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Regeneration and productivity of aspen grown on repeated short rotations

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REGENERATION AND PRODUCTIVITY OF ASPEN GROWN ON REPEATED SHORT ROTATIONS

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Because of the increasing demand for wood fiber, considerable research has been devoted to short rotation, full tree utilization systems, which are designed to produce the maximum amount of wood fiber in the shortest time. Quaking aspen (*Populus tremuloides* Michx.) is a likely candidate for these systems because it produces good quality wood fiber at a young age. However, the effects that repeated cropping would have on the aspen's coppicing ability have had little attention. Therefore, we conducted this study to decribe the productivity and other characteristics of repeatedly cropped aspen.

STUDY AREAS

The study areas are located within 13 km of each other on the Chippewa National Forest, Minnesota. The soils are well-drained Warba sandy to fine sandy loams and are considered good aspen sites. The climate is continental, averaging 20 °C in July and 64 cm annual precipitation. The topography is level to gently rolling and the elevation is 400 to 410 m. The areas had been commercially logged for aspen during spring and early summer 2, 4, and 8 years prior to study installation (table 1). Treatment plots were located where suckers were uniformly dense and unimpeded by residual overstory.

Table 1.–Parent stand summary

			Aspen yield	
Rotation schedule (yr)	Site index[1]	Stand age	Merchantable volume[2]	Total tree[3]
	m	*yr*	*m³/ha*	*t/ha*
8	24.4	42	77	31
4	22.9	31	55	23
1	21.3	47	77	31

[1] At 50 years.

[2] To 10.2 cm top; from sale records.

[3] Oven-dry weight, except leaves, above 15 cm stump. Estimated from Schlaegel (1975). These figures are for merchantable trees and species only and probably underestimate total standing crop by at least 50 percent.

METHODS

All woody stems on five circular 810 m^2 (16 m radius) treatment plots were clipped and removed on 1[1]-, 4-, and 8-year cycles beginning May 1970. Two plots were installed in each the 4- and 8-year cycles and one plot was installed in the 1-year cycle. Stems were clipped during the dormant season to maximize aspen suckering (Brinkman and Roe 1975). Five circular 16.2 m^2 (2.27 m radius) sample plots were systematically clustered at the center of each of the five treatment plots. The minimum distance between sample plots and treatment plot boundary was 8.4 m to exclude edge effects on sucker stocking and growth.

The aspen from the first clipping of the sample plots was used to develop stand equations for aerial dry weight of total trees (except leaves) and of wood based on stem diameter and height measurements (Perala 1973). Thereafter, these equations were applied to yearly diameter and height measurements, including the cropping years.[2] Other woody stems from the sample plots were weighed fresh by species at each cropping but were not measured during intervening years. Several stems of each of these other species of estimated mean size were subsampled to determine oven-dry weights (105°C oven) at each cropping. During the first 2 years, aspen coppice (ramets) was recorded as either root suckers or stump and root collar (S/RC) sprouts.

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[1] *This sucker stand was 2 years old at first clipping but was clipped annually thereafter.*

[2] *Except for the 1-year rotation after the second cropping– it became more convenient to dry and weigh entire plot clippings.*

Curvilinear multiple regression analysis was performed on data from the 25 measurement plots to determine how stand characteristics influenced the sizes of both aspen S/RC sprouts and suckers (dependent variables).

The independent variables were:

X_1, ortet (parent) age (years);
X_2, ortet stem density (1,000's/ha);
X_3, ortet mean weight (g/stem);
X_4, sucker density (1,000's/ha);
X_5, S/RC sprout density (1,000's/ha); and
X_6, mean weight of suckers or S/RC sprouts, as appropriate, (g/stem).

All variables in both equations were significant at the 0.05 level.[3]

RESULTS AND DISCUSSION

Initial Sucker Stand Characteristics

If expressed as mean annual increment, the short rotation yields are much less than would be achieved on conventional (40 year) complete tree fiber rotations (table 2).

Table 2.—*Mean annual, increments of short rotations compared to conventional rotations*

Stand age, years	8	4	2
Site index, m	24	22.5	21
MAI (wood component) t/ha/yr	1.52	1.73	.47
MAI, conventional, t/ha/yr[1]	2.66	2.45	2.24
Ratio, short rotation ÷ conventional	.57	.71	.21

[1] From Perala (1977).

Wood specific gravity was similar to mature stands (Schlaegel 1975) but moisture content (mainly because of seasonal variation) and bark percent were considerably higher and bark specific gravity was lower (table 3). Bark percent decreased as stand age increased but the other physical properties did not vary significantly with age.

Repeated Crop Yields

Regeneration and yield of aspen decreased as cropping frequency increased. Regeneration and yield on the 1-year rotation declined steadily through the fourth crop and precipitously thereafter (fig. 1). The decline in yield through the fourth crop was a function of both a reduction in number of stems regenerated and mean stem size. After the fourth cropping, mean stem size remained essentially unchanged. After 7 annual croppings, aspen regeneration ceased.

Table 3.—*Yield and properties of young aspen sucker stands*

Stand age (yr)	Dominant height	Mean dbh	Basal area	Number of stems	Total fresh weight	Oven dry weight Total	Oven dry weight Wood	Oven dry weight Bark	Moisture	Bark	Specific gravity Wood	Specific gravity Bark
	m	*cm*	*m²/ha*	*1,000's/ha*		. . . .*t/ha*			. . .*Percent* . . .			
8	6.7	2.8	8.99	14.9	36.2	16.3	12.2	4.18	121	25.5	0.391	0.509
4	4.4	1.4	6.46	44.0	22.4	9.55	6.91	2.64	135	27.6	0.378	0.451
2	2.3	—	—	73.1	3.41	1.50	0.94	0.56	128	37.6	0.386	0.449
[1]1	1.3	—	—	75.2	0.87	0.40	0.22	0.18	120	44.5	0.415	[2]

[1] First 1-year cropping of the original age 2 stand.

[2] Not determined.

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[3] *Coefficients and other statistics are not given here but are available from the author on request. Response to each variable was depicted graphically while holding all other variables at constant mean values.*

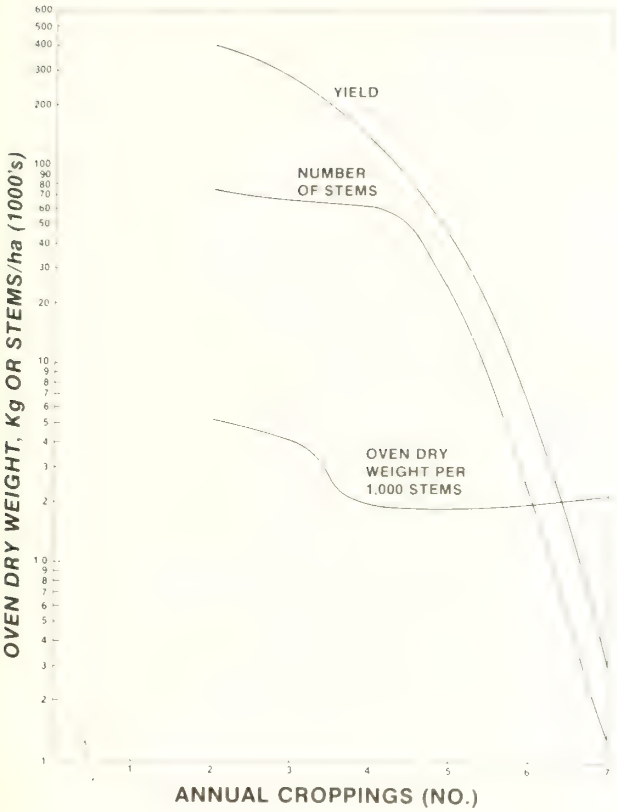

Figure 1.— *Regeneration and oven-dry aboveground yield of aspen coppice (except leaves) on successive 1-year croppings. The first cropping was omitted because it was at age 2.*

The 4-year rotation tended toward the same results— number, vigor, and total yield declined with each cycle (figs. 2 and 3). However, it would take at least several more cycles to completely eliminate aspen.

The 8-year rotation produced two-thirds less sprouts and one-third less total yield on the second cycle (figs. 2 and 3), but the results are confounded by feeding damage by hares (*Lepus americanus*) during the winters following the fifth and sixth growing seasons. Hares girdled some of the smaller stems, which died a year or two later without resprouting. However, even if the hare damage had not occurred, the estimated total yield of the second cycle was still 10 percent less than the first cycle (Perala 1973). Because the largest stems survived, the average size of three dominant stems was compared at the end of each cycle as well as between dominant regenerated stems (table 4).

Table 4.— *Comparison of dominant stems at end and beginning of successive 8-year rotations*

	End of 8-year rotation		Beginning of 8-year rotation	
Cycle	Mean dbh	Mean height	Mean basal diameter	Mean height
	cm	*m*	*cm*	*m*
1	4.7	6.7	—	—
2	4.6	6.5	1.1	1.52
3	—	—	1.1	1.43

None of these comparisons were statistically different. Furthermore, of the 10 plots, 5 had larger dominants at the end of the first cycle and 5 at the end of the second. All in all, the results for the 8-year rotation do not suggest significant physiological impairment to aspen productivity.

Character of Regeneration

In contrast to mature stands which produce suckers almost exclusively, most of the aspen regeneration in all rotations were stump and root collar sprouts (table 5).

Table 5.—*Stump and rootcollar sprouts regenerated on short rotations*

	Stump and root collar sprouts		
Ortet age	Percent by weight	Percent by number	Per stump
8	58	57	3.9
4	88	82	1.6
2	60	63	0.6
1	58	59	0.5

S/RC sprouts did not differ significantly in growth and survival from suckers during the first 2 years when this data was gathered.

S/RC sprouting in aspen has rarely been reported before. Maini (1968) reports they are occasionally found on aspen up to sapling size in Canada and Baker (1925) found that S/RC sprouts accounted for 9 percent of the sprout regeneration after mature Utah aspen were felled. In this present stand, the stumps were cut so low that stump and root collar sprouts could not be differentiated. The propensity to regenerate S/RC sprouts is probably related to the strong tendency for suckers to

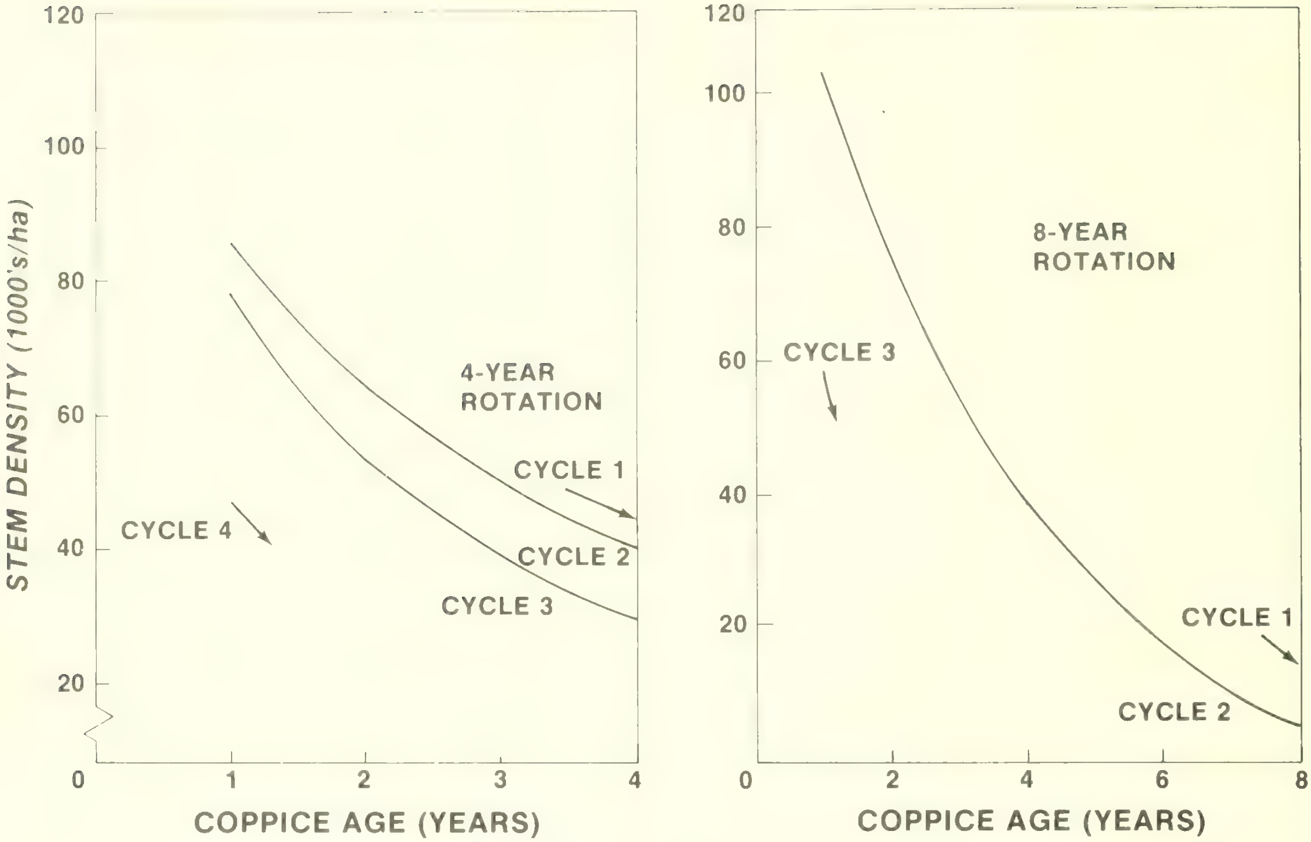

Figure 2.— *Regeneration and survival of aspen coppice on 4- and 8-year rotations. Arrows indicate expected trends.*

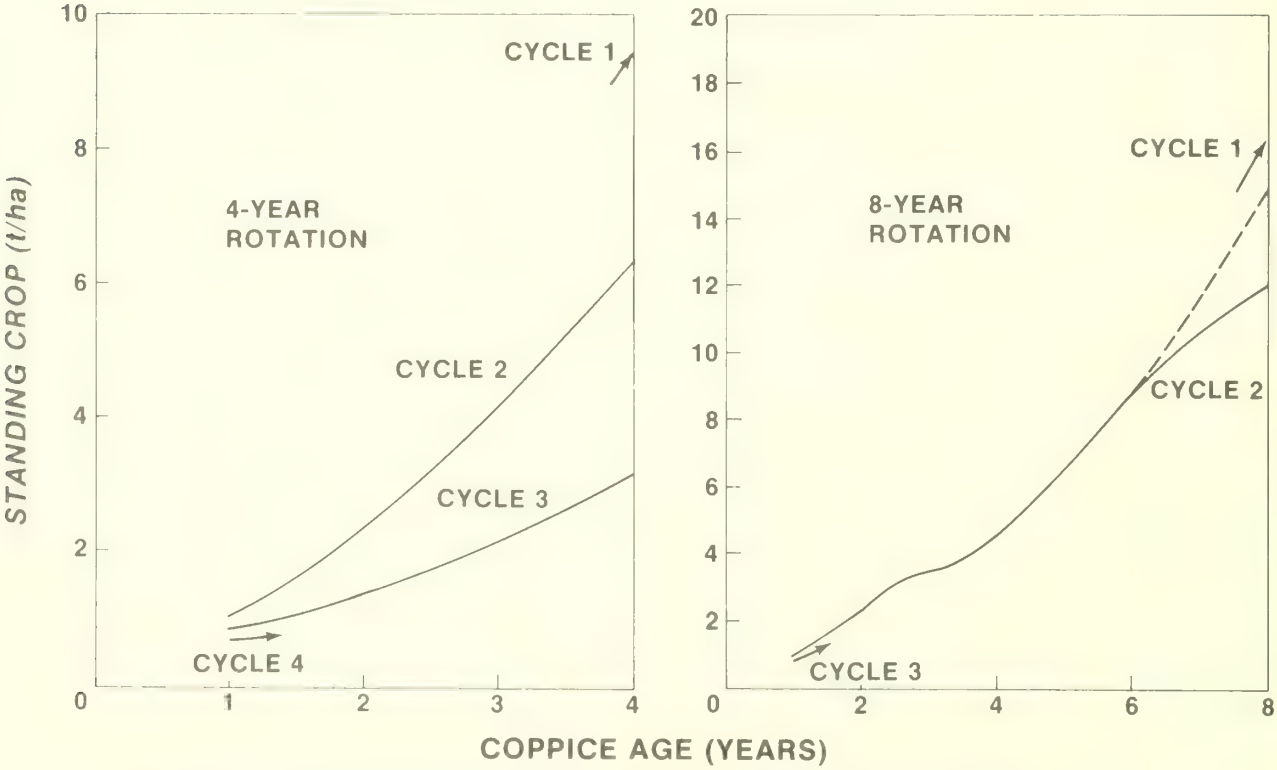

Figure 3.—*Standing crop (total stem oven-dry weight) of aspen coppice on 4- and 8-year rotations. Arrows indicate expected trends. Dashed line indicates the expected trend without hare damage (Perala 1973).*

regenerate in groups from localized areas about 6 cm in length along the aspen root (Sandberg and Schneider 1953). Usually only single stems survive but apparently these localized areas can continue to dominate sprout reproduction.

The most striking results of the regression analysis were that sucker and S/RC sprout mean weights (MW) responded in opposite sign to 4 of the 6 independent variables :

Independent variable	Sucker MW	S/RC sprout MW
Ortet age	increased	maximum at age 4
Ortet number	decreased	increased
Ortet mean weight	decreased	increased
Sucker density	increased	decreased
Stump/root collar sprout density	increased	decreased
Other ramet mean weight	increased	increased
R_2	.92	.97
Sy.x, percent of arithmetic Y	15	12

One exception was ortet age where sucker mean weight (MW) rose asymptotically to age 8 while S/RC sprout MW peaked at age 4, and then began to decline. This indicates that S/RC sprouting capacity decreases with age and with the approach to full suckering capacity.

The positive S/RC responses probably reflect a direct relation of general ramet-ortet vigor; i.e., vigor begets vigor. The negative responses may reflect competition. For example, S/RC sprout MW declined with both sucker and S/RC density while, in contrast, sucker MW increased with both sucker and S/RC density. This suggests that suckers dominate S/RC sprouts.

Clearly, the physiology of aspen S/RC sprouts and root suckers differ, most importantly in the culmination of S/RC sprouting at about age 4, followed by the increasing dominance of suckers. This may, in turn, reflect the rate of aspen root system development. Because of carbohydrate depletion, the parent root system in age 4 stands may be less able to produce suckers than it is in age 2 stands, and new roots for sucker production likely are not as extensive in age 4 as in age 8 stands. Thus, the total amount of roots capable of producing suckers may be at their lowest level at about age 4.

Nutrient Limitations

Nutrients were not studied but the magnitude of nutrients removed can be estimated from exisitng data (Einspahr 1977) and compared to nutrient reserves for a Warba soil (Alban *et al.* 1978) similar to this study. The total biomass removals in the 1-year rotation over 9 cycles would extract no more than 2 percent of the available soil nutrients (or total N). The estimated removals in three cycles of the 4-year rotation ranged from 2 percent of total N to 13 percent of exchangeable K. Corresponding values for two cycles of the 8-year rotation are 2 percent N to 17 percent K. Thus, the relatively greater reductions in yield with shorter rotations are *inversely* related to nutrient removals. Therefore, the only reasonable conclusion is the declines in yield can be almost wholly ascribed to regenerative stress.

The magnitude of nutrients removed on longer aspen rotations can also be estimated from existing data. Generally, the concentration of above-ground nutrients excluding leaves declines with age (Einspahr 1977). However, when the values for tree nutrient concentrations are multiplied by mean annual biomass increment (Perala 1973), mean annual accumulation of nutrients approximately parallels the accumulation of biomass and both culminate at nearly the same age (fig. 4).

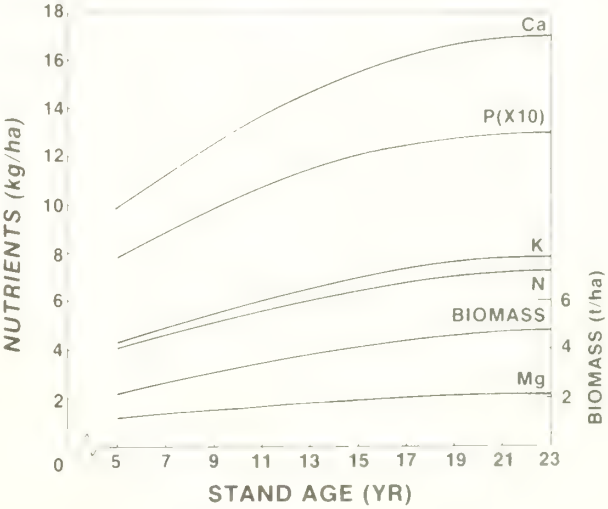

Figure 4.– Mean annual above-ground accumulation of nutrients and biomass in aspen (except leaves). Integrated from Einspahr (1977) and Perala (1973).

Therefore, nutrient removals are largely proportional to biomass removals and little adjustment can be made in rotation length to minimize nutrient removals without reducing fiber yields.

Other Species

The yield of other woody species was not altered as dramatically by repeated cropping as was aspen (table 6). The total yield of other woody species in the 1-year rotation was reduced by about 60 percent at the third cropping and remained stable thereafter. In the first crop, these species comprised about 20 percent of the total yield; by the seventh crop, their percentage increased to almost 100!

Total yield of these other species under the longer rotations was stable. However, species differed greatly in their ability to withstand repeated cropping. It appears that red oak, mountain maple, red maple, and green alder are decreasers and the juneberry-cherry group, red-osier dogwood, and possibly bur oak are increasers. Hazel was persistent and maintained high productivity. The drop in hazel yield on the second 8-year cycle can be almost wholly attributed to hare feeding damage.

These other woody species added about one-fourth more to the total yield at the first 4- and 8-year rotation and up to two-thirds more to the third crop of the 4-year rotation.

CONCLUSIONS

The failure of aspen to withstand rotations of 4 years or less confirms the findings of Berry and Stiell (1978). Furthermore, their conclusion that aspen productivity cannot be sustained on rotations of up to about 10 years is also largely substantiated by this study. Considering that (1) Berry and Stiell's second 8-year rotation regenerated 80 percent of the biomass regenerated in the first cycle; (2) that my study at the beginning of the third cycle of the 8-year rotation regenerated 93 percent of the second cycle regeneration biomass; and (3) that in both studies productivity of 8-year

Table 6.—*Yield of other hardwoods and shrubs*

		Hardwoods					Shrubs				
Rotation	Cycle	*Betula papyrifera*	*Quercus macrocarpa*	*Quercus rubra*	*Acer rubrum*	Other	*Corylus* sp.	Juneberry, cherry[1]	*Cornus stolonifera*	Other	Total
		kg ha^{-1}									
8	1	242	135	—	—	—	3,234	362	172	[2]	4,291
	2	352	669	—	—	—	2,137	909	155	[3]	4,229
4	1	—	100	50	15	—	1,368	43	3	[4]	2,053
	2	—	88	37	35	—	1,682	80	14	[4]	2,484
	3	—	84	11	0	—	1,356	107	22	[4]	1,992
		presence (x)									*kg ha*$^{-1}$
1	1		x	x	x	(5)	x	x	x	(6)	166
	2	x	x	x	x	(5)	x	x	x	(6)	147
	3		x	x	x		x	x	x	(6)	56
	4		x	x		(5)	x	x	x	(6)	68
	5		x	x		(5)	x	x	x	(6)	74
	6		x	x			x	x	x		69
	7		x	x			x	x	x		71

[1] *Amelanchier* sp., *Prunus pensylvanica*, *P. virginiana*

[2] *Alnus crispa*, 97 kg ha; *Acer spicatum*, 32; *Dirca palustrus* and *Crataegus* sp., 17.

[3] *Salix* sp., 6; *Acer spicatum*, 1.

[4] *Salix* sp. - 90, 276, 256; *Alnus crispa* - 384, 272, 155; cycles 1 - 3 in order

[5] *Tilia americana*, *Acer saccharum*, *Fraxinus nigra*.

[6] *Salix* sp., *Acer spicatum*.

rotations was diminished much less than in 3-, 4-, and 5-year rotations, it seems reasonable to conclude, as did Berry and Stiell, that rotations of at least 15 years are unlikely to impair aspen regenerative and productive capacity. Because short rotation yields are at least 25 percent less than can be gained under longer rotations approaching culmination of MAI, it seems unlikely that financial rotations would be prescribed that approach these limits imposed by regeneration requirements.

Rotation length is not a factor in reducing nutrient losses in cropped aspen because nutrient extraction is directly a function of biomass extraction (leaves not considered). This is not to say, however, that nutrient management is not important in short rotation systems. On the contrary, short rotations timed to coincide with maximum mean annual increment will maximize nutrient extraction. Whether fertilization will be required to maintain productivity under such systems still remains a question.

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Regeneration and productivity of aspen cannot be sustained on rotations shorter than about 8 years. Productivity losses on short rotations are physiological and morphological rather than nutritional in nature. Stump and root collar sprouts, which are rare in mature stands, were more numerous than root suckers.

OXFORD: 231:613:176.1 *Populus tremuloides*. KEY WORDS: *Populus tremuloides*, suckers, sprouts, productivity, physical properties.

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Plant a tree...trees give oxygen.

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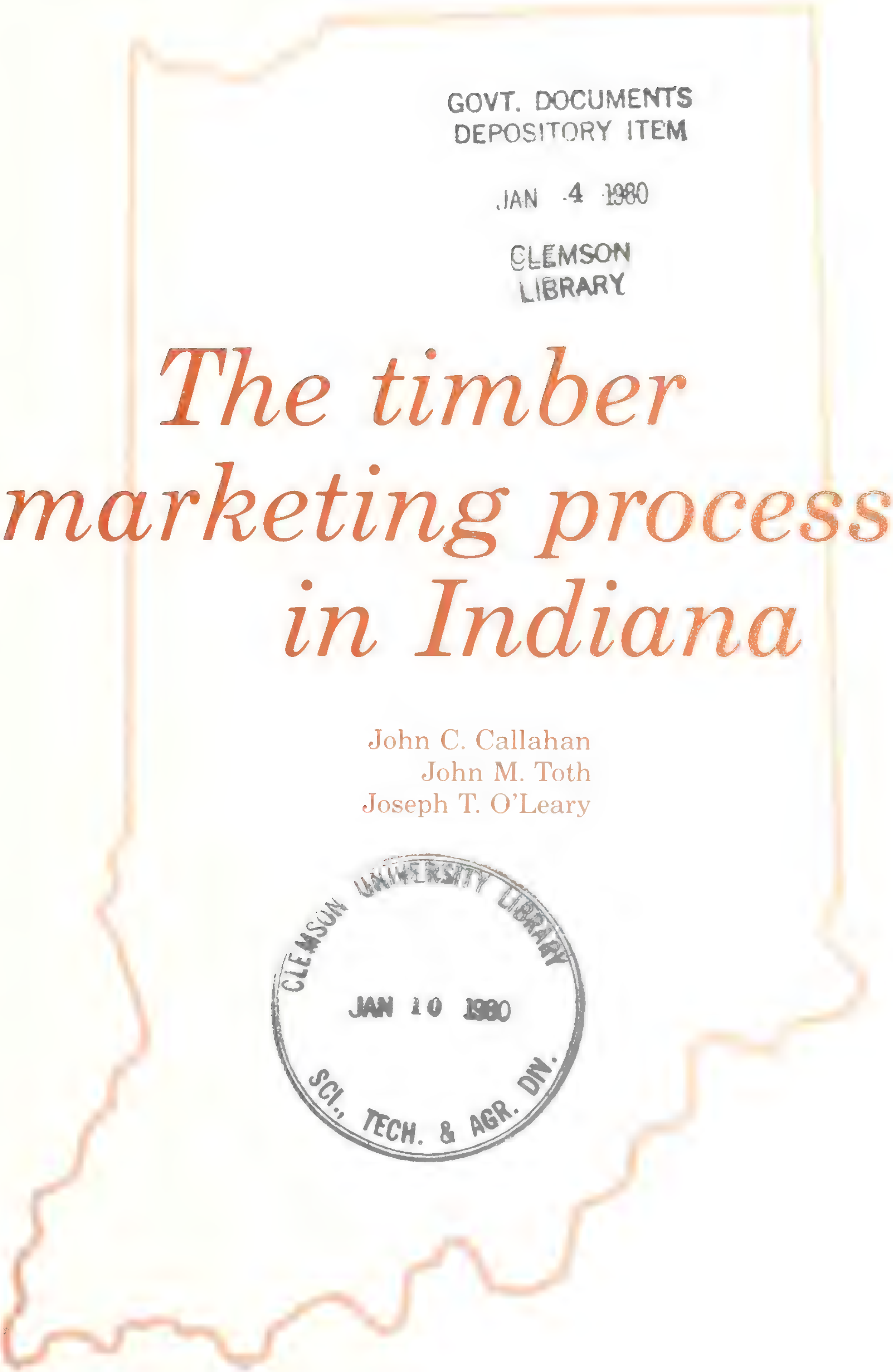

The timber marketing process in Indiana

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THE TIMBER MARKETING PROCESS IN INDIANA

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SALE OF PRIVATE WOODLAND IN INDIANA

Although each nonindustrial, private landowner in the East owns only a few acres, collectively this group owns most of the commercial forest land in the entire Country. These owners and their forest resources have taken on added significance in recent years because of the renewed and more vigorous interest of the public sector and environmental groups in the potentials of increased nonindustrial private forest timber production.

