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Economies of Forest Tract Size in Southern Pine Harvesting

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INTRODUCTION

Economies of forest tract size are crucial in determining the economically available wood supply in the United States. High average costs for forestry operations on small tracts-diseconomies of size—usually stem from high move and set-up costs for heavily mechanized activities. The most capital intensive operations, such as regeneration and harvesting, exhibit the highest average costs on small tracts. Growing reliance on capital-intensive operations is increasing concerns about economies of tract size.

Economies of size in forest harvesting create the most immediate impacts on profitability and wood supply. If harvest costs promise to exceed revenues, the timber on a tract will not be cut. Regeneration and timber stand improvement affect future wood availability, while harvesting costs and revenues determine present supplies. Therefore, this research focused on tract size economies in forest harvesting.

Theoretical Basis

Economies of size refer to the variation in average unit costs possible by varying the size of the operation (Gregersen and Contreras 1979). Economies of size are achieved when per unit costs decline as the size of the plant changes; diseconomies occur when unit costs increase (Heady 1952). Studies of economies of size rest on the determination and interpretation of the firm's long run average cost curve, which is in turn composed of many short run average cost curves (fig. 1).

Empirical evidence suggests that the long run average cost curve for most industries is "L-shaped", indicating economies of size up to a point, but beyond that output level, average costs neither rise nor fall when size is increased. The point at which average costs cease to fall is known as the point of minimum optimum scale (Bain 1969, Pratten 1971).

In forest land operations, both short run and long run average cost curves are likely to be L-shaped since diseconomies are unlikely until very large acreage sizes are reached. Concern over diseconomies of small tract size is more relevant in forestry.

Better utilization of technology and mechanization, specialization of workers and equipment, reduction of resource indivisibilities, and other factors create economies of large size (Chamberlain 1948, Doll and Qrazem 1978, Heady 1952, Pratten 1971). Most economies of large size in forestry are achieved by spreading the initial fixed costs for capitalization and transport of machinery over a larger output. Extensive specialization of workers and equipment offers little advantage in forestry because very few land areas or harvesting crews are large enough to take advantage of these economies. Better utilization of large-scale technology and mechanization may provide some economies of size, but it is much less important than spreading of initial fixed costs.

The economic-engineering or synthetic firm approach for estimating economies of size is the best available method to examine the effect that tract size alone has on production costs, so it was used in this study. It is also the only method for estimating the potential average costs which firms could achieve using modern technologies (French 1977, Madden 1967).

Forestry Literature

Forestry literature on economies of size is sparse. Some authors have examined economies of size in forest manufacturing (Buford 1974, Buongiorno and Gilless 1980, Dobie 1971, Granskog 1978, Mead 1966) and logging (Berndt et al. 1979). Only a few studies, most of which are foreign, have examined economies of forest tract size.

Sutton (1968, 1969, 1973) determined that per acre overhead costs in New Zealand for relatively small forests (2,000 acres) were about five times those of a very large forest (292,000 acres). In Norway, Noer (1975) found that, compared to 50 hectare tracts, 5 hectare parcels had per hectare forest management costs almost twice as high. Even 20 hectare tracts had overall forest management costs about 25 percent greater than 50 hectare parcels. In Sweden, Andersson (1965) compared highly mechanized methods to conventional forestry. Tracts less than 30 to 40 hectares had rapidly increasing costs, especially in highly mechanized operations.

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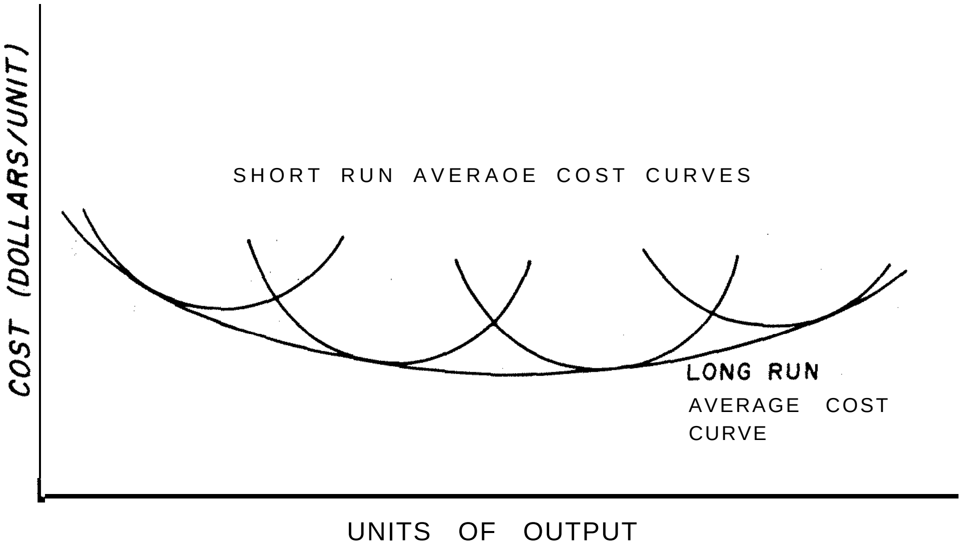

Figure 1.-The ***long run average cost curve.***

Row (1973, 1974, 1977, 1978) examined economies of size and the profitability of southern pine growing. Fixed costs were reportedly the primary determinant of average costs for forestry operations and the size of the fixed costs was directly related to the level of mechanization.

Row concluded that most economies of large size could be obtained in 80 acre tracts. For smaller tracts, fewer management regimes had rates of return which would be greater than an owner's alternative rate of return. At 20 acres, only intensive management of natural stands yielded positive returns. For 10 acre tracts, no management regimes offered an acceptable investment opportunity.

Statistical cost research performed by Wikstrom and Alley (1967) on National Forests revealed that, for most forest management practices, costs per acre increased rapidly with decreases in size of area, particularly for areas smaller than 40 to 50 acres. Gardner (1981) also found economies of size in forest regeneration. However, acceptable rates of return could be achieved on tracts as small as 10 acres, assuming no stumpage discounts were received. Thienpont (1976) concluded that tract size was not critical in harvesting as long as labor-intensive bobtail operations were available for cutting small tracts.

MODELING PROCEDURES

The modeling procedures used in this study were aimed at estimating short, run average cost curves for harvesting timber on different sized tracts using a range of harvest system mechanization levels. The process entailed developing a stand model, gathering harvesting productivity and cost information, assembling a range of harvest systems and determining their overhead costs, simulating the harvesting process, developing short run average cost curves, and analyzing the results (fig. 2).

Stand Model

Most studies have found that harvesting productivity varies proportionately with tree size class (Hypes 1979, Hypes and Stuart 1979, Plummer 1977, Tufts 1977) and have accordingly published diameter-based productivity tables. Therefore, a flexible stand model was used to account for productivity variations corresponding to diameter class distributions.

Species.-Average harvest cost estimates were based on a model stand of loblolly pine. It is the most common and widely spread southern species, the most valuable for pulpwood and timber products, and the subject of most productivity studies. Productivity and cost estimates for all southern species should be somewhat interchangeable.

Tree Volumes.-The loblolly tree volumes by diameter breast height (dbh) used for this study (fig. 3) were adopted from Hypes and Stuart (1979) and Plummer (1977), who based them on regression equations developed during the American Pulpwood Association Harvesting Research Project (HRP) . These publications represent the most reliable data available for use without modification. The remaining productivity studies were adapted to fit their model trees. The average height and merchantable height for loblolly trees were also taken from HRP literature (Lanford and Cunia 1971).

Stand Characteristics.-Stand characteristics were developed by working backward from an average

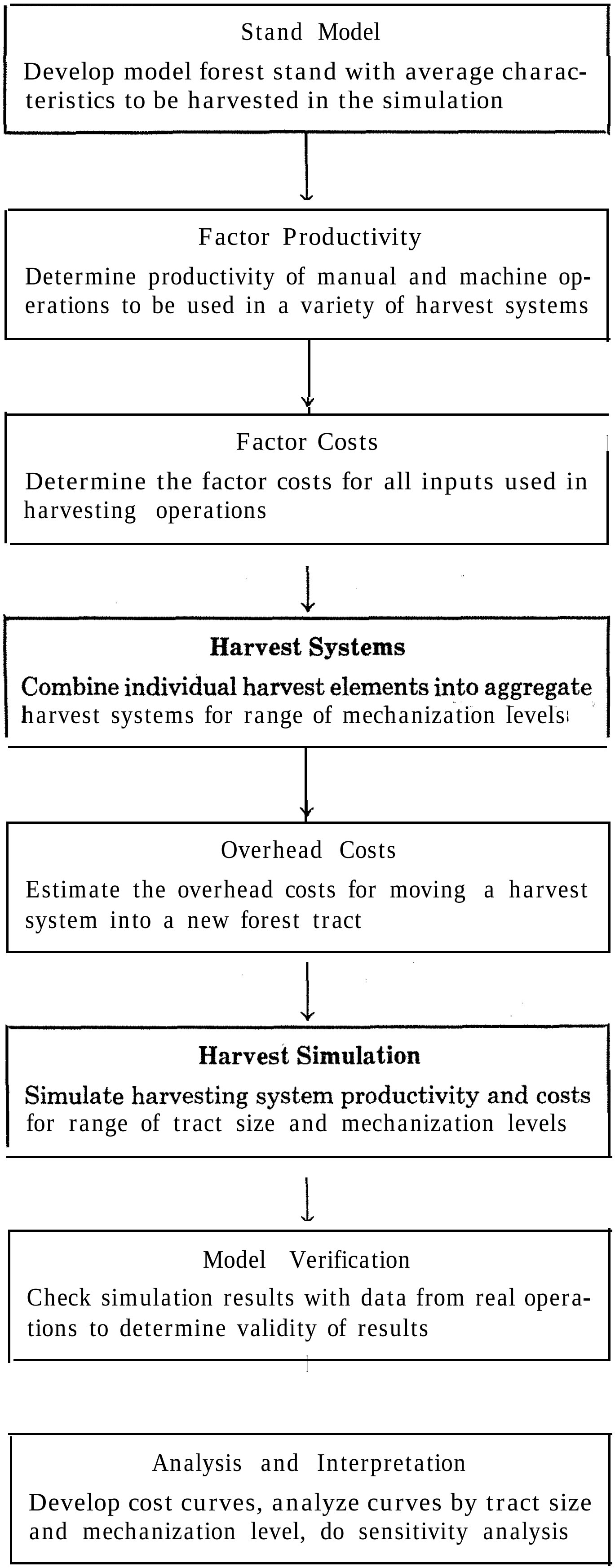

Figure 2.—*Modeling* ***steps in estimating economies*** *of forest* ***tract size in Southern Pine harvesting.***

Table ***b--Typical stand description***

Species: Loblolly pine, unthinned natural stands
Age: 25 years
Site index: 70 feet at 50 years
Basal area: 80 square feet per acre
Total cubic feet yield of wood and bark: 1,897 ft^3 per acre
Cubic feet yield of wood and bark to 4" top: 1,591 ft^3 per acre
Standard cord yield of wood and bark to 4" top: 17 2/3 cords per acre (cubic feet yield divided by 90 cubic feet per cord)

volume per acre to be cut in the stand. Conversations with forest industry employees and current forest survey data in the South indicate that typical yields for loblolly pine range from 10 to 20 cords per acre, with an average in the upper teens. Most industrial stands in the South are being clearcut at an average age of 25 to 30 years old. Using this information as a guide, a "typical" stand was chosen from natural stand loblolly yield tables developed by Burkhart et al. (1972).

