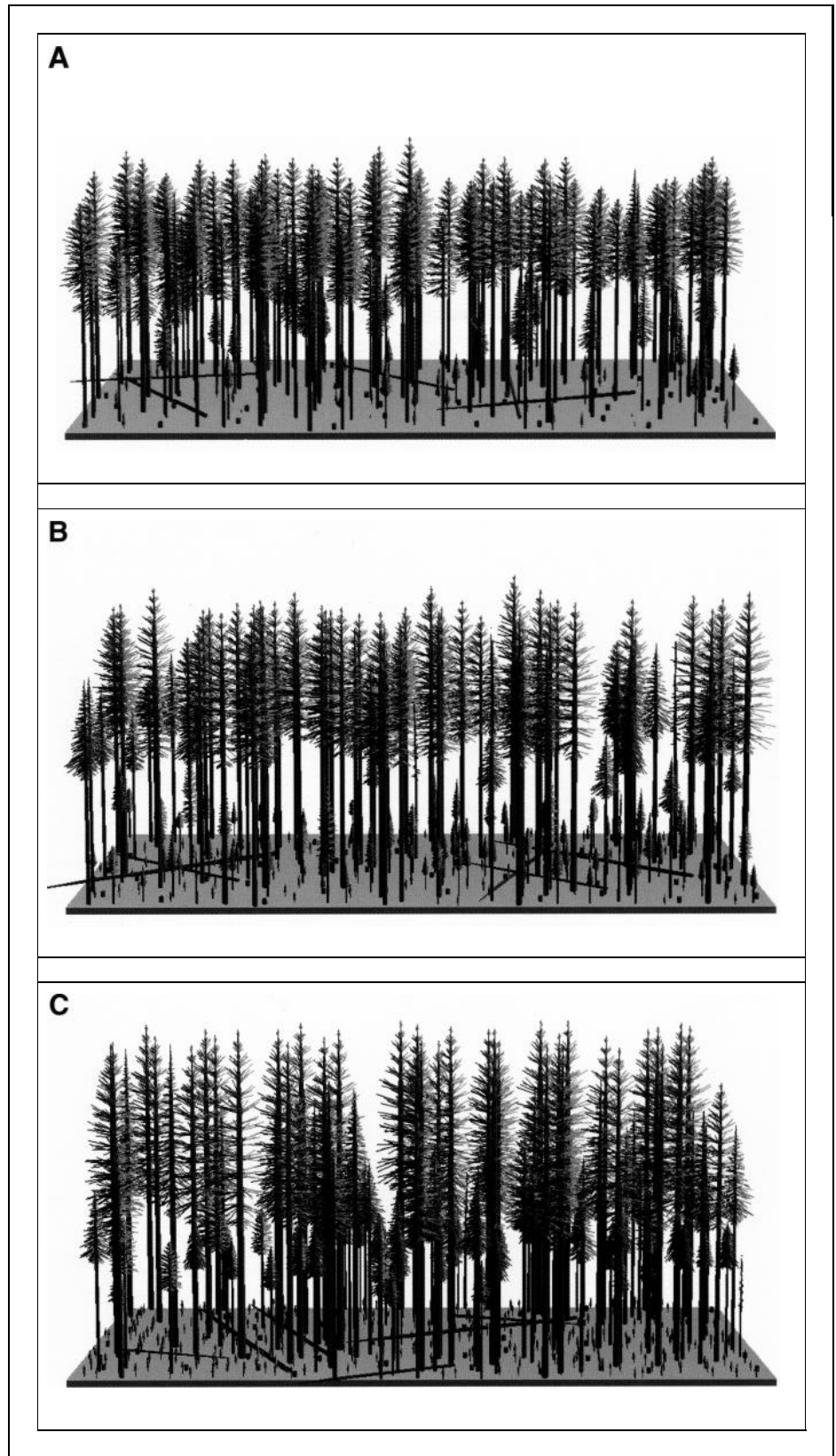
Figure 47-Projected appearance of the continued thinning regime at age (A) of first thinning, (B) first thinning +30, and (C) first thinning + 75.
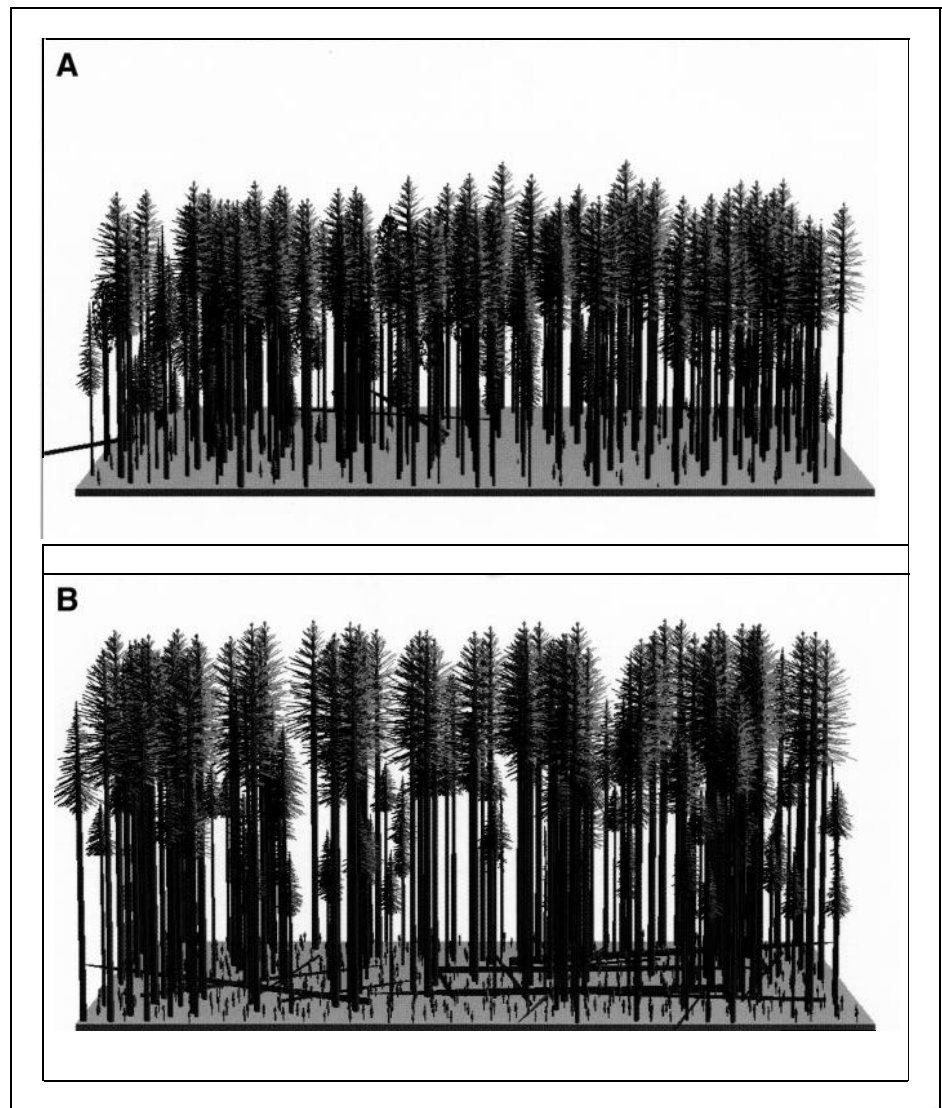
Figure 48-Projected appearance of the unthinned stand at (A) year 1, and (B) year 75 after establishment of the experiment.