Research addressed to investment and productivity questions pertaining to small forest land holdings has been extensive during the past 35 years. A review of previous marketing studies revealed that woodland owners sold timber infrequently and were rarely informed of current market prices. As a result, timber was often sold at less than fair market value.

Because knowledge about the initiation of timber sales and post-logging attitudes of owners appeared to be limited, the objectives of this study were:

1. To describe the timber marketing process and procedures used by the Indiana nonindustrial private forest landowner when selling timber.
2. To determine if the economic and environmental results of the timber sale affect the landowner's disposition toward future woodland management activities and timber sales.
3. To determine the factors in the marketing process that influence the outcome of the sale from the seller's perspective.

PROCEDURE

Data Collection

A personal interview with a highly-structured questionnaire was used to obtain information in four general areas:

1. Demographic characteristics of the landowner and site characteristics of the owner's woodland property.
2. The negotiation process and actual timber sale procedure.
3. The content of the timber sale contract.
4. The landowner's reaction and attitudes after the sale, and his disposition toward future timber sales and management activities.

Structured responses (check the box, circle a number) were requested wherever possible, although many questions, particularly those relating to the landowner's reactions and attitudes, were left open-ended. Only one interviewer was used and a minimum of "prompting" was done during the interview to discourage the possibility of the landowner giving responses "the-interviewer-wanted-to-hear."

Choosing the Sample Population

The number and geographical distribution of timber sales in Indiana each year is unknown. Based on an annual cut of 300 million board feet and an average sale volume of 60,000 board feet (Indiana Department of Natural Resources 1978), there may be as many as 5,000 sales in Indiana each year. The names of all timber sellers, therefore, could not be obtained without an intensive canvas.

By contacting the District Foresters of the Indiana Department of Natural Resources (IDNR) and timber buyers and by consulting the Purdue University Timber Marketing Bulletin, we came up with the names of 329 people who had sold timber in Indiana in the previous 18 months. We concentrated on sales in the unglaciated forested area of southern Indiana where 70 percent of the State's wooded areas are located and we tried to include a representative sample of sales in which a professional forester participated, sales in which the landowner acted alone, and sales in which an industrial timber buyer participated.

Because we felt the sample of landowners might not come from a normally distributed population, we applied Lilliefor's test for normality to three sets of collected ordinal-level data—volume of timber sold, total price received for the timber, and the number of acres within the sale area. In all three instances, the null hypothesis of normality was rejected with a confidence level greater than 99 percent. As a result, nonparametric statistical analysis was used in evaluating the data. Wilcoxon's rank-sum test (Wilcoxon 1945, Hollander and Wolfe 1973) and the Kruskal-Wallis test (Kruskal and Wallis 1952, Conover 1971) were used for this analysis.

Contacting Potential Respondents

Approximately 6 weeks before the survey was begun, all 329 potential respondents were sent a letter, describing the purpose of the survey and requesting their voluntary cooperation. Enclosed with the letter was a postcard that the landowner was requested to complete, sign, and return. The letter and postcard emphasized that cooperation was voluntary and any information given during the interview would be kept strictly confidential. If no reply was received to the initial letter within 3 weeks, a second letter was sent along with another reply postcard.

The number of people who had sold timber and who agreed to participate in the interview process was 182. Interviews were conducted during a 14-week period throughout central and southern Indiana. A total of 159 interviews was obtained.

Interview Procedure

During the interview, the woodland owner was encouraged to speak freely and discuss any and all aspects of the timber sale. The interviewer asked specific questions only when it became apparent that the landowner was not going to touch on a particular aspect of the sale without prompting. Most landowners were willing and even eager to provide opinions about their timber sale.

Sample Population Characteristics

The woodland owners interviewed for this study had higher incomes, better educations, and held more professional jobs than those forest landowners studied in previous marketing surveys (Sutherland and Tubbs 1959, McClay 1963, Worley 1960) and than the average population (table 1). The median age of landowners was 56.5 years and the median tenure of ownership was 15.5 years. Two-thirds of the landowners interviewed were 50 years of age or older.

Although the average tenure of ownership was 15.5 years, examination of the distribution of the tenure indicates a recent, rapid turnover in forest land ownership—25 percent of the landowners owned their forested property for 5 years or less. Evidence indicates that the professional/management portion of the sample is the least tenured and the group buying much of the Indiana forested land. Among the landowners interviewed, 52 percent of those who are classified as professionals or managers have owned their land for 5 years or less, compared to only 21 percent of the farmers.

Eighty-eight of the landowners live on or adjacent to their forest land and many of the remaining owners live just a few miles from the property. Eighteen of the landowners (11 percent) live more than 25 miles from their timbered property and several live more than 100 miles from it. Typically, professional/management/administrative people reside at a distance from their forested land and farmers lived on or adjacent to their woodland.

Table 1.—*Median age, tenure, and income of the landowners surveyed*

Occupation	**Frequency**		**Age**	**Tenure**	**Annual income**
	Number	*Percent*	*Years*	*Years*	*Dollars*
Farmer	48	30	54.0	15.0	15,000
Retired	38	24	68.5	24.0	8,000
Professional	23	15	49.0	5.0	25,000
Management/Administrative	19	12	49.0	6.0	19,000
Salesman	10	6	53.5	10.5	20,000
Laborer	6	4	48.0	11.0	17,500
Craftsman	5	3	43.0	5.0	12,000
Housewife/Widow	5	3	63.0	15.0	15,000
Other	5	3	49.5	13.5	16,500
Total	159	100			
Overall Sample Median			56.5	15.5	15,043

RESULTS

The Timber Marketing Process

The usual timber sale negotiation was not a lengthy process. About 30 percent of the sale agreements were completed after just 1 day of negotiation and most (about 55 percent) were consummated within 1 week. More than 75 percent of the sales were completed within 30 days after the buyer and seller first made contact with each other and 95 percent were completed within 4 months. In 80 percent of the cases the timber was cut and removed from the property within a 4-month period after the sales agreement was completed.

Reasons for selling

The most common response to why the landowner was selling the timber was that it was mature and ready to be cut. The woodland owner's need for immediate cash was the second most common reason (17 percent). If the landowner revealed the specific need for the money received from the timber sale, it was usually either to improve or upgrade a farming operation or to purchase a major durable good.

Contrary to expectations, it was the seller who usually took the initiative in the marketing process. In the sample of sales studied, sellers took the initial step in 85 percent of the cases. Buyers sought out the seller in only 10 percent of the cases. In a few cases a forester triggered the sale through suggestions to the timber owner.

More than 90 percent said that they didn't have any negotiating problems. Those who cited problems listed distrust of the top bidder, no appraised value to judge the merits of submitted bids, or apprehension due to the few number of bids.

In most instances (70 percent) the seller was seemingly not concerned about the personal character and integrity of the buyer. Buyers were chosen solely on the basis of price in about two-thirds of the cases. However, in one sale out of five the buyer was selected on the basis of reputation, previous dealings, or recommendations of others. In 127 of the 159 sales, the sellers knew that the purchaser was licensed by the IDNR and that the seller was entitled to protection under State statute. Thirty sellers didn't know whether the buyer was licensed or not and only 2 believed that the purchaser of their timber was unlicensed.

Methods of determining price

Competitive bidding was used to set the price for the timber in half of the sales. Although this would seem to indicate a more competitive marketing situation than that found in other States, it is more likely a reflection of the larger number of sales in which a professional forester was involved (63 percent) because foresters normally advise the landowner to sell by competitive bid.

The person initiating the sale process influenced the method of price determination. In 52 percent of the owner-initiated sales, the price was set by competitive bidding. However, only 13 percent of the prices in timber buyer-initiated sales were set by competitive bidding. All seven sales that were initiated by a consulting forester were concluded by competitive bidding.

Requesting bids from a large number of buyers did not guarantee more than one bid. Seventy-one sales (45 percent) were made on the basis of only one bid. In 22 of those sales the landowner indicated that more than one buyer had been contacted but only a single offer had been received. These sales usually involved small volumes of low-value timber. In 59 sales the timber buyer's offer was accepted by the landowner without question or negotiation.

In 10 sales the timber was not sold as stumpage. In these cases, the landowner was paid a percentage of the delivered mill price for his timber. All but one of the landowners was satisfied with this method of selling and felt that the logger had an incentive to seek the best possible price from all local mills.

Knowledge of fair market prices

Efficient marketing implies both the buyer and seller are aware of the value of the commodity changing ownership. Many of the landowners (54 percent) sold their timber without knowledge of its current market value. Two-thirds of the landowners interviewed either had no idea or only a vague notion of the value of the timber they were selling. This deficiency appeared to be one of the major obstacles to effective timber marketing.

Use of a professional forester

One hundred sales (63 percent) were conducted with the assistance of either an IDNR service forester or a private forestry consultant—78 with the assistance of an IDNR forester and 22 with a private consultant.

Ninety-one of the 100 landowners were completely satisfied with the performance of the professional forester. Of the nine people who were not satisfied, three used consultants, and six used IDNR foresters. The common complaints among those landowners using the IDNR forester was the inability of the forester to appraise their timber (IDNR regulations prohibit the forester from doing an appraisal) and the long waiting period necessary to obtain the State forester's services. The three woodland owners dissatisfied with the services of the private consultant had differing complaints related only to the conduct of their individual sale.

Significant differences were noticed in the marketing process between those sales with and without a professional forester, and between those sales involving an IDNR forester and a private consultant. Chi-square tests for independence indicated landowners who used a professional forester during the sale generally:

1. had a larger number of buyers bidding on the timber;
2. used a written contract to sell the timber;
3. sold a larger volume of timber (more than 20,000 board feet); and
4. sold stumpage by competitive bid as opposed to accepting the buyer's first offer for the timber.

No significant relation was noted between the use of a professional forester and the landowner's (1) age, (2) tenure of ownership, (3) education, (4) annual income, (5) reason for selling, or (6) knowledge of timber market prices.

Because the private consultant handled virtually every detail of the sale with which he was involved, little variation in marketing procedures was noted. All 22 consultant-handled sales were concluded with a written contract, and 14 percent of the sales involving an IDNR forester were completed with an oral agreement. Although many landowners complained about the extended wait for the services of the IDNR forester, this apparently did not cause significant numbers of them to utilize the services of a private consultant even when the stated reason for selling their timber was the need for immediate cash.

The timber sale contract

Seventy-five percent of the timber sales were concluded with a written contract. In about 40 percent of the sales made under contract, the buyer either provided his firm's contract form or completed the "standard" Indiana timber sale contract form. The IDNR forester or consultant assisted the woodland owner with contract language in approximately 45 percent of the cases. Rarely (7 sales) did the owner acknowledge that he had prepared his own timber sale contract.

Volumes sold and payments received

Except for 10 sales in which the owner and logger shared on a percentage basis the sawmill's payments to the logger, all sales were paid for on a lump sum basis. Only four sellers of stumpage reported that there had been a payment problem. Forty-one of the owners did not know how much of their timber had been sold. Of those that did know how much had been sold, the average volume was about 60,000 board feet. The amount received for the sales ranged from $33 to $93,000 with an average of $6,550. In those sales where competitive bidding was used to determine the price paid to the woodland owner, the difference in price between the low bid and the high bid ranged from 2 to 300 percent and averaged 70 percent.

In those sales where both the amount of money received and the volume of timber sold was available, the average price ranged from $20 to $360 per thousand board feet and averaged $105 per thousand board feet.

Post-Sale Reactions and Attitudes

Twenty-five percent of the landowners indicated they were dissatisfied with the condition of their property after logging. Reasons varied, but some felt they had only themselves to blame because they had either not obtained a written contract or had failed to insert adequate protection clauses in the contract. However, many landowners who had such protection clauses in their contracts were also dissatisfied with the resulting condition of the property and no correlation was found between the specifications of the contract and the resulting expressed condition of the landowner's property. The interviewees felt it would be a waste of their time and money to prosecute those loggers in violation of the contract.

Eighty-four percent of the landowners felt they had received a fair price for their timber. However, some of the landowners stated that they were only vaguely aware of timber prices and were in a poor position to judge a fair market value.

Eighty-four percent of the owners said they were planning to sell more timber from the same property sometime in the future. Eleven landowners indicated they had plans to develop or sell the property and three said they would not sell any more timber as a direct result of the outcome of their most recent sale.

To test for the effect of the landowner's knowledge of timber prices on the average price received, the sales were segregated into two groups: those where the landowner claimed to have some knowledge of his timber's value prior to the sale and those where the landowner admitted knowing nothing about timber prices. The test for an increase in average price per thousand board feet due to the landowner's knowledge of the timber market was significant at the 90 percent confidence level, but not at the 95 percent level. The Hodges-Lehmann estimate for the average difference in price showed that those landowners who had some idea of the timber's value received $19 more per thousand board feet than those landowners who had no idea of the timber's value.

Wilcoxon's test was used to check if the presence of more than one bidder increased the average price received by the landowner. Again, the test was significant at the 90 percent confidence level but not at the 95 percent level. The Hodges-Lehmann estimator for the average difference in price showed that when there were two or more bidders the price increased $13 per thousand board feet.

The Kruskal-Wallis test was used to see if the method of price determination, reason for selling, or volume of timber sold had an effect on the price received. However, none of these factors proved significant. Even less significant were the effects of who initiated the timber sale and the use of a professional forester.

Perhaps the most surprising finding of this analysis is the lack of effect on price when a professional forester is involved, particularly in view of the significance of the other variables. Those sales with a professional forester generally had a larger number of buyers bidding on the sale. Yet, although the number of buyers bidding appears to influence the price received, the use of a forester does not. The explanation for this apparent contradiction may be the type of timber offered for sale by the two groups. The data indicate that sales without the help of a professional forester included higher-quality timber than those sales with the help of a forester. A possible explanation for this difference may be found in the marketing process. In 16 percent of the sales involving some walnut veneer timber, the trees to be sold were chosen either by the landowner or a professional forester. However, in those sales where the timber buyer was allowed to choose the trees to be cut, veneer quality walnut was sold in 28 percent of the cases. This difference, though not substantial, may account for the lack of difference in average price between those sales with and without a professional forester. If given his choice, the buyer would most likely pick the most valuable trees in the woodland and would thus be able to offer a higher average price per board foot for the entire amount of timber sold.

Plans for Future Sales and Timber Management

The reactions and attitudes of the landowner following the timber sale may affect his disposition toward future timber sales and management. Two factors are important: (1) was the landowner satisfied with the price received for his timber?, and (2) was the owner satisfied with the condition of the woodland after logging? Displeasure with either may discourage future sales.

Statistical tests were applied to determine if the average price received per thousand board feet and the condition of the property affected the landowner's plans for future timber sales. A chi-square test showed a fairly significant degree of association between price and plans for future sales (90 percent confidence level). However, Wilcoxon's test on the same data was considerably less significant (less than 80 percent confidence). The landowner's perception of the post-sale condition of the property apparently had little or no effect on the landowner's decision to sell timber in the future. Neither the price received nor the condition of the property appeared to influence the landowner's plans for future timber management because both tests of these factors were not significant.

HIGHLIGHTS

The woodland owners interviewed were not typical of those described in previous studies. Those cooperating in the study were more affluent, more likely to be professionally employed, more often lived in an urban environment, and had in most cases utilized the assistance of a forester in making the sale. In 90 percent of the sales, the seller initiated the marketing process. Although most owner's professed to be market knowledgeable, more than 70 percent were not familiar with or had only vague notions about timber prices and the value associated with their trees. Those who did have price knowledge received on the average $19 per thousand board feet more than those that didn't.

The presence of a forester in the sale proceedings made it more likely that the timber would be sold under contract and that competitive bidding would be used to establish fair market value (70 percent of forester-assisted sales). However, spirited bidding by more than three bidders tended to be the exception rather than the usual bidding situation.

More than 90 percent of the woodland owners using professional foresters in the marketing process were completely satisfied with their performance. However, landowners utilizing IDNR foresters commonly complained about the regulation that prevented district foresters from appraising their timber prior to offering it for sale. Average prices received by landowners utilizing IDNR foresters were not found to be significantly different from the prices received by owners dealing directly with timber purchasers. However, forester-associated sales were more likely to have had competitive bidding (positive effect on price) and were more likely to contain lower quality timber (negative effect on price).

Fully 25 percent of the timber sellers were dissatisfied after the timber had been sold and cut, because of the price received or because of the residual condition of the land and timber. However, this did not seem to affect the owners' decisions with respect to future harvests.

The most serious deficiencies in the marketing process appeared to be a lack of available timber price information and/or estimates of the fair market value of the owner's timber prior to sale. This was particularly evident when landowners directly approached timber buyers and accepted their first offer and in those other cases where there were less than three bidders. The admonition of foresters to landowners that they should secure at least six bids for their timber to be assured of a fair market value appears to be correct but realistically unobtainable. Less than 16 percent of the sellers reported that they had received more than three bids for their timber.

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USDA FOREST SERVICE
RESEARCH PAPER **NC-178**

Weights and dimensional properties of shrubs and small trees of the Great Lakes conifer forest

Peter J. Roussopoulos and Robert M. Loomis

North Central Forest Experiment Station
Forest Service, U.S. Department of Agriculture

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Presents equations for estimating biomass and woody size class distributions for shrubs and small trees (< 2.5 cm d.b.h.) of 17 northeastern Minnesota species. Relations between stem diameter at 15 cm above ground and plant height, crown length, and stem diameter at ground are also given.

OXFORD: 521.1:531:518(77). KEY WORDS: forest fuels, size classes, component weights, fuel modeling.

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WEIGHTS AND DIMENSIONAL PROPERTIES OF SHRUBS AND SMALL TREES OF THE GREAT LAKES CONIFER FOREST

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Biomass estimates are often used in determining primary productivity of ecosystems, quantifying energy pathways and nutrient cycles, anticipating product yields from harvest activities, evaluating wildlife habitats, and appraising forest flammability. Accordingly, biomass information needs and estimation methods have been discussed frequently in the literature of several disciplines. Specific information requirements vary substantially, though, depending on the context of the problem being considered.

One of the most information-demanding uses is the assessment of wildland fire behavior potential (Rothermel 1972), requiring quantitative estimates of available fuel weights by condition (living or dead) and by size category.

Studies reporting data suitable for fuel modeling in Great Lakes conifer forests (Rowe 1959) are rare, especially for the unmerchantable parts of a forest community such as small trees and shrubs (Ohmann *et al.* 1976, Crow 1977, Telfer 1969). Although these reports have some value for fuel evaluation, they fail to estimate component weights by dead or live categories or by size classes as desired for fire behavior prediction. A recent study by Brown (1976) devised estimating equations for 25 shrubs of the northern Rocky Mountains. Equations were presented to estimate foliage and stemwood with a table of percentages of stemwood within specific fuel size classes for species groups.

To appraise upland forest fuels and wildfire potential for the Boundary Waters Canoe Area in northeastern Minnesota, above ground biomass equations were developed for locally prominent shrubs and small trees. The resulting equations are presented herein, with primary emphasis on applications involving fuel modeling and fire behavior prediction.

METHODS AND ANALYSIS

Shrubs and small trees (<2.5 cm d.b.h.) were collected during July and August of 1976 on the Kawishiwi Ranger District of the Superior National Forest in northeastern Minnesota (47°50′N and 91°45′W). Stems were cut at groundline and were taken to the Kawishiwi Field Laboratory for processing. Seventeen different species were sampled, each represented by at least 20 collected stems. For each sample stem, the following sample measurements were recorded: stem diameter at ground level and at 15 cm above ground level to the nearest 0.25 cm (measurement of diameter at 15 cm above ground avoids the region of high stem taper normally found at groundline); plant height, and length (depth) of crown to the nearest 15 cm. Each plant was divided into components of foliage and woody parts. Dead and live woody parts were also separated. All woody parts[1] were further separated into size classes by diameter: 0 to 0.6 cm, 0.6 to 2.5 cm, and 2.5 to 7.6 cm. These size groups correspond to the 1-, 10-, and 100-hour timelag fuels described in the National Fire Danger Rating System by Deeming *et al.* (1972). Each component group was weighed to the nearest 0.1 gram and its moisture content determined by subsampling and ovendrying for 24 hours at 105 C. All fresh weights were converted to ovendry in this manner.

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[1] Hereafter, "woody" refers to the woody parts of the plant; i.e., the composite of wood and bark.

To facilitate subsequent mathematical representation, measured dry weights of wood attributable to the three mutually exclusive size classes were arithmetically combined into the inclusive size classes: 0-0.6 cm, 0-2.5 cm, and 0-7.6 cm.

Regression analysis was used to relate component dry weights to stem diameter at 15 cm height. Analysis of variance and graphical analysis were used to compare regression equations for individual species and explore possibilities for grouping similar species.

Total plant weight, foliage weight, total wood weight (live and dead), and live wood weight, all in grams dry weight (Y), were regressed with stem diameter (X), measured in cm at a height of 15 cm, using the allometric model:

$$Y = aX^b \qquad (1)$$

Regression coefficients were estimated using the logarithmic transformation of equation (1). The "a" coefficient was adjusted for bias inherent in this procedure (Baskerville 1972).

For each stem, the dry weights of all woody material less than 0.6 cm in diameter and all woody material less than 2.5 cm in diameter were divided by the overall weight for total wood and for live wood only. These ratios (Y) represent the proportional contribution of size classes 0 to 0.6 cm and 0 to 2.5 cm, inclusive, to the weight of the live and the total woody components. They were regressed against the stem diameter (X) at a height of 15 cm using the hyperbolic model:

$$Y = X/(a + bX) \qquad (2)$$

The regressions were performed using the following linearized form:

$$X/Y = a + bX \qquad (3)$$

In this form, the dependent variable (X/Y) is used only to evaluate the coefficients "a" and "b" for subsequent use in equation (2).

To help evaluate the bulk density and vertical distribution of understory fuels, linear regression equations were also developed for plant height and crown length on the stem diameter at 15 cm in height. These were statistically forced through the origin to produce a simple ratio estimator for plant height and crown length. Although this approach may be questionable for small plants (since all plants less than 15 cm tall are predicted to have zero height and crown length), the resulting errors are deemed negligible within the diameter range of principal interest. Even for smaller stems, the height and crown length measurement resolution (± 7.5 cm) tends to minimize the importance of potential underestimates.

RESULTS AND DISCUSSION

In all, 460 stems were collected and processed representing 14 deciduous species of trees and shrubs and three coniferous trees (table 1). For all species, the range of sampled stem diameters was 0.3 to 5.1 cm at 15 cm above ground. All species were represented over the bulk of this interval except *Diervilla lonicera, Lonicera canadensis,* and *Rosa acicularis*. These small shrubs rarely attain stem diameters outside the range sampled. Total above ground dry weight per stem ranged from 1 to 2,714 grams dry weight for all species.

Component Weights

Regression statistics were calculated for dry weights of all above ground components, foliage, total wood, and live wood (table 1). Examination of the coefficients of determination (r^2) shows reasonably good fits for all species except *Diervilla lonicera* and *Lonicera canadensis*. These low r^2 values may be partially due to the narrow range (0.2 cm for *Diervilla*) of sampled stem diameters compared to the measurement resolution (± 0.12 cm).

Meaningful species groupings, to facilitate aggregate modeling of forest communities for broad fuel appraisal, were illusive. No statistically defensible groups could be found that were applicable for all four dependent variables. The three species groups appearing in table 1 were derived through graphical comparisons of the regression equations. Though the F-test did not fully support these groups, differences among the individual "within-group" equations were generally not meaningful, from a practical standpoint, over the expected range of stem diameters. Extreme individual species estimates of "total" weight varied about 20 percent from the group estimate for the combined 11 species at a common 1.6-cm base diameter.

The regression equations agree quite well with those of Ohmann *et al.* (1976) except for *Corylus cornuta,* where their estimates show somewhat

Table 1.—*Sample size and regression coefficients*[1] *for estimating component dry-weights of shrubs and small trees (< 2.5 cm d.b.h.)*

Species	Stems collected	Range of stem diameters	Total				Foliage				All wood				Live wood			
			a	b	r^2	Sy·x	a	b	r^2	Sy·x	a	b	r^2	Sy·x	a	b	r^2	Sy·x
Abies balsamea	25	0.5-3.3	72.715	2.250	0.96	80	29.319	2.011	0.94	38	42.904	2.404	0.97	50	41.330	2.394	0.97	49
Acer rubrum	36	0.3-4.1	60.367	2.342	.94	278	13.082	1.840	.91	25	45.947	2.505	.93	274	45.085	2.480	.92	246
Acer spicatum	25	0.3-4.3	73.182	2.259	.95	141	17.305	1.696	.89	26	54.779	2.407	.95	122	52.384	2.417	.95	127
Alnus spp	28	0.8-4.1	63.280	2.380	.93	164	14.725	1.828	.90	18	48.762	2.509	.90	164	48.077	2.484	.90	160
Amelanchier spp	27	0.5-4.1	71.534	2.391	.93	174	10.478	1.988	.83	21	60.997	2.445	.94	160	58.333	2.458	.91	160
Betula papyrifera	23	1.3-3.6	76.316	2.279	.93	73	14.717	1.529	.66	17	62.830	2.378	.93	75	61.956	2.376	.92	77
Cornus rugosa	27	0.3-3.6	74.114	2.457	.96	124	17.131	2.093	.93	13	55.886	2.591	.96	136	54.629	2.551	.95	132
Corylus cornuta	36	0.3-2.5	62.819	2.420	.89	46	12.115	2.010	.81	8	50.154	2.523	.90	47	49.245	2.503	.90	44
Diervilla lonicera	21	0.3-0.5	14.211	1.217	.45	4	3.082	.613	.19	1	12.269	1.608	.53	3	9.276	1.445	.59	1
Lonicera canadensis	25	0.3-1.0	33.900	1.793	.68	5	5.319	1.275	.39	2	28.899	1.942	.67	4	28.017	2.020	.69	4
Picea spp.	25	0.5-3.3	65.757	2.287	.97	68	36.288	2.047	.95	42	28.670	2.566	.98	38	27.806	2.543	.97	34
Populus spp.	27	0.5-3.3	46.574	2.527	.96	52	10.828	2.052	.87	19	35.264	2.657	.97	41	34.906	2.655	.97	41
Prunus spp.	25	0.8-3.8	68.041	2.237	.90	155	12.382	2.024	.77	42	55.076	2.306	.87	152	54.235	2.253	.86	143
Rosa acicularis	23	0.3-1.3	83.240	2.837	.83	9	22.853	2.282	.79	3	63.140	3.224	.82	9	60.282	3.214	.83	8
Salix spp.	25	0.5-3.0	55.925	2.594	.96	113	12.280	2.120	.94	32	43.316	2.726	.95	96	42.495	2.721	.95	95
Sorbus americana	24	0.5-3.8	44.394	3.253	.95	350	8.083	2.601	.93	11	35.960	3.427	.95	407	35.585	3.425	.95	398
Thuja occidentalis	38	0.3-5.1	68.423	1.863	.94	86	35.288	1.442	.90	36	30.800	2.244	.94	62	30.632	2.232	.94	59
Abies balsamea & *Picea* spp	50	0.5-3.3	69.167	2.267	.97	73	32.743	2.033	.94	48	35.691	2.480	.96	59	34.483	2.464	.96	52
Diervilla lonicera & *Lonicera canadensis*	46	0.3-1.0	25.879	1.636	.60	5	4.340	.944	.30	1	22.768	1.913	.60	4	20.190	1.898	.63	4
Eleven species[2]	303	0.3-4.1	62.134	2.460	.93	155	12.573	2.006	.86	24	48.944	2.577	.93	152	47.780	2.567	.92	146

[1] Regressions are of the form $Y = aX^b$ where Y is the component weight in grams, X is the stem diameter in centimeters measured 15 centimeters above ground, and a and b are regression coefficients from the table. Weights are expressed in grams of total above ground material (Total), foliage (Foliage), dead and live woody parts (All wood), and live woody parts only (Live wood) for 17 species or genera and 3 species combinations.

[2] *Acer rubrum, Acer spicatum, Alnus* spp., *Amelanchier* spp., *Betula papyrifera, Cornus rugosa, Populus* spp., *Corylus cornuta, Prunus* spp., *Salix* spp., *Sorbus americana.*

lower weights— especially at the larger stem diameters. We found this species similar to *Alnus* spp., *Amelanchier* spp., and *Salix* spp.—genera that Ohmann *et al.* combined also. Because their samples were collected in the same general location, and because they also used stem diameter measured at a height of 15 cm as the independent variable, close agreement is not surprising. Brown (1976) and Telfer (1969), on the other hand, used stem diameter at ground level.