Selected stand characteristics at harvest are listed in table 1. Stands were assumed to be clearcut for pulpwood only on flat to gently sloping terrain. One-way haul distances to the mill were assumed to be 30 miles for all harvest systems.

Stand Distribution.-The stand distribution in figure 4 was used as the basis for subsequent productivity rate distributions developed for the study. It is based roughly on tables by Plummer (1977) and Feduccia et al. (1979) for natural and planted loblolly pine, respectively. Figure 5 charts the volume per acre by diameter class.

Factor Productivity

Productivity of harvest systems is the basis underlying harvest costs. Likewise, productivity rates for individual manual or machine operations are the basis for this research.

Productivity estimates were measured in or converted to production of cubic foot output of wood per operating hour, as opposed to scheduled hour. The operating hour basis is more useful since its ratio to scheduled hours (commonly referred to as availability) may vary widely depending on the machine, the operator, the maintenance, the harvest species, or other factors.

Availability or utilization figures for various machines and harvest operations were obtained from company interviews and literature sources, such as Hypes and Stuart (1979), Plummer (1977, 1979, 1980), and Warren (1977). Technically, availability

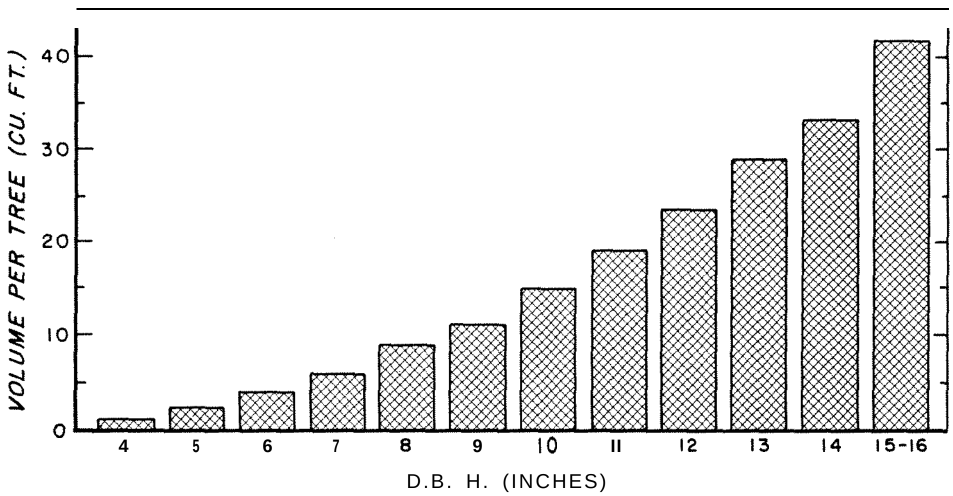

Figure 3.—*Pine tree volumes at each diameter (average dbh=9.4 inches).*

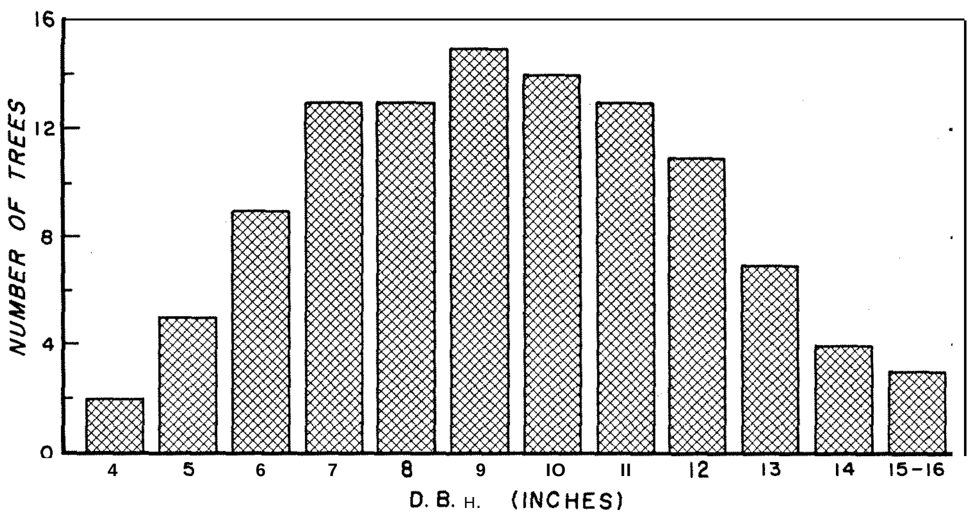

Figure 4.—*Model pine stand distribution.*

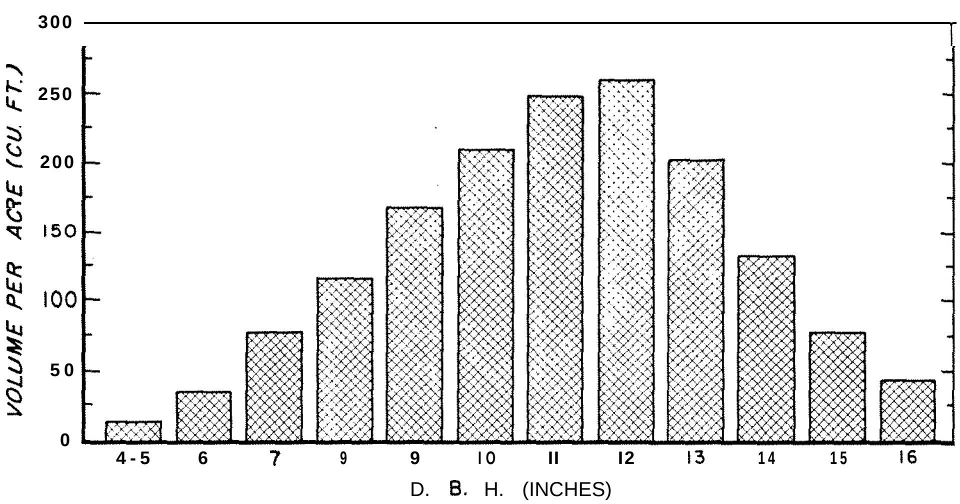

Figure *S.-Volume per acre by dbh class (total volmue/acre=1,591 cu. ft.)*

is defined as the percentage of scheduled hours a machine is not broken down and is capable of performing work. Utilization means the percentage of scheduled hours a machine or man is actually operating or productive. In practice, the terms are used rather loosely. Both generally indicate operating hours as a percent of scheduled hours. Appendix table A2 includes the utilization figures for machines.

Several methods were used to determine productivity estimates by dbh class. Productivity by stem size class for loblolly pine was often given directly in tables or graphs. Data on a large number of harvest functions were available in this form. Examples include chainsaw felling, limbing, bucking, and topping (Hypes and Stuart 1979, Plummer 1977, Tufts 1977); forwarding (Tufts 1977); and limited-area feller-bunchers and whole-tree chippers (Plummer 1977).

Data which appear to have more statistical reliability can be generated from regression equations for predicting productivity rates by tree size and/or skid distance. Clair (1977) developed such equations for knuckleboom loaders and rubber-tired cable skidders and worked with Matthes et al. (1977) in developing regression equations for chainsaw felling. Unpublished forest industry records also provided information on productivity rates.

The productivity rates which were selected for use in this research are summarized in appendix table Al. Skidding and forwarding travel rates, load sizes, and fixed load and unload times, used by the simulation program to estimate function productivity rates, are summarized in appendix tables A8 to All. A complete summary of all the productivity information gathered on harvesting southern pines is also available (Cubbage 1981a).

Factor Costs

Current factor costs for harvesting equipment, labor, entrepreneurship, and stumpage were used in the analysis. Costs were indexed to 1980 prices, and most of the data were collected in early 1980.

Machines-Several methods could be used to calculate the costs of machines used in harvesting. These include the capital recovery method, a cash flow basis, or machine rate calculations. The latter were used because they are widely accepted in the forest industry, are easy to work with and understand, and provide good *average* cost estimates for the life of the machine. The machine rates are the total of the overhead (fixed) costs and operating (variable) costs per operating hour, excluding the cost of the operator. Machine rates were calculated using procedures described by the American Pulpwood Association (1965), Matthews (1942), Miyata (1980) and Warren (1977).

Appendix table A2 summarizes the machine rate costs for harvesting equipment commonly used in the South. Again, more complete calculations are summarized by Cubbage (1981a, 1981b).

Much of the operating cost information comes from data published by Hypes and Stuart (1979) or Plummer (1979, 1980). Some operating costs for bulldozers, road graders, cable skidders, and grapple skidders were obtained from cost tables in the Cost Reference Guide (1980). Much current operating cost data were gathered from southern forest industries with logging crews. For the machine rate calculations, gasoline and diesel fuel were assumed to average $1.00 to $1.10 per gallon, engine oil 75¢ per quart, and hydraulic oil $2.80 per gallon.

Purchase price information for harvesting machines was usually determined by informal discussions with forest equipment dealers in the South. University and industry personnel familiar with purchase prices were consulted for corroboration and for price estimates not provided by dealers. Delivered prices for individual machines were aggregated by class to determine an average price for a type of machine.

Salvage values for equipment and trucks were taken often from tables published by Hypes and Stuart (1979). Green Guide (1980) estimates of average resale values for construction equipment and log skidders also were used for salvage values. Equipment having no published salvage value usually was assumed to be salvaged for 20 percent of the purchase price. Expected life spans and yearly use rates were taken from Hypes and Stuart (1979), Plummer (1979), Tufts (1977), and Warren (1977).

The informal survey of equipment dealers was also used to determine the average insurance rates for logging equipment. In-woods logging equipment, such as bulldozers, skidders, and feller-bunchers, had average insurance rates of about $4 per $100 of purchase price for the life of the machine. Equipment used at the deck, such as loaders, slashers, or chippers, had an insurance rate of about $1.25 per $100 of the purchase price.

Insurance rates for logging trucks and trailers are south-wide averages for physical damage insurance and 100/300/100 liability coverage. The information was obtained on a state-by-state basis from the Fred S. James Company in South Carolina which insures logging equipment throughout the South. Corroborating rate quotes were obtained from Transportation Associates Inc. and Carver General Insurance Company in Louisiana.

Annual license, tags, and taxes costs are based on the sum of local, state, and federal taxes and any licenses required for operation. While the distribution of costs between tags and taxes varies from state to state, the totals are usually similar. A telephone sampling of several states in the South was used to determine average state tags and taxes costs for use in the machine rate calculations. The machine rate taxes figure also includes federal highway taxes calculated per IRS Publication 349 (Internal Revenue Service 1979).