Glossary[1]

accessory system-a silvicultural system that does not fit within other conventionally recognized classifications, usually involving the creation or maintenance of two age classes.

age class (cohort)-a distinct aggregation of trees of more or less similar age originating from a single natural disturbance or regeneration cutting.

basal area--the cross-sectional area of tree stem(s) at standard height (usually 4.5 feet); the total of such values on a per unit area basis (=stand basal area) is a stand attribute widely used in stocking and thinning guides.

CAI-abbreviation for current annual increment.

clearcutting method-a method of regenerating an even-aged stand in which a new age class develops in a fully exposed microclimate after removal, in a single cutting, of all trees in the previous stand. Regeneration may be from natural seeding, direct seedling, planted seedlings, or advance reproduction. Harvesting may be done in groups or patches (group or patch clearcutting) or in strips (strip clearcutting). In the clearcutting system, the management unit or stand consists of the individual clearcut stand.

clearcutting with reserves-a clearcutting method in which varying numbers of reserve trees are left to attain goals other than regeneration.

clone-a group of individuals of identical genotype, usually arising from vegetative propagation.

commercial thinning-a thinning in which the trees removed have value at least equal to the cost of harvest. Abbreviated CT.

culmination age-age at which mean annual increment (usually in volume) of a stand attains its maximum.

current annual increment-growth rate per year at a specified point in time. Abbreviated as CAI.

density-(l) number of individuals per unit area (in ecology); (2) any measure expressing degree of competition (loose usage in forestry).

ecology-the study of relations between plants (and animals) and their environment.

ecosystem-a distinguishable community of plants and animals interacting with the physical factors of its environment.

even-aged stand-a stand of trees containing a single age class, usually considered to include a range in tree ages of less that 20 percent of the rotation.

forest-an area supporting trees, ordinarily including multiple ages, species, and conditions.

forest management--the practical application of scientific, economic, and social principles to the administration and working of a forest property for specified objectives.

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[1]See also Ford-Robertson 1971, Society of American Foresters 1993.

genotype--the genetic composition of an individual organism.

group selection method-a method of regenerating uneven-aged stands in which trees are removed and new age classes established in small groups. Maximum width of groups is approximately twice the height of mature trees. The management unit or stand in which regeneration, growth, and yield are regulated is an aggregation of such groups.

intolerant-lacking the ability to grow in shade of or in competition with other and taller plants.

landscape-a view or vista of scenery; hence, an area of considerable size including multiple stands and (often) multiple uses and ownerships.