To facilitate comparison with the results of these studies, the relation between the 15-cm stem diameter and basal stem diameter was examined. Scatter diagrams suggested that ground diameter could be predicted from the 15-cm diameter using simple linear regressions. The resulting coefficients were remarkably similar for all species (table 2). Telfer's (1969) weight predictions for woody plants in eastern Canada, after diameter adjustment, were also in close agreement. Brown's (1976) equations, on the other hand, yielded lower weight estimates for most species, perhaps partially due to the different environmental conditions of the northern Rocky Mountains. Both Brown and Telfer predicted greater weights for *Lonicera* spp. at larger diameters (Brown's weights were lower than Telfer's). Brown had the broadest diameter range for *Lonicera* (0.3 to 1.7 cm); Telfer's was similar to this study (0.1 to 0.7 cm).

Woody Size Classes

Examination of scatter diagrams revealed that the proportional contributions of the 0- to 0.6-cm and 0- to 2.5-cm (inclusive) size classes to total woody weight are discontinuous functions of stem diameter. They equal 1.0 at low stem diameters and fall quickly away from this value above some "critical stem diameter" near the upper size class limit. To ensure realistic size class predictions on both sides of this discontinuity, two measures were necessary. First, for each size class we found the diameter of the smallest stem that contained woody material in the next larger size class. Naturally, these values were close to the upper diameter limits—about 0.5 cm for the 0- to 0.6-cm class and 2.1 cm for the 0- to 2.5-cm class—and varied little among species. Stems with diameters below

Table 2.—*Regressions through origin ($y = bx$) for height and crown length, and linear regressions ($y = a + bx$) for basal stem diameter versus stem diameter (cm) at 15 cm above ground level*

Species	Height (meters)			Crown length (meters)			Basal diameter (cm)				
	b	Sy·x	n	b	Sy·x	n	a	b	r^2	Sy·x	n
Abies balsamea	0.7094	0.2902	25	0.6455	0.2876	25	0.0684	1.1302	0.9216	0.2929	25
Acer rubrum	1.3761	.5851	33	.9522	.6927	33	.0003	1.1675	.9649	.2039	36
Acer spicatum	1.2100	.4989	22	.7443	.4093	22	.1645	1.0485	.9499	.2488	25
Alnus spp.	1.1289	.8339	6	.5331	.9089	6	.1409	1.0225	.9592	.1695	28
Amelanchier spp.	1.3176	.3496	17	.8061	.3114	17	.0142	1.1037	.9815	.1569	27
Betula papyrifera	1.5720	.5564	21	.9837	.7265	21	.1713	1.0452	.9376	.1968	23
Cornus rugosa	1.1728	.6782	29	.6860	.4204	27	.0243	1.0828	.9714	.1505	27
Corylus cornuta	1.5314	.3192	36	.9510	.3085	36	.1894	.9226	.9476	.1214	36
Diervilla lonicera	1.3268	.1389	21	.8179	.1520	21	.1062	.8818	.5216	.1126	21
Lonicera canadensis	1.2184	.2402	25	.7488	.1876	25	.0809	.9780	.7346	.1188	25
Picea spp.	.5772	.1769	25	.5050	.1389	25	.0715	1.1241	.9711	.1858	25
Populus spp.	1.2515	.5219	27	.8136	.6473	27	.1294	1.0517	.9643	.1752	27
Prunus spp.	1.2183	.5750	19	.7943	.3435	19	.1151	1.0676	.9417	.2094	25
Rosa acicularis	1.4505	.1967	23	.8661	.1609	23	.0338	1.0412	.8412	.1092	23
Salix spp.	1.2747	.5282	17	.7497	.4044	17	.0502	1.1730	.9810	.1543	25
Sorbus americana	1.5018	.4470	24	.9532	.4532	24	.0263	1.1373	.9735	.1370	24
Thuja occidentalis	.6290	.2256	38	.6063	.2124	38	.1853	1.0906	.9556	.2925	38
All coniferous	.6350	.2518	88	.5884	.2441	88	.1293	1.1058	.9514	1.4084	88
All deciduous	1.3293	.5156	318	.8342	.4923	318	.0434	1.1072	.9670	1.0127	372

these values were deleted from the respective size class regressions. This eliminated samples from the "flat" section of the curve where the proportional size class contribution is 1.0 and allowed separate mathematical representation of the "flat" and "falling" curve sections. Second, the critical stem diameter—the point separating the two sections—was defined from the coefficients of each hyperbolic regression as a /(1−b). The regression equation applies only to stem diameters above this value, which results in the following expression for the fractional contribution of each size class (Y) in terms of stem diameter (X):

$$Y = \begin{cases} 1.0, \text{ for } 0 < X < \dfrac{a}{(1-b)} (\text{"flat" section}) \\ \dfrac{X}{(a+bX)}, \text{ for } \dfrac{a}{(1-b)} \leq X \; (\text{"falling" section}) \end{cases} \qquad (4)$$

Regression coefficients were calculated for use with equation (4), both for all wood and for live wood only (table 3). For the < 0.6 cm size class regressions, *Diervilla lonicera* was the only species that had no samples with stem diameters more than 0.5 cm. Regressions were performed for all other species. *Diervilla, Corylus cornuta, Lonicera canadensis, Rosa acicularis,* and *Sorbus americana* were exempted from the 0.0 to 2.5 cm size class regression analysis because each had less than five sampled stems that were 2.1 cm or more in diameter. Good fits were obtained for most of the remaining species with this model. Regressions were also run for the three species groups used earlier. Again, analysis indicated the combinations to be reasonable and practical, though statistically not fully justifiable.

Actual weight estimates for each size class can be obtained by multiplying the appropriate fractional weight contribution estimate (equation (4), table 3), times the corresponding predicted wood weight (equation (1), table 1). Weights of the 0.6- to 2.5-cm and > 2.5-cm size classes, as well as dead wood weights may be found by subtraction.

At small stem diameters, below about 0.5 cm, the entire woody component is within the 0- to 0.6-cm size class (fig. 1). As stem diameter increases above this point, the fractional contribution of this class drops quickly to an asymptote at 0.14 (for the grouped 11 deciduous species), while the 0.6- to 2.5-cm class becomes prominent. At roughly 2.3 cm, material greater than 2.5 cm appears and the middle size class begins to fall

Table 3.— *Regression statistics for estimating fractional weight contributions of woody components by size class and condition (live or dead) for 17 species and 3 species combinations of northern Minnesota shrubs and small trees. The regression model is X/Y = a + bX, where independent variable X is stem diameter (cm) measured 15 cm above ground level and Y is the fraction by weight attributed to each indicated size class.*

	All woody parts ≤0.6 cm divided by all woody parts					Live woody parts ≤0.6 cm divided by live woody parts					All woody parts ≤2.5 cm divided by all woody parts					Live woody parts 2.5 cm divided by live woody parts				
Species	a	b	r^2	Sy·x	n	a	b	r^2	Sy·x	n	a	b	r^2	Sy·x	n	a	b	r^2	Sy·x	n
Abies balsamea	−0.8141	2 3989	0 924	0.6129	25	−1.0298	2 6303	0 911	0 7324	25	-4 2677	2 8728	0 940	0 3290	9	-4 7586	3 0867	0 928	0 3887	9
Acer rubrum	−6.2520	10.3120	718	5 9481	33	−7 4744	11.5724	734	6 5710	33	-6 0540	3 5985	805	1.1121	8	−6 2718	3 7192	687	1 3304	8
Acer spicatum	−4.7664	7.6075	925	2.1277	23	−5.3703	8 5717	.913	2 6055	23	8 6441	4 1621	939	7271	6	8 8463	4 2436	940	7397	6
Alnus spp	−4.2928	6 9640	854	2.3184	28	−5.0621	7.7270	821	2 9061	28	−3 8505	2.8249	946	5092	6	-3 9024	2 8765	940	5463	6
Amelanchier spp.	−4.0400	6 8436	918	2.1167	27	−4.4118	7 2891	905	2 4477	27	6 4998	4 0315	911	7414	6	−7 0820	4 2563	906	8053	6
Betula papyrifera	−5.8830	7.7092	915	1.7199	23	−7.1140	8 5998	898	2.1135	23	6 0057	3 5414	973	2942	10	−6 4097	3 7084	972	3138	10
Cornus rugosa	−2.6090	5.6040	752	2.1095	24	−3.2924	6 4142	788	2 2932	24	.4652	1 1927	978	1039	7	− 4892	1 2027	976	1092	7
Corylus cornuta	−2.0501	4.6178	896	8202	33	−2.5036	5 2050	904	8849	33	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)
Diervilla lonicera	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)
Lonicera canadensis	−.8217	2 6503	.939	1054	15	−.8217	2 6503	939	1054	15	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)
Picea spp	−.7873	2.5976	964	4800	25	− 9063	2 8078	952	6046	25	−4 0003	2.7137	922	3528	9	−4 2958	2 8364	938	3236	9
Populus spp	−4.8321	8 2591	841	3.1064	27	−4.5801	8 3773	829	3 2937	27	−6 3969	3 1764	910	5263	9	−6.4176	3 7228	911	5235	9
Prunus spp	−2.0843	5.1685	.721	1 6514	24	−2 4157	5.8313	694	2 1243	24	−4 7809	3 1011	984	6872	5	−4 7884	3.1078	987	6857	5
Rosa acicularis	−1.1971	3 3862	911	2203	17	−1.1971	3 3862	911	2203	17	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)
Salix spp	−4.1190	7 4681	760	4 4845	23	−4.1282	7 7257	792	4 2844	23	6 0504	3 5769	760	1 1493	9	−6 1529	3 6205	772	1 1484	9
Sorbus americana	−10.0310	15.1988	932	2 9887	24	−9.9149	15 4869	929	3.1181	24	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)
Thuja occidentalis	−4.8576	5 8264	843	3 0684	36	−6.3768	6 9339	797	4 2709	36	8 3000	4 3000	940	1 1477	13	9 4581	4 7387	939	1 3232	13
Abies balsamea & Picea spp	−.8239	2.5127	939	5789	50	−.9923	2 7343	926	6987	50	−4 0207	2 7498	926	.3331	18	−4 3792	2 9042	924	3590	18
Diervilla lonicera & Lonicera canadensis	−.8342	2 6645	943	0785	26	− 8359	2 6636	944	.0782	26	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)	(1)
Eleven species	−4.0271	7.3193	691	4.1284	296	−4.4322	7 9182	703	4 3433	296	−5.0517	3 1742	656	1.1939	72	−5.1878	3 2378	650	1 2344	72

[1] Range of diameters insufficient to perform regression.

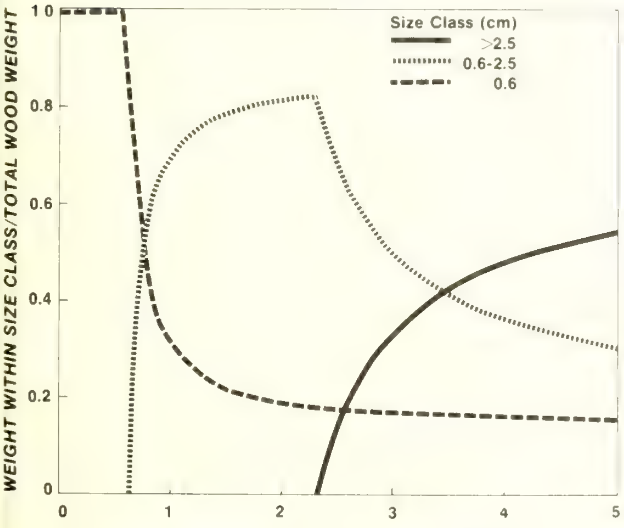

Figure 1.—*Fractional size class composition (by weight) of total stem and branchwood component versus stem diameter for a group of eleven species.*

toward its asymptote at 0.18. Once established, the largest class rises throughout the range of sampled stem diameters.

Also of interest for flammability appraisal is the "dead-to-live" ratio of stemwood. This may be found either by size class or for the entire stem by subtracting the appropriate "live woody parts" estimate from the corresponding "all woody parts" estimate, and dividing the difference by the estimate for the live. Dead-to-live ratios are often more easily interpreted in terms of shrub flammability than are actual component weights.

Plant Height and Crown Length

Besides the quantity and size distribution of fuel materials, spatial distribution or fuel arrangement also influences flammability. Knowledge of total heights and crown lengths of understory vegetation can be helpful in modeling forest fuels for predicting fire behavior. Equations were developed to predict these dimensions using 15 cm stem diameter as the predictor variable. Regression analysis using a forced 0-intercept was used (table 2). To preserve the noteworthy differences in slope coefficients for coniferous versus deciduous species, only two grouped regressions were performed. Plant heights for the conifers were roughly half those of deciduous plants with the same stem diameter. The crown length ratios for coniferous samples (crown length/total height) are characteristically 1.5 times those of deciduous species. These statistical observations are confirmed by physical experience and seem to justify the chosen species combinations.

SUMMARY

Using regression equations presented in this paper, one may estimate the quantity and vertical distribution of understory fuels by component, live or dead, and wood size categories from inventories of easily measured plant dimensions. If only plant heights or only stem diameters at ground level are known, the measurements can be converted to stem diameter at 15 cm, the predictor variable for component weights and size class proportions. The estimating equations can be used with the most confidence within the diameter ranges sampled for individual species and do not apply to trees larger than 2.5 cm d.b.h.

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Summer moisture contents of understory vegetation in northeastern Minnesota

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SUMMER MOISTURE CONTENTS OF UNDERSTORY VEGETATION IN NORTHEASTERN MINNESOTA

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The behavior and effects of forest fires are often influenced by the character of the living understory vegetation. Grasses, ferns, shrubs, mosses, tree reproduction, and herbaceous plants may either contribute actively to the energy of a fire, or they may serve as a heat sink and retard fire propagation and intensity. This can mean the difference between a beneficial, easily managed fire, and a detrimental fire that is difficult to control. Whether living surface fuels play an active or passive role in the combustion process depends largely on their abundance and moisture content. These factors are quantitatively addressed in state-of-the-art models of fire behavior (Rothermel 1972, Albini 1976) and in the National Fire Danger Rating System (Deeming *et al.* 1977).

Although ongoing research holds promise for developing the capability to simulate live fuel moisture changes through knowledge of physical processes governing plant-water relations (Howard 1978, Running 1978), currently available methods of predicting live fuel moisture content, without actual field measurement, are somewhat primitive. The algorithm proposed by Deeming *et al.* (1977) for fire danger rating represents the most comprehensive effort to date to provide a generally applicable model. It considers the predominant type of vegetation (annual or perennial), the phenological stage of development, vegetative adaptation to moisture stress as reflected in the humidity provinces of Thornthwaite (1931), and antecedent precipitation and evaporative demand of the atmosphere. This method seems to work well in the northern Rocky Mountains and in other portions of the western United States, but it has not been thoroughly validated.

Measured moisture contents of tree and shrub foliage have been reported in several studies representing diverse geographic areas (Olsen 1960, Philpot 1963, Reifsnyder 1961, Jameson 1966, Johnson 1966, Van Wagner 1967, Blackmarr and Flanner 1968, Gary 1971, Countryman 1974, Russell and Turner 1975). Herbaceous moistures, on the other hand, are not as well documented. Although many ecologists, range and wildlife scientists, plant physiologists, and fire scientists measure herbaceous moisture contents regularly, little of this information is formally reported. The few published studies indicate that moisture contents of grasses and forbs growing under generally similar conditions are related (Turner 1972) and that many plants common to the West show "a decided decrease in moisture content" as the growing season advances (Richards 1940). The degree to which these observations apply in other geographic regions, however, has not been fully established.

To assess the potential flammability of forests in the Boundary Waters Canoe Area (BWCA) in northeastern Minnesota (Roussopoulos 1978), moisture contents and fresh-to-dry weight conversion factors were required for common grasses, herbs, mosses, and small shrubs.[1] This paper presents and examines summer moisture content measurements for 21 groups of understory plants that are common to the Great Lakes Forest Region (Rowe 1959). Results are useful for a variety of fire management activities including estimating living fuel biomass and predicting fire control difficulty and/or fire effects for actual or anticipated fires. They also offer a preliminary basis for validating the National Fire Danger Rating System herbaceous moisture model (Deeming *et al*. 1977) in the upper Midwest.

METHODS

Field sampling of living herbs, mosses, and small shrubs for gravimetric moisture content determination was conducted in mature forest stands about 20 km south of Ely, Minnesota (47° 50′ N, 91° 45′ W). Sampling began on June 24, after the period of primary plant growth, and ended on August 26, 1976. Throughout this period, plants representing 21 plant categories (individual species, genera, or groups of related species) found commonly in upland forest communities of the area were collected at intervals of one to several days. Forty-two subsamples were taken between 2:00 and 4:00 p.m. each sample day (3 subsamples each from 14 plant groups). Sampling frequency for individual species or species groups varied approximately in proportion to the percent cover each represented.

Each subsample consisted of at least 5 grams fresh weight of a single species or plant group. All above-ground plant parts were included. Subsamples were sealed in metal cans and transported at once to the laboratory where they were weighed, dried at 105C for at least 16 hours, and reweighed to the nearest 0.1 gram. Dry weight conversion factors (CF) were computed for each subsample (dry weight/fresh weight) and a daily average was determined for each subsample triplet. These were converted to moisture contents (MC) by:

$$MC = \frac{100}{CF} - 100 \qquad (1)$$

At the end of the sample period, the time series of daily moisture content percentage values were examined and compared on the basis of magnitude and seasonal trend. Graphical analysis, t-tests, and regression analysis were the principal analytical methods used.

RESULTS AND DISCUSSION

The number of sample days for each sampling category ranged from 3 for starflower (*Trientalis borealis*), false solomon's seal (*Smilacina racemosa*), and twinflower (*Linnaea borealis*) to 21 for large-leaved aster (*Aster macrophyllus*) and wild sarsaparilla (*Aralia nudicaulis*) (table 1). Sample size reflects the relative contribution to understory plant cover in the sampling vicinity.

Averages of seasonal moisture content percents ranged from 138 for Labrador tea (*Ledum groenlandicum*) to 1,027 for bluebead-lily (*Clintonia borealis*).

Scatter diagrams showed downward seasonal trends in moisture content values for most plant groups, which reflects the influence of phenological development as well as the 1976 summer drought (Dickson 1976). Collections were made during the afternoon, the time of day when moisture stress with decreased moisture content would be most likely to occur due to an imbalance between absorption and transpiration rates. Despite the drought, however, the observed trends were generally more subtle than has been reported for western plants (Richards 1940). Linear regression equations fit the time series data reasonably well and had significant correlation coefficients for Labrador tea, large-leaved aster, and for bluebead-lily (fig. 1). Many species, such as wild lily-of-the-valley (*Maianthemum canadense*) on the other hand, showed no significant seasonal trend (fig. 1). To gain a clearer picture of the seasonal moisture responses by sampling group, average moisture content values and corresponding conversion factors for all sampled plant groups were stratified by early (June 24 - July 24) and late (July 25 - August 26) sampling periods (table 1).

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[1] *Moisture content is weight loss expressed as a percentage of oven-dry weight: moisture content percent =*

$$\left(\frac{\textit{green weight—ovendry weight}}{\textit{ovendry weight}}\right) \times 100$$

The conversion factor is the number that, when multiplied by green weight, yields oven dry weight: (conversion factor = oven dry weight ÷ green weight).

Table 1.—*Moisture content of some grasses, forbs, mosses, and small shrubs in northeastern Minnesota*[1]

Plant group	All (June 24-Aug. 26)				Early (June 24-July 24)				Late (July 25-Aug. 26)			
	Sample day	Moisture content	Conversion factor	Standard error of the mean	Sample day	Moisture content	Conversion factor	Standard error of the mean	Sample day	Moisture content	Conversion factor	Standard error of the mean
	No.	Percent			No.	Percent			No.	Percent		
Labrador tea (*Ledum groenlandicum*)	10	138	(.42)	7	3	160	(.38)	13	7	128	(.44)	7
Blueberry[2] (*Vaccinium* spp.)	17	151	(.40)	6	12	157	(.39)	7	5	136	(.42)	7
Clubmoss[3] (*Lycopodium* spp.)	15	153	(.40)	8	11	156	(.39)	10	4	144	(.41)	11
Grasses[4]	10	170	(.37)	13	6	189	(.35)	17	4	142	(.41)	10
Rubus[5] (*Rubus* spp.)	4	208	(.32)	22	—		( )		4	208	(.32)	22
Spreading dogbane (*Apocynum androsaemifolium*)	6	217	(.32)	22	4	197	(.34)	27	2	259	(.28)	26
Twinflower (*Linnaea borealis*)	3	239	(.29)	41	2	270	(.27)	47	1	178	(.36)	
Bracken fern (*Pteridium aquilinum*)	13	248	(.29)	10	10	258	(.28)	11	3	211	(.32)	18
Wild sarsaparilla (*Aralia nudicaulis*)	21	253	(.28)	6	13	258	(.28)	7	8	244	(.29)	11
Strawberry[6] (*Fragaria* spp.)	11	258	(.28)	14	8	271	(.27)	14	3	224	(.31)	34
Bunchberry (*Cornus canadensis*)	17	261	(.28)	7	12	270	(.27)	6	5	237	(.30)	12
Bush honeysuckle (*Diervilla lonicera*)	5	290	(.26)	31	5	290	(.26)	31	—		( )	
False solomon's seal (*Smilacina racemosa*)	3	304	(.25)	28	3	304	(.25)	28	—		( )	
Pearly everlasting (*Anaphalis margaritacea*)	4	319	(.24)	49	2	390	(.20)	36	2	247	(.29)	53
Other ferns[7]	5	326	(.23)	30	2	388	(.20)	12	3	284	(.26)	29
Wood horsetail (*Equisetum sylvaticum*)	4	340	(.23)	9	1	335	(.23)		3	342	(.23)	13
Starflower (*Trientalis borealis*)	3	369	(.21)	7	3	369	(.21)	7	—		( )	
Large-leaved aster (*Aster macrophyllus*)	21	380	(.21)	15	14	418	(.19)	12	7	305	(.25)	17
Dwarf solomons seal (*Maianthemum canadense*)	17	393	(.20)	14	11	403	(.20)	17	6	374	(.21)	23
Sweet coltsfoot (*Petasites spp.*)	4	560	(.15)	70	2	523	(.16)	147	2	597	(.14)	72
Bluebead-lily (*Clintonia borealis*)	15	1,027	(.09)	35	10	1,071	(.09)	34	5	939	(.10)	69

[1] Moisture content percent equals (100 × moisture content ÷ oven dry weight). Conversion factor equals (oven dry weight ÷ green weight); dry weight = conversion factor × green weight.

[2] *Vaccinium myritilloides* and *V. angustifolium* are predominant.

[3] *Lycopodium clavatum* and *obscurum* are predominant.

[4] *Carex* spp. and *Oryzopsis asperifolia* are predominant.

[5] *Rubus strigous* and *R. pubescens* are predominant.

[6] *Fragaria vesca* and *F. virginiana* are predominant.

[7] *Athyrium* spp., *Onoclea sensibilis*, and *Osmunda cinnamomea* are predominant.

For all sampling groups represented by at least three sample days in each half of the season, moisture content was lower during the late sampling period. The difference between the early and late mean moisture contents (expressed as a percentage of the seasonal average) for the groups with at least 10 sample collections ranged from 7 percent for wild lily-of-the-valley to 30 percent for large-leaved aster—with a mean of 16 percent. Groups showing less than 10 percent difference between early and late means were club-mosses (*Lycopodium* spp.), wild sarsaparilla, and wild lily-of-the-valley. Groups with a difference between early and late means of from 10 to 20 percent were blueberry (*Vaccinium* spp.), bracken fern (*Pteridium aquilinum*), strawberry (*Fragaria* spp.), bunchberry (*Cornus canadensis*), and bluebead lily. And those groups with a difference of more than 20 pecent between early and late means were Labrador tea, grasses, and large-leaved aster. These substantial variations among sampling groups may be due in part to species-related differences in morphology, phenological development, rooting characteristics, stomatal activity, etc., as well as micro-environmental preference.

Admittedly, our sample was not adequate to conclusively identify and characterize seasonal moisture responses. It is also possible that the late

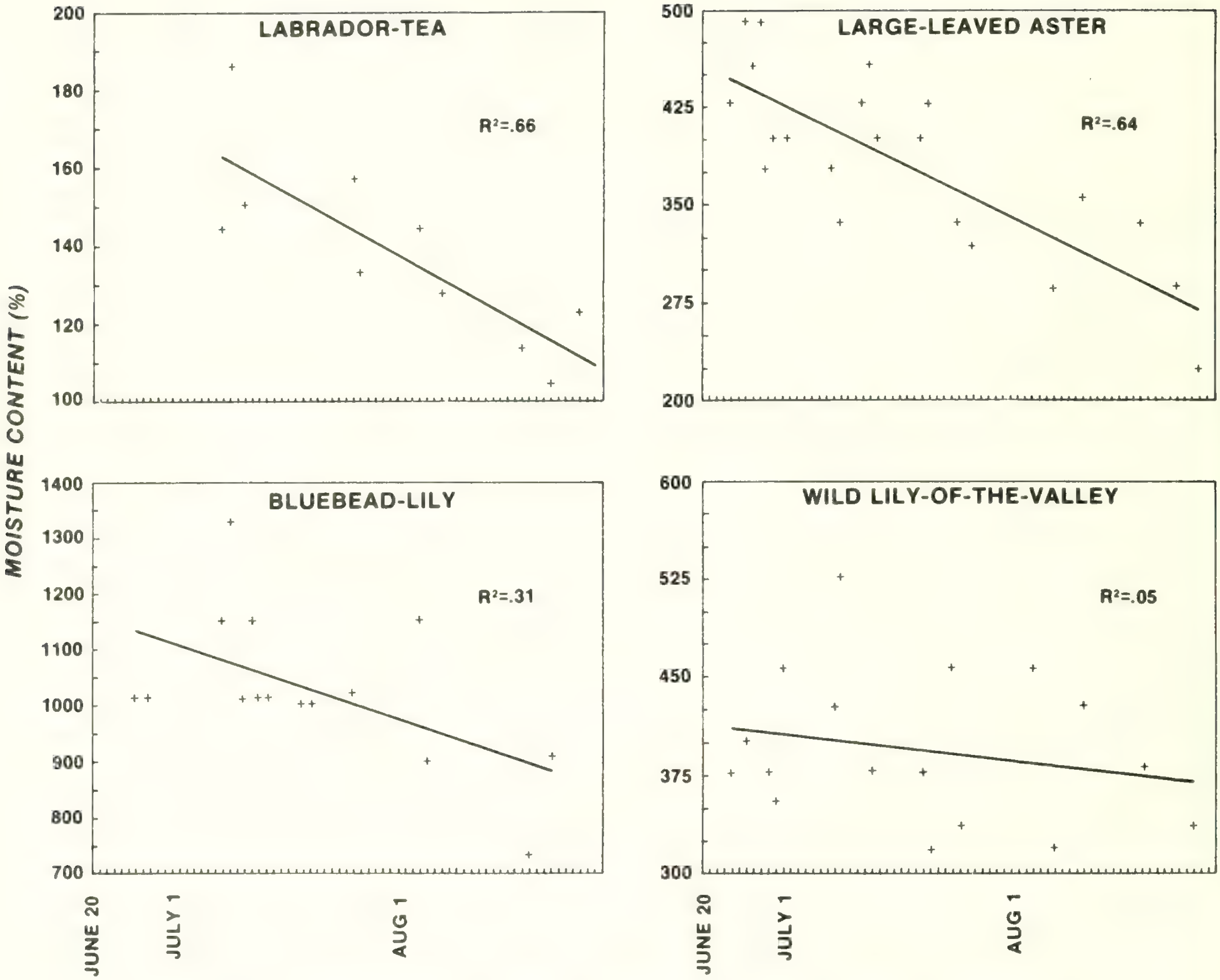

Figure 1.—*Plant moisture content percentages for some species found under mature upland stands in northeastern Minnesota.*

summer drought of 1976 produced atypical plant moisture trends in the sample area. Nonetheless, the average moisture content values obtained here compare favorably with reported values for similar environments of the U.S.S.R. (Svanidze and Khidasheli 1973), and they may be useful in developing crude estimates of dry-weight biomass from field-fresh weights or in predicting forest fire behavior and effects.

One question frequently asked by land managers concerns the suitability of the National Fire Danger Rating System (NFDRS) herbaceous fuel moisture algorithm (Deeming *et al*. 1977) for predicting actual fire behavior or evaluating fuel flammability. Available methods of predicting fire spread rates, intensities, and flame lengths (Rothermel 1972, Albini 1976) require that quantitative estimates of living fuel moisture be developed where these fuels are significant. Use of a simple plant moisture model such as that employed for fire danger rating would be desirable if acceptable accuracy could be achieved. Because fire danger rating is concerned mainly with identifying relative levels and trends in fire potential for the most serious situations anticipated on broad rating areas, it is uncertain whether the NFDRS herbaceous moisture algorithm would be appropriate for other, possibly more demanding, applications. To gain insight on this question, we computed the

NFDRS herbaceous moisture at weekly intervals (Burgan *et al*. 1977) using 1976 observations from the nearest fire weather station. Herbaceous moisture values were computed for all four "climate classes" and plotted for the entire sampling period (fig. 2). All four of these curves show only slightly reduced moisture contents in the late season, which is what we observed for most of the plant groups sampled.