Average interest costs were computed based on a 12 percent annual interest rate per year levied against the Average Annual Investment. Calculating interest costs as a percent of Average Annual Investment is a standard procedure used by forest harvesting engineers (Kurelek 1976, Matthews 1942, Miyata 1980, Warren 1977). Deciding on the appropriate interest rate was another matter.

Conversations with southern industry personnel and equipment dealers indicated no uniform interest rate in 1980. Dealer rates ranged from 7 to 12 percent add-on. Add-on rates from 7 to 9 percent for company-backed or established customers were possible at the dealers. However, many dealers said that established loggers could get considerably cheaper loans through local banks. Annual interest rates as low as 9 to 11 percent *were* still common and rates seldom rose above 13 to 14 percent.

Given the range of rates existing in 1980, a reasonable choice was flexible. For the machine rate calculations, 12 percent annual interest was optimistically chosen as appropriate. This is rather low compared to the inflationary rates experienced in late 1980 and 1981. However, few people were buying equipment at the inflectionary levels; they tried to finance equipment at lower rates or to defer purchases.

The machine rate calculations should reflect 1980 calendar year costs. They have been reviewed by academic and industrial forest harvesting specialists. The machine rate average costs must be used with caution. Actual cash expenses for fixed costs, such as interest payments and insurance, will be higher than average in early years and lower in later years. Conversely, operating costs tend to be low when a machine is new but increase with age.

Labor.-Labor costs (table A3) were based on estimates by forest industry personnel of the contractor wage rates in their area and an American Pulpwood Association survey summarized by Hypes and Stuart (1979). Wages were calculated on a scheduled hour basis rather than a production hour or production incentive basis.

Fringe benefits such as vacation pay, health insurance, or bonus pay are not paid currently by most southern independent contractors. Therefore, they were excluded from the analysis. Current federal law exempts overtime pay for crews of eight or less. Independent owner/operators who employ more than eight persons must pay overtime and include it in their cost calculations, although it was omitted for simplicity in this paper.

Worker's compensation payments were calculated at their mean level for the South based on an American Pulpwood Association (1979) survey. A similar 1980 survey (American Pulpwood Association 1980) indicates that rates declined slightly, but the 1979 figures were considered more representative. Unemployment compensation payments in the South average about three percent of payroll for state and federal contributions and were included as such. All employers and employees must pay social security taxes on their salaries, so cost were levied accordingly. Logging owner/operators need not pay worker's compensation on their own salaries; therefore none was included as a cost for them.

Total social legislation costs by type of system are summarized in table A4. All shortwood systems pay rates according to the pulpwood only class. Tree-length or full-tree operations which could sort out sawtimber or other products were charged at the pulpwood and sawtimber classification rates.

Entrepreneur Profit.-As Madden (1967) stressed, the calculation of profit for an owner/operator firm is crucial in cost calculations. Profit was assumed to equal the salary of the owner/operator. Profits for logging operations vary widely depending on, for example, the owner, the operation, and the cost accounting method. Most logging firms are averse to revealing their profit. These problems led to standardized profit (salary) assumptions being made (table A5). Small, less capital-intensive operations were assumed to make less profit than large ones. Profit assumptions were graduated by size of operation, so the relative levels probably reflect reality.

Stumpage.-The use of stumpage and delivered to mill prices in the analysis created several problems. Prices vary considerably from month to month and year to year. Choosing the appropriate stumpage and F.O.B. mill price can be somewhat arbitrary. Timber Mart South (1979, 1980) provides an excellent source of average prices. Table A6 lists the reported average southern pine price ranges from July 1979 to July 1980 for stumpage and products delivered to the mill and prices which were used as "typical." Late 1980 prices were not considered because they were depressed below "normal" levels. Mill prices were determined also for use in discussions of harvest system profitability.

Harvest Systems

Various harvest systems were modeled to determine the effects of mechanization on average harvest costs. The study analyzed shortwood, long log, tree-length, full-tree, and whole-tree harvest operations by combining productivity and cost data for individual operations into complete systems (table 2). Harvest *systems* currently prevalent in the South *were* examined. Systems declining in use or experimental equipment were not. The general descriptions of systems modeled provided the basis for balanced equipment and manpower spreads (tables 3 and 4). Table 5 displays the total 1980 investment required for each harvest system.

Harvest Simulation

Mathematical calculations, linear programming, or computer simulation can be used to estimate average costs by tract size. Simulation was chosen since it should be faster and more accurate in performing numerous harvest cost calculations. Also, it is superior at modeling the actual harvesting process and all its interactions.

After reviewing the harvest simulation programs available, the Harvest System Simulator (HSS) program (Stuart 1980, 1981) was selected to simulate the productivity and estimate costs of the modeled harvest systems. The program requires that the input productivity rates implicitly include stand features. Harvest system balances depend on volume controls used as program inputs which regulate harvest inventories for each harvest function. Poor program inputs will generate poor results. This analysis attempts to avoid both.

Simulation Inputs.-To clarify the modeling procedures used, a brief summary of the important simulation inputs follows. Each harvest system required the harvest function productivity rates, equipment and manpower spreads, equipment costs, and wages to be used as inputs. Stumpage and overhead costs for owner/operator profit were also needed.

All systems were assumed to operate 5 days per week, 9 hours per day, and 32 to 44 weeks per year, depending on the system. Each system's harvests were simulated for the range of tract sizes which seemed practical for its mechanization level, varying from 0 to 360 acres. Non-productive times, such as breaks (2 per day), lunch, and machine breakdowns and idle time (varied according to machine utilization rates), were used as inputs to convert scheduled time to productive time. Volume inventory controls were also needed for each harvest function (i.e. felling, skidding, loading) to prevent excessive build-ups of wood. Apendix tables A8 through All summarize the relevant simulation inputs.

Haul Costs.-The HSS program could simulate haul time and costs directly, but it was more convenient to calculate them by hand and put them into the program as pre-calculated costs (table A7). Using the machine rate calculations and a 30 mile haul distance for all *systems,* the machine costs equaled the cost per mile multiplied by the number of miles and divided by the load in cords. Labor costs equaled the wage per hour multiplied by the roundtrip time and divided by the load.

Table ***2.-Southern pine harvesting operations examined***

A. Stump bobtail. Chainsaw fell, limb, top, and buck into 5'3" bolts; hand load with bigstick (boom and cable) loader onto 4 cord tandem straight truck; haul

B. Bobtail and tractor. Chainsaw fell, top, and limb; farm tractor skid to roadside; buck into 5'3" bolts; load onto 5 cord tandem straight truck with bigstick loader; haul

C. Skidder and truck. Chainsaw fell, top, and limb; choker skid to landing; load onto 5 cord tandem straight truck with small hydraulic loader; haul

D. Semi-mechanized shortwood. Shear with tree shear; limb and top with chainsaw; skid with medium size choker skidder; buck with chainsaw at deck; load with small knuckleboom loader onto tractor-trailer truck; haul

E. Highly mechanized shortwood. Fell and bunch with rubber-tire feller-buncher; skid with medium to large size grapple skidder; delimb with iron gate delimber; buck into 5'3" wood with hydraulic slasher; load with medium knuckleboom loader onto tractor-trailer truck; haul

F. Shortwood prehauler. Fell, delimb, top, and buck with chainsaw; Ioad with attached knuckleboom onto forwarder; forward to landing; load onto tractor-trailer truck; haul

G. Skidder long log. Fell, limb, and top with chainsaw; skid with small to medium size choker skidder; buck at landing into long logs with chainsaw; load with large knuckleboom loader onto tractor-trailer rig; haul

H. Manual tree-length. Fell, limb, and top with chainsaw; skid with medium size choker skidders; load with large knuckleboom loader onto tractor-trailer truck; haul

I. Highly mechanized full-tree. Fell and bunch with rubber-tire feller-buncher; skid with large grapple skidder; delimb with iron gate delimber: load with large knuckleboom onto tractor-trailer truck; haul

J. Limited-area full-tree. Fell and bunch with tracked, limited-area feller-buncher; skid with ***large*** grapple skidder; delimb with iron gate delimber; load with large knuckleboom loader onto tractor-trailer truck; haul

K. Whole-tree chipping. Fell and bunch with rubber-tire feller-buncher; skid with large grapple skidders; chip with large whole-tree chipper and blow into chip van; haul with tractor-trailer truck

Table *3.-Harvest system equipment*

System \ Equipment	chainsaw	tree shear on dozer	rubber-tire feller-buncher	limited-area feller-buncher	farm tractor	70 hp choker skidder	90 hp choker skidder	110 hp choker skidder	120 hp choker skidder	110 hp grapple skidder	shortwood forwarder	bigstick loader	14,000 lb. knuckleboom	20,000 lb. knuckleboom	gate delimber	hydraulic slasher/loader	22" chipper	spare skidder/dozer	4 cord straight truck	5 cord straight truck	truck tractor	pole trailer	bundle-bucker trailer	shortwood trailer	chip van	6x6 van forwarder	lowboy	pickup	service/crew truck
A. Stump bobtail	2											1							1										
B. Bobtail and tractor	2				1							1								1								1	
C. Skidder and truck	3					1							1							2									
D. Semi-mech. shortwood	2	1						1					1								2			4			1	1	
E. Highly mech. shortwood	1		1							1				1	1	1		1			2			4			1	1	1
F. Shortwood prehauler	3										1										1			2				1	
G. Skidder long log	2						1						1								1		2					1	
H. Manual tree-length	5							1	1					1							2	2	2				1	1	1
I. Highly mech. full-tree	1		2							2				1	1			1			3	3	3				1	1	1
J. Lmtd.-area full-tree	1			1						2				1	1			1			3	3	3				1	1	1
K. Whole-tree chip	1		2							2							1	1			3				6	1	1	1	2

Table 4.—*Harvest system manpower*

System	Supervisor	Saw hand	Equipment operator	Truck driver	Mechanic	Total
A. Stump bobtail	I/3	2	1/3	1/3		3
B. Bobtail and tractor	1/3	1-1/3	1	1/3		3
C. Skidder and truck	1/2	2-1/2	1-1/2	1-1/2		6
D. Semi-mech. shortwood	1/3	2	2-1/3	2	1/3	7
E. Highly mech. shortwd.	1/2		3	2	1/2	6
F. Shortwood prehauler	1/3	3	1	2/3		5
G. Skidder long log	1/2	1-1/2	1-1/2	1-1/2	....	5
H. Manual tree-length	1	3	2-1/2	2	1/2	9
I. Highly mech. full-tree	1		4-1/2	3	1/2	9
J. Lmtd.-area full-tree	1		3-1/2	3	1/2	8
K. Whole-tree chip	1		5	3	1	10

Table *5.-Total harvest system investment costs, 1980 purchase prices*

Harvest system	Equipment in-woods	Hauling and support eqpt.	Total
	----	dollars ----	
A. Stump bobtail	2,700	13,500	16,200
B. Bobtail and tractor	30,600	27,000	57,600
C. Skidder and truck	74,500	47,000	121,500
D. Semi-mech. shortwood	146,500	146,000	292,500
E. Highly mech. shortwood	197,700	170,600	367,700
F. Shortwood prehauler	41,500	61,000	102,500
G. Skidder long log	80,000	76,600	156,600
H. Manual tree-length	156,500	170,600	327,100
I. Highly mech. full-tree	321,700	231,400	553,100
J. Limited-area full-tree	301,700	231,400	533,100
K. Whole-tree chip	456,000	259,500	715,500

Table 6.-*Average time spent in moving a logging operation to a new job site*

No. skidders in the operation	Average number of employees	Percent of moves made during work week	Avg. time required to move during week	Avg. no. employees used to move on weekend	Avg. time required to move on weekend
			hours		*hours*
0	1.50	20	1.0	2.0	2.0
1	3.45	55	3.4	1.8	4.1
2	4.67	67	4.3	2.8	5.6
3	13.00	0		2.0	6.0
4	12.75	67	6.0	3.0	6.0
over 4	11.00	72	6.7	7.0	8.0
overall	6.30	60	4.4	2.8	4.8

Source: Watts and Watson 1978.