MAI-abbreviation for mean annual increment.

mean annual increment-average growth rate of a stand up to a specified point in time. Calculated as the sum of present volume plus volume of any thinnings, divided by age. Abbreviated as MAI.

old growth-a stage in stand development characterized by advanced age, large trees, layered structure, and abundant woody debris. Usually applied to stands that have had no human intervention.

PAI-abbreviation for periodic annual increment.

periodic annual increment-an approximation to current annual increment (most commonly in volume), calculated as the difference between measurements at two points in time, divided by number of years between the two measurements. Abbreviated as PAI.

precommercial thinning-an early thinning removing trees too small to have commercial value, usually done to improve spacing. Synonym, **respacing.** Abbreviated as PCT.

regeneration-(l) newly established plants, (2) the process by which new plants are established.

regeneration method-a technique or set of techniques for securing regeneration.

reproduction-synonym for regeneration.

reserve-(l) a tree or group of trees, left unfelled in a stand that is being regenerated, and kept for part or whole of the next rotation (synonym, **standard);** (2) an area set aside for some specific purpose, such as a natural reserve.

respacing-an early thinning done to improve spacing that does not remove trees of commercial value.

rhizome-a modified belowground stem that grows horizontally and produces roots, leaves, and suckers at irregular intervals.

roguing-systematic removal of undesirable individuals, as in a seed orchard.

rotation-age of final harvest.

seed-tree method-an even-aged regeneration method in which a new age class develops from seedlings that germinate in fully exposed microenvironments after

removal of all the previous stand except a small number of trees left to provide seed. Seed trees are removed after regeneration is established.

selection, group-a silvicultural system involving removal of scattered groups of mature trees at frequent intervals, leading to a groupwise uneven-aged condition.

selection, individual tree-a silvicultural system involving removal of scattered individual trees at frequent intervals, thereby leading to an unevenaged condition with regeneration in clumps of size equivalent to the space occupied by a single large tree.

selection method-a collective term for the **single tree selection** and **group selection** methods, which create and maintain an uneven-aged structure by removing some trees in all size classes, either singly, in small groups, or in strips.

selective cutting-a loose term for any form of cutting that removes only part of a stand. Often incorrectly used as a synonym for selection system. Undesirable because of confusion introduced by past use of the term for destructive high-grading practices.

shelterwood method-a method of regenerating an even-aged stand in which a new age class develops beneath the partially shaded microenvironment provided by the residual trees (overwood). Harvesting may be done uniformly throughout the stand **(uniform shelterwood),** in groups or patches **(group shelterwood)** or in strips **(strip shelterwood).** The overwood is removed once the regeneration is established.

shelterwood with reserves-a variant of the shelterwood method in which some or all of the shelter trees (overwood) are retained, to attain goals other than regeneration. The resulting stand may be two-aged or may tend toward an uneven-aged condition as a consequence of both an extended period of regeneration establishment and the retention of reserve trees that may represent one or more age classes.

silvicultural system-a planned program of silvicultural treatment over the life of a stand, extending from regeneration through intermediate operations to harvest and regeneration.

silviculture-the body of techniques used to manipulate stand environments and direct stand and tree development to create or maintain desired conditions.

simulation model-a mathematical or graphical system that attempts to represent and predict the development of trees and stands in response to environment, initial stand condition, and stand treatment.

single-tree selection method-a method of creating new age classes in uneven-aged stands in which individual trees of all size classes are removed more or less uniformly thoughout the stand to achieve desired stand structural characteristics. Synonymous with **selection, individual tree,** above.

site-(l) a physical location; (2) a class or numerical measure of soil productivity.

site preparation-a collective term for various measures that can be taken to alleviate conditions unfavorable to prompt and adequate regeneration.

slash-the residue of tops, branches, and other unused material left on the ground after harvest.

stand-a contiguous group of trees sufficiently uniform in age class distribution, composition, and structure, and growing on a site of sufficiently uniform quality, to be a distinguishable unit.

stand management--the practical application of scientific and economic knowledge through silvicultural measures designed to direct development of a stand toward desired objectives.

thinning-removal of a portion of trees in a stand to promote development of the remaining trees and vegetation and to secure income prior to final harvest, while retaining the even-aged character of the stand.

tolerant-having the ability to become established and grow under shade of or in competition with taller plants.

two-aged stand-a stand composed of two distinct age classes that are separated in age by more than 20 percent of rotation age (based on the older age class).

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We discuss the historical development of silviculture in the Pacific Northwest and review the silvicultural practices currently available to forest managers. We then point out how these practices can be modified and used to maintain and produce wildlife habitat, diverse stand structures (including those usually associated with old forests) and pleasing scenery, while also producing wood products. Most of the silvicultural knowledge needed to design and implement regimes for integrated production of these multiple values already exists.

Keywords: Ecosystem management, multiple use, silvicultural systems, wildlife habitat, thinning, landscape management, forest ecology, Douglas-fir.