To facilitate comparison with the field results, average calculated moisture contents were determined for the season and for both early and late sampling periods (table 1). In addition, corresponding observed plant moisture contents were calculated as a weighted mean of the moisture content values for all plant groups (table 2). The relative contribution of each plant group to total understory biomass (dry weight) from a broad-scale fuel inventory conducted roughly 50 km from the sample area (Roussopoulos 1978) provided the weighting coefficients for this computation. The mean NFDRS moisture contents for each climate class were also computed for this period and are substantially lower than the observed values. The approximate prediction errors are -63 percent, -66 percent, -70 percent, and -75 percent, respectively, for NFDRS climate classes 1, 2, 3, and 4. The fact that climate class 3 yielded the second largest underprediction is especially significant because it is the one recommended for rating fire danger in the eastern United States (Deeming *et al*. 1977).

Examination of the seasonal moisture trends, on the other hand, reveals slightly better agreement. The difference between the early and late weighted measurement means was roughly 18 percent of the seasonal average, while the NFDRS computations yielded corresponding values of 6, 9, 10, and 15 percent, respectively, for climate classes 1 through 4. The NFDRS herbaceous moisture algorithm is much better at representing relative changes—the principal intent of fire danger rating—than it is at predicting actual values. The errors identified above should be closely examined to determine their significance in applications requiring absolute plant moisture content predictions.

For the NFDRS fuel model G (dense conifer forest with heavy detritus accumulations), we predicted selected fire behavior properties using both measured and calculated mean herbaceous moisture contents (table 2). Fire behavior estimates were computed for climate class 1 and 4 to present the range produced by NFDRS. Fire behavior prediction errors resulting from the use of calculated moisture contents were expressed as percentages of the predictions based on measured moisture:

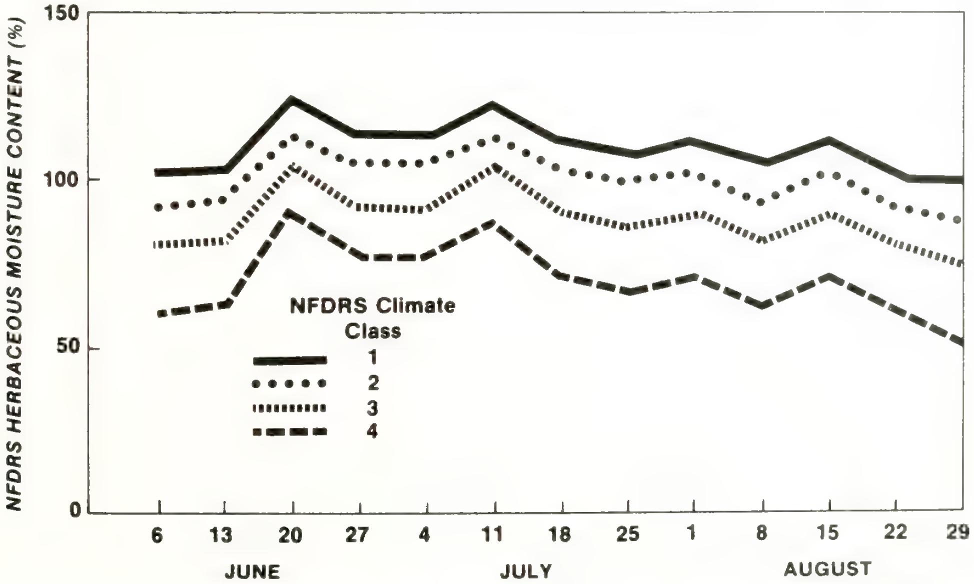

Figure 2.– Manually calculated National Fire Danger Rating System (NFDRS) herbaceous moisture contents for all four climate classes at Ely, Minnesota, 1976.

Table 2.—*Average measured moisture contents and National Fire Danger Rating System (NFDRS) herbaceous moisture predictions by sampling period*

(In percent)

Sampling period	Weighted mean of measured moisture contents	NFDRS herbaceous moisture content			
		Climate Class 1	Climate Class 2	Climate Class 3	Climate Class 4
All (June 24-August 26)	299	112	103	91	74
Early (June 24-July 24)	319	115	107	95	78
Late (July 25-August 26)	264	108	98	86	67

$$E(\%) = \frac{V_c - V_m}{V_m} \bullet 100 \qquad (2)$$

Where: E = the percentage error in a predicted fire behavior characteristic (e.g. spread rate, flame length, etc.) using the NFDRS herbaceous fuel moisture

V_c = the predicted value obtained using the calculated NFDRS herbaceous fuel moisture

V_m = the predicted value obtained using the corresponding weighted mean of measured moisture contents (table 2).

Fuel moistures for the 10, 100, and 1,000 hour timelag fuels were assumed constant at 10, 15, and 15 percent, respectively, for all computations. For 1 hour timelag fuel moisture contents ranging from 5 to 15 percent and effective windspeeds ranging from 4 to 9 m/sec (10 to 20 m.p.h.), forward spread rate (m/min) was overestimated by roughly 55 to 100 percent using the NFDRS climate class 1 herbaceous moisture content, and by 70 to 150 percent using the climate class 4 value. Estimated spread rate for a 1 hour timelag fuel moisture of 5 percent and a windspeed of about 9 m/sec (20 m.p.h.) was 2.4, 4.9, and 6.1 m/min (7.9, 16.1, and 20.0 ft/min) for measured, estimated climate class 1, and estimated climate class 4 fuel moisture values, respectively. Energy release component was overestimated by about 5 to 15 percent and 15 to 25 percent, respectively, for climate class 1 and climate class 4, while corresponding error ranges for flame length predictions were overestimated by 25 to 45 percent and 35 to 75 percent. Estimated flame length predictions for a 1 hour timelag fuel moisture of 5 percent and a windspeed of about 9 m/sec (20 m.p.h.) were 1.2, 1.7, and 2.0 meters (3.8, 5.6, and 6.6 feet) for measured, estimated climate class 1, and estimated climate class 4 fuel moisture values, respectively. Indiscriminant use of the calculated live fuel moistures to predict fire behavior for some planning and operational activities, therefore, would likely result in overly conservative decisions—possibly leading to inefficient use of fire management resources.

The moisture content prediction errors noted above do not significantly compromise the usefulness of the NFDRS herbaceous moisture algorithm for fire danger rating in the Lake States in terms of its intended purpose. Predicted and measured relative herbaceous moisture trends agree. Thus, the NFDRS algorithm may be used to estimate relative fire behavior trends for a season. Uses requiring greater precision, such as comparisons of Lake States fuel moistures with western species, or estimation of absolute values for rate of spread and intensity are questionable unless actual field fuel moisture measurements are obtained. The average moisture content values reported here are appropriate when general estimates are needed for planning over broad areas in Great Lakes conifer forests.

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Give a hoot...don't pollute!

USDA FOREST SERVICE
RESEARCH PAPER **NC-180**

A provisional assessment of **triclopyr herbicide** for use in Lake States' forestry

Donald A. Perala

North Central Forest Experiment Station
Forest Service, U.S. Department of Agriculture

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1980

A PROVISIONAL ASSESSMENT OF TRICLOPYR HERBICIDE FOR USE IN LAKE STATES' FORESTRY

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A new herbicide is needed that controls a broad spectrum of hardwoods, is safe for releasing conifers, and breaks down rapidly in the forest environment without moving from the site. The commonly used 2,4-D [(2,4-dichlorophenoxy) acetic acid] does not control most northern hardwoods; though 2,4,5-T [(2,4,5-trichlorophenoxy) acetic acid] controls more hardwoods (especially oaks), it may not continue to be available for forest management. Picloram (4-amino-3,5,6-trichloropicolinic acid) controls most Lake States hardwoods (Perala 1971, 1974, Perala and Williams 1970), but because it is such a broad spectrum herbicide its use will likely be limited to site preparation rather than for aerial release of conifers.

A recently developed chemical, triclopyr, (3,5,6-trichloro-2-pyridinyloxyacetic acid), controls a broad spectrum of broadleaf weeds (Haagsma 1975). It is taken up by both foliage and roots, is readily translocated in the growing plant, and induces auxin-like responses similar to the action of 2,4-D and 2,4,5-T. It is available as a water soluble triethylamine salt in Garlon 3A Herbicide[1] comprising 3 lbs a.e. per gallon. Breakdown in the soil depends on microbial activity when temperature and moisture are favorable. In the laboratory, 50 percent breakdown occurs in 10 to 46 days at 35C. Field trials elsewhere show the breakdown rate is intermediate between that of 2,4,5-T and picloram (Haagsma 1975). Toxicity to birds and fish is very low, and moderate to animals.

The objectives of this study were threefold: (1) compare rate-response curves of some typical Lake States hardwoods to triclopyr, (2) estimate the persistence and mobility of triclopyr in forest soil, and (3) evaluate the safety of triclopyr to white spruce during aerial release and for planting after site preparation. Aerial release of conifers is not a currently registered use of triclopyr. However, forest site preparation is a registered use as long as conifer planting is deferred until six months after treatment.

STUDY AREA

The study area is located near Grand Rapids, Itasca County, Minnesota. The topography is rolling and soils are loamy but variable, ranging from sand to silt to clay. Soil drainage ranges from poorly-to well-drained. Mean July temperature and April to September rainfall are 66° F and 18 inches, respectively. The dominant vegetation is pole-size northern hardwood forest (table 1). According to Kuchler (1964) the potential natural vegetation is maple-basswood forest, indicating relatively high soil fertility. Some of the forest has been converted to white spruce [*Picea glauca* (Moench.) Voss] plantations where quaking aspen suckers comprise 86 percent of competitors and no other species makes up more than 5 percent.

TREATMENTS AND METHODS

Triclopyr, alone at three rates and in combination with 2,4-D and Tordon 101 Mixture[2] Herbicide, was compared with Tordon 101 Mixture as a standard in six 5-acre site preparation treatments (table 2). Triclopyr was also compared to a standard conifer release formulation of 1:1 mixture of

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[1] *Mention of trade names does not constitute endorsement of the products by the USDA Forest Service.*

[2] *The Dow Chemical Company. Contains 2 lbs. 2,4-D + .54 lbs. a.e. picloram per gallon as triisopropanol-amine salts.*

Table 1.—*Average basal area and DBH for sample trees for six site preparation treatments*

Species Common name	 Scientific name	Stand basal area[1]	Sample tree quadratic mean d.b.h.
		ft²/acre	*inches*
White birch	*Betula papyrifera* Marsh.	15.8	7.2
Red maple	*Acer rubrum* L.	12.3	5.5
Quaking Aspen	*Populus tremuloides* Michx.	36.5	9.5
Northern red oak	*Quercus rubra* L.	17.7	8.1
American basswood	*Tilia americana* L.	3.9	7.0
Sugar maple	*Acer saccharum* Marsh.	16.2	3.8
Others[2]		4.2	6.7
Total or Average		106.6	7.7

[1] Also mean number of trees sampled per treatment.

[2] Balsam poplar (*Populus balsamifera* L.), green ash (*Fraxinus pennsylvanica* Marsh.), American elm (*Ulmus americana* L.), eastern hophornbeam (*Ostrya virginiana* (Mill.) K. Koch.), yellow birch (*Betula alleghaniensis* Britton).

Table 2.—*Rates of application of various chemicals for different treatments*

Treatment	Chemical Triclopyr[1]	 2,4-D	 Picloram[2]	 2,4,5-T[3]	Total
	. . . *Rate, lbs a.e. per acre* . . .				
Site Preparation[4]					
1	1.5	—	—	—	1.5
2	3.0	—	—	—	3.0
3	4.5	—	—	—	4.5
4	1.5	[5]4.0	—	—	5.5
5	1.5	[2]2.0	0.5	—	4.0
6	—	[2]2.0	0.5	—	2.5
Spruce Release[6]					
7	0.375	—	—	—	0.375
8	0.75	—	—	—	0.75
9	1.125	—	—	—	1.125
10	—	[3]1.5	—	1.5	3.0

[1] As Garlon 3A Herbicide.

[2] As Tordon 101 Mixture.

[3] As Esteron Brush Killer.

[4] In 8 or 10 gallons water mix per acre; 5 acres per treatment.

[5] As Esteron 99 Concentrate.

[6] In 4 gallons water mix per acre; 10 acres per treatment.

2,4-D and 2,4,5-T[3] (table 2) on four 10-acre areas. All areas were sprayed on the morning of July 28, 1975, by a helicopter equipped with a conventional boom fitted with "raindrop" nozzles for drift control. Temperatures that afternoon and for the next 3 days reached the low 90's. Calculated soil moisture (Thornthwaite and Mather 1955) on the 28th was 8.93 inches for the upper 6.7 feet of soil profile, or 74 percent of field capacity. The GDD sum [growing degree days, °F = ½ (daily maximum + daily minimum) − 40; positive values summed over period of interest] for the 1975 season had reached 2073° F. Soil moisture and GDD were calculated using standard weather station data (U.S. Department of Commerce 1975) averaged for Pokegama Dam and Remer #2 located 020°, 12 miles; and 250°, 11.5 miles, respectively, from the study site. Neither soil moisture nor GDD sum (an index of plant maturity) were considered limiting, but the high temperatures during and after spraying may have increased herbicide volatility or reduced herbicide activity. Winds during spraying did not exceed 5 mph.

On April 27, 1976, 100 white spruce 2-2 stock were planted in each of the six site preparation treatments. On May 11 and 12, 1976, forty 0.8-inch diameter soil cores were extracted for a bioassay for residual herbicides on a systematic grid from each of site preparation treatments 1, 2, 3,

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[3] *Esteron Brush Killer, the Dow Chemical Company. Contains 2 lbs. per gallon each of 2,4-D and 2,4,5-T propylene glycol butyl ether esters.*

and 6 (table 2) and from an adjacent untreated area. The soil cores were separated into 0- to 4-inch and 4- to 12-inch strata and randomly combined into four composite samples of ten per stratum. This method is believed to provide estimates of 10 percent, 95 percent confidence for most soil properties (Alban 1974), including, presumably, those that would influence herbicide behavior in the soil. The samples were stored at 38° F until a greenhouse bioassay similar to Leasure's (1964) was begun in June. Soybeans were planted in the herbicide treatment samples and in control samples spiked with a standard series of 0, 10, 100, and 1,000 ppb of either triclopyr or picloram (as Tordon 101 Mixture). After 22 days, plants were compared visually, harvested, ovendried, and weighed. Residual herbicide in treatment samples was assayed by interpolating from dose-response curves (fig. 1) developed from the standard series plant dry weights. The assay was confirmed by the visual comparisons.

One year after treatment 10 sample points were systematically located down the center of each of the six site preparation treatments. A 10-basal area factor prism was used to select an average of 11 sample trees at each point for dbh measurements, crown kill estimates to the nearest 10 percent, and presence of sprouting. In each of the four conifer release treatments, 40 white spruce were systematically selected and rated for release effectiveness based on estimated number of years before need for another release (0 = immediate need, 20 = 1 year . . . 100 = 5 or more years), and herbicide injury to the spruce.

RESULTS AND DISCUSSION

Bioassay.—The dose-response curves (fig. 1) were constructed from standard series aerial weights of soybeans for triclopyr, and the entire plant for picloram. Soybeans weighed more when grown

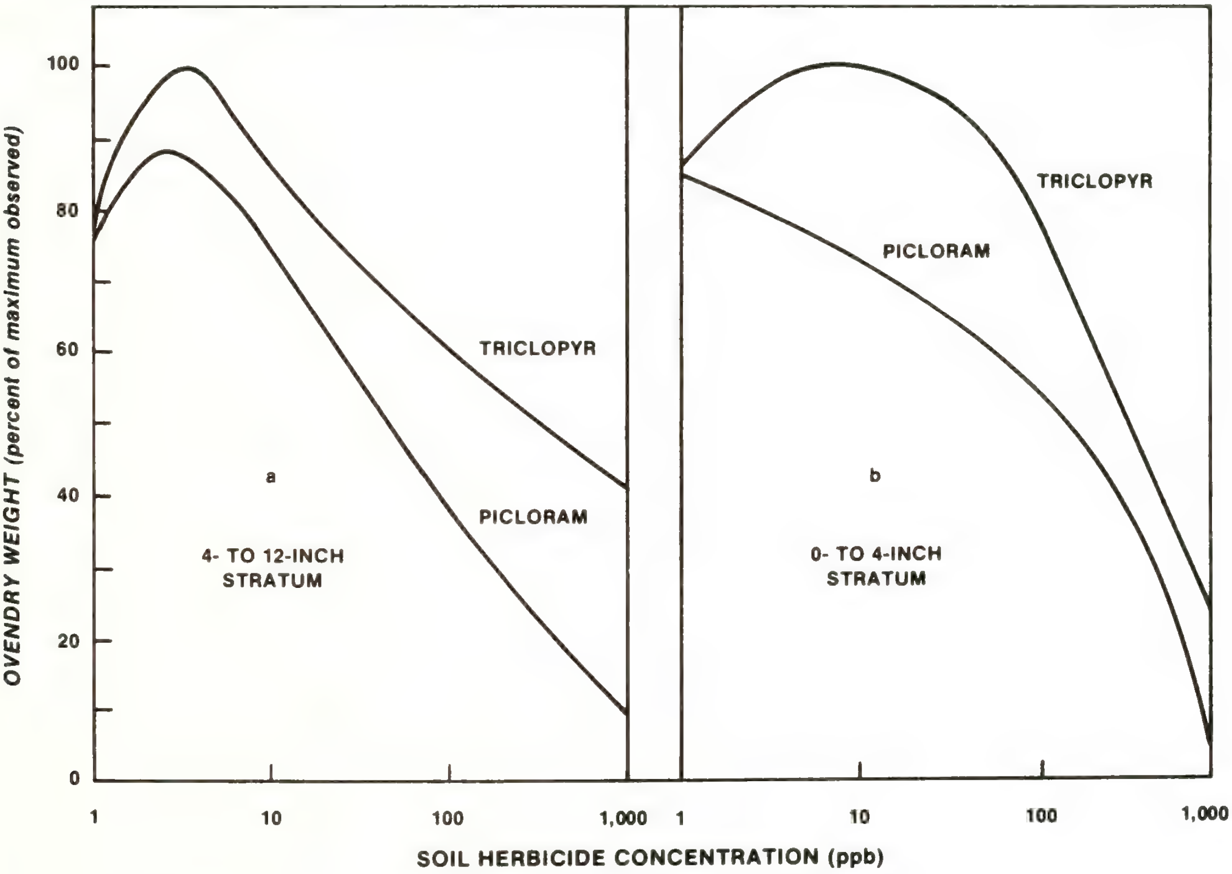

Figure 1.—*Dose-response curves for soybeans grown in control soils spiked with 0, 10, 100, and 1,000 ppb triclopyr or picloram (as acid equivalents). In the figure, 0 ppb is assigned a value of 1 ppb to accommodate the logarithmic scale. The peak response in (a) is estimated from treatment sample data (see text).*

with 10 ppb triclopyr than when grown without herbicide in both the 0- to 4-inch and 4- to 12-inch strata. Furthermore, plants grown in the 4-to 12-inch strata from both the triclopyr and picloram treatments exceeded the weight of 10 ppb plants. Apparently, soybean growth is stimulated by both herbicides at low concentrations. Accordingly, the dose-response curves were modified by extrapolating to the peak response found in treatment soils. In the future, standard series soil dosages should extend into the 1-10 ppb range and perhaps even lower.

The soybean bioassay recovered less than 10 percent of the triclopyr applied for site preparation and about 13 percent of the picloram, and practically all herbicide was found in the 0- to 4-inch stratum (table 3). Even with 16.4 inches of precipitation between herbicide application and soil sampling (U.S. Department of Commerce 1975, 1976), both triclopyr and picloram strongly resisted leaching.

It cannot be interpreted that the unrecovered herbicide was broken down entirely by microbiological activity because the amount of herbicide actually reaching the forest floor is unknown. Other losses include volatilization, photo-degradation, drift, and vegetation absorption and uptake, none of which were measured here. However, triclopyr was nearly as persistent as picloram after 2012 GDD between application and sampling. This is 54 percent of 1975 seasonal GDD at the study site.

The percent recovery of triclopyr varied inversely with rate applied (table 3). This anomaly has been noted before for picloram (Perala 1974). One possible explanation is that low application rates are insufficient for the rapid adaptation and multiplication of soil micro-organisms responsible for herbicide degradation.

Survival and growth were good in the planted white spruce in the site preparation treatments and no detectable herbicide injury was found. In light of the soybean bioassay, the retention of herbicide in the 0- to 4-inch soil stratum effectively prevented herbicide contact with seedling roots.

Site preparation.—Top-kill increased with rate of triclopyr applied and varied considerably by species (fig. 2). White birch was easily top-killed as was red maple at the highest rate. Extrapolation to rates of 6 lbs a.e. per acre suggest good top-kill of red oak and basswood as well. Quaking aspen and especially sugar maple were much more resistant.

Triclopyr top-killed white birch and red maple better than did Tordon 101 Mixture, but the latter was superior on quaking aspen, basswood, and sugar maple (table 4). When triclopyr was applied in combination with 2,4-D or Tordon 101 Mixture, top-kill was either only slightly changed, or in the

Table 3.—*Recovery of triclopyr and picloram from four site preparation treatments by soybean bioassay*

Treatment	Soil weight per acre	Maximum possible herbicide concentration	Concentration recovered[1]	Recovery
	lb × 10⁻⁶	*ppb*	*ppb*	*Percent*
0- to 4-inch STRATUM				
1 (Triclopyr)	0.711	[2]2,110	200	9.5
2 (Triclopyr)	.745	4,030	220	5.5
3 (Triclopyr)	.768	5,860	140	2.4
6 (Picloram)	.745	670	86	12.8
4- to 12-inch STRATUM				
1	2.049	[3]660	4	0.6
2	2.212	1,290	4	0.3
3	2.196	2,000	4	0.2
6	2.275	190	3	0.5

[1] Concentration recovered is based on the ovendry weight of the total plant for picloram and on aerial parts only for triclopyr. Plants harvested 22 days after sowing.

[2] Figures in this column for the 0- to 4-inch stratum assume all herbicide reached the soil surface and remained in the 0- to 4-inch stratum.

[3] Figures in this column for the 4- to 12-inch stratum assume herbicide not recovered in the 0- to 4-inch stratum leached unaltered to, and accumulated in, the 4- to12-inch stratum.

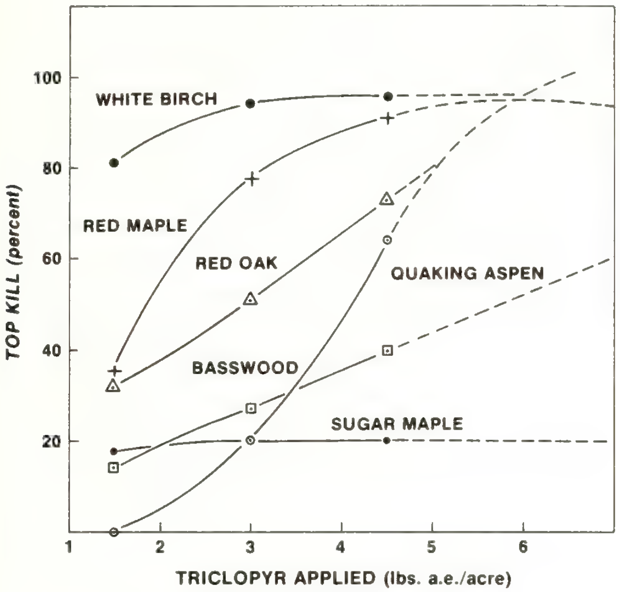

Figure 2.—*Hardwood top-kill response curves to triclopyr applied at 1.5, 3.0, and 4.5 lbs a.e. per acre. Dashed lines are extrapolated trends.*

Table 4.—*Top-kill of species in site preparation tests 4, 5, and 6*

Species	Topkill Triclopyr + 2,4-D	 Triclopyr + Tordon 101 Mixture	 Tordon 101 Mixture
	Percent		
White birch	100 (+4)[1]	69 (−27)	61 (−31)
Red Maple	57 (−37)	18 (−70)	35 (−34)
Quaking aspen	50 (+2)	53 (+17)	61 (+38)
Northern red oak	84 (−4)	50 (−16)	53 (+9)
American basswood	i[2]	58 (+13)	100 (+88)
Sugar maple	8 (−12)	21 (+1)	73 (+53)

[1] Numbers in parentheses indicate departures from the triclopyr rate-response curves in figure 2 on an equivalent total herbicide rate basis.

[2] i=Insufficient observations.

case of red maple and white birch (especially with Tordon 101 Mixture), greatly reduced. Thus, little or no synergistic action of triclopyr in combination with 2,4-D or picloram is evident. Rather there seems to be antagonistic or blocking action with strong species interaction.

A plot of sprouting percent over top-kill for triclopyr (fig. 3) indicates the root-kill character of the herbicide. Triclopyr tended to root-kill basswood, sugar maple, and red oak when top-kill was high. White birch sprouting was controlled moderately well but sprouting of red maple was poorly controlled and suckering of aspen not at all.

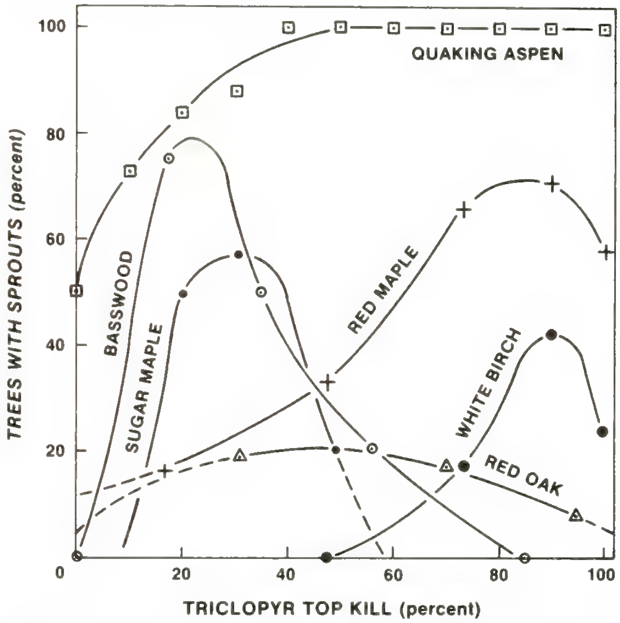

Figure 3.—*Hardwood sprouting response curves over increasing top-kill by triclopyr. Dashed lines are extrapolated trends.*

Sprouting of these species in treatments 4, 5, and 6 was compared to the sprouting expected if sprouting followed the curves in fig. 3. Tordon 101 Mixture (either alone or with triclopyr) controlled sprouting as well or better than triclopyr alone, especially aspen suckering (table 5).

Spruce release.—Triclopyr effectively released white spruce at a rate of 1⅛ lbs a.e. per acre (fig. 4). Effectiveness was equal to that of 2,4-D + 2,4,5-T at 3 lbs per acre. Extrapolation of the effectiveness-rate response curve suggests that rates of 1.5 - 2.0 lbs a.e. per acre would exceed 90 percent effectiveness. It seems unlikely that this increased rate would significantly injure white spruce since absolutely no herbicide injury was found at all.

Table 5.—*Sprouting of species in site preparation tests 4, 5, and 6*

Species	Sprouting Triclopyr + 2,4-D	Triclopyr + Tordon 101 Mixture	Tordon 101 Mixture
		Percent	
White birch	59 (+31)[1]	20 (+2)	18 (+1)
Red maple	25 (−14)	14 (−4)	0 (−25)
Quaking aspen	91 (−3)	64 (−31)	47 (−47)
Northern red oak	13 (0)	6 (−12)	0 (−16)
American basswood	i[2]	0 (−23)	0 (0)
Sugar maple	13 (+8)	0 (−26)	4 (−6)

[1] Numbers in parentheses indicate departures from the triclopyr sprouting curves in figure 3 on an equivalent top-kill basis.

[2] i=Insufficient observations.

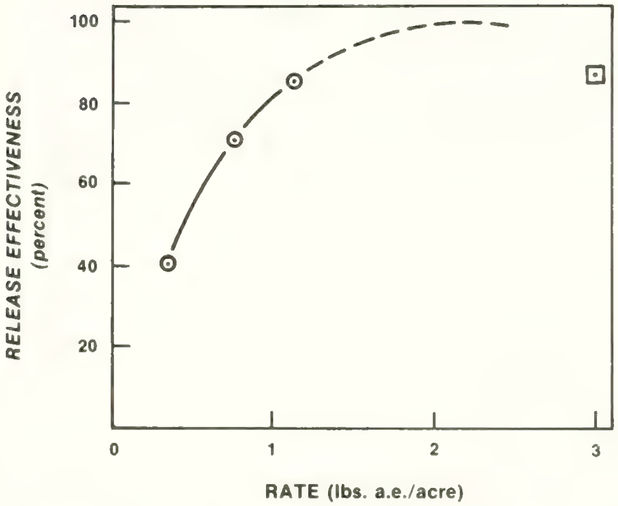

Figure 4.—*Rate response curves showing the effectiveness of conifer release from competing vegetation (primarily aspen suckers) in a white spruce plantation sprayed with triclopyr at rates of 0.375, 0.75, and 1.125 lbs a.e. per acre. Circles = triclopyr; dashed line = extrapolated trend; square = 2,4-D + 2,4,5-T at 3 lbs a.e. per acre.*

CONCLUSIONS

1. Triclopyr and picloram are unlikely to be leached out of intact forest floor and upper soil strata high in organic matter.
2. Triclopyr and picloram degradation rates in forest floor do not differ greatly during at least the first half-season (measured in GDD) after application.
3. White spruce bare-root stock may be safely planted where the forest floor is undisturbed the next spring after site preparation with either triclopyr or picloram.
4. White birch and red maple are readily top-killed with 4.5 lbs a.e. per acre triclopyr. Rates of 6 lbs per acre would likely top-kill red oak and basswood as well.
5. Sugar maple and quaking aspen are more readily top-killed with Tordon 101 Mixture than with triclopyr.
6. Triclopyr mixtures with 2,4-D or Tordon 101 Mixture are not as effective as triclopyr or Tordon 101 Mixture alone at the same total rate.
7. Compared to triclopyr, Tordon 101 Mixture reduced sprouting.
8. Rates of 1-2 lbs a.e. triclopyr are highly effective and safe for release of white spruce when sprayed at about 2100 seasonal GDD (2-3 weeks after shoot growth is completed).
9. Further study should test forestry uses of triclopyr at higher rates than used in this study.