Move Cost

Fixed or overhead costs of harvesting tracts of timber are the critical elements creating economies of size. Sale administration and layout, moving into a tract, and fixed charges for idle equipment cause high average costs for small tracts. High fixed costs require large outputs in order to minimize their contribution to average costs. Of all the overhead costs in harvesting, the move costs for transportation and idle equipment are the most important in determining economies of size (Walbridge 1967, Thienpont et al. 1976). Therefore these costs were examined in this study. Sale and administration costs may also be significant (Kronrad et al. 1980), but they are likely to be similar for all harvest systems. Systems with different mechanization levels are likely to have greatly different move costs, owing to the fixed costs for idle equipment and wages for non-productive employees.

Little literature is available on the cost of moving harvest operations. McDermid (1969) found that highly mechanized tree-length operations are by far the most expensive to move. Bobtail operations were the cheapest to move. He found that highly mechanized shortwood, partially mechanized shortwood, and partially mechanized longwood system had similar move costs.

Move Times.-An American Pulpwood Association report prepared by Watts and Watson (1978) provided a basis for estimating the cost of moving harvest operations. Their survey of 32 independent Mississippi loggers and pulpwood producers determined the average time required for logging operators to plan and execute a move. They found that large operations usually move during the week, with the move taking one-half to three-quarters of a work day (table 6).

Alternative Costing Methods.-The best method of estimating the costs of moving from tract to tract is moot. Costs for transporting the equipment from one site to the next and wages paid to employees who are not productive during the move should be included. Similarly, a charge for the ***fired*** costs of non-productive equipment should be included as a cost item also. Employee wages and equipment fixed costs would constitute a system rate cost for the move.

The value of production foregone during the move might also be included as an expense in addition to the system rate cost. The total of the system rate costs and foregone production costs were estimated by the HSS computer program. Move time and transportation costs for each harvest system were used as inputs into the simulation program, which then calculated the total cost to harvest the first piece of wood-a proxy for move cost. This cost was used in the harvest cost estimates by tract size.

Comparative System Cost.-Table 7 summarizes the relevant move cost calculations by harvest system. Obviously, small systems cost less to move than large systems. They require less time to move and have lower fixed costs to be borne during the move. The stump-to-stump bobtail system has virtually no move costs. Small partially mechanized systems (B,C,F,G) cost $200 to $500 to move. Large partially mechanized systems (D,H) take $600 to $800 to move and highly mechanized systems (E,I,J,K) require $1000 to $2400 to move.

Model Verification

The results of the modeling process and harvest simulation were checked to determine whether they were acceptable. Table 8 summarizes some comparisons between the simulation results and actual logging productivities and costs.

Generally, the simulation results appear reasonable. Weekly production estimates developed by the

Table 7.—*Harvest system move costs*

Harvest system	Move time	Transport costs	Payroll costs	System rate per hour[1]	Sytem rate expenses per move[2]	Foregone production	Total move costs: Manual calculations[3]	Total move costs: Simulation program[4]
	hours	*dollars*				*cords*	*dollars*	
A	2.0	0	0	35	0	0	0	8
B	4.0	85	24	50	152	4	237	1'78
C	4.0	85	24	112	320	8	405	403
D	4.3	33	191	161	474	15	507	600
E	6.0	141	211	18'7	837	25	978	993
F	4.3	85	105	79	267	11	352	332
G	4.3	81	104	108	311	10	419	502
H	4.3	76	259	186	549	28	625	759
I	6.0	154	322	269	1103	62	1256	1237
J	12.0	225	542	254	2069	119	2294	2399
K	12.0	241	817	311	2599	155	2840	2382

'Total of wages per hour, machine fixed and operating costs per hour, overhead equipment costs, and owner/operator salary per hour.

[2]Same as [1], minus fixed and operating costs of operating haul trucks and operating costs of non-productive haul trucks and harvest equipment, times the hours to move.

[3]System rate expenses per move plus transport costs, manually calculated.

[4]System rate expenses per move plus transport costs, as calculated by the Harvest System Simulator computer program.

HSS program tend to be high because each week was set up having five full days and crews working only 32 to 44 weeks per year to approximate the appropriate number of operable days in a year. In reality, many work weeks consist of fewer than five days because of bad weather and the logging crew works all year. Simulated yearly production is somewhat closer to reported average system productivity rates. System costs are not affected by the number days per week as long as the total number of days per year remain the same.

The simulated harvest costs per cord indicate that most systems are unprofitable. This is misleading because all the systems have 1980 equipment costs. Logging crews are actually using some older equipment purchased for lower prices, so they could still make a profit at prevailing mill prices. The 1980 cost data indicate that either mill prices or logging productivity must be increased for logging operations to remain profitable in the future.

One may also examine the validity of the simulation results by comparing relative productivity and costs among systems. The relative differences seem reasonable, with more mechanized systems being more productive. Relative system costs are close to those calculated by Tufts (1979) in a thinning study. He found bobtail and prehauler operations quite economical, with tree-length operations being less expensive only on stands averaging more than nine inches dbh. Mechanized full-tree harvest systems were the least expensive roundwood harvesting method. Costs for whole-tree chipping were somewhat higher, but the system had modeled one skidder and one feller-buncher, which suggestions underutilization of the chipper.

Overall, the synthetic logging firm modeling process and simulation results seem valid. Productivities and costs fall within realistic ranges and comparative system differences are reasonable.

DATA ANALYSIS

The HSS program was used to estimate the average cost per cord for tracts of various sizes, ranging from 0 to 360 acres. Replications were used in the cost estimates because they were easier and cheaper to run on the computer than numerous individual estimates and allowed more statistical tests.

Cost Curve Derivation

Short run average cost curves were determined for each system using linear regression with tranformations of the simulated cost data. Harvest cost per cord was the dependent variable and acres the independent variable. Quadratic, cubic, log, and inverse transformations were tried in order to find the best functional form for each harvest system.

The multiple linear regression package BMDP1R (Biomedical Computer Programs 1977) was used to perform the analysis. The coefficient of determination (R^2), significance of the regression (F ratio), significance of the coefficients (t tests), and standard error (s_e) of the estimate were examined to select the best form of the short run average cost curves. Also, residual and normal plots were examined according to accepted techniques to eliminate undesirable functions (Daniel and Wood 1971, Draper and Smith 1966, Johnston 1972, Truong 1980, Wonnacott and Wonnacott 1979).

Short Run Average Cost Curves.-Inverse function short run average cost curves were developed for all harvest systems except A and B. A's best form was a linear function and B's was a quadratic. Dummy variables were used to account for a cost data idiosyncrasy of some tract sizes-multiples of 25 or 30 acres having lower average costs than mutiples of 40 acres. The dummy variables were considered significant at alpha equal to 0.10. Regressions with non-significant dummy variables were recalculated without the dummies in the regression. Table 9 presents the relevant statistical parameters for the final cost equations selected, including the dummy variables.

The dummy variables account for variation in tracts of 25- or 30-acre multiples and merely lower the intercept for cost estimates at those points. Since the lower costs were merely an idiosyncrasy of the computer-simulated cost data and not a real world difference, the dummy variables and coefficients were dropped entirely from the equations, providing the most realistic estimates of harvest costs per cord. The final harvest cost equations are summarized in table 10.

Long Run Average Cost Curve.-Economic theory dictates that an envelope curve below and tangent to the short run average cost curves is, by definition, the long run average cost curve. Derivation of an envelope curve for the harvest systems modeled proved to be quite difficult, however.

Figure 6 graphs the short run average cost curves for systems A through K. Drawing a continuous curve under *all* the harvest system cost curves is not possible, primarily because system A has virtually no overhead costs. A kinked freehand envelope curve can be drawn under the cost curves or the lowest cost segments can be combined into a scalloped long run average cost curve. However, statistiscal estimation of the envelope curve was not possible. Attempts were unsatisfactory because a regression including data from A at small acreages raised the cost curve far above what it was determined to be by system I at large acreages. Therefore, the conclusions regarding economies of tract size were drawn from the comparison and analysis of important harvest system short run average cost curves and trends in system selection.

Comparing Harvest Systems

With short run average cost curves derived for all systems, comparisons in relative system costs can be made. Systems may differ in overhead costs, costs at minimum optimum size, or both. Numerical, graphical, and statistical procedures may be used for comparisons among harvest systems.

Numerical Techniques.-The cost equations in table 10 permit ranking of the harvest systems by minimum cost level or by size of logging chance at which they reach that cost. Table 11 ranks the 11

Table *&-Productivity and cost of simulated and actual operations*

System	Simulated weeks worked per year	Simulated productivity cords per: Week	Simulated productivity cords per: Year	Reported average literature productivity cords per: Week	Reported average literature productivity cords per: 50 wk. yr.	Simulated minimum cost/cd. FOB mill	Southern average FOB mill price/cd.
						------- dollars	-------
A. Stump bobtail	32	50	1600	26	1300	40.97	38.00
B. Bobtail and tractor	36	40	1440	30	1500	49.11	38.00
C. Skidder and truck	40	90	3600	90	4500	57.04	38.00
D. Semi-mech. shortwood	40	160	6400	150	7500	46.92	38.00
E. Highly mech. shortwood	44	190	8360	150	7500	44.79	38.00
F. Shortwood prehauler	42	110	4620	80	4000	41.30	38.00
G. Skidder long log	40	105	4200	120	6000	45.50	38.00
H. Manual tree-length	44	290	12,760	250	12,500	41.88	38.00
I. Highly mech. full-tree	44	465	20,460	350	17,500	37.66	38.00
J. Lmtd.-area full-tree	44	445	19,580	350	17,500	37.54	38.00
K. Whole-tree chipping	42	580	24,360	350	17,500	33.96	31.68

Sources: Simulated Productivity-Harvest System Simulator.
Literature Productivity-Systems A-H Watson et al. 1978; Systems I-K Glenn Plummer, Georgia Kraft Co., personal communication.
Southern Average F.O.B. Mill Price-Timber Mart South 1979, 1980.

Table *S.-Regression statistics for the* final *harvest system cost curves*

Harvest system	Coefficient of determination	Standard error	F ratio	Student's t: B_1 (acres) Value	B_1 (acres) Significance level	B_2* (dummy or acres?) Value	B_2* Significance level
A. Stump bobtail	.95	.071	70	8.3	.001		....
B. Bobtail and tractor	.96	.1416	230	-1.4	.189	5.687	.0001
C. Skidder and truck	.99	.0885	2371	65.3	.0001	-2.1	.034
D. Semi-mech. shrtwd.	.94	.2747	356	25.4	.0001	-2.13	.038
E. Highly mech. shrtwd.	.96	.3643	1374	37.1	.0001	....	
F. Shortwood prehauler	.68	.4025	35	6.8	.0001	—3.169	.003
G. Skidder long log	.90	.3873	193	18.5	.0001	-1.717	.093
H. Manual tree-length	.94	.4791	457	29.1	.0001	-3.399	.001
I. Highly mech. full-tree	.96	.6418	925	41.3	.0001	-5.7	.0001
J. Lmtd. area full-tree	.98	.7693	3007	54.8	.0001		
K. Whole-tree chip	.99	.7402	2269	65.8	.0001	-3.516	.001

*Square acres for system B; dummy variable for remaining systems when found significant at alpha=.10.

Table 10.—*Final cost curves selected*

Harvest system	Final cost curve equation
A. Stump bobtail	$Y=40.97+0.02(X)$
B. Bobtail and farm tractor	$Y=49.177-0.016(X)+0.001(X^2)$
C. Skidder and truck	$Y=56.88+17.920(1/X)$
D. Semi-mechanized shortwood	$Y=46.682+20.835(1/X)$
E. Highly mechanized shortwood	$Y=44.369+38.891(1/X)$
F. Shortwood prehauler	$Y=41.125+9.894(1/X)$
G. Skidder long log	$Y=45.261+21.75(1/X)$
H. Manual tree-length	$Y=41.418+39.941(1/X)$
I. Highly mechanized full-tree	$Y=37.089+74.506(1/X)$
J. Limited-area full-tree	$Y=37.230+119.389(1/X)$
K. Whole-tree chipping	$Y=33.092+139.67(1/X)$
where: Y=harvest cost (dollars per cord)	
X = tract size harvested (acres)	

Table *IL-Rank of harvest systems by minimum* acreage *size required to reach minimum cost level*

Bank	System	Acres required to reach minimum cost: 5% slope level	1% slope level	HSS simulated move cost
				dollars
1	A. Stump bobtail	0	0	8
2	B. Bobtail and tractor	8	8	178
3	F. Shortwood prehauler	14	31	403
4	C. Skidder and truck	19	42	600
5	D. Semi-mech. shortwood	20	46	993
6	G. Skidder long log	21	47	332
7	E. Highly mech. shortwood	28	62	502
8	H. Manual tree-iength	28	63	759
9	I. Highly mech. full-tree	39	86	1237
10	J. Lmtd.-area full-tree	49	109	2399
11	K. Whole-tree chipping	53	118	2382

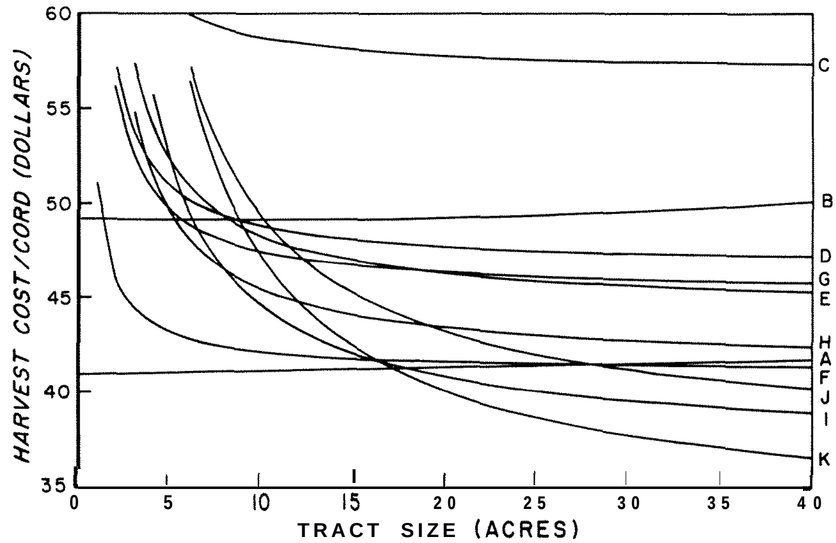

Figure C-*Harvest system short run average cost curves by* acres, *graph from 0 to* 40 *acres to depict intersections.*

systems according to the average size at which they approach their minimum cost. System A is minimum at the intercept. System B, a quadratic function, has a minimum point at 8 acres. The remaining systems (inverse functions) are assumed to approach their minimum cost (horizontal level) when the first derivative of the cost function equals 0.01 (the crook of the L). The 0.05 level is also included.

Similarly, the harvest systems are ranked according to the level of their minimum cost in table 12. System A has a minimum cost at zero acres, system B at eight acres, and systems C through K at infinity.

Graphical Techniques.-Graphs of the equations in table 10 facilitate viewing cost curve intersections and differences in levels. Two forms of graphical relationships are appropriate. First, plots of harvest cost per cord versus acres allows comparison of the actual cost curves for different systems by tract size (figs. 6 and 7). Second, linearized transformations of cost per cord versus l/acres are useful (fig. 8). Linearized plots aid inspections for differences in slope and level among harvest systems. Lines which cross in the linearized plot indicate that systems probably have different slopes (overhead costs). Parallel lines indicate that systems seem to have similar overhead costs; different levels of parallel lines suggest that the average minimum costs are different. Statistical tests among systems were performed to test the significance of the visual differences.

Since the plots of 11 harvest systems on one graph tend to be quite crowded, bar chart comparisons (fig. 9) may be preferred for inspections of costs at different tract sizes.

Statistical Tests.—Two tests were used to insure that the apparent differences among harvest systems were statistically significant. The two bobtail systems had different functional forms, so were different by definition, The method of group regressions (Freese 1964, 1967; Snedecor and Cochran 1967) was used to test for differences in slope and level among the nine linearized inverse cost functions. Different slopes indicated significantly different overhead costs and different levels (intercepts) indicated significantly different minimum average costs.

Harvest systems with overhead cost differences of about $200 or less usually had similar slopes. Systems with differences of $300 or more always had different slopes, as would be expected. Also, systems J and K, which had similar overhead costs but widely different ultimate cost levels, had significantly different slopes.

The Bonferroni Significant Difference Test (Miller 1966) was used on the data in the cost curve tails (table 13) of the nine inverse functions to determine whether their mean ultimate average cost levels were significantly different. The test determined that at the one percent alpha level, differences of 64 cents or more were statistically significant. Therefore, only the harvest system pairs of full-tree systems I and J and prehauler system F and tree-length system H were not significantly different. The statistical tests confirm the apparent rank order differences among harvest system average costs.

Overall *Differences.-The* rankings, graphs, and statistical tests support conclusions about differences among harvest systems. Highly mechanized full-tree systems (I and J) have the lowest average cost for harvesting roundwood, about $37.50 per cord. System I is the lowest cost roundwood system on tracts 17 acres and larger and system J is second from 27 acres and up. However, they require about 85 and 110 acres respectively to reach their minimum optimum tract size according to the cost equations. This corresponds to the minimum tract sizes these systems actually seem to require in practice. Tract sizes of 60 acres for system J and 40 acres for system I would incur average costs at least $1 per cord more, which most operators would surely try to avoid.

Bobtail truck system A, shortwood prehauler system F, and manual tree-length system H fall at the next roundwood average cost level of about $41.50 per cord. Each requires considerably different acreages to reach the minimum optimum tract size—about 1 acre for A, 30 for F, and 60 for H. Again, these acreage guides seem reasonable compared with actual experience. The bobtail system has the lowest average costs of all systems up to 17 acres, followed closely by the prehauler system. Average cost for the bobtail system increase only slightly throughout its range up to 40 acres. The prehauler system average costs increase only slightly down to 10 to 15 acres, and the tree-length system down to 30 to 40 acres, Beyond their lowest limits, costs rise appreciably.

Table 12.—*Rank of harvest systems by minimum cost levels*

Bank	Harvest system	Cost per cord at minimum
		dollars
1	K. Whole-tree chip	33.09
2	I. Highly mechanized full-tree	37.09
3	J. Limited-area full-tree	37.23
4	H. Manual tree-length	39.94
5	A. Stump bobtail	40.97
6	F. Shortwood prehauler	41.13
7	E. Highly mechanized shortwood	44.37
8	G. Skidder long log	45.26
9	D. Semi-mechanized shortwood	46.88
10	B. Bobtail and tractor	49.11
11	C. Skidder and truck	56.88

Whole-tree chipping system K has the lowest average cost for harvesting pulpwood ($34 per cord). However, it receives a lower revenue ($31.68 per cord versus $38 per cord) resulting from a less desirable product. Therefore, the whole-tree chip system probably falls between the efficient full-tree systems and tree-length systems in profitability. In addition, it requires 120 acres to reach its minimum optimum tract size. Tracts less than 80 acres have average harvest costs over $1 per cord more.

Partially mechanized shortwood (D) , highly mechanized shortwood (E) and long log (G) systems were generally not cost competitive in average southern

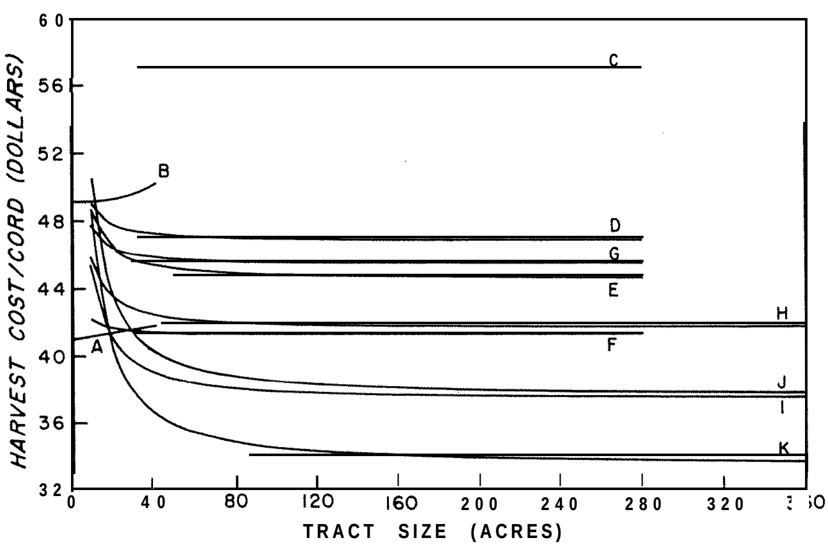

Figure 7.-Harvest *system short run average cost curves by acres, graph for complete range of data simulated for all systems.*

pine pulpwood harvesting conditions, with costs averaging $45 to $49 per cord. They had both high move costs and high average costs-the worst combination for all tract sizes. Small scale operations using straight trucks and farm tractors (B) or small skidders (C) had excessive average costs ($49 and $57 per cord) on all tracts.