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OXFORD: 231.324. KEY WORDS: Northern hardwoods, herbicide degradation, picloram, 2,4-D,2,4,5-T.

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20

Twenty-year results of the Lake States JACK PINE seed source study

Richard M. Jeffers
Raymond A. Jensen

North Central Forest Experiment Station
Forest Service, U.S. Department of Agriculture

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TWENTY-YEAR RESULTS OF THE LAKE STATES JACK PINE SEED SOURCE STUDY

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Jack pine (*Pinus banksiana* Lamb.) is an important pulpwood species in the Lake States. It grows under a wide variety of environmental conditions and exhibits considerable phenotypic variation both within and among stands. Knowledge of genetic variation in this species is basic to a jack pine tree improvement program for the Lake States.

In 1951 the North Central (then the Lake States) Forest Experiment Station and the University of Minnesota began a regional seed source study to determine the nature and extent of genetic variation in jack pine. Private, State, and Federal forestry agencies collected seed from 29 natural stands in Minnesota, Wisconsin, and Michigan. Seedlings produced from those seed collections were planted at 17 locations in the three Lake States and at a single location in Ontario.

This paper includes data on survival, total height, diameter, volume per tree, and volume per acre 20 years after planting at 14 locations in the Lake States.

LITERATURE REVIEW

Results of plantings at one or more locations have already been published by various cooperators.

Stoeckeler and Rudolf (1956) reported on height growth at age 2 and change in needle color in fall at ages 1, 2, and 3 at the Hugo Sauer Nursery at Rhinelander, Wisconsin. Changes in fall needle color were found to be associated with latitude of seed source (the more northerly the seed source the more purplish the needles). Height growth of 2-0 stock was negatively correlated with latitude of seed source and positively correlated with normal annual sum of average daily temperatures of 50°F or above (growing degree days) at seed origin.

Arend *et al.* (1961) reported on 5-year results in three Lower Michigan plantations. Tree height differences among seed sources were significant at all three locations.

Survival and height growth 5 years after planting were also reported at six locations in Minnesota by Jensen *et al.* (1960), but statistical analyses were not included.

Alm *et al.* (1966) found highly signifcant differences among seed sources in height and diameter growth after 9 years in a plantation at the University of Minnesota Cloquet Forestry Center in Carlton County, Minnesota.

King (1966) reported on 10-year height growth of trees from 26 sources common to 11 plantings in Minnesota, Wisconsin, and Michigan and from a local commercial seed source (different at each location). At 10 locations there were significant differences in total tree height among test seed sources. At almost all locations test seed sources from nearest the planting sites outgrew the commercial nursery stock. King concluded that selection of "good" jack pine stands for seed collection appears worthwhile in the species, but selection of tested nonlocal stock may offer even greater improvement.

Utilizing the data reported by King (1966) and data from the Ontario planting, Morgenstern and Teich (1969) reported increases in height were obtained by planting trees 2 to 3° north of their seed origin.

Rudolph (1964) described variation among trees from different seed sources in lammas growth and prolepsis in four Minnesota and two Wisconsin plantings. He found significant differences in these traits among 30 seed sources in the Cloquet plantation and significant differences among 10 widely distributed seed sources evaluated at all locations.

Variation among seed sources in susceptibility to several insects and diseases has been found in several of the plantings. Batzer (1961, 1962) found significant differences among sources in incidence of white pine weevil (*Pissodes strobi* (Peck)) in two northern Minnesota plantings.

Arend *et al.* (1961) evaluated three plantings in Lower Michigan after 5 years and found significant differences among seed sources in incidence of white pine weevil, bark beetles (*Pityophthorus* spp.), and redheaded pine sawfly (*Neodiprion lecontei* (Fitch)), but no significant differences among sources in eastern gall rust (*Cronartium quercuum* (Berk.) Miy. ex Shirai) incidence.

King (1971) reported on variation among seed sources in incidence of white pine weevil, eastern pineshoot borer (*Eucosma gloriola* Heinrich), and eastern gall rust at 11 locations in Minnesota, Wisconsin, and Michigan. He found significant differences among sources in white pine weevil incidence, and concluded that Lower Michigan sources are the best to use as a starting point in a white pine weevil resistance breeding program.

Eastern pineshoot borer was found in eight of the 11 plantations evaluated after 5 years, but no significant differences among sources in borer incidence could be shown. However, after 10 growing seasons in the field, there were significant differences among seed sources in borer incidence in two Wisconsin and one Upper Michigan plantings.

King found eastern gall rust after 10 years in every plantation he examined. In seven plantations in which more than 15 percent of the trees were infected, differences among seed sources in gall rust incidence were significant.

Trees from the northernmost sources showed high rust incidence while those from southern sources had the lowest rust incidence. King suggested that trees from the sourthern portion of the range have been subjected to more intense gall rust infection, and have developed some resistance to it, while those from farther north, where the alternate hosts are not as abundant, have not been subjected to as severe a selection for resistance.

King and Nienstaedt (1965) described variation among seed sources in needlecast (*Davisomycella (Hypodermella) ampla* (Dav.) Dank) incidence in a western Upper Michigan and a southern Wisconsin plantation. They found significant differences among sources in susceptibility to the needlecast fungus at both locations, indicating that susceptibility to this disease is under direct genetic control.

Information published to date has given considerable insight into the development of this study. Significant differences among seed sources have been found for several traits, including height and diameter growth, lammas growth and prolepsis, and pest incidence. Variation among seed sources in most traits appears to be clinal, and individual genotypes react strongly to different test environments. Northern and southern sources contribute most to this interaction, while middle-latitude sources contribute little.

Yeatman (1974) showed that tree height at 5 years was ineffective in predicting tree height at 19 years for 12 Ontario seed sources grown at the Petawawa Forest Experiment Station. Variation in tree height at 11 years, however, was very effective in predicting height at 19 years and provided a sound basis for selection of the better seed sources. King's (1966) data and our data on Lake States jack pine substantiate Yeatman's results.

METHODS

Seed Sources and Plantation Establishment

In 1951 and early 1952 seed was collected from 29 jack pine stands in Minnesota, Wisconsin, and Michigan. Each collection was made from dominant and codominant trees in a stand considered good for its locality.

Seed from all 29 stand collections was sown in the spring of 1952 in both the General Andrews State Nursery at Willow River, Minnesota, and in the Hugo Sauer State Nursery at Rhinelander, Wisconsin.

Two-year-old seedlings were planted by nine cooperating agencies at 17 locations, one in the fall of 1953 and 16 in the spring of 1954. Seedlings produced at the Genral Andrews Nursery were used to establish six plantations in Minnesota and two plantations in western Wisconsin. Seedlings produced at the Hugo Sauer Nursery were used to establish four additional plantings in Wisconsin and five plantations in Michigan.

At each location a randomized complete-block design with four replications was used. Each source was represented in each replication by a square 64-tree plot with trees planted at a spacing of 5 × 5 feet. In addition to the selected seed sources, each replication contained one seedlot of stock supplied by a commercial nursery in the same area as the test plantation. Very little is known about the origin of the commercial stock in many instances.

Because of shortages of seedlings from a few sources, substitutions were made at several locations. Data for 26 seed sources (table 1, fig. 1) common to 14 locations[1] (fig. 1, table 2) are presented here.

Measurements

Survival, height, and diameter

In the fall of 1973, 20 years after establishment, the trees were evaluated for survival, total height, and diameter. Survival data are based on the 64 trees originally planted in each plot.

To save time and expense in tree measurement, a statistical sample was selected from each plantation. The sample was based on variances obtained with the 10-year measurements of height and d.b.h. plus an assumption that means and their standard errors would increase about in the same proportion between 10 and 20 years, which proved valid. We first determined that measuring trees on all four replications was the best procedure. To determine number of trees to be measured per plot, an estimate of the standard error of a source mean was plotted against number of trees measured per plot for both height and d.b.h. The standard error increased slowly as the number of trees measured decreased from 64 to about 15, and increased more rapidly as numbers were reduced further. The proportional increase in standard error between measurement of 15 and eight trees per plot was 17 percent for height and 24 percent for d.b.h., and the decrease in number of trees measured was 47 percent. The standard error increased more rapidly as sample size decreased further. Taking costs and estimated standard errors into account, we

Table 1.—*Jack pine seed source origins*[1]

Seed source	County	Latitude	Longitude	Growing degree days[2]	Average January temperature
		°N	°W		°F
			MINNESOTA		
1589	Cass	47.4	94.4	9,200	5
1590	Cass	47.0	94.6	9,400	7
1591	Itasca	47.5	94.1	9,100	5
1592	Lake	47.7	91.2	7,400	10
1593	Cook	48.0	90.3	6,700	14
1594	St. Louis	48.1	92.4	8,500	5
1595	Pine	46.0	92.6	9,500	10
1596	Pine	46.4	92.8	9,000	9
1597	Becker	47.1	95.4	8,900	4
1600	Cass	46.8	94.4	9,400	6
1601	Beltrami	47.5	95.0	8,600	5
1602	Itasca	47.8	93.3	8,800	6
			WISCONSIN		
1605	Bayfield	46.7	91.0	9,000	13
1606	Forest	46.0	88.9	8,500	12
1608	Burnett[3]	45.9	92.1	10,000	10
1609	Marinette	45.2	88.3	9,600	14
1610	Oneida	45.8	89.8	9,000	10
1611	Wood	44.4	89.7	10,000	13
			MICHIGAN (Upper Peninsula)		
1612	Gogebic	46.2	89.2	8,500	12
1613	Ontonagon	46.6	89.0	8,800	15
1614	Alger	46.3	86.7	8,100	15
1615	Chippewa	46.3	84.8	8,000	15
1621	Luce	46.6	85.4	7,900	16
			MICHIGAN (Lower Peninsula)		
1616	Manistee	44.2	86.2	10,100	22
1617	Ogemaw	44.2	84.1	9,600	19
1618	Alpena	45.0	83.5	9,000	19

[1] Data from Stoeckeler and Rudolf (1956).

[2] Normal annual sum of average daily temperatures of 50°F or above.

[3] Not planted at University of Minnesota CFC (Plantation 6).

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[1] *One source planted at 13 locations only.*

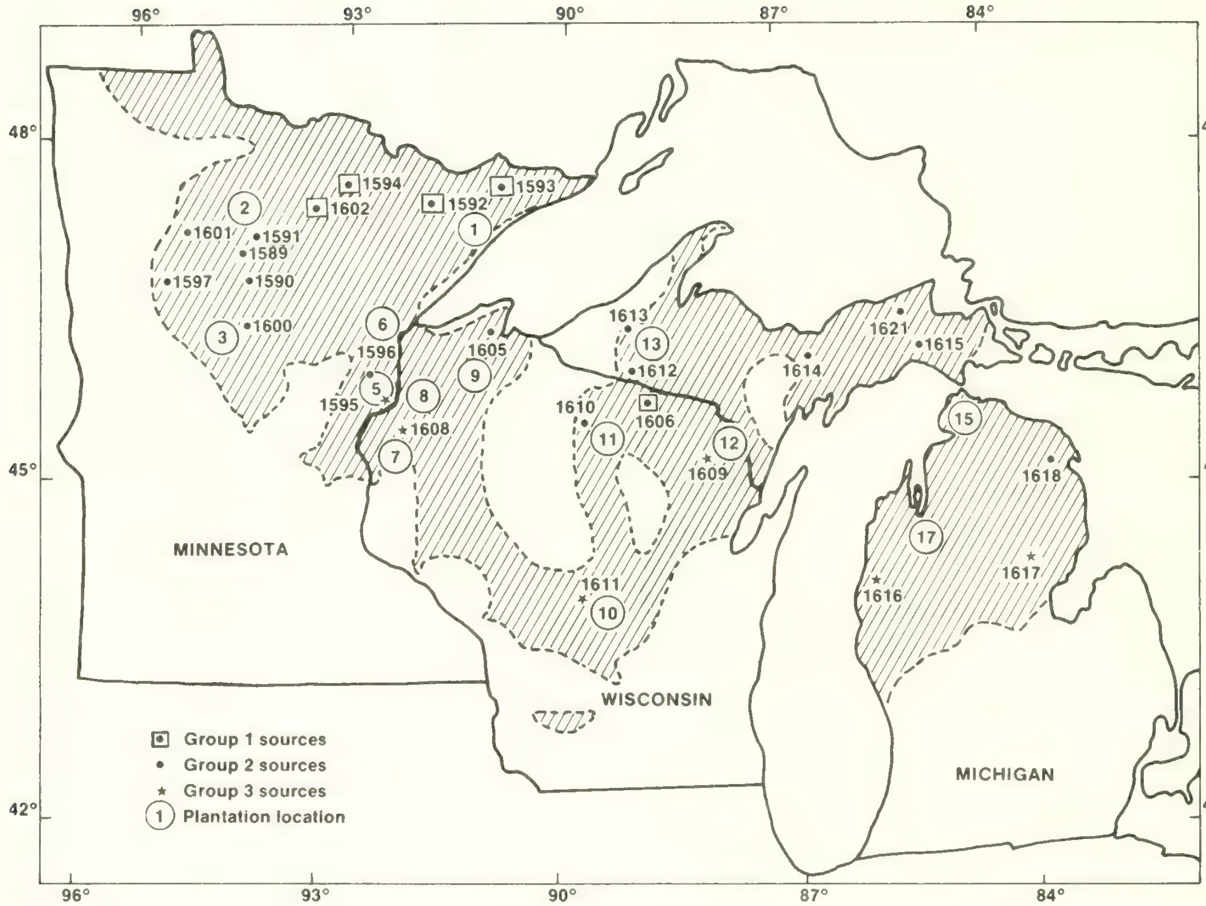

Figure 1.—*Location of seed sources and plantations included in 20-year measurements. Shaded area shows natural range of jack pine (Rudolf and Schoenike 1963).*

decided to measure eight trees per plot. Total height was measured to the nearest 0.5 foot and diameter to the nearest 0.1 inch.

Volume

An equation for estimating volume of a tree from its height and d.b.h. was developed for a subsample of trees, made up of 10 of the 26 sources at each of three plantations: Burnett County Forest (CF), Argonne Experimental Forest (EF), and Ottawa National Forest (NF). A single tree with height and diameter approximating the average height and diameter of the eight measured trees was selected from each of the 10 seed sources in each of the four replications. Sample trees were cut as close to the ground as possible and all limbs removed. The stems were cut into eight equal-length sections and the volume of wood in each section was determined using the volume formula for the frustum of a cone.

By using transformations of the Behre equation of tree form (Bruce 1972), we found that although there appeared to be some slight differences in form among the three plantations, there were no apparent differences in form among sources. Consequently, this prediction equation was used for estimating tree volume for all seed sources at all locations:

$$\text{Vol (cu ft)} = .1781 + .3361\,(\text{d.b.h.})^2\text{ht} - (.01/\text{d.b.h.})$$

Total volume per acre was estimated for each plot by taking (average volume per tree) × (number of trees per acre initially = 1,740) × (proportion survival).

Table 2.—*Location of jack pine plantations*

Number	Forest	County	Plantation establishment	Latitude	Longitude	Growing degree days	Average January temperature
				°N	°W		°F
			MINNESOTA				
1	Superior NF[1]	Lake	USDA For. Serv.	47.6	91.1	7,400	10
2	Chippewa NF	Beltrami	USDA For. Serv.	47.4	94.5	8,600	5
3	Pillsbury SF	Cass	Minn. Cons. Dep.	46.4	94.5	9,400	6
5	General Andrews EF	Pine	Minn. Cons. Dep.	46.4	92.8	8,700	9
6	Univ. Minn. CFC	Carlton	Univ. Minn.	46.7	92.5	8,500	8
			WISCONSIN				
7	Burnett CF	Burnett	Burnett Co.	45.6	92.8	10,000	10
8	Mosinee IF	Washburn	Mosinee Pap. Co.	46.2	92.0	10,000	10
9	Chequamegon NF	Bayfield	USDA For. Serv.	46.3	91.4	9,000	13
10	Nepco IF	Wood	Nekossa-Edwards Pap. Co.	44.2	89.8	10,000	13
11	Argonne EF	Forest	USDA For. Serv.	45.8	89.0	8,500	12
12	Marinette CF	Marinette	Marinette Co.	45.7	88.0	9,600	14
			MICHIGAN (Upper Peninsula)				
13	Ottawa NF	Ontonagon	USDA For. Serv.	46.3	89.2	8,500	12
			MICHIGAN (Lower Peninsula)				
15	Univ. Mich. BS	Emmet	Univ. Mich.	45.5	84.7	8,700	17
17	Fife Lake SF	Grand Traverse	Mich. Cons. Dep.	44.5	85.4	9,700	18

[1] NF: National Forest; SF: State Forest; EF: Experimental Forest; CFC: Cloquet Forestry Center; CF: County Forest; IF: Industrial Forest; BS: Biological Station.

Statistical Procedures

Analyses of variance

Two-way analyses of variance by source and replication were performed for survival, height, diameter, volume per tree, and volume per acre for each plantation. Combined analyses of data from all locations were also run for these variables. Because variances were quite different among plantations, log transformations of the data were used in the combined analyses to bring about homogeneity. Data on volume per acre from plantations at Pillsbury State Forest (SF) in Minnesota and Nepco Industrial Forest (IF) in Wisconsin were not included in the combined analysis because the transformation gave logs of negative values.

From the two-way analysis of variance for each plantation, an estimate of the "true" variation among sources was obtained as a "component of variance" after allowance for random variation (Snedecor and Cochran 1967). The corresponding standard deviations, denoted by $\hat{\sigma}_s$, represent the variability among sources. In tables 3-7, estimated ranges among sources (plantation mean $\pm 2\hat{\sigma}_s$), are shown for each plantation. These ranges would include 95 percent of a normal distribution, and approximately 95 percent of a distribution with moderate deviation from normal. It does not appear that the distributions of "true" values for sources differ markedly from normal, so that a value equal to the plantation mean $+ 2\hat{\sigma}_s$ would represent a source near the top of the distribution, while a value equal to the plantation mean $- 2\hat{\sigma}_s$ would represent a source near the bottom. These points are more stable than the maxima and minima of the observed means and were used to assess the potential gain from proper seed source selection for a given location. A few sources will have values outside this range, so this treatment is conservative. In the case of tree survival, values were calculated using the arcsin transformation and then transformed back. The range of variation among sources is much greater for some plantations than for others.

Grouping of sources

Because mean values for a single source at an individual plantation had fairly large standard errors, we tried grouping plantations and also sources. However, grouping of plantations was not very successful, primarily because of large differences among plantations.

We found that sources could be arranged into three broad groups based on simple correlation coefficients among individual sources over the 14 plantations for measurements of height, d.b.h., and volume per tree. The separation was clearest for height, where 83 percent of the correlation coefficients between pairs of sources in the same group were 0.95 or above, as compared with 11 percent for sources not in the same group. For d.b.h., correlations were lower and less consistent. Fifty-two percent of the correlations between pairs of sources in the same group were greater than 0.90, compared with 25 percent for sources in different groups. Results for volume per tree were intermediate, with 82 percent of the correlation coefficients in the same group greater than 0.90 compared with 49 percent for sources in different groups.

A few sources correlated well with both group two and group three sources, and could have been assigned to either group. A few sources that did not fit closely into any group were put into the group having the best agreement.

Correlations

For each plantation, simple correlations were run between (a) average source survival, height, diameter, volume per tree, and volume per acre and (b) growing degree days and latitude of seed origin. Simple correlations among sources were also run between heights at 5 and 10 years, 5 and 20 years, and 10 and 20 years, after planting for each of 13 locations where measurements from the three periods were available.

RESULTS AND DISCUSSION

Survival

Average tree survival 20 years after plantation establishment varied from 53 percent at Pillsbury SF in central Minnesota to 92 percent at Fife Lake SF in Lower Michigan (table 3). Survival at six locations was less than 80 percent. Much of the initial mortality at these locations was attributed to inadequate cultural treatment after planting, and insect and animal damage. Much continuing mortality is attributable to reduced tree vigor resulting from insect and disease incidence (King 1971, King and Nienstaedt 1965). Continuing mortality is most prevalent at locations with high incidence of gall rust. Trees with galls on main stems are particularly susceptible to breakage from high winds, ice, and heavy, wet snows.

Seed sources showed considerable variation in survival at all locations; differences were significant at all locations except the University of Michigan Biological Station (BS). In the combined analysis, differences among plantations and seed source × location interactions were significant.

Five of eight plantations exhibiting high variability among sources in survival had high gall rust incidence. The southernmost plantation, Nepco IF, showed much greater variation than the other plantations. This plantation not only had a high incidence of gall rust (King 1971), but also a high incidence of needlecast (King and Nienstaedt 1965) and root tip weevil (*Hylobius rhizophagus* M.B. & W.). At this location, northern Minnesota sources had very poor survival and high gall rust and needlecast incidence, while sources from the southern portion of the species range had good survival and relatively low rust and needlecast incidence.

At 10 of the 14 locations, the source from nearest the planting site (local) was among the top eight of the 26 sources in survival. At 12 locations survival of the local source exceeded that of the commercial source by 4 to 33 percent. At the remaining two locations, University of Minnesota Cloquet Forestry Center (CFC) and the University of Michigan BS, survival of both local and commercial sources was between 85 and 90 percent and differed by less than 1 percent. Survival of commercial sources was relatively low, compared with other sources, at most locations.

Survival was related to similarity between climate and length of growing season at seed origin and at the plantation location. In the seven plantations having cooler climates and shorter growing seasons (growing degree days of 8,700 or less), best survival was attained by trees from Minnesota

Table 3.—*Survival percent of jack pine seed sources*

MINNESOTA

Seed source	1 Superior NF**[1]	2 Chippewa NF*	3 Pillsbury SF**	5 General Andrews EF**	6 Univ. Minn. CFC*	7 Burnett CF**	8 Mosinee IF**	9 Chequamegon NF**	10 Nepco IF**	11 Argonne EF**	12 Marinette CF**	13 Ottawa NF**	15 Univ. Mich. BS	17 Fife Lake SF**
Mean	82	81	53	85	85	85	79	63	65	68	86	77	90	92
Range[2]	93	87	68	92	90	94	95	77	89	79	93	89	95	96
	67	76	38	78	81	76	61	50	37	55	79	65	86	88
MINNESOTA														
1589	84	83	58	91	87	85	82	67	52	71	91	83	90	95
1590	73	88	60	78	81	88	85	57	59	71	91	78	94	92
1591	88	81	60	88	91	86	82	73	43	65	89	79	86	91
1592	[3]91	79	47	88	89	71	64	46	45	69	79	86	91	93
1593	92	88	52	90	88	70	74	57	34	72	90	88	93	96
1594	89	82	48	83	84	78	62	50	41	70	73	77	89	89
1595	78	80	55	88	90	88	88	71	70	67	86	82	90	91
1596	82	86	68	[3]90	[3]86	89	88	71	74	73	86	74	91	94
1597	77	85	56	85	90	84	81	59	63	67	84	74	89	95
1600	85	87	[3]62	84	86	88	91	68	54	69	88	77	91	93
1601	79	[3]85	61	89	86	89	80	68	60	68	87	70	93	95
1602	81	83	43	88	84	79	59	52	46	77	77	81	85	89
WISCONSIN														
1605	81	81	64	84	84	84	89	[3]72	66	71	85	73	86	89
1606	76	74	27	78	79	81	71	55	59	[3]69	78	75	80	83
1608	82	84	58	84	—	[3]89	[3]90	82	70	66	91	82	93	95
1609	68	82	53	86	75	93	86	63	80	60	[3]86	71	87	91
1610	88	79	39	89	83	88	74	62	86	66	91	67	96	91
1611	76	82	64	73	86	91	94	61	[3]83	48	88	57	92	95
MICHIGAN (Upper Peninsula)														
1612	85	78	32	84	90	84	76	68	67	68	87	[3]85	88	94
1613	84	77	54	86	89	88	76	57	60	68	86	84	88	93
1614	91	85	54	85	84	84	77	71	71	73	80	78	87	90
1615	90	80	55	89	89	88	74	59	75	81	90	82	91	90
1621	87	72	52	91	86	87	70	65	76	75	89	89	96	89
MICHIGAN (Lower Peninsula)														
1616	73	71	45	84	87	89	86	71	89	60	86	70	93	[3]94
1617	65	83	51	73	75	91	85	56	81	53	91	66	86	95
1618	78	75	59	88	84	84	82	67	74	59	86	79	[3]88	91
COMMERCIAL SEED SOURCE														
	87	73	52	76	87	65	71	50	50	64	79	78	89	89

[1] Significant differences among seed sources: * = 5 percent; ** = 1 percent.

[2] Estimated range (plantation mean ± $2\hat{\sigma}_s$).

[3] Seed source nearest planting site (local).

and Upper Michigan. The majority of these trees was from areas having less than 9,000 growing degree days.

Conversely, at the other seven locations (9,000 growing degree days or more) best survival was attained by trees from areas having warmer climates and longer growing seasons than at the planting site. Included in this group were sources 1596 and 1600 from Minnesota, sources 1608, 1609, 1611 from Wisconsin, and sources 1616 and 1617 from Lower Michigan. Predominating among the sources with the poorest survival at these locations were the four northernmost sources—1592, 1593, 1594, and 1602 from Minnesota—and source 1606 from northern Wisconsin. Source 1606, from the coldest site in Wisconsin, was among the sources showing lowest survival at 10 of the 14 locations.

High incidence of gall rust at several of the warmer locations, including the Pillsbury SF, Burnett CF, Mosinee IF, Chequamegon NF, and Nepco IF (King 1971), probably resulted in increased mortality. Furthermore, since seed sources vary in their susceptibility to gall rust, the high incidence at these locations could have caused the increased variation among seed sources in survival. In general, seed sources with the highest rust incidence had the poorest survival.

Height

Average tree height in the plantations ranged from 18.9 feet at the University of Michigan BS in northern Lower Michigan to 33.3 feet at the Pillsbury SF in central Minnesota (table 4). There were significant differences in tree height among sources at all locations except the University of Minnesota CFC; the combined analysis showed that differences among plantations and seed source × location interaction were significant.

The estimated superiority of a source at the top of the distribution (plantation mean + $2\hat{\sigma}_s$) compared with one at the bottom (plantation mean − $2\hat{\sigma}_s$), as a percent of plantation mean, varied from 10 percent at the University of Minnesota CFC to 49 percent at Mosinee IF. In general, variation among sources within plantations increased with the number of growing degree days at the planting site, but variation was not significantly correlated with latitude of plantation or site quality (based on average plantation height). The greatest variation among seed sources in tree height occurred at locations with high incidence of gall rust; sources from northern Minnesota had the slowest growth and highest gall rust incidence, while sources from the southern portion of the species range in Minnesota, Wisconsin, and Michigan had the greatest height growth and lowest rust incidence.

In general, the "best" seed sources were local ones and those within 100 miles south of the planting site. The number of growing degree days for these sources was nearly equal to or greater than the number at the planting site. Trees from the local source exceeded the average plantation tree height by 2 to 19 percent at all locations; the local source was among the seven tallest sources at 13 locations. At 11 locations, the local source exceeded the commercial source by 4 to 13 percent.

Except at the Superior NF, where northeastern Minnesota sources were the best, one or more of the three Lower Michigan sources were among the five tallest sources at all locations. At eight plantations, one of the Lower Michigan sources was the tallest. Other sources producing the tallest trees at several locations were 1595, 1596, 1600, and 1601 from Minnesota, and 1610 from northern Wisconsin.

Six sources produced the shortest trees at several locations: 1592, 1593, 1594, and 1602 from northeast Minnesota (the four northernmost sources), source 1606 from northern Wisconsin, and source 1621 from Upper Michigan. All six of these sources have less then 8,900 growing degree days.

Diameter

Average plantation tree diameter varied from 3.15 inches at the Mosinee IF to 4.75 inches at the Pillsbury SF (table 5). Average tree diameter for a source was significantly and positively correlated with average tree height for the source at each location.