Sensitivity Analyses

Sensitivity analyses tested the effects of changes in assumptions on the cost curves for selected harvest systems. Only system H and I were analyzed. They are low-cost systems currently employed in the South. Tree-length systems similar to H are the most common and may be considered as primarily manual systems. Systems similar to I, a highly mechanized full-tree system, are becoming more popular and may be considered primarily mechanized systems. Sensitivity analyses using these two systems provides information for the most popular systems in the South, as well as insights regarding comparative effects of parameter changes on manual versus mechanized systems.

Parameter Changes.-Effects of changes in tract shape, stand volume, input productivity rates, overhead costs, and fuel costs were tested. The cost curves were estimated for a limited acreage in the sensitivity analyses (0 to 120 acres at the most). They were compared with new cost curves derived for the same range from the original data. Therefore, differences in curves were due only to differences in the data, not computational methods.

The limited data sets generated in the sensitivity analyses prohibited statistical hypothesis testing, so only numerical and graphical comparisons were made. Earlier comparison tests among harvest systems indicated that numerical and visual differences were usually statistically significant. A similar pattern would probably emerge in the sensitivity analyses if enough data points could be simulated.

Results.-Table 14 summarizes the average cost equations derived for the sensitivity analyses. Numerical interpretation of the equations or means is straightforward. For inverse functions, the intercept represents the minimum cost level at infinity. Regressions with lower intercepts ultimately have lower average harvest costs per cord. The slope of the regression is a proxy for the number of acres required to approach the minimum cost. Lower slope coefficients indicate that the minimum cost level is reached more quickly than high coefficients.

The sensitivity analyses reveal that highly mechanized harvest system I always retained its minimum average cost advantage over manual tree-length system H, even with the changes in assumptions. When

Table 13.—*Mean cost per cord in cost curve tails by harvest system*

Rank	System	Meancost per cord	Observations	Data range
		dollars	*number*	acres
1	K	33.96	18	160-360
2	J	37.541	18	160-360
3	I	37.661	26	120-360
4	F	41.302	13	80–280
5	H	41.882	21	120-360
6	E	44.79	19	80–280
7	G	45.40	15	80–280
8	D	46.92	17	80-280
9	C	57.04	12	80-280

*Average costs for systems J and I not significantly different, alpha=.01 (64¢).
[2]Average costs for systems F and H not significantly different, alpha=.01 (64¢); are significantly different at alpha =.05 (54¢).
Note: all other system costs are significantly different at alpha=.01.

the tract size was changed from square to rectangular, the highly mechanized system became only slightly better than the manual tree-length system.

However, in all other sensitivity analyses, the highly mechanized full-tree system actually improved its competitive position. When productivity rates are reduced similar percentages in each, manual systems' costs increased more than mechanized systems'. Even at input rates only 75 percent as productive, the mechanized system retained its cost advantage over the manual system operating at full productivity rates.

The stand model in the research had a volume of 17.67 cord per acre. Sensitivity of costs to low volumes (10 cords per acre) and high volumes (27.2 cords per acre) was tested. High volumes provided no cost advantage for the tree-length system but reduced average costs about $2.50 per cord for the mechanized system. Low volumes increased minimum average costs a modest $4 per cord for the mechanized system and a hefty $14 per cord for the manual system.

In the modeling, only move costs were used as estimates of initial overhead costs for harvesting a new tract. In practice, there are additional, unquantified overhead costs for sale administration, purchase by the logger, and harvesting layout. In a Massachusetts study, Kronrad et al. (1980) found that consulting forester charges averaged $30 per acre for administering cordwood sales, or $2400 for an 80 acre tract. Gregersen et al. (1980) calculated an average administrative cost of $4 per acre for cost-share programs. For 80 acres, this would be $320. Watts and Watson (1978) found that checking out a job site

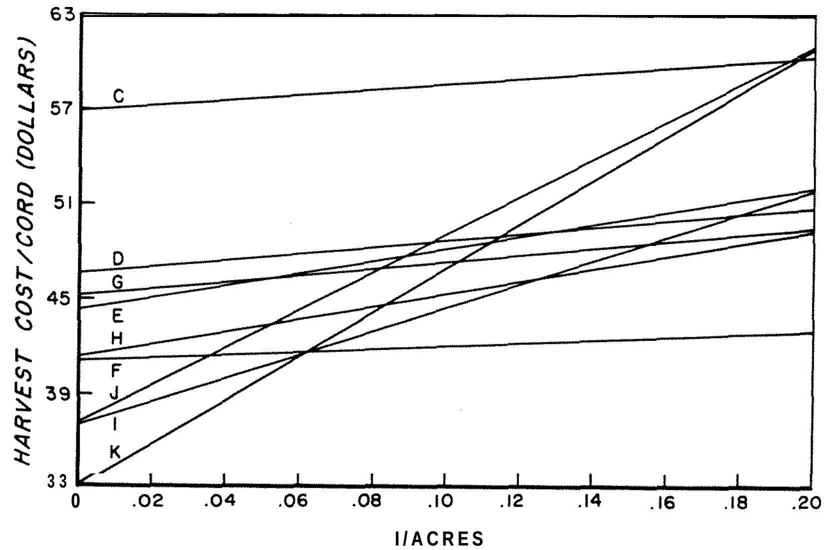

Figure *&-Harvest system short run average cost curves by I/acres, systems C-K.*

usually took about four hours, although they did not estimate the cost.

The range of costs for harvest administration, purchase, and layout indicates their importance. Since precise estimates of these costs are not available, overhead costs of $500 and $2000 were added in the sensitivity analysis to test the effects on the cost curves.

On the whole, it appears that added overhead costs will not affect the ultimate average cost level for a system, but will make small tracts less profitable by increasing the optimal tract size considerably-one and one-half to two times the original acreage size for $500 and $2000 in added costs, respectively. Also, added overhead costs will increase the point at which manual systems reach their minimum economic size until any advantages from in lower move costs is negated.

Increases in fuel and lubrication costs increased average harvest costs for manual tree-length system H more than for highly mechanized system I. Apparently, chainsaw and choker skidders use more fuel *per unit of output* than the highly efficient feller-bunchers, grappel skidders, and gate delimbers when both systems are operating at their full production levels.

CONCLUSIONS

Tract size is important in determining average harvest costs. The spreading of the initial fixed costs for moving and setting up a harvest system are the primary causes for economies of size. Large mechanized systems have higher move and set-up costs than small systems; therefore, they require a larger acreage size in order to minimize the effect of overhead costs on average costs. The implications for economies of tract size depend on the trends in harvest system selection and forest policies.

Harvest System Trends

Harvest equipment and system adoption in the United States has generally followed an evolutionary, rather than revolutionary, path. This trend is likely to continue, with the systems producing wood for the lowest cost tending to dominate harvesting as producers pursue a Darwinian equipment selection process. Current trends in labor availability and factor costs favor some systems over others.

Shortwood.-Two factors are contributing to the decline in use of shortwood systems. First, the most economical shortwood systems-the stump-to-stump bobtail truck and shortwood prehauler-rely heavily on manual labor to fell, limb, top, and buck trees with a chainsaw and to hand-pile bolts in the woods. The number of men willing to perform such strenuous work has been declining for decades. In addition, bobtail systems have traditionally relied on minimum wage labor which is increasingly hard to hire. Therefore the two labor-intensive operations, although cost-effective, are likely to continue declining in numbers.

Second, shortwood systems will decline in use because increasing mechanization proves to increase,

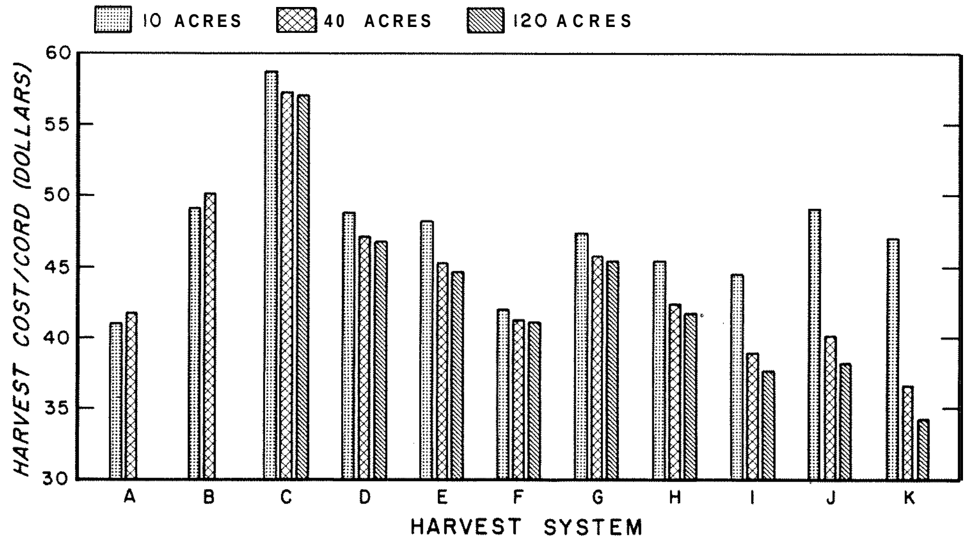

Figure 9.—Comparative system minimum average costs.

not decrease, average harvest costs. Mechanized systems which use tree-length or full-tree skidding and manual or mechanized bucking at the deck are significantly more costly than other shortwood, tree-length, or full-tree systems. Bucking is an extra function which generates no financial return, penalizing mechanized shortwood systems. Shortwood harvesting also prevents sorting and selling high-value products.

Manual Tree-Length.-Many loggers in the South have adopted tree-length logging and trucking operations. The harvesting simulation results confirm the wisdom of this practice. On tracts larger than 40 acres, manual tree-length operations compare favorably in cost with the labor-intensive stump bobtail system and shortwood prehauler system. The tree-length systems maintain low costs but eliminate over one-half the hand labor required in the low-cost shortwood systems, increasing chances for system survival.

Tree-length systems also enable a producer to move from a low-volume operation to a high-volume operation with correspondingly larger gross profits. Low cost shortwood systems usually do not produce more than 100 cords per week. Tree-length operations may increase weekly production per crew up to 250 to 300 cords per week.

Tree-length logging is currently the most popular system in the South and will continue to supplant shortwood operations. Despite the cost advantage of highly mechanized full-tree systems, tree-length systems should remain popular through the 1980s. Compared with highly mechanized systems, chainsaw and choker skidder systems are a less costly step in mechanization and have lower fixed costs to be borne when economic conditions are depressed and mills limit wood purchases. Also, they have lower move costs, are more adaptable to rough or wet land, and are useful in irregular stands with large timber or for such jobs as pulling trucks.

Highly Mechanized Full-Tree.-Highly mechanized full-tree harvest systems have the lowest average harvest costs per cord for roundwood products. The rubber-tired feller-buncher grapple skidder system and the tracked limited-area feller-buncher system had similarly low ultimate average harvest costs per cord. Both were cheaper than manual tree-length systems on average sites, although the limited-area feller-buncher system required larger tracts to reach its cost minimum. The highly mechanized full-tree system proved to be better yet on sites with low or high volumes, for increases in fossil fuel costs, or in increased overhead costs. It is also advantageous for multiple-product operations.

The cost advantages suggest that highly mechanized feller-buncher grapple skidder operations will continue to increase in number and dominate pine roundwood harvesting wherever terrain and institutional considerations permit. Rough or swampy terrain may limit their use and they may not have comparative cost advantages in thinnings, hardwood cutting, or sawtimber harvesting.

Institutional factors inhibiting rapid adoption of highly mechanized systems include high investment costs and high interest rates. Forest industry policies will also affect their adoption. Before loggers invest in high-priced mechanized systems, they need assurance that they can harvest and sell wood in high volumes. Imposition of quotas in soft markets or closing of mills due to strikes could quickly bankrupt

Table 14.—*Sensitivity analysis costs for comparisons*

System	Acreage size	Parameter of interest	Regression (ave.) cost
H	O-40	base data	Y =40.353+48.556 (l/X)
		50% productivity rates	Y=58.288+65.292(1/X)
		75% productivity rates	Y =46.347+49.318 (l/X)
		poor shape	Y =41.223+49.808 (l/X)
H	O-100	base data	Y =40.869+44.595 (l/X)
		low volume	Y=54.599+46.343(1/X)
		high volume	Y=42.508+20.613(1/X)
		$500 added overhead	Y=41.322+85.441(1/X)
		$2090 added overhead	Y=40.937+269.128(1/X)
I	O-100	base data	Y=36.272+80.641(1/X)
		50% productivity rates	Y=43.649+118.970(1/X)
		75% productivity rates	Y=37.902+83.879(1/X)
		poor shape	Y=40.914+41.394(1/X)
		low volume	Y=40.251+148.634(1/X)
		high volume	Y=33.744+56.064(1/X)
		$500 added overhead	Y =35.082+ 135.624 (l/X)
		$2000 added overhead	Y=35.265+296.878(1/X)
H	40	base data	$\bar{Y}$=41.98 s=.12
		1.5 × fuel costs	$\bar{Y}$=43.49 s=.12
		2.0 × fuel costs	$\bar{Y}$=44.61 s=.18
I	100	base data	$\bar{Y}$=37.46 s=.18
		1.5 × fuel costs	$\bar{Y}$=37.60 s=.09
		2.0 × fuel costs	$\bar{Y}$=39.01 s=.08

Where: Y=harvest cost (dollars per cord)
X=tract size harvested (acres)

capital-intensive operations dependent on high production to make payments on equipment.

The sensitivity analyses and recent productivity studies indicate' that the cost advantages arising in the simulations may even be understated. Highly mechanized full-tree systems seem certain to increase in popularity. Highly mechanized systems may not approach their minimum cost level until tract sizes reach 80 to 120 acres, but are, cost-competitive with manual tree-length systems on tracts as small as 10 acres. Adaptations such as low ground pressure tires or tracks may make the feller-bunchers and skidders more suited to less ideal terrain conditions.

Whole-Tree Chip.-Pulpwood production using the whole-treechipping system was the lowest cost operation 'by a wide margin. However, the whole-tree chip simulation assumed that the model stand would be purchased for the same price that prevails for conventional products and receive a 25 percent overrun without any additional stumpage cost. Sophisticated sellers realize that chipping systems harvest greater volumes and may demand greater stumpage prices. Also, lower revenues per cord make the systems less profitable than the highly mechanized full-tree systems. In addition, the chipper is a large consumer of energy.

The whole-tree chip system is probably more profitable than tree-length systems on average stands, even if a bonus were paid for volume overruns. When the dirty chips can be mixed with other mill roundwood or used to make special products, whole-tree chipping may be the most profitable harvesting method. If any economical method is adopted for cleaning the chips, it may rival the highly mechanized full-tree systems in popularity. Also, sorting out high-value butt portions for veneer or lumber could make "whole-tree" chipping more competitive.

Tract Size Effects

Harvest system trends indicate that future movements along the long run average cost curve will consist of shifts to tree-length and highly mechanized full-tree systems. Bobtail operations will persist due to ease of entry and exit for small operators, low capital investment, and cost competitiveness. However, their use is decreasing and their share of roundwood harvest is likely to be less than 5 to 10 percent of the volume in the near future. Consequently, bobtail operations will be insufficient to harvest all the small tract offerings.

The situation is smiliar with the shortwood prehauler system. It is economical on small tracts but waning in numbers. Except in Louisiana, very few shortwood forwarders are used in the South, probably due to lack of available manual labor. The shifts to more capital-intensive harvest systems with high moving costs are causing concern for economies of tract size.

Determining the point of minimum optimum size on the dominant tree-length and full-tree systems influences the conclusions regarding tract size problems. For L-shaped cost curves, the cost function slope and concomitant acreage sizes and costs at various intervals is useful in defining the minimum optimum size level (table 15). Judgement seems to indicate that the two percent slope level is an optimistic break for determining the point at which economies of tract size are reached. Indeed, the one percent level may be a defensible choice.

Using the 2 percent slope level as a criterion, there are serious cost problems on small tracts. The manual tree-length system incurred excessive harvest costs on tracts less than 45 acres. The highly mechanized full-tree system required at least 62 acres to reach its minimum optimum size.

In timber harvesting, as in all productive activities, equilibrium prices move toward the lowest cost incurred by the most efficient firms. As efficient shortwood operations decrease in number and contribute less to total roundwood harvests, only the very efficient highly mechanized full-tree harvest systems and less efficient tree-length systems are likely to remain. In order to maximize their profits, loggers will tend to move to more efficient short run average cost curves, moving downward and right on those curves.

Forest industry pricing will reflect the productivity increases and movements along the long run average cost curve. They will pay comparatively lower mill prices or contract prices to equilibrate their prices with the minimum cost point on the logger's long run average cost curve and eliminate excessive profits gleaned by efficient loggers. This is the crux of the economies of size issue in forestry. If loggers mechanize to achieve high production and concomitant low average harvest costs, small acreages become uneconomical to harvest at equilibrium prices.

Even if a variable rate were allowed, tracts less than 20 to 30 acres probably would not be worth the increased harvest costs per cord. Acreages less than 20 acres will be exceedingly expensive to harvest and even tracts less than 50 acres will be significantly more costly. Other forest harvesting and forest management literature suggests that 50 acres is the minimum size for avoiding high average costs as well. These acreage guidelines are flexible, depending on the volume per acre. High volume stands will be more economical at smaller acreages and low volume stands or thinnings will require larger acreages.

Policy Implications

High costs on small tracts suggest that forest management should be concentrated on tracts 40 acres or more in size. Tracts less than 40 to 60 acres are likely to receive such a penalty in harvesting costs alone that they would not be very economic.

For cost efficiency, sawtimber harvests may require smaller acreages than pulpwood harvests. However, sawtimber harvests imply that pulpwood thinnings may be required, especially in plantations. The lower volumes removed in thinnings will require

Table *15.-Acres required to obtain a given percent slope level and associated harvest costs per cord, Systems H and I*

Slope level	H. manual tree-length		I. highly mechanized full-tree	
	Tract size	Cost per cord	Tract size	Cost per cord
percent	*acres*	*dollars*	*acres*	*dollars*
50.0	9	45.86	12	43.30
25.0	13	44.49	17	41.47
10.0	20	43.42	27	39.85
5.0	28	42.84	39	38.71
2.0	45	42.31	62	37.99
1.0	64	42.04	87	37.64
0.1	203	41.61	276	37.04

even larger acreages for economical operation than those found in this research, exacerbating the tract size problem. On the whole, the literature and this research support the conclusion that large tracts (50 to 125 acres) have, significant economic advantages over small tracts (less than 50 acres). Average costs increase rapidly on tracts below 50 acres and are prohibitive on tracts below 10 to 20 acres.

To maximize economic efficiency, forest policies should encourage pulpwood and timber production on large tracts. Timber growing assistance, such as the Forestry Incentive Program and Agricultural Conservation Program, should have minimum acreage requirements of at least '20 to 40 acres. The Forest Service and forest industries should mandate pulpwood pine harvests of at least 40 to 80 acres, rather than having regulations favoring small maximum clearcut sizes. Cooperative forest management and industrial forestry assistance programs should also be slanted toward large acreages.

Forest policies which favor large tract sizes seem inequitable to small forest owners. Consequently, the policies might run aground on the basis of political considerations. Harvesting small areas may be preferable for environmental reasons. The wisdom of sacrificing economic efficiency in favor of equity or environmental criteria must be debated and decided by forest policy makers.

The net effect of increased timber harvest costs on small tracts depends on the policies pursued by forest industry and the federal and state governments. If a market solution is accepted, prices and contractor rates would remain at equilibrium (minimum cost) levels and small tracts would become uneconomical to harvest. Economic roundwood supplies would be reduced, shifting supplies on small tracts to the future, and causing pulpwood prices to increase in real terms. Increased prices might in turn bring forth increased pulpwood production.

Forest industries could deal with high average costs on small tracts by incorporating the differences into their pricing structure and accepting some high-cost wood. They still would have to determine the minimum tract size for paying the added average harvest costs, but variable pricing would make fewer acres unprofitable to harvest than would flat rate equilibrium pricing.

If variable pricing and market pricing alternatives are deemed unacceptable, government could act to reduce effects of increased harvest costs on small tracts. Costs to the landowner could be decreased via incentive programs or tax advantages, offsetting higher harvest costs. Direct payments to loggers could be used also to make up the difference between large and small tract average costs, and might be more efficient.

Given the relatively low size at which most economies of size are reached (about 100 acres), efforts to aggregate tracts might be successful in reducing average harvest costs. However, costs of aggregation must not exceed the harvest cost savings. Intermediate technology, the often proposed solution for high costs on small tracts, is not likely to reduce average costs. Small-scale equipment suffers from high fixed costs for development and assembling, making it inherently more expensive than more productive larger equipment.

Forest planners and policy makers must consider the costs and benefits of the alternatives for overcoming diseconomies of size. Environmental or equity criteria or negative public opinions of large tract harvesting may outweigh the benefits of economic efficiency alone. The optimal solutions to the problem depend on the objectives, values, and criteria used in decision-making. Optimal solutions may also vary by geographic region, depending on the institutions and forest types in existence.

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Appendix

Tables for Production Information, Input Costs, and Simulation Inputs for Harvest Systems

Table Al.-Averages *of production rate distributions used**

Harvest machine function	Average production (ft^3 per productive hour)	Literature bases
Chainsaw fell, limb, top, and buck	222	Plummer 1977
Chainsaw fell, limb, and top	382	Hypes and Stuart 1979
Chainsaw limb and top	792	Hypes and Stuart 1979, Plummer 1977
Tree shear fell	1,179	Curtin and Bunker 1972, White 1969
Rubber-tire feller-buncher fell	1,072	American Pulpwood Association 1977
Limited-area tracked feller-buncher fell	1,479	Fowler 1972
Hand pile 5'3" bolts	307	Plummer 1977
Chainsaw buck 5'3" bolts at deck	493	Hypes and Stuart 1979
Chainsaw buck long logs	526	Hypes and Stuart 1979
Bobtail forward	4,815	manual calculations
Hydraulic slash and load 5'3" bolts	602	Plummer 1977
Bigstick load at stump	138	Hypes and Stuart 1979
Bigstick load at deck	190	Hypes and Stuart 1979
Small knuckleboom load-shortwood	945	Hypes and Stuart 1979
Medium knuckleboom load-tree length	1,848	Clair 1977
Whole-tree chip	2,830	Plummer 1977

*Actual productivity rates used were put in the simulation program as frequency distributions based on stand diameter distributions; see Cubbage 1981b for details.