A combined analysis with data from all locations showed significant tree diameter differences among sources and plantations, and a significant seed source × plantation interaction.

Table 4.—*Average height of trees from jack pine seed sources as a percent of the plantation mean*

Seed source	1 Superior NF**[1]	2 Chippewa NF **	3 Pillsbury SF **	5 General Andrews EF **	6 Univ. Minn. CFC	7 Burnett CF **	8 Mosinee IF **	9 Chequamegon NF **	10 Nepco IF **	11 Argonne EF **	12 Marinette CF **	13 Ottawa NF **	15 Univ. Mich. BS**	17 Fife Lake SF **
Mean (ft)	23.3	23.9	33.3	27.5	29.4	25.9	23.5	27.2	23.8	30.1	29.2	29.3	18.9	19.4
Range[2] (ft)	24.8	25.6	37.3	30.0	30.8	27.8	29.3	30.3	28.7	32.0	31.8	31.8	21.0	21.1
	21.8	22.2	27.3	25.0	28.0	21.6	17.7	24.1	18.9	28.2	26.7	26.8	16.7	16.7
MINNESOTA														
1589	103	99	100	109	99	99	106	104	96	99	106	102	103	104
1590	100	102	102	100	99	100	106	99	95	101	102	102	102	102
1591	100	100	103	101	102	98	101	99	98	90	94	98	97	95
1592	[3]104	102	99	97	100	87	71	87	91	100	92	88	98	97
1593	103	95	89	84	95	86	79	95	83	98	93	93	94	93
1594	101	91	89	92	94	79	71	86	81	99	91	92	90	87
1595	92	104	104	109	99	109	116	104	107	94	101	99	100	105
1596	101	105	102	[3]104	[3]105	105	108	103	103	102	98	101	101	102
1597	105	105	104	103	100	103	107	100	98	104	100	100	101	99
1600	99	105	[3]109	103	101	103	113	106	94	102	101	101	99	99
1601	106	[3]107	105	98	102	105	104	103	102	104	101	100	106	102
1602	106	95	90	97	100	89	83	92	89	101	92	100	94	95
WISCONSIN														
1605	94	102	103	95	94	99	101	[3]102	95	101	102	104	98	96
1606	101	93	82	94	88	90	92	96	95	[3]102	100	100	90	96
1608	101	100	107	102	—	[3]110	[3]109	106	109	94	101	101	103	103
1609	96	101	104	101	97	107	111	101	116	100	[3]103	101	101	99
1610	104	105	101	105	106	104	104	104	111	103	104	105	106	105
1611	94	95	104	106	97	107	115	97	[3]113	89	99	91	104	98
MICHIGAN (Upper Peninsula)														
1612	99	104	100	99	106	105	101	104	99	101	100	[3]105	98	100
1613	104	101	102	104	102	96	95	99	90	106	105	103	96	98
1614	97	98	98	97	103	100	98	94	98	98	99	97	92	89
1615	99	97	96	98	100	97	91	98	92	102	98	102	96	97
1621	96	91	94	96	101	93	92	96	95	97	92	97	96	89
MICHIGAN (Lower Peninsula)														
1616	98	99	106	105	102	116	117	109	122	102	107	105	115	[3]119
1617	98	101	100	102	101	114	106	105	118	102	112	104	114	111
1618	99	105	108	99	103	104	106	112	111	106	105	109	[3]108	115
COMMERCIAL SEED SOURCE														
	107	96	104	94	105	97	97	97	102	98	98	101	111	113

[1] Significant differences among seed sources: ** = 1 percent level.

[2] Estimated range (plantation mean $\pm 2\hat{\sigma}_s$).

[3] Seed source nearest planting site (local).

Table 5.—*Average diameter of trees from jack pine seed sources as a percent of the plantation mean*

Seed source	1 Superior NF	2 Chippewa NF	3 Pillsbury SF **[1]	5 General Andrews EF	6 Univ. Minn. CFC	7 Burnett CF **	8 Mosinee IF **	9 Chequamegon NF *	10 Nepco IF **	11 Argonne EF **	12 Marinette CF *	13 Ottawa NF **	15 Univ. Mich. BS*	17 Fife Lake SF **
Mean (in)	3.77	3.59	4.75	3.65	3.88	3.47	3.15	4.16	3.48	4.46	3.99	4.01	3.27	3.31
Range[2] (in)	3.95	3.83	5.37	3.88	4.03	3.75	3.65	4.56	3.82	4.90	4.30	4.43	3.50	3.62
	3.59	2.98	4.13	3.42	3.73	3.19	2.65	3.76	3.14	4.02	3.68	3.59	3.04	3.00
MINNESOTA														
1589	106	94	92	105	93	98	103	105	100	102	100	103	107	104
1590	104	97	93	101	100	96	100	105	91	93	103	97	100	100
1591	100	98	103	101	98	95	96	92	102	90	95	94	95	91
1592	[3]100	105	108	97	99	93	77	91	96	95	96	82	96	92
1593	99	90	80	85	96	95	88	94	88	97	91	86	102	102
1594	97	92	89	94	92	90	78	83	95	91	96	92	90	88
1595	93	109	109	116	99	106	113	104	103	102	104	100	104	110
1596	99	105	95	[3]99	[3]105	99	102	97	98	93	103	103	105	101
1597	99	101	104	100	95	99	101	103	97	105	100	99	96	103
1600	100	101	[3]110	103	101	97	108	108	92	97	107	102	98	95
1601	105	[3]105	97	101	99	100	104	101	103	104	101	104	106	97
1602	106	92	105	98	106	92	87	96	97	93	98	101	99	99
WISCONSIN														
1605	95	103	96	96	99	101	96	[3]102	99	96	105	106	104	101
1606	101	106	95	97	90	98	104	102	108	[3]105	103	104	91	105
1608	101	98	107	97	—	[3]108	[3]104	95	107	95	96	91	104	102
1609	99	100	98	100	112	105	109	104	103	107	[3]104	99	97	97
1610	100	105	109	99	109	97	99	99	101	104	98	103	102	104
1611	105	104	107	113	101	105	105	100	[3]102	98	98	104	98	98
MICHIGAN (Upper Peninsula)														
1612	100	109	109	99	106	106	105	112	103	105	94	[3]107	102	99
1613	101	96	102	103	99	99	95	94	94	103	105	102	97	99
1614	101	95	90	100	99	101	102	91	101	91	99	92	95	94
1615	93	103	92	103	94	98	99	100	96	102	97	103	98	98
1621	94	95	88	98	103	95	102	99	95	99	86	96	98	96
MICHIGAN (Lower Peninsula)														
1616	98	99	113	100	97	109	110	97	111	113	112	109	109	[3]109
1617	109	96	101	105	109	112	103	116	113	113	111	114	110	105
1618	93	105	107	95	100	101	104	107	105	112	101	106	[3]100	115
COMMERCIAL SEED SOURCE														
	103	94	106	102	111	103	97	107	112	102	102	103	100	107

[1] Significant differences among seed sources: * = 5 percent; ** = 1 percent.

[2] Estimated range (plantation mean ± $2\hat{\sigma}_s$).

[3] Seed source nearest planting site (local).

There was a significant negative correlation between average plantation diameter and survival ($r = -0.696$). Thus, considering all 14 plantings as a whole, high mortality resulted in reduced competition and, hence, greater growth. The relation among sources within plantations was much more complex. D.b.h.-survival correlations were significant at six locations; they were negative at the University of Minnesota CFC, Argonne EF, and Ottawa NF, but positive at the Burnett CF, Mosinee IF, and Nepco IF.

Seed sources varied significantly in tree diameter at all locations in Michigan and Wisconsin, but at only one location in Minnesota, the Pillsbury SF (table 5). Variation among sources in diameter was significantly and negatively correlated with average plantation survival, but was not correlated with growing degree days, latitude, or site quality of plantation. Variation among sources was greatest at the Pillsbury SF and least at the Superior NF.

The average of the coefficients of variation among sources over all plantations was significantly less for diameter than for height. This substantiates Funk's (1975) conclusion for white pine that height is a better indication of genetic differences than diameter.

Superiority of trees from local sources was not as evident for diameter as for height. Local sources ranked among the top eight of the 26 sources at only eight locations. They did, however, equal or exceed the average tree diameter of all sources at all locations.

In general, trees from the Lower Michigan sources had the greatest average diameter; at least one of these sources was among the best sources at 10 of the locations, and all three Lower Michigan sources were among the top five sources at the Nepco IF and Argonne EF in Wisconsin, and at the Ottawa NF and Fife Lake SF in Michigan. Source 1595 from Pine County, Minnesota, was among the top five sources at three Minnesota and two northwest Wisconsin locations. And source 1612 from western Upper Michigan was among the five best sources at three locations in Minnesota, three in Wisconsin, and at the Upper Michigan location.

Sources 1595 and 1618, which were among the best in diameter growth at several locations, were among the poorest at the Superior NF. And except at the Superior NF, sources 1592, 1593, and 1594 from northeastern Minnesota were among the five poorest sources at 8, 9, and 11 locations, respectively. Also among the five poorest sources at six locations were 1614 and 1621 from Upper Michigan.

Volume

Volume per tree

Average volume per tree ranged from 0.67 cubic feet at the University of Michigan BS to 2.09 cubic feet at the Pillsbury SF (table 6). Sources varied significantly in volume per tree at all locations except the University of Minnesota CFC, and the combined anlysis showed significant differences among plantations and a significant seed source × location interaction.

Frequently, volume per tree may be affected by stand survival. However, in this study correlations between average seed source volume per tree and survival were significant at only four locations. The correlations between these traits were positive at the Burnett CF, Mosinee IF, and Nepco IF, but negative at the Ottawa NF. Because volume per tree is a function of diameter squared, the relations between survival and diameter at these locations also explain the relations between survival and volume per tree.

The estimated superiority of a source at the top of the distribution (plantation mean + $2\hat{\sigma}_s$) compared with one at the bottom (plantation mean $- 2\hat{\sigma}_s$), as a percent of the plantation mean, varied from 13 percent at the University of Minnesota CFC to 94 percent at the Burnett CF.

Variation among sources within plantations in volume per tree was greater than the variation among sources in survival, height, and diameter. Variation among sources in this trait was not significantly correlated with growing degree days or latitude at the planting site. Unusually large variation among sources in volume per tree occurred at the Pillsbury SF in Minnesota. Not surprisingly, variation among sources in diameter was also greatest at this location. Variation among sources was relatively high at all locations in Wisconsin and in western Upper Michigan, while relatively low at the remaining four locations in Minnesota and at both locations in Lower Michigan. In general, variation among sources in volume per

Table 6.—*Average volume per tree of trees from jack pine seed sources as a percent of plantation mean*

Seed source	1 Superior NF	2 Chippewa NF *	3 Pillsbury SF **	5 General Andrews EF *	5 Univ. Minn. CFC	7 Burnett CF **	8 Mosinee IF **	9 Chequamegon NF **	10 Nepco IF **	11 Argonne EF **	12 Marinette CF **	13 Ottawa NF **	15 Univ. Mich. BS	17 Fife Lake SF **
Mean (cu. ft)	.99	.94	2.09	1.09	1.28	.95	.75	1.36	.89	1.69	1.34	1.36	.67	.69
Range[2] (cu. ft)	1.10	1.08	2.75	1.29	1.36	1.57	1.05	1.70	1.18	2.04	1.62	1.67	.80	.87
	.88	.80	1.43	.89	1.20	.68	.45	1.02	.60	1.34	1.06	1.05	.54	.51
							MINNESOTA							
1589	112	89	85	116	88	95	108	112	97	101	104	105	113	108
1590	107	96	89	101	99	93	102	109	81	90	106	96	101	99
1591	99	98	106	101	100	91	94	85	100	77	87	87	90	83
1592	[3]103	111	113	90	98	79	52	74	86	90	86	65	91	85
1593	101	78	59	65	88	81	68	85	70	92	80	72	97	97
1594	95	79	73	83	81	69	53	64	78	84	85	82	78	73
1595	82	120	120	137	96	117	136	109	110	97	108	100	105	120
1596	101	112	91	[3]103	[3]114	101	108	95	99	88	102	104	107	103
1597	101	104	111	101	92	99	106	107	92	111	99	99	94	102
1600	100	105	[3]127	109	103	98	122	120	82	95	113	104	97	91
1601	115	[3]115	97	100	100	103	108	104	105	111	102	106	115	95
1602	116	82	101	94	110	79	68	87	87	86	90	101	93	93
							WISCONSIN							
1605	87	108	95	89	93	98	91	[3]104	93	94	109	113	104	97
1606	103	103	75	88	77	91	99	101	107	[3]110	105	105	79	104
1608	103	96	119	95	—	[3]122	[3]112	95	122	86	93	84	108	105
1609	94	101	97	99	121	115	122	107	116	111	[3]108	99	95	95
1610	104	113	117	103	121	97	99	99	110	108	99	109	106	110
1611	104	101	114	128	98	114	120	95	[3]113	86	95	98	98	95
							MICHIGAN (Upper Peninsula)							
1612	99	118	116	96	115	114	108	126	103	111	91	[3]116	101	97
1613	106	94	104	108	101	94	87	89	82	110	114	105	92	96
1614	98	89	81	99	99	101	102	80	99	83	97	83	86	82
1615	87	101	82	101	89	93	90	97	86	104	92	108	93	94
1621	87	83	74	92	104	87	95	93	86	94	71	89	94	86
							MICHIGAN (Lower Peninsula)							
1616	94	97	132	103	96	130	129	101	141	125	128	120	128	[3]131
1617	113	92	101	110	116	137	108	136	139	127	131	132	128	117
1618	89	114	121	90	101	104	111	123	120	130	106	118	[3]105	143
							COMMERCIAL SEED SOURCE							
	112	88	113	101	125	101	91	108	124	101	100	105	108	124

[1] Significant differences among seed sources: * = 5 percent; ** = 1 percent.

[2] Estimated range (plantation mean ± $2\hat{\sigma}_s$).

[3] Seed source nearest planting site (local).

tree was greater at locations with high gall rust incidence.

The local source exceeded the plantation average by 3 to 31 percent at all locations and the commercial source by 2 to 27 percent at nine locations. Because volume per tree was determined from the diameter squared and height, ranking of sources for volume per tree was similar to that for diameter.

Volume per acre

In terms of productivity, volume per acre is the most important trait we studied. Average volume per acre ranged from 1,041 cubic feet at the University of Michigan BS in Lower Michigan to 2,012 cubic feet at Marinette CF in northeastern Wisconsin (table 7). The best plantations, Pillsbury SF and the University of Minnesota CFC in Minnesota, and Argonne EF and Marinette CF in Wisconsin, produced 1,899 to 2,012 cubic feet of wood per acre. At each of these locations, average height exceeded 29 feet and average diameter was greater than 3.8 inches. The poorest plantations, Mosinee IF and Nepco IF in Wisconsin, and the University of Michigan BS and Fife Lake SF in Michigan, however, produced only 1,041 to 1,112 cubic feet of wood per acre. Average height at these locations was less than 24 feet while average diameter was less than 3.5 inches. In addition to poor site quality, growth at the Mosinee IF and Nepco IF was probably also affected by high incidence of gall rust and/or other pests.

A combined analysis with data from all locations showed significant differences in this trait among sources and plantations, and a significant seed source × location interation.

Except at the University of Michigan BS, correlations between average seed source volume per acre and height were greater than those between volume per acre and diameter.

Differences in volume per acre among seed sources were considerable at all locations, and statistically significant at 11 locations; variation among sources was not significant at the Chippewa NF, University of Minnesota CFC, and Argonne EF (table 7). The least variation among seed sources in volume per acre occurred at the University of Minnesota CFC, while the greatest variation among sources occurred at the Nepco IF. High variability among sources also occurred at the other plantations having high gall rust incidence, including the Pillsbury SF, Burnett CF, Mosinee IF, and Chequamegon NF. The estimated superiority of a source at the top of the distribution (plantation mean + $2\hat{\sigma}_s$) compared with one at the bottom (plantation mean − $2\hat{\sigma}_s$), as a percent of the plantation mean, was 136 percent at the Nepco IF. Differences of this magnitude indicate that tremendous losses in volume production may occur if the wrong seed sources are used in a planting program.

Local sources yielded the greatest volume per acre at the Superior NF, Chippewa NF, and Pillsbury SF in Minnesota, and at the Ottawa NF in Upper Michigan. Local sources ranked among the 10 best sources at all locations. Local sources exceeded the commercial sources at 11 locations, ranging from 15 percent better at the Fife Lake SF to 51 percent better at the Burnett CF. However, the commercial source produced more wood per acre than the local source at the Superior NF, at the University of Minnesota CFC, and at the University of Michigan BS.

The best seed sources included 1595 and 1600 from Minnesota and 1616, 1617, and 1618 from Lower Michigan. The four northeastern Minnesota sources—1592, 1593, 1594, and 1602—and source 1606 from a cold location in Forest County, Wiscosnin, were the poorest sources overall. However, at the northernmost plantation, Superior NF, sources 1592, 1593 and 1602 were among the best, while sources 1595, 1616 and 1618 were among the worst.

Grouping of Seed Sources

As indicated previously, the sources could be arranged into three broad groups based on simple correlation coefficients among individual sources over the 14 plantations for height, diameter, and volume per tree. Correlations among sources within each group were high whereas correlations among sources in different groups were lower. It turned out that this division of sources coincided with a geographical distribution into a northern group (Group 1 sources), central group (Group 2 sources), and southern group (Group 3 sources) (table 8, fig. 1). They follow in a general way the more detailed seed collection zones developed by Rudolf (1956). The results from this study support the concept of geographic seed zones in jack pine;

Table 7.—*Average volume per acre of trees from jack pine seed sources as a percent of plantation mean*

Seed source	1 Superior NF**[1]	2 Chippewa NF	3 Pillsbury SF **	5 General Andrews EF *	6 Univ. Minn. CFC	7 Burnett CF **	8 Mosinee IF **	9 Chequamegon NF **	10 Nepco IF **	11 Argonne EF **	12 Marinette CF **	13 Ottawa NF **	15 Univ. Mich. BS	17 Fife Lake SF **
Mean (cu. ft)	1408	1330	1899	1616	1900	1420	1061	1493	1045	1968	2012	1814	1041	1112
Range[2] (cu. ft)	1660	1520	2777	1912	[3]1900	1955	1654	2086	1755	2287	2509	2142	1277	1427
	1156	1140	1021	1320	1900	885	468	900	335	1649	1515	1486	805	797
MINNESOTA														
1589	114	91	97	125	91	94	111	119	79	106	110	114	113	111
1590	96	102	100	92	96	94	106	92	73	94	112	97	105	100
1591	106	98	123	105	106	91	95	99	66	72	89	90	86	82
1592	[4]115	106	105	94	102	65	41	55	56	92	79	73	92	86
1593	114	85	59	68	90	68	61	75	38	99	84	83	101	101
1594	104	80	66	80	80	62	41	51	50	87	72	83	78	71
1595	79	119	128	142	102	120	149	120	118	98	108	108	105	119
1596	101	118	111	[4]107	[4]115	105	117	108	113	96	101	101	109	105
1597	95	109	117	100	97	97	106	95	88	111	97	97	94	106
1600	104	113	[4]148	107	100	101	138	129	66	97	115	103	99	92
1601	111	[4]120	113	105	101	106	106	113	93	111	103	97	120	98
1602	115	84	79	97	109	73	50	71	63	100	83	109	88	90
WISCONSIN														
1605	86	108	111	88	92	96	100	[4]118	95	102	108	108	100	93
1606	96	94	38	80	73	86	88	81	93	[4]112	95	103	70	93
1608	103	100	132	93	—	[4]126	[4]125	123	130	86	98	90	112	107
1609	78	102	98	100	105	125	129	106	140	98	[4]108	89	91	93
1610	112	110	87	108	117	100	90	98	139	105	105	93	114	108
1611	97	102	139	109	99	121	139	92	[4]140	63	98	71	101	98
MICHIGAN (Upper Peninsula)														
1612	103	115	67	94	122	111	102	135	102	112	91	[4]129	99	98
1613	110	90	105	110	105	96	82	80	75	110	115	114	90	97
1614	111	94	81	99	98	99	95	87	107	91	91	86	83	80
1615	96	99	84	106	93	94	82	90	95	126	95	115	95	92
1621	93	74	72	99	106	87	83	96	97	105	74	104	101	82
MICHIGAN (Lower Peninsula)														
1616	84	86	111	103	98	135	137	113	187	113	127	110	132	[4]134
1617	90	93	94	95	104	145	113	121	168	100	137	113	122	121
1618	85	106	135	94	100	101	112	132	128	114	106	121	[4]103	141
COMMERCIAL SEED SOURCE														
	119	79	110	91	129	75	79	87	94	94	92	107	107	119

[1] Significant differences among seed sources: * = 5 percent; ** = 1 percent.

[2] Estimated range (plantation mean ± $2\hat{\sigma}_s$).

[3] Estimate of $\hat{\sigma}_s$ is 0 in this case.

[4] Seed source nearest planting site (local).

Table 8.—*Growing degree days and January temperature of seed sources within groups*

Group 1			Group 2			Group 3		
Seed source	Growing degree days	January temp.	Seed source	Growing degree days	January temp.	Seed source	Growing degree days	January temp.
		°F			°F			°F
1592	7,400	10	1589	9,200	5	1595	9,500	10
1593	6,700	14	1590	9,400	7	1608	10,000	10
1594	8,500	5	1591	9,100	5	1609	9,600	14
1602	8,800	6	1596	9,000	9	1611	10,000	13
1606	8,500	12	1597	8,900	4	1616	10,100	22
Average	7,980	9.4	1600	9,400	6	1617	9,600	19
			1601	8,600	5	Average	9,800	14.7
			1605	9,000	13			
			1610	9,000	10			
			1612	8,500	12			
			1613	8,800	15			
			1614	8,100	15			
			1615	8,000	15			
			1618	9,000	19			
			1621	7,900	16			
			Average	8,790	10.4			

based on our data, however, the large number of subdivisions proposed by Rudolf appears to be unwarranted for jack pine.

Group 1 corresponds to Rudolf's collection zones 5 and 6. This group includes the four northeastern Minnesota sources, 1592, 1593, 1594, and 1602, and source 1606 from Forest County, Wisconsin. Although source 1606 does not belong to this group geographically, it does belong to it climatically. Forest County, Wisconsin, is poorly covered by weather stations and many sites in the area are colder than the weather records indicate. Therefore, this seed source is probably characterized by a climate with fewer growing degree days than shown in table 1. Group 1 sources represent the most severe climate, with an average of 7,980 growing degree days and an average January temperature of 9.4°F.

Group 3 corresponds to Rudolf's milder zones 2 and 3. Sources in this group include 1595, 1608, 1609, 1611, 1616, and 1617. These are the sources from the southern portion (mildest climate) of the species range in Minnesota, Wisconsin, and Michigan. Sources 1600, 1610, and 1618 and possibly others appear to be borderline between Groups 2 and 3. Group 3 sources have an average of 9,800 growing degree days and an average January temperature of 14.7°F.

Group 2, which includes the remaining 15 sources, corresponds to Rudolf's broad seed collection zone 4. Group 2 sources have an average of 8,790 growing degree days and an average January temperature of 10.4°F. Variation among Group 2 sources in these climatic variables is considerable

It is obvious that genetic variation in Lake States jack pine is continuous, expressing adaptation to climatic and other environmental factors. In some cases, the species shows adaptation to local conditions—source 1606, for example. Grouping of sources was done to bring out broad patterns of genetic variation.

Table 9 enables comparison of seed source group means for height, diameter, volume per tree, and volume per acre. In each section, column 1 gives the mean value for Group 1; columns 2 and 3 show the ratios of the other two group means to the

Table 9.—*Comparison of seed source groups for height, diameter, and volume*

		Height (Group)			Diameter (Group)			Volume/tree (Group)			Volume/acre (Group)		
	Plantation[1]	1	2	3	1	2	3	1	2	3	1	2	3
		Ft.	*Percent of group 1*		*In.*	*Percent of group 1*		*Ft.*^{3}	*Percent of group 1*		*Ft.*^{3}	*Percent of group 1*	
1	Superior NF	[2]24.0	98	94	3.80	99	100	1.029	96	95	[2]1532	93	81
11	Argonne EF	30.1	101	97	4.29	104	109	1.565	109	114	1931	105	95
2	Chippewa NF	[2]22.7	107	105	3.48	104	104	.854	113	112	1193	115	112
6	Univ. Minn. CFC	[2]28.0	107	105	3.75	103	106	1.166	112	115	1723	113	111
13	Ottawa NF	[2]27.7	108	106	[2]3.74	108	110	[2]1.160	121	124	1635	116	107
17	Fife Lake SF	[2]18.2	106	113	3.22	102	107	.629	109	122	[2]982	112	127
12	Marinette CF	[2]27.4	107	111	3.86	103	108	[2]1.197	112	124	[2]1662	122	136
15	Univ. Mich. BS	[2]17.6	107	114	[2]3.12	105	108	[2].584	114	126	[2]891	118	129
5	General Andrews EF	[2]25.5	109	113	[2]3.43	106	112	[2].919	120	133	[2]1355	122	127
9	Chequamegon NF	[2]24.8	111	114	[2]3.88	108	110	[2]1.122	125	131	[2]995	159	169
3	Pillsbury SF	[2]29.9	113	116	4.53	104	111	[2]1.757	119	135	[2]1320	149	168
7	Burnett CF	[2]22.3	117	128	[2]3.25	106	115	[2].758	122	153	[2]1006	139	182
10	Nepco IF	[2]20.8	113	131	[2]3.38	101	109	[2].760	112	145	[2]628	157	245
8	Mosinee IF	[2]18.6	129	142	[2]2.74	116	123	[2].512	150	179	[2]595	182	236
	Average	24.1	26.3	27.1	3.60	3.78	3.94	1.001	1.156	1.266	1246	1538	1653

[1] Plantations arranged according to magnitude of differences between group means for height and volume per acre.

[2] At least one significant difference exists among groups at 5 percent level.

mean for Group 1 × 100 percent. The least variation among groups occurred at planting sites with fewer than 8,700 growing degree days, and the greatest variation occurred at sites with 9,000 or more growing degree days. Plantings with the greatest variation also had high incidences of gall rust. The sources in Group 1 had the highest rust incidence, while sources 1595, 1608, and 1611 from Group 3 had the lowest rust incidence (King 1971). Genetic variation in susceptibility to rust probably accentuated the differences among groups at locations with high rust incidence, such as the Burnett CF, Mosinee IF, Chequamegon NF, and Nepco IF.

Growing Season and Daylength at Seed Origin

To determine the relation between growing season or daylength at seed origin and performance variables, simple correlations were run for each plantation between (a) growing degree days and daylength (latitude) at seed origin and (b) survival, height, diameter, volume per tree, and volume per acre (table 10). Survival at the Superior NF, General Andrews EF, Argonne EF, and Ottawa NF—four of the coldest locations—was significantly and negatively correlated with growing degree days, and positively correlated with latitude at seed origin. At the Burnett CF, Mosinee EF, and Nepco IF—three of the warmest locations—survival was significantly and positively correlated with growing degree days and negatively correlated with latitude at seed origin.

Height at the Superior NF, Chippewa NF, University of Minnesota CFC, and Argonne EF was not significantly correlated with growing degree days at seed origin. Correlations between these variables at all other locations, however, were significant, with coefficients ranging from 0.44 at the Ottawa NF to 0.80 at the Mosinee IF.

Correlations between height and latitude at seed origin shifted from a significant positive correlation ($r = 0.54$) at the northernmost plantation (Superior NF), through nonsignificant correlations, to increasing negative correlations with decreasing latitude of plantation. These results show that the effect of latitude at seed origin on height varies with latitude at the planting site (fig. 2). Graphs showing equally dramatic shifts could also have been drawn for survival and volume per acre.

At the northernmost plantations, no significant correlations were found between seed source diameter and growing degree days or latitude at seed

Table 10.—*Simple correlation coefficients between variables and (a) degree days or (b) latitude at seed origin*

	Plantation[1]	Growing degree days	Lat.	Survival		Height		Diameter		Vol./tree		Vol./acre	
				Degree days	Lat.	Degree days	Lat.	Degree days	Lat.	Degree days	Lat.	Degree days	Lat.
			°N										
1	Superior NF	7,400	47.6	[2]−0.69	0.63		0.54					−0.47	0.64
2	Chippewa NF	8,600	47.4		.40								
6	Univ. Minn. CFC	8,500	46.7		.41								
3	Pillsbury SF	9,400	46.4			.58		.58	−.43	.62	−.45	.60	
5	General Andrews EF	8,700	46.4	−.45	.50	.75	−.45	.59	−.44	.64	−.42	.44	
9	Chequamegon NF	9,000	46.3	.44		.60	−.58		−.47	.45	−.52	.54	−.49
13	Ottawa NF	8,500	46.3	−.60	.57	.44	−.44	.54	−.61	.52	−.61		
8	Mosinee IF	10,000	46.2	.69	−.54	.80	−.65	.60	−.66	.71	−.68	.76	−.66
11	Argonne EF	8,500	45.8	−.60	.71				−.66		−.56		
12	Marinette CF	9,600	45.7			.60	−.67	.62	−.50	.64	−.59	.66	−.62
7	Burnett CF	10,000	45.6	.76	−.63	.73	−.77	.61	−.82	.68	−.83	.75	−.84
15	Univ. Mich. BS	8,700	45.5			.60	−.63			.49	−.50	.41	−.42
17	Fife Lake SF	9,700	44.5			.58	−.64		−.56	.44	−.63	.45	−.60
10	Nepco IF	10,000	44.2	.52	−.87	.71	−.88	.55	−.71	.66	−.84	.64	−.93

[1]Plantations are arranged from north to south.