Table A2.—*Machine costs, utilization, and life (1980)*

Equipment	Purchase price	Salvage value	Life yrs	Op hrs (mis)[1] per year	Cost per operating hr (mi)[2] Fixed	Operating	Total	Utilizations (availability)
	------. dollars ------				----------dollars		------	percent
Chainsaw-straight blade	500	0	1	1200	.47	3.00	3.47	50
Dozer with shear	65,500	32,750	5	1200	12.88	9.00	21.88	65
Small feller-buneher	55,000	11,000	3	1300	16.69	12.45	29.14	65
Medium rubber-tire f.b.	70,000	13,500	4	1300	17.53	10.25	27.78	65
Lmtd.-area flr.-bnchr.	120,000	18,000	5	1200	28.92	16.54	45.46	60
70 h.p. cable skidder	40,000	8,000	4	1300	9.96	8.20	18.16	67
90 h.p. cable skidder	46,000	10,000	4	1300	11.34	10.08	21.42	67
110 h.p. cable skidder	47,000	5,500	5	1200	11.52	11.11	22.63	67
120 h.p. cable skidder	60,000	6,000	5	1200	14.84	12.43	27.27	67
70-90 h.p. grapple skidder	48,000	10,000	4	1200	12.90	9.73	22.63	67
110 h.p. grapple skidder	62,000	16,500	5	1200	14.12	11.76	25.88	67
High-speed tracked g.s.	180,000	22,000	5	1200	44.01	31.98	75.99	65
Farm tractor skidder	27,000	5,400	5	1000	7.60	7.40	15.00	65
Shortwood forwarder	40,000	8,000	4	1300	9.96	7.74	17.70	64
Longwood forwarder	55,000	11,000	4	1300	13.70	10.00	23.70	64
Bigstick loader	2,600	260	5	720	.95	2.14	3.09	(90)
Small knuckleboom	27,000	8,000	5	1000	6.47	12.00	18.47	65
Medium knuckleboom	42,000	13,700	5	1000	9.86	12.00	21.86	65
Used truck for loaders	6,000	600	3	1000	3.20	3.00	6.20	65
Hydraulic slasher	8,000	0	4	1000	2.70	.70	3.40	67
Gate delimber	1,700	340	5	1500	.27	.12	.39	(90)
Medium chipper	82,000	16,400	5	1500	13.89	15.07	28.26	80
Large chipper	174,000	27,000	5	1500	30.27	24.04	54.31	80
Small used bulldozer	24,500	4,900	5	500	13.80	8.04	21.84	65
Medium new bulldozer	75,320	44,000	5	1200	14.00	13.00	27.00	65
Road grader	65,000	40,000	5	1200	10.50	14.97	25.47	65
Bob truck dead tandem	13,000	3,000	3	24,000	.26	.53	.79	
Bob truck live tandem	20,000	9,000	4	24,000	.28	.55	.83	
½ ton pickup	7,000	1,500	3	25,000	.13	.12	.25	
Service/crew truck	25,000	5,000	3	25,000	.42	.19	.61	
Diesel truck-tractor	45,000	10,000	5	60,000	.24	.40	.64	
Shortwood trailer	9,000	2,000	6	66,666	.03	.07	.10	
Bundle-bucker trailer	9,000	2,000	6	66,666	.03	.07	.10	
Pole trailer	7,800	2,000	6	66,666	.03	.05	.08	
Chip van	10,000	4,300	8	37,500	.05	.07	.12	
Lowboy-25 ton	12,500	4,000	10	5,000	.39	.05	.44	

'Operating hours (miles) per year: number of hours (miles) equipment is actually being used each year; woods equipment (i.e. feller-buncher, skidder, loader, grader, dozer) in hours, road equipment (i.e. truck, trailer) in miles.

*Cost per operating hour: fixed cost includes depreciation, interest, taxes, and insurance; operating cost includes fuel and lubrication, tire or track costs, and repair and maintenance (including labor).

[3]Utilization is percent of scheduled time machine is actually used. Availability for bigstick loader and gate delimber is percent of scheduled time they are not broken down-available to be used.

Table A3.—*Labor* rates and approximate *weekly hours by labor class*

Position	Wage per hour	Approximate hours per week
	dollars	
Unskilled general labor: bobtail truck system	3.50	45
Unskilled general labor: small mechanized operations	5.00	40
Saw hands: medium to large operations	6.00	45
General equipment operators: small skidders, chippers	6.00	45
Special equipment operators: skidders, loaders, feller-bunchers	6.50	45
Truck driver: straight truck	6.00	40
Truck driver: tractor-trailer	7.00	50
Mechanics	8.00	50

Table A4.—*Social legislation costs-percent paid per dollar of base pay*

Cost item	Worker's compensation classification	
	Pulpwood only 2705	Pulywood and sawtimber 2701
	------ ____ *percent* . _____ ----	
Social Security	6.13	6.13
Worker's Compensation	30.00	22.00
Unemployment Compensation	3.00	3.00
Total	39.13	31.13

Table *AS-Profit or salary of the entrepreneur by system*

Description of logging operations	Systems	Annual profit or salary
		dollars
Stump bobtail	A	9,000
Bobtail and farm tractor	B	10,000
Small mechanized operations	C,D,G	14,000
Prehauler system	F	16,000
Large operations	E,H,I	24,000
Highly mechanized operations	J,K	30.000

Table A6.—*Average southern pine stumpage and F.O.B. mill prices July 1979-Jul.y 1980*

Product	Range High	Range Low	Typical
	-------- *dollars*	--------	
Pulpwood stumpage (standard cord)	11.97'	10.90	11.70
Pulpwood FOB mill (standard cord)	39.72	36.65	38.00
Sawtimber stumpage (MBF Scribner)	154.45	107.77	142.00
Sawlogs FOB mill (MBF Scribner)	192.64	157.92	180.00
Dirty Chips FOB mill (green ton)	12.38	9.18	12.00

Source: Timber Mart South 1979, 1980.

Table A7.—*Haul harvest system—30 mile haul*

System(s) and transportation equipment	Cords per load	Machine costs: Cost/mile Truck	Machine costs: Cost/mile Trailer	Machine costs: cost per cord	Labor costs: Wages Hrly. rate	Labor costs: Wages Fringe	Labor costs: Hours per load	Labor costs: cost per cord	Total cost per cord
		dollars				*percent*		*dollars*	
A Dead tandem bobtail	4	.79		11.85	owner/operator		4	0.00	11.85
B Live tandem bobtail	5	.83		9.96	owner/operator		4	0.00	9.96
C Live tandem bobtail	5	.83	....	9.96	6.00	39	4	6.67	16.63
D,E,F Tractor-trailer truck, pulpwood trailer	10	.64	.10	4.44	7.00	39	4.5	4.38	8.82
G,H,I,J Tractor-trailer truck, pole trailer, or bundle-bucker trailer	8	.64	.09	5.48	7.00	31	4	4.58	10.06
K Tractor-trailer truck. chip van	10	.64	.10	4.56	7.00	31	4.5	4.13	8.69

Table A8.—***Operating days per year and tract sizes simulated by operation***

Harvest system	Yearly operating times: Days/year	Yearly operating times: Weeks/year[1]	Tract sizes simulated (acres): 5–40[2]	Tract sizes simulated (acres): 5–280[3]	Tract sizes simulated (acres): 5–360[4]
A. Stump bobtail	160	32	x		
B. Bobtail and tractor	180	36	x		
C. Skidder and truck	200	40		x	
D. Semi-mechanized shortwood	200	40		x	
E. Highly mechanized shortwood	220	44		x	
F. Shortwood prehauler	210	42		x	
G. Long log	200	40		x	
H. Manual tree-length	220	44			x
I. Highly mechanized full-tree	220	44			x
J. Limited-area full-tree	220	44			x
K. Whole-tree chip	210	42			x

[1] 5 days per week, 5 shifts per week, 9 scheduled hours per day.
[2] 5,10,15,20,30, and 40 acre tracts.
[3] 5,10,15,20,30,40,50,60,70,80,90,100,120,160,200,240, and 280 acre tracts.
[4] 5,10,15,20,30,40,50,60,70,80,90,100,120,160,200,240,280,320, and 360 acre tracts

Table A9.—*Travel rates for in-woods machines or activities*

Machine or activity	Travel rate
	feet per minute
Man with chainsaw	88
Man piling wood	176
Tracked dozer with tree shear	164
Rubber-tired feller-buncher	264
Limited-area feller-buncher	176
Farm tractor	264
Choker skidder-70 horsepower	350
Choker skidder-90 horsepower	350
Choker skidder-110 horsepower	350
Choker skidder-120 horsepower	350
Grapple skidder-110 horsepower	350
Shortwood forwarder	453
Bobtail truck in woods	88

Source: personal discussions with industrial and academic harvesting experts and manufacturer's equipment specification sheets.

Table A10.—*Load capacities for skidders or forwarders*

Machine	Load capacity
	cubic feet
Farm tractor	23
Choker skidder-70 horsepower	60
Choker skidder-90 horsepower	68
Choker skidder-l 10 horsepower	90
Choker skidder-120 horsepower	112
Grapple skidder-110 horsepower	110
Shortwood forwarder	180

Source: personal discussions with industrial and academic harvesting experts and manufacturer's equipment specification sheets.

Table *AX-Fired times and productivity rates used for loading and unloading skidders or prehaulers*

Machine	Fixed time to load & unload (minutes)	Loading & unloading production (ft^3/produc. hr.)
Farm tractor	2.46	561
Choker skidder-70 horsepower	4.7	766
Choker skidder-90 horsepower	4.7	862
Choker skidder-110 horsepower	4.7	1150
Choker skidder-120 horsepower	4.7	1404
Grapple skidder-110 horsepower	3.3	1818
Gate delimber (110 hp grp. skid.)	1.4	4285
Grapple skidder-110 horsepower plus gate delimb fixed time	4.7	1395

Calculations to convert time into cubic feet of production:
(1) 1 hour/fixed time per load = loads per hour
(2) loads per hour × load capacity (ft^3) = production (ft^3/hr.)
Source: personal discussions with industrial and academic harvesting experts and various unpublished literature.

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1982. Economies of forest tract size in southern pine harvesting, U.S. Dep. Agric., For. Serv., Res. Pap. SO-184, 27 p., South. For. Exp. Stn. New Orleans, La.

This pub&cation provides model and data **analyses** for determining optimum tract sizes for forest harvests.