[2]Only correlations significant at the 5 and 1 percent levels are given (Significance levels r = 0.39—5 percent, r = 0.50—1 percent).

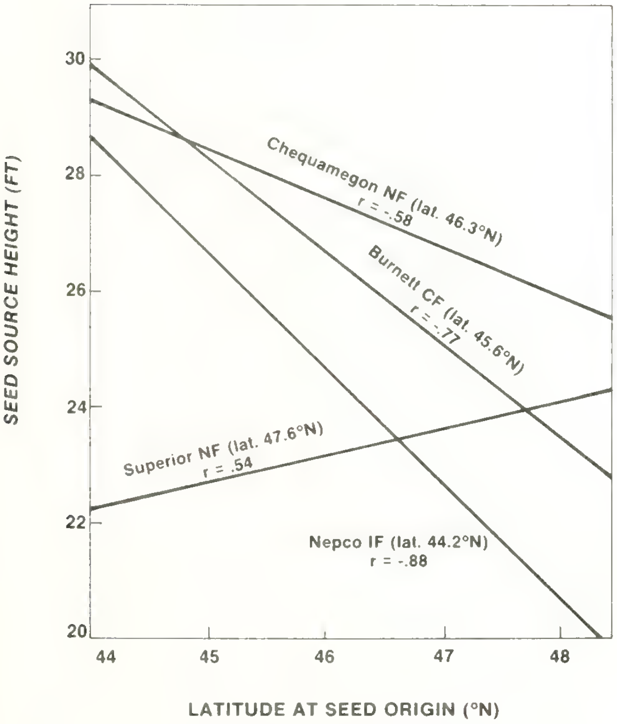

Figure 2.—*Linear regression: average height on latitude at seed source origin.*

origin. At seven of the remaining locations, the correlations between diameter and growing degree days at seed origin varied from 0.54 to 0.62, while the correlations between diameter and latitude tended to increase negatively with decreasing latitude of plantation.

As one might expect, the correlations between volume per tree and growing degree days or latitude were very similar to those between diameter and the latter variables. The correlations between volume per acre and growing degree days or latitude at seed origin were similar to those between height and growing degree days or latitude at seed origin. Only at the Superior NF was the correlation coefficient significant and negative (r = −0.47) for growing degree days at seed origin; at nine of the remaining locations the correlations between volume per acre and growing degree days at seed origin were significant and positive.

Latitude of seed source appeared to influence growth more than growing degree days at seed origin in the northernmost and southernmost plantations, while growing degree days at seed origin appeared to influence growth more than latitude of seed source in middle latitude plantings. The data for height, diameter growth, and volume production of trees from 26 seed sources 20 years after planting add further support to the findings of Morgenstern and Teich (1969) for phenotypic stability of height growth (based on height growth of 16 of the same sources 10 years after planting). Their results and ours show that sources from northeastern Minnesota (Group 1 sources) and from the southern portion of the jack pine range in Minnesota, Wisconsin, and Michigan (Group 3 sources) contribute most to the genotype × environment interactions while those from middle latitudes (Group 2 sources) contribute little to the interactions. Morgenstern and Teich suggested that an apparent reason for these differences is the distance from origin of seed to the planting site (this distance being the least for middle latitude seed sources).

Comparison of Height Growth at 5, 10, and 20 Years

Coefficents of determination ($r^2 \times 100$) between 5-, 10-, and 20-year mean heights among sources at 13 locations are included in table 11. At nine locations, 67 to 92 percent of the variation in height at 20 years was accounted for by height at 10 years. The highest coefficients of determination between 10 and 20 years were found for locations with milder climates. At the coldest locations—Superior NF, Chippewa NF, University of Minnesota CFC, and Argonne EF—less than 60 percent of the variation in height at 20 years could be accounted for by height at 10 years.

Our results indicate that height at age 5 is not a reliable estimate of height at age 20. Less than 67 percent of the variation in height at age 20 could be accounted for by variation in height at age 5.

The coefficients of determination for height at 10 and 20 years for nine locations in the Lake States are similar to or exceed the coefficients of determination for Ontario jack pine heights measured at 11 and 19 years at the Petawawa Forest Experiment Station in Ontario (Yeatman 1974). Therefore, by the time regional jack pine tests are 10 to 15 years old, they can in most cases be used to develop reliable seed source recommendations. Exceptions are tests on the coldest sites, where final differentiation of response may be delayed.

Table 11.—*Coefficients of determination ($r^2 \times 100$) between 5-, 10-, and 20-year mean heights among sources*
(In percent)

	Plantation	5 and 10 years	5 and 20 years	10 and 20 years
1	Superior NF	58	14	41
2	Chippewa NF	35	5	38
3	Pillsbury SF[1]	86	46	74
5	General Andrews EF[2]	56	48	72
6	Univ. Minn. CFC	64	22	58
7	Burnett CF	76	52	81
8	Mosinee IF	49	40	92
9	Chequamegon NF	42	38	86
10	Nepco IF	66	56	76
11	Argonne EF	72	25	49
12	Marinette CF	79	66	83
13	Ottawa NF	55	28	67
17	Fife Lake SF	77	61	90

[1] Heights measured at 5, 11, and 20 years.

[2] Heights measured at 5, 13, and 20 years.

SEED COLLECTION RECOMMENDATIONS

In general, the study results 20 years after planting support the seed collection recommendations made by King (1966) based on results 10 years after planting. If jack pine is to be planted in the Lake States for relatively short rotation pulpwood production (30 to 40 years), the results of this test can be used with confidence.

In any planting program, environmental conditions such as climate, photoperiod, soils, nursery treatment, planting techniques, and damage from insects and diseases interact with the genetic makeup of the plant material and may drastically alter results. To realize the greatest yields in jack pine we must minimize these interactions and we must use the best genetic material for the locale and the best techniques available for raising planting stock and establishing and managing plantations. The first step is careful seed source selection based on the best available information.

Where local seed sources appear to be superior, as in the Minnesota plantations, we recommend using seed from selected stands near the planting site. However, where superiority of nonlocal sources is indicated, as in the Wisconsin plantings, we recommend a cautious approach. In these instances the forest manager might consider mixing seed from selected local stands with seed from the recommended nonlocal seed sources, to insure against possible failure of nonlocal material at later ages.

It is obvious from this study that using the "wrong" seed source will result in considerable volume losses. Using the "right" seed source, however, can result in modest to substantial gains in volume production.

The following recommendations should be followed for planting jack pine in the Lake States:

1. Collect seed from young to middle-aged stands having uniform, normal stocking on good sites.
2. Collect seed from individual trees with good growth and form and little or no evidence of serious pest incidence.
3. In Minnesota use seed collected from selected stands near the planting site.
4. In Wisconsin, at locations having less than 9,100 growing degree days, use seed from selected stands near the planting site and mix with seed from selected proven stands in Upper and Lower Michigan. At warmer locations use seed collected from the southern portion of the species range in Lower Michigan.
5. In Upper Michigan use seed from selected stands near the planting site. In Lower Michigan use seed from the southern portion of the species range in Lower Michigan.

SEED PRODUCTION AREAS

The results of this study can be used to develop jack pine breeding populations for the Lake States. Seed source groups 1, 2, and 3 define effective breeding zones within which we can identify the best stands and best trees on which to base programs for genetic improvement.

The best stands in each breeding zone should be relocated and converted into seed production areas (SPA's). If the original stands are no longer in existence, it may be necessary to use other good jack pine stands in the immediate vicinity. King (1973) recommended that the best stands should be thinned to about 60 trees per acre on the basis of spacing, growth rate, and form. Commercial quantities of seed of better quality than those presently available should be available from these stands within 5 years. When seedlings from these seed collections are available, trees in the SPA's can be harvested and the sites replanted with seedlings originated from the same SPA's. By following this procedure, the genetic integrity of the selected stands will be maintained.

The following stands are recommended for conversion to SPA's:

Zone 1 (Rudolf's (1954) collection zones 5 and 6)
- 1592 Lake County, Minnesota
- 1602 Itasca County, Minnesota

Zone 2 (Rudolf's zone 4)
- 1600 Cass County, Minnesota
- 1610 Oneida County, Wisconsin
- 1612 Gogebic County, Michigan
- 1618 Alpena County, Michigan

Zone 3 (Rudolf's zones 2 and 3)
- 1595 Pine County, Minnesota
- 1596 Pine County, Minnesota
- 1608 Burnett County, Wisconsin
- 1609 Marinette County, Wisconsin
- 1611 Wood County, Wisconsin
- 1616 Manistee County, Michigan
- 1617 Ogemaw County, Michigan

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Variation among Lake States jack pine seed sources in survival, total height, diameter, volume per tree, and volume per acre grown for 20 years at 14 locations in the Lake States are presented and discussed. Seed collection and seed production area recommendations are included.

OXFORD: 232.12:174.7 *Pinus banksiana* (77). KEY WORDS: seed source recommendations, genotype-environment interaction, juvenile-mature correlations, breeding zones.

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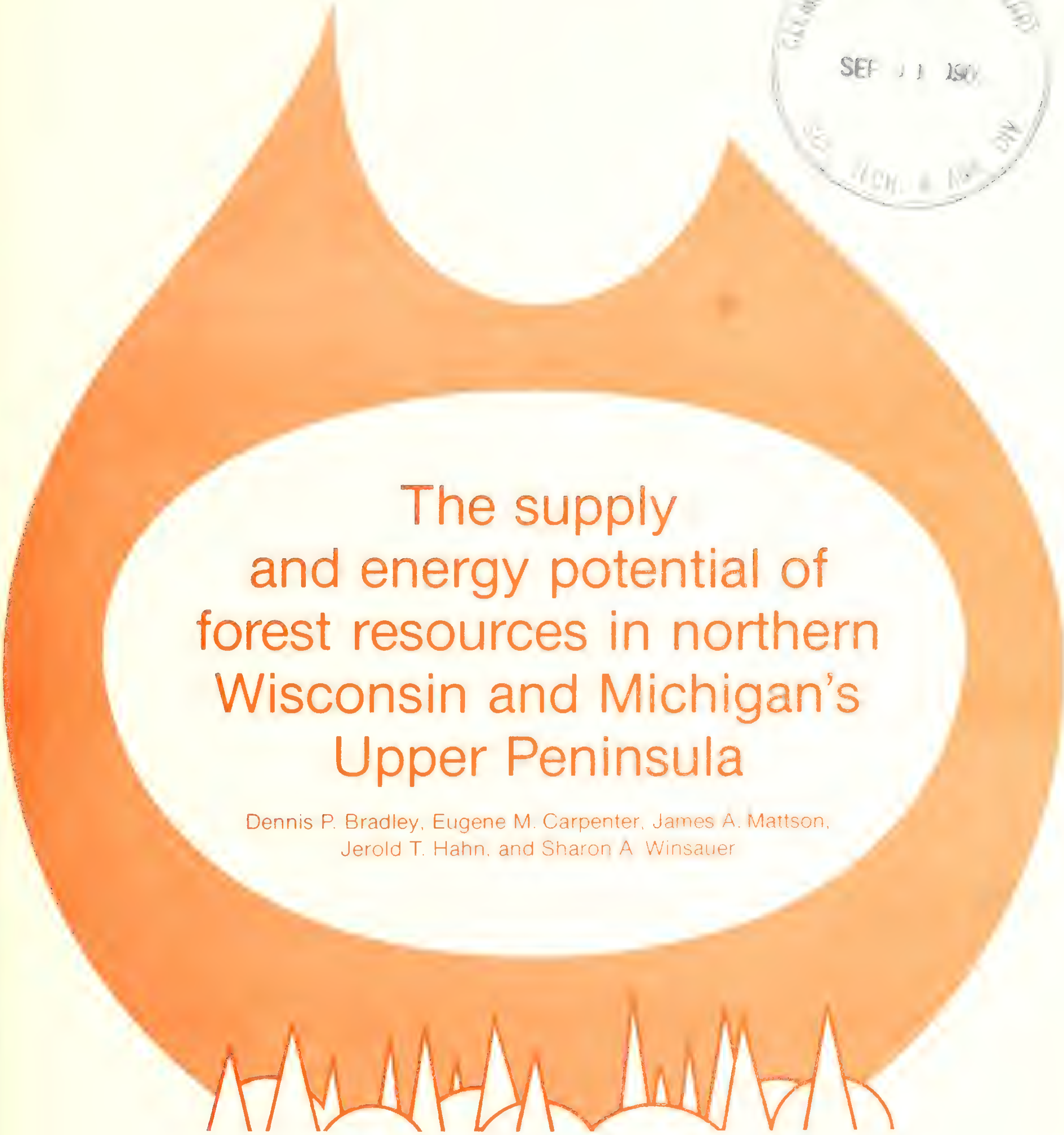

The supply and energy potential of forest resources in northern Wisconsin and Michigan's Upper Peninsula

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THE SUPPLY AND ENERGY POTENTIAL OF FOREST RESOURCES IN NORTHERN WISCONSIN AND MICHIGAN'S UPPER PENINSULA

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Studies have shown that wood fuel has only a small potential for alleviating the national energy shortage; however, the opportunities for the pulp and paper industry are excellent. Because it is close to the wood resource, skilled in wood harvest and transport, familiar with wood properties, and already providing close to half of its energy needs from wood residues, the pulp and paper industry is ideally suited to gain complete energy independence through the use of wood-based fuels.

This report contains two related assessments of forest energy potential. First, a detailed study (fig. 1) was made of Mead Corporation's pulp and paper mill in Escanaba, Michigan. This mill has a procurement area covering most of Michigan's Upper Peninsula and a small part of northeastern Wisconsin. Second, a broader evaluation was made for 10 of the 21 pulp and paper mills in the four Forest Survey Units of northern Wisconsin and Upper Michigan (fig. 2).

For both the case study and the regional analysis, four questions were asked:

1. How much wood is annually harvestable for solid wood products, for wood fiber, and/or wood fuel?
2. How much will it cost to harvest and deliver?
3. What are the energy requirements of the mill or mills, their current sources of energy, and their individual opportunities for converting to wood fuel?
4. At what prices can wood fuel compete with fossil fuels and purchased electricity?

The first two questions address the **supply** of wood and the last two the **demand.**

This study integrates existing forest survey methods, which describe physical characteristics, with methods that add essential economic perspectives. Traditionally, Forest Survey identifies current forest conditions and suggests appropriate strategies for national and regional forest management. Although these analyses have important economic implications, primarily in regard to regional timber balances, they are not designed to answer economic questions of greatest interest to indiviual firms: where is the harvestable timber, and how much will it cost to harvest and transport? While the specific objective of this report is to assess forest energy potentials in northern Wisconsin and Michigan, our approach, which combines silvicultural projections with harvest and transport cost estimates, should have wide application in forest resource appraisals.

The study assumes that field chipping will be a part of all the harvest systems considered and that chips will be produced from the pulpwood portions of trees as well as from branches, tops, rough and rotten trees, and small sound trees. When the quantity of saw logs warrants it, they will be recovered before chips, but round pulpwood **will not** be considered. In other words, only two products will result: saw logs and chips.

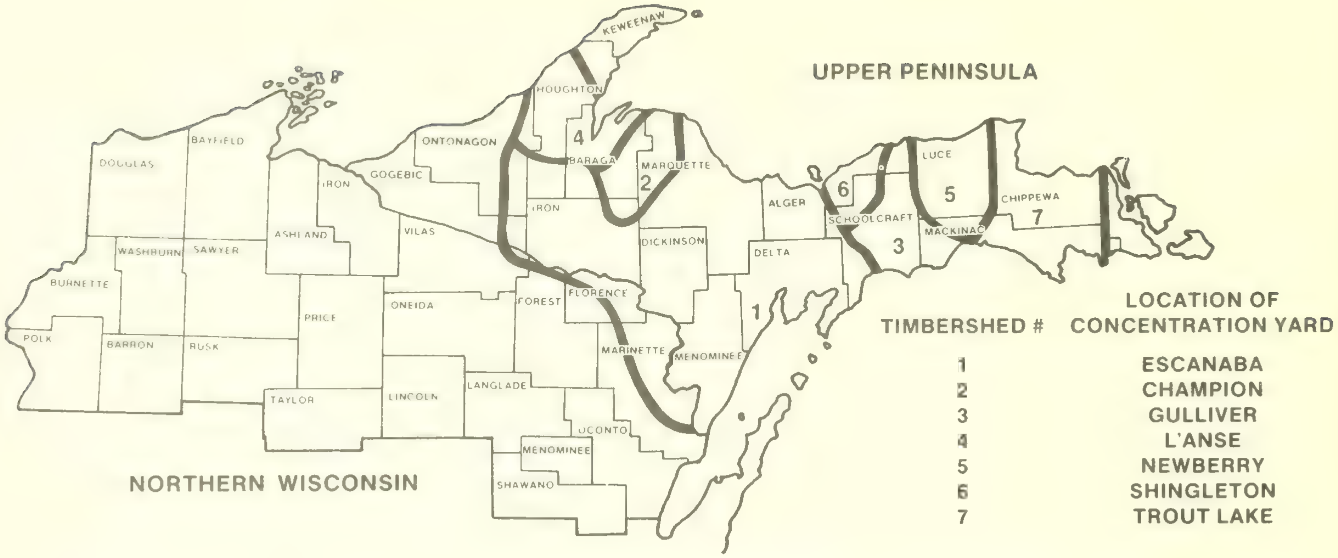

Figure 1.—*Seven timbersheds for Mead Corporation's Escanaba, Michigan, mill.*

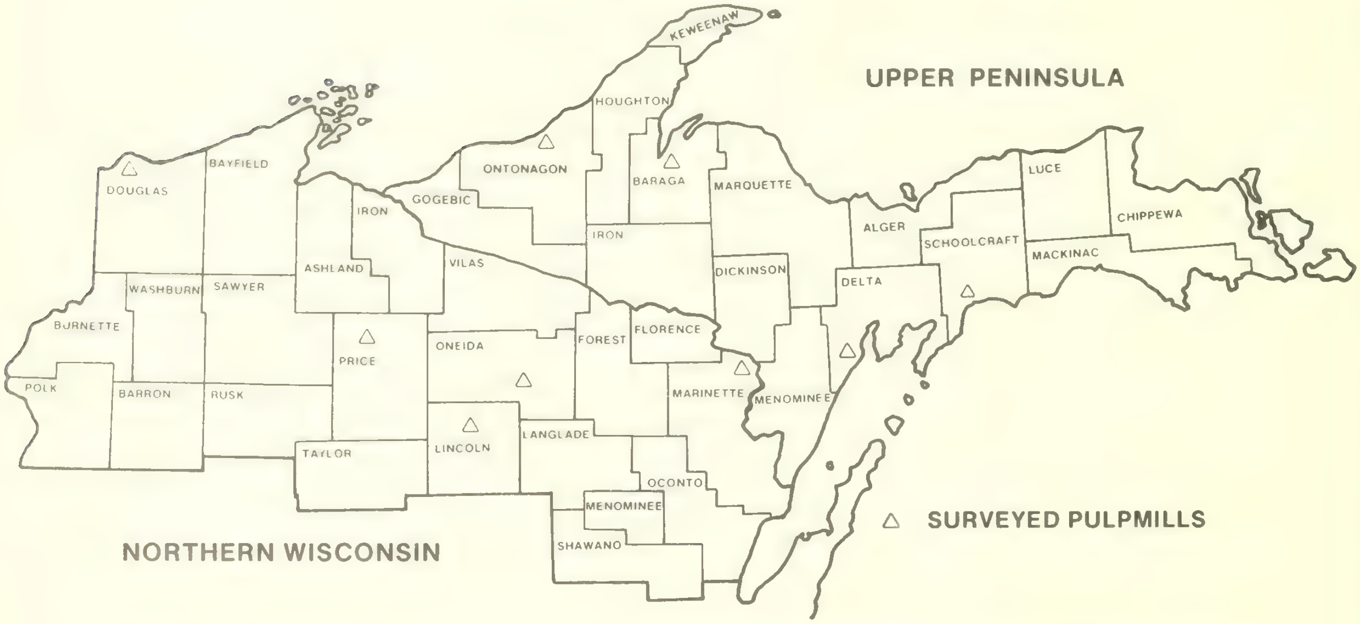

Figure 2.—*Forest residues energy program study area and the locations of surveyed pulpmills.*

This is a considerable departure from current practices. But the productivity of chippers, the rapidly improving technology for cleaning and sorting chips, and the difficulties of recovering branches, tops and similar residues in any other way all point to the need for this assumption. The ultimate use of the chipped portion will depend on many factors, but it seems likely that the industry will find the way to "pulp the best and burn the rest".

METHODS

Five major tasks were carried out for both the regional analysis and Mead case study.

1. Using field plot data, a "managed harvest" procedure was used to calculate the amount of timber that should be cut each year from each of 164 "harvest opportunities". Each harvest opportunity represents the area and timber volume having the same general characteristics such as type, age, size, and stocking. These characteristics in turn determine harvest method as well as harvest costs.

2. Given tree size and stocking characteristics for each of these 164 harvest opportunities, harvest costs were estimated using a computer simulation of the selected harvest systems.

3. Transport cost distributions were determined by measuring the distance from plot to delivery point for all plots in each harvest opportunity and assuming similar distributions of transport costs for all the volume each harvest opportunity represents.

4. A mill energy study based on detailed interviews and a brief engineering analysis was used to estimate total wood requirements and the price that wood residues would have to meet to be competitve for each mill.

5. Finally, mill price and supply curves were compared to see if both fuel and fiber requirements could be met by the forest resource.

Managed Harvest Procedure

Central to this analysis was a "managed harvest" procedure developed by the Renewable Resource Evaluation Project (RREP) of the North Central Forest Experiment Station (NCFES).

It must be emphasized that Managed Harvest is based on existing forest conditions and does not represent a fully regulated or intensively managed harvest level. **However, managed harvest is the amount of timber that should be cut each year for the next 10 years[1] to move the forest toward a more fully regulated condition.** This approach extends previous methods used to calculate "allowable" or "desirable" cut. In simplest terms, **a regulated forest** has an even distribution of trees in each age class, and a constant proportion is harvested each year and immediately regenerated to begin the cycle anew. **An unregulated forest,** in contrast, has an uneven distribution of age classes which, if harvested under strict age or tree size rules, would result in widely fluctuating annual harvests. By this definition, existing forests, whether public or private, are generally unregulated.

Previous measures of timber supply conducted by the NCFES in Michigan and Wisconsin provided almost 4,700 sample plots for this study. In addition, 4,300 sample plots were provided from surveys carried out by the State of Michigan and Mead Corporation, for a total of 9,000 plots.

Deciding how to achieve a more regulated forest requires a set of rules for determining how each timber stand should be treated in the next 10-year planning period. The set of rules we used was adopted from guides used on National Forests in the Lake States and follows recommended silvicultural practices (table 1). From this regional consensus, 20 type/site index combinations were identified. Each combination elicits a recommendation from the guide—whether to cut it, thin it, or leave it alone. An example of the guide recommendations for the paper birch type is shown in a "decision tree" format (fig. 3).

Based on the timber management guides and the two basic silvicultural systems practiced in the Lake States (even-aged and uneven-aged management), three harvest methods were assumed for this study:

1. **Clear cutting of:** Even-aged types at or past rotation age, any stand so poorly stocked that maintaining the few trees to rotation age is not economical, and stands judged unsuitable for the site (should be converted to another type).
2. **Thinning of:** Selected types (both even-aged and uneven-aged) of less than rotation age or mature size, but for which stocking is too dense for best growth.
3. **Selection improvement cutting of:** Saw log stands of northern hardwood, oak-hickory, and swamp hardwood types. In this category, harvesting will be assumed to take place in two stages. First, because full-tree skidding of large, mature trees damages residual crop trees, saw log trees will be cut manually, bucked in the woods, and forwarded as logs to the landing. Second, a mechanized relogging operation will recover saw log tops, cull trees, and undersized trees scheduled for cutting.

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[1] *Ten years is an arbitrary projection period based on the current Renewable Resource Evaluation Project schedule to remeasure each State. In 10 years, a new survey will identify different forest conditions and calculate a new managed harvest.*

Table 1.—*Timber management guide summary*[1]

Forest type	Site index	Rotation age	Management objective[2]	Schedule of intermediate cuts		
				Stand age	Minimum BA	Residual BA
		Years		*Years*	------------ *sq. ft./acre*	------------
Jack pine	<60	50	PW	([3])	—	—
	60+	60	PW	([3])	—	—
Red pine	all sites	100	ST	0-20	([4])	—
				20-90	100	90
White pine	all sites	120	ST	20-110	130	110
Balsam fir	all sites	50	PW	([3])	—	—
White spruce	all sites	90	ST	35-80	130	100
Black spruce	<40	100	PW	([5])	—	—
	40+	70	PW	([5])	—	—
Tamarack	all sites	100	PW	([5])	—	—
Northern white-cedar	all sites	100	ST	([5])	—	—
Aspen	<60	40	PW	([3])	—	—
	60+	50	PW/ST	([3])	—	—
Paper birch	<60	50	PW	([3])	—	—
	60+	80	ST	30-50	95	70
Swamp hardwoods	all sites	120	ST	30-100	100	75
Oak	<60	—	convert	([6])	—	—
	60+	100	ST	30-60	115	90
				70-80	90	65
				90	75	45
Northern Hardwoods	<45	—	convert	([6])		
	45+	([7])	ST	all ages	110	90
Nonstocked[8]	all sites	—				

[1] All stands at or above rotation age are clearcut.

[2] ST = Sawtimber PW = Pulpwood.

[3] No intermediate cuts, clearcut at rotation age.

[4] Remove overstory if one remains.

[5] No intermediate cuts, strip cut at rotation age.

[6] Clearcut and convert to a more desirable type.

[7] The objective is to achieve and maintain 90 sq. ft of basal area distributed 60 sq. ft. in sawtimber, 20 sq. ft. in poletimber, and 10 sq. ft. in samplings. All cull and short log trees are removed first.

[8] These stands have less than the minimum basal area required for type classification.

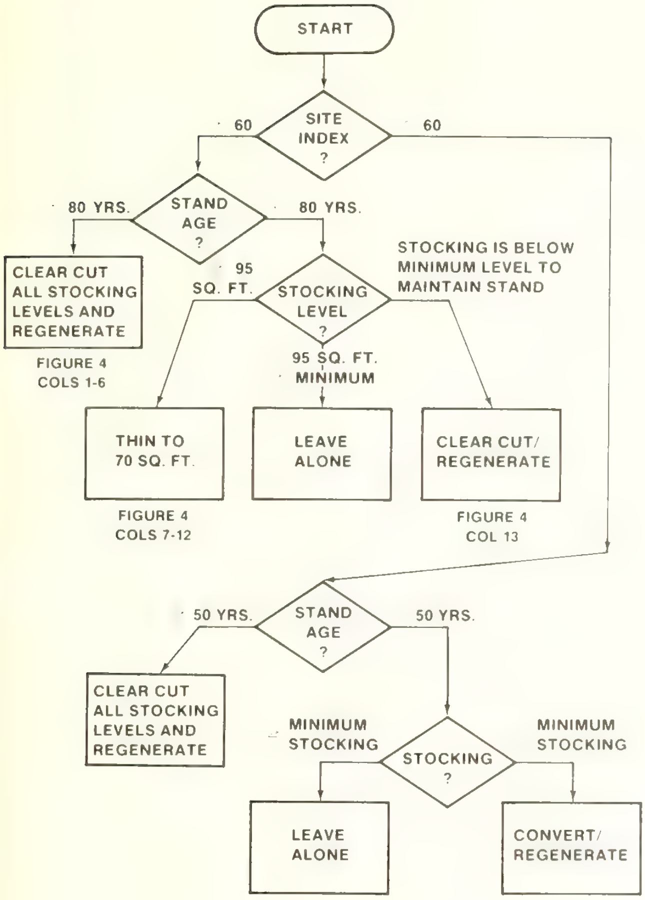


Figure 3.—*Management guide for paper birch type.*

Ordinarily, a calculation of harvested volume includes only sound, straight portions of trees—material larger than 4 inches for pulpwood, 7 inches for softwood saw logs, and 9 inches for hardwood saw logs. It ignores rough, rotten, and short-log trees, cull sections, branches, tops, and trees less than 5 inches d.b.h. In addition, areas with less than 3 cords of "usable" material per acre are considered uneconomical to log and are left out. However, because fuel is an ideal use for much of this material, our analysis of plot data includes these very significant quantities.

In this report, managed harvest tonnages are presented in terms of (1) saw log portions of trees, (2) pulpwood portions of trees, (3) rough and rotten trees, (4) branches, tops, and saplings (trees less than 5 inches d.b.h.).

Forest Survey has traditionally measured volume in cubic feet. However, in this study the green weight per cubic foot was determined for each species in the study area; these factors were used to convert volume to weight:

Species	Pounds/cu. ft.
White pine	37
Red pine	49
Jack pine	40
White spruce	36
Black spruce	42
Balsam fir	46
Hemlock	50
Tamarack	48
Northern white-cedar	32
Oak	60
Yellow birch	56
Sugar maple	56
Red maple	51
Beech	58
White ash	48
Black ash	52
Balsam poplar	50
Cottonwood	48
Paper birch	52
Bigtooth aspen	49
Quaking aspen	47
Basswood	44
Black cherry	48
Elm	55

Harold Young at the University of Maine was the principal source of information for developing crown and sapling weight estimates. A universal equation (Young 1977) relating d.b.h. to complete tree weight in pounds was modified to determine total tree weight by d.b.h. for all species. Correction factors were then used to adjust these weights for individual species. Young estimates total tree weight to be distributed 20 percent stump and roots, 55 percent bole, and 25 percent tops and limbs. When only above-stump components are considered, the distribution is approximately 69 percent bole and 31 percent tops and limbs. Based on this distribution, the top and limb weight was estimated from the bole weight. These crown weights were then adjusted for poletimber and sawtimber trees, by species, using factors developed from various biomass studies.

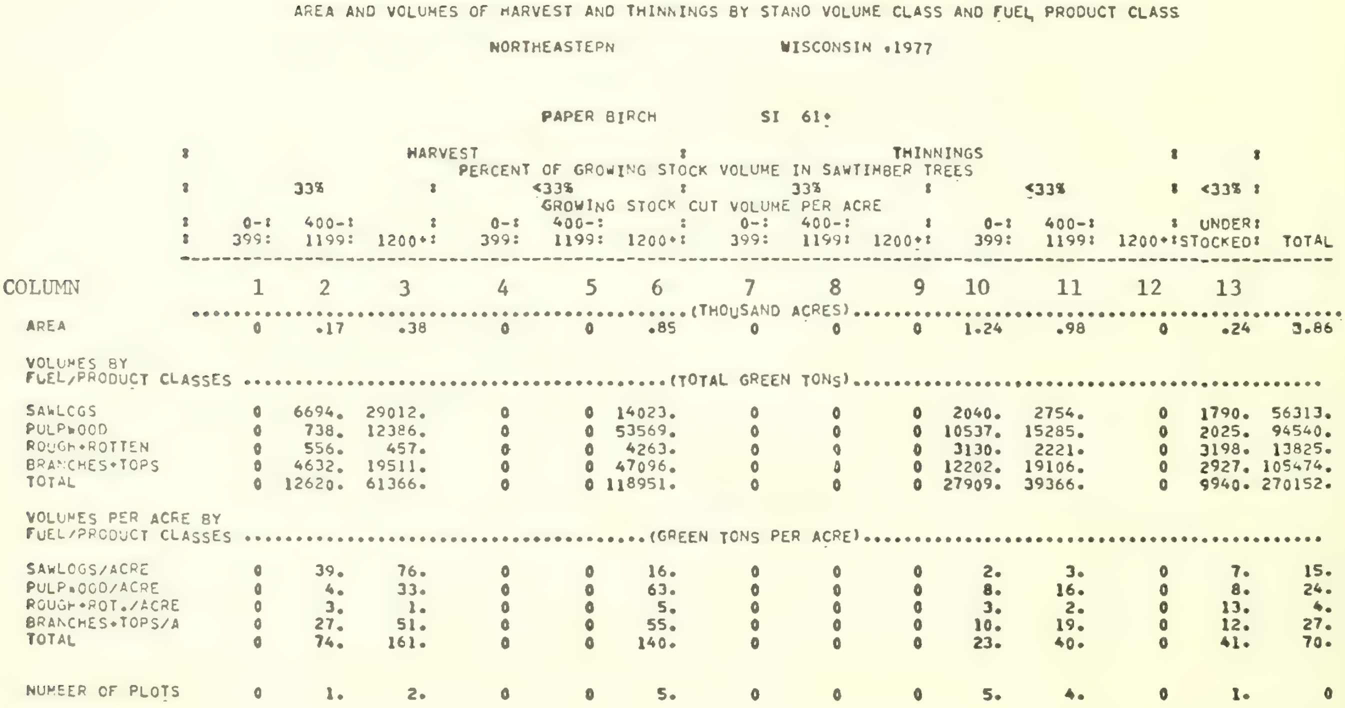
Based on the timber management guides, the managed harvest program, and the inventory plots, we developed a set of 20 computer-generated type/site index tables. The general characteristics of these tables are shown for paper birch/site index ≥ 60 (fig. 4). Each table has 13 columns summarizing area, total tonnage, tons per acre, and other average stand characteristics. Columns one through six report areas and tonnages from clear cuttings. Columns seven through 12 report areas and tonnages from thinnings of stands that are to continue in the same type and for which management will proceed normally to rotation. Column 13 reports tonnages and areas too sparse to justify maintaining them to merchantable sizes.

Altogether, there are 260 possible columns summarizing harvest opportunities. However, because some types never require a thinning and other existing types will not be maintained, the number of harvest opportunities can be reduced to 164. Average d.b.h. and basal area for each of these 164 harvest opportunities are used in the subsequent estimation of harvest costs.

Harvest Costs

Using a computer-based harvest system simulator, which models the harvesting equipment and production in various stands, harvest costs were estimated for each of the 164 harvest opportunities. The simulators used in this study were written in GPSS (IBM 1974) and represent the activities of the machines and operating rules for harvesting various stands of trees (Bradley *et al.* 1976, Bradley and Winsauer 1976a). These models duplicate the essential features of typical whole-tree chipping systems and the relogging harvest system.

Thirty-three hypothetical stands representing most combinations of six average stand diameters (3 to 18 inches d.b.h.) and six basal areas (30 to 180 square feet) were developed. Selected characteristics of these stands are shown in table 2.



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                          AREA AND VOLUMES OF HARVEST AND THINNINGS BY STAND VOLUME CLASS AND FUEL PRODUCT CLASS

                                         NORTHEASTEPN                   WISCONSIN .1977


                                                     PAPER BIRCH           SI  61.

                  :                   HARVEST                     :                  THINNINGS                :        :
                                         PERCENT OF GROWING STOCK VOLUME IN SAWTIMBER TREES
                  :        33%         :           <33%           :        33%        :         <33%          :  <33%  :
                                              GROWING STOCK CUT VOLUME PER ACRE
                  :    0-:   400-:           :    0-:   400-:           :    0-:   400-:        :    0-:   400-:        :  UNDER:
                  :   399:   1199:   1200+:   399:   1199:   1200+:   399:   1199:  1200+:   399:   1199:  1200+:STOCKED:  TOTAL
                  -------------------------------------------------------------------------------------------------------------
COLUMN                 1      2       3        4        5      6        7       8       9     10       11      12      13

                  ..........................................(THOUSAND ACRES)...............................................
  AREA                 0    .17     .38        0        0    .85        0       0       0   1.24      .98       0     .24    3.86

  VOLUMES BY
  FUEL/PRODUCT CLASSES .....................................(TOTAL GREEN TONS).........................................

  SAWLOGS              0  6694.  29012.        0        0 14023.        0       0       0  2040.    2754.       0   1790.  56313.
  PULPWOOD             0   738.  12386.        0        0 53569.        0       0       0 10537.   15285.       0   2025.  94540.
  ROUGH+ROTTEN         0   556.    457.        0        0  4263.        0       0       0  3130.    2221.       0   3198.  13825.
  BRANCHES+TOPS        0  4632.  19511.        0        0 47096.        0       0       0 12202.   19106.       0   2927. 105474.
  TOTAL                0 12620.  61366.        0        0 118951.       0       0       0 27909.   39366.       0   9940. 270152.

  VOLUMES PER ACRE BY
  FUEL/PRODUCT CLASSES ...................................(GREEN TONS PER ACRE).......................................

  SAWLOGS/ACRE         0    39.     76.        0        0    16.        0       0       0     2.       3.       0      7.     15.
  PULPWOOD/ACRE        0     4.     33.        0        0    63.        0       0       0     8.      16.       0      8.     24.
  ROUGH+ROT./ACRE      0     3.      1.        0        0     5.        0       0       0     3.       2.       0     13.      4.
  BRANCHES+TOPS/A      0    27.     51.        0        0    55.        0       0       0    10.      19.       0     12.     27.
  TOTAL                0    74.    161.        0        0   140.        0       0       0    23.      40.       0     41.     70.


  NUMBER OF PLOTS      0     1.      2.        0        0     5.        0       0       0     5.       4.       0      1.      0
```

Figure 4.—*Managed harvest output table for paper birch/site index 60.*

Table 2.—*Selected characteristics of the 33 test stands used in the harvest simulation*

Average d.b.h.	Average height	Basal area (square feet per acre) 30	60	90	120	150	180
TREES PER ACRE (number)							
Inches	*Feet*						
3	39	486	967	1,452	—	—	—
6	43	129	265	395	526	660	790
9	51	61	123	186	246	308	370
12	57	36	72	108	143	179	215
15	62	24	47	71	94	118	141
18	66	17	34	50	67	84	101
GROSS VOLUME (cubic feet per acre)							
3	39	613	1,221	1,833	—	—	—
6	43	756	1,511	2,267	3,023	3,778	4,534
9	51	896	1,793	2,689	3,585	4,482	5,378
12	57	1,002	2,005	3,007	4,009	5,012	6,014
15	62	1,086	2,171	3,257	4,342	5,428	6,513
18	66	1,182	2,363	3,545	8,727	5,908	7,090
TREE SPACING (feet)							
3	39	9.5	6.7	5.5	—	—	—
6	43	18.4	12.8	10.5	9.1	8.1	7.4
9	51	26.7	18.8	15.3	13.3	11.9	10.7
12	57	34.8	24.6	20.1	17.5	15.6	14.2
15	62	42.6	30.4	24.8	21.5	19.2	17.6
18	66	50.6	35.8	29.5	25.5	22.8	20.8

Detailed machine speeds and capacities were collected from a number of sources and supplied to the simulator. Machine operating characteristics are as follows:

Two feller bunchers were considered in this study. The first is a rubber-tired, frame-steered machine with an accumulating shear mounted in front. This machine must drive up to each tree. The second feller buncher has a rotating boom and accumulating shear mounted on crawler tracks. It does not have to approach each tree, but can swing and extend the shear while maintaining a fairly straight path.

Bunches are picked up with an hydraulic grapple mounted on a rubber-tired, frame-steered skidder. Only one kind and size of skidder was considered in this analysis. At the landing, bunches are disassembled by the chipper's loader, chipped and blown immediately into a waiting van. When warranted, saw logs are first bucked, set aside and only the tops are chipped.

Two chipper sizes were used, based on maximum acceptable butt diameter: small (12 inches and less) and large (22 inches and less).

Full-tree skidding and saw log sorting at the landing in thinned or selectively cut sawtimber stands of oak-hickory, northern hardwoods, and swamp hardwoods result in too much damage to remaining crop trees. For these types, and in stands with average d.b.h. greater than 9 inches and basal areas in excess of 90 square feet, saw logs are assumed to be removed by a short log operation, with the remaining material harvested by a topwood harvester.

The topwood harvester which is undergoing development at the Forest Engineering Laboratory in Houghton, Michigan, has a rotatable and highly maneuverable shear mounted on a rubber-tired, frame-steered chassis. In addition to felling and bunching non-saw-log trees, its flexible shear is used to sever large limbs and compact the tops from the large sawtimber trees cut earlier. The compacted tops and other smaller trees can then be removed with little damage to the remaining stand.

Given the equipment specifications and test stands, the simulator was used to select the combination of equipment that produced maximum net revenue per hour for each of the three harvest methods. Tables 3, 4, and 5 show the configuration, productivity, and cost of each system finally chosen. These decisions were reached by the following procedures:

1. Costs per hour were calculated for each machine, based on estimated purchase price, machine life, scheduled and actual hours to be worked each year, and cost of repairs, wages, insurance, taxes, fuel, and lubricants.

2. Overhead costs and a margin for profit and risk were added to machine costs.

3. Various combinations of machines, their speeds, capacities, costs, and the stand description were tested by the simulator. Each computer run resulted in an estimate of production per hour in cubic feet and tons. Because the chipper was the limiting factor, the number of skidders was increased until skidder output closely matched the chipper and net revenue per hour was maximized.

4. The simulated production rates were adjusted to realistic levels using industry-developed estimates of achievable operator efficiency and machine utilization.

Table 3.—*Harvest systems selections—equipment, output, and cost—for clearcuts*

SYSTEM OUTPUT (green tons per hour)

	Basal area (square feet per acre)					
D.b.h.	**30**	**60**	**90**	**120**	**150**	**180**
3[1]	6.00R[2]	6.03R	5.95R	—	—	—
6	22.34R	23.19R	19.89	20.46	22.15	22.66
9	35.93R	38.13R	33.85	34.44	36.10	36.78
12	46.40R	43.39	48.80	51.56	53.49	55.11
15	61.43	65.84	68.24	71.83	73.49	74.42
18	85.93	86.19	91.42	94.91	00.67	02.54
SYSTEM COST (dollars per green ton)						
3[1]	20.78R	20.40R	20.43	—	—	—
6	8.03R	7.56R	8.60	8.38	7.82	6.72
9	4.74R	4.39R	4.81	4.70	4.49	4.40
12	3.56R	3.69	3.28	3.08	2.96	2.87
15	2.78	2.43	2.33	2.19	2.13	2.10
18	2.05	1.91	1.74	1.65	1.56	1.50

[1] Two skidders and small chipper; for all other diameters, 3 skidders and large chipper.

[2] R = rubber-tired feller-buncher; No R = track-type feller buncher.

Table 4.—*Harvest system selections-equipment, output, and cost for thinning*

SYSTEM OUTPUT (green tons per hour)

	Basal area (square feet per acre)				
D.b.h.	**60**	**90**	**120**	**150**	**180**
6[1]	22.40R[2]	22.80R	23.20R	23.20R	24.40R
9	34.50R	37.60R	38.70R	38.90R	39.06R
12	47.07R	54.29R	54.89R	46.44	48.77
15	62.45	61.61	61.52	68.81	66.49
18	82.85	86.13	84.21	90.37	91.43
SYSTEM COST (dollars per green ton)					
6[1]	7.95R	7.71R	7.46R	7.34R	7.05R
9	4.95R	4.47R	4.31R	4.22R	4.17R
12	3.54R	3.03R	2.96R	3.44	3.27
15	2.77	2.68	2.61	2.33	2.38
18	2.11	1.91	1.94	1.79	1.74

[1] For all diameters, 3 skidders and large chipper.

[2] R = rubber-tired feller-buncher; No R = track-type feller buncher.

Table 5.—*Harvest system selections—equipment[1], output, and cost for relogging*

SYSTEM OUTPUT (green tons per hour)

	Basal area (square feet per acre)			
D.b.h.	**90**	**120**	**150**	**180**
9	15.28	15.28	15.28	15.28
12	13.96	13.96	13.96	13.96
15	16.05	16.05	16.05	16.05
18	22.05	22.05	22.50	22.05
SYSTEM COST (dollars per green ton)				
9	13.85	12.77	12.41	12.16
12	13.35	12.99	12.87	12.71
15	11.21	11.00	10.76	10.73
18	8.11	8.04	8.00	7.94

[1] Equipment used: 1 topwood harvester, 3 grapple skidders, 1 large chipper, for all conditions.

Because the sawmill industry is concerned about the loss of saw logs due to field chipping, we identified stand conditions that would justify sorting saw logs before chipping. First, all species were ranked by their relative "woods run" saw log prices. Second, 2,000 board feet or roughly 10 tons per acre was arbitrarily chosen as the minimum tonnage recoverable during chipping for the most valuable saw logs. The minimum recoverable tonnages for the other types were then ranked accordingly:

Type	**Minimum saw log tonnage per acre**
Jack pine	no saw logs recovered
Red pine	12
White pine	12
Balsam fir	no saw logs recovered
White spruce	15
Black spruce	no saw logs recovered
Tamarack	no saw logs recovered
Northern white-cedar	10
Aspen	20
Paper birch	10
Elm-ash-cottonwood	15
Oak-hickory	10
Northern hardwoods	10

Finally, after all 164 harvest opportunities were matched to the proper cell in the three harvest-cost matrixes, all stands not relogged and having more than the minimum saw log tonnage for the type were assumed to be harvested by a field chipping and saw log sorting system. The cost of chips from this combined operation was increased as follows:

$$\text{Cost of chips} = \text{"chips-only" cost/ton} \times \left(\frac{1 + \text{sawtimber tons/acre}}{\text{total tons/acre}}\right).$$

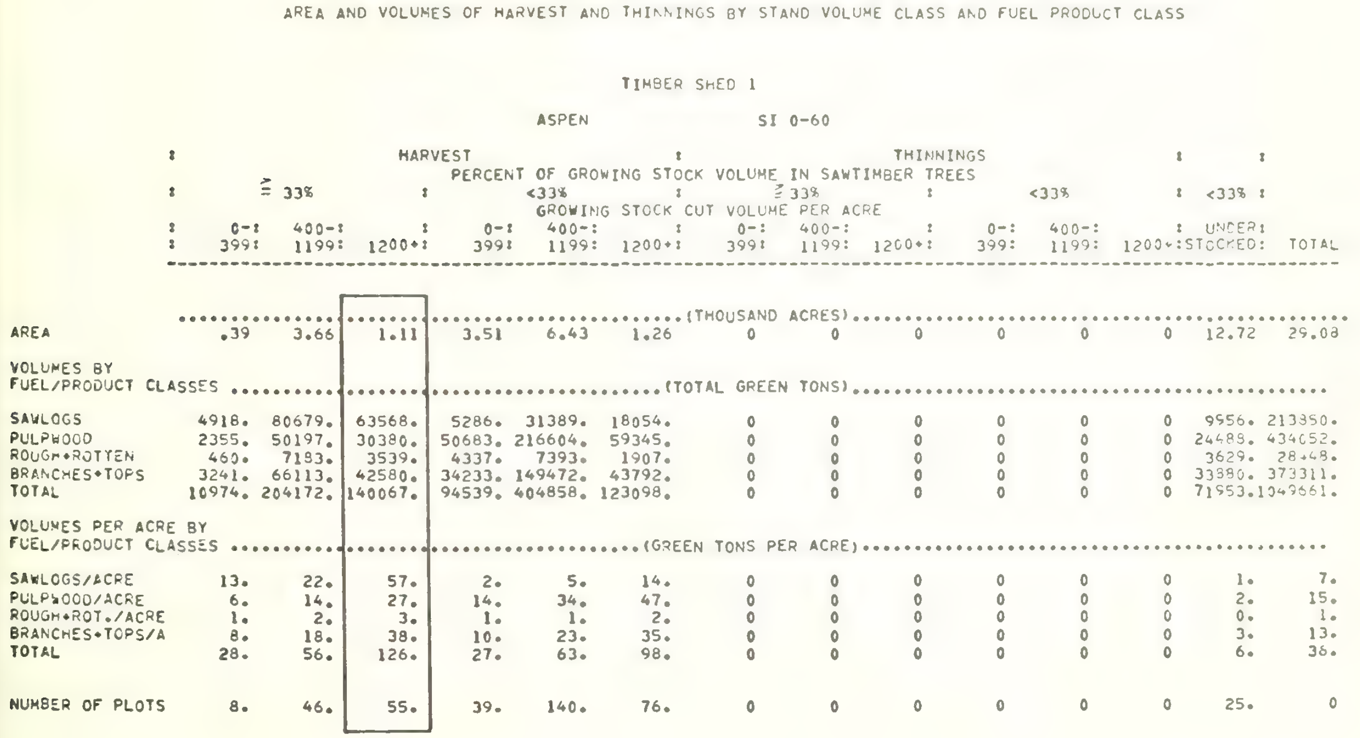
Thus, if an aspen stand had a "chips-only" cost of $6.00/ton, a sawtimber volume of 26 tons/acre, and a total volume of 100 tons/acre, the cost of chips from the saw log and chip operation would be $6.00 $\times \left(1 + \frac{26}{100}\right) =$ $7.56/ton.

Transport Costs

Recall that each harvest opportunity summarizes the acreage and volume of an entire type/site index, age, harvest method, cutting level, etc. Some of the stands in a harvest opportunity are close to the road and to delivery points, while others are far away. By measuring the transport distance from each plot to delivery point, we were able to estimate the distribution of transport distances and costs for each harvest opportunity. The process required one assumption: total harvestable areas and tonnages in the entire harvest opportunity are distributed by distance and cost to delivery point in the same proportion as sample plot areas and tonnages.

In the Mead case study, distances from the plots in each of seven timbersheds were measured to the mill or concentration yard. For the regional analysis, because eventual delivery points were unknown, distances were measured from each plot to the county center. However, when managed harvest was summarized for each survey unit, all counties were combined into one transport cost distribution. The analysis assumed that all chipped material would be hauled in 35-ton vans using per-ton charges provided by Mead Corporation.

An example of managed harvest output is shown in figure 5 for Mead timbershed 1 (aspen-type/site index < 60). The boxed-in portion (column 3) shows one harvest opportunity. Using a "harvest and transport cost program" based on a method called ACCESS (Bradley 1972), the 55 plots from column 3 in the managed harvest table were distributed in a "harvest and transport cost table" (fig. 6). Each plot represents 1/55 of the area in column 3, but the plots are now distributed across the table by distance to delivery point.



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                        AREA AND VOLUMES OF HARVEST AND THINNINGS BY STAND VOLUME CLASS AND FUEL PRODUCT CLASS


                                                         TIMBER SHED 1

                                                ASPEN                   SI 0-60

                   :                    HARVEST                   :                  THINNINGS                   :        :
                                            PERCENT OF GROWING STOCK VOLUME IN SAWTIMBER TREES
                   :       ≥ 33%          :           <33%         :          ≥ 33%         :          <33%          :  <33% :
                                             GROWING STOCK CUT VOLUME PER ACRE
                   :    0-:   400-:       :     0-:   400-:        :    0-:   400-:        :    0-:   400-:        : UNDER:
                   :   399:   1199:  1200+:    399:   1199:  1200+:    399:   1199:  1200+:    399:   1199:  1200+:STOCKED:  TOTAL
                   ------------------------------------------------------------------------------------------------------------------


                   ..................................................(THOUSAND ACRES)...............................................
AREA                    .39   3.66   1.11     3.51    6.43    1.26      0       0       0       0       0       0   12.72   29.08

VOLUMES BY
FUEL/PRODUCT CLASSES ..............................................(TOTAL GREEN TONS).............................................

SAWLOGS              4918.  80679.  63568.   5286.  31389.  18054.      0       0       0       0       0       0   9956. 213350.
PULPWOOD             2355.  50197.  30380.  50683. 216604.  59345.      0       0       0       0       0       0  24488. 434052.
ROUGH+ROTTEN          460.   7183.   3539.   4337.   7393.   1907.      0       0       0       0       0       0   3629.  28448.
BRANCHES+TOPS        3241.  66113.  42580.  34233. 149472.  43792.      0       0       0       0       0       0  33380. 373311.
TOTAL               10974. 204172. 140067.  94539. 404858. 123098.      0       0       0       0       0       0  71953.1049661.

VOLUMES PER ACRE BY
FUEL/PRODUCT CLASSES ............................................(GREEN TONS PER ACRE)............................................

SAWLOGS/ACRE           13.     22.     57.      2.      5.     14.      0       0       0       0       0       0      1.      7.
PULPWOOD/ACRE           6.     14.     27.     14.     34.     47.      0       0       0       0       0       0      2.     15.
ROUGH+ROT./ACRE         1.      2.      3.      1.      1.      2.      0       0       0       0       0       0      0.      1.
BRANCHES+TOPS/A         8.     18.     38.     10.     23.     35.      0       0       0       0       0       0      3.     13.
TOTAL                  28.     56.    126.     27.     63.     98.      0       0       0       0       0       0      6.     36.


NUMBER OF PLOTS         8.     46.     55.     39.    140.     76.      0       0       0       0       0       0     25.      0
```
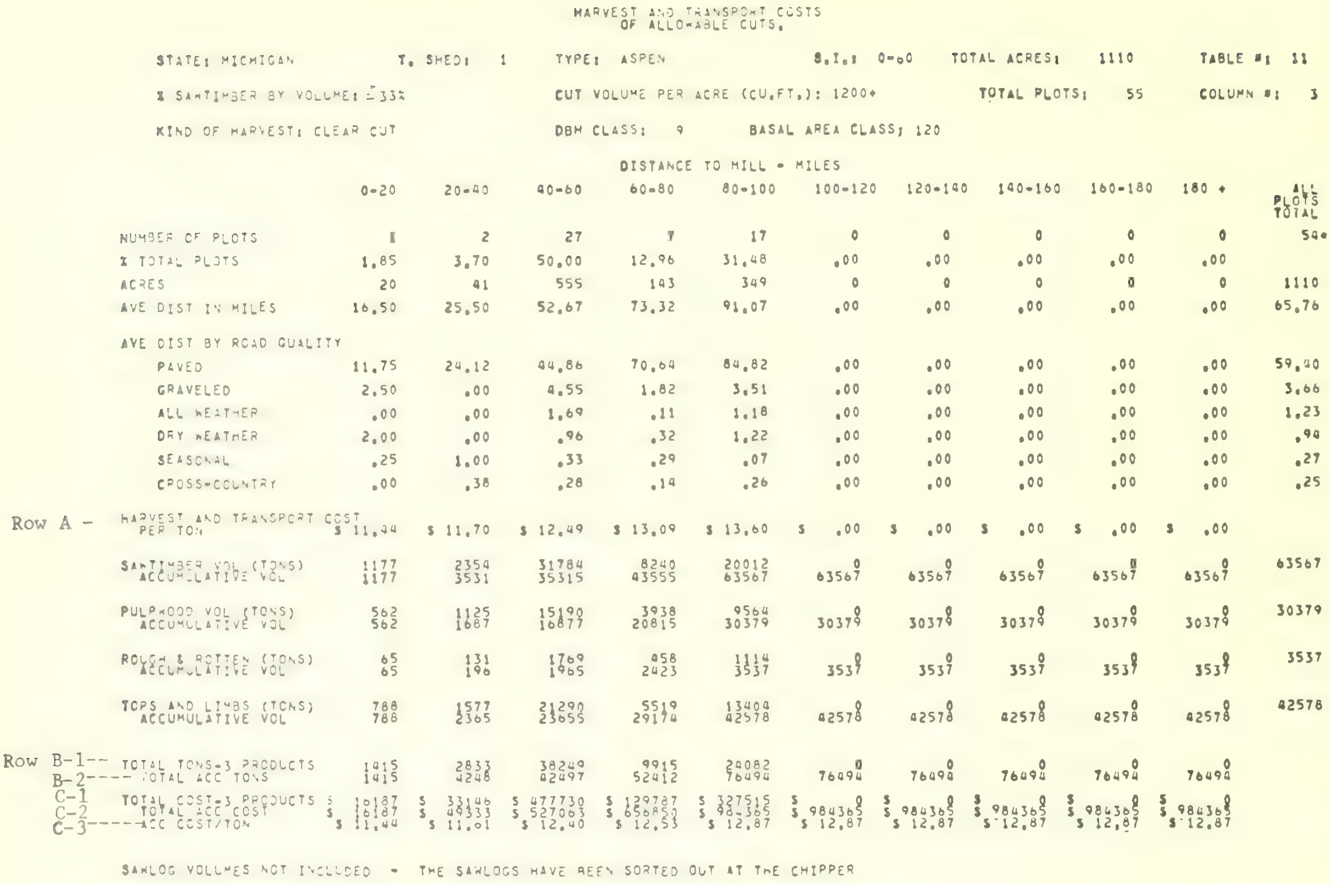

Figure 5.—*Example of managed harvest output table.*



```
                                       HARVEST AND TRANSPORT COSTS
                                           OF ALLOWABLE CUTS.

          STATE: MICHIGAN           T. SHED:   1      TYPE:  ASPEN                 S.I.: 0-60    TOTAL ACRES:    1110        TABLE #:  11

          % SAWTIMBER BY VOLUME: ≥33%                 CUT VOLUME PER ACRE (CU.FT.): 1200+             TOTAL PLOTS:    55        COLUMN #:   3

          KIND OF HARVEST: CLEAR CUT                  DBH CLASS:   9       BASAL AREA CLASS: 120

                                                                DISTANCE TO MILL - MILES
                                    0-20      20-40     40-60     60-80     80-100    100-120   120-140   140-160   160-180   180 +       ALL
                                                                                                                                      PLOTS
                                                                                                                                      TOTAL
       NUMBER OF PLOTS                 1         2        27         7        17         0         0         0         0         0       54*
       % TOTAL PLOTS                1.85      3.70     50.00     12.96     31.48       .00       .00       .00       .00       .00
       ACRES                          20        41       555       143       349         0         0         0         0         0      1110
       AVE DIST IN MILES           16.50     25.50     52.67     73.32     91.07       .00       .00       .00       .00       .00     65.76

       AVE DIST BY ROAD QUALITY
           PAVED                   11.75     24.12     44.86     70.64     84.82       .00       .00       .00       .00       .00     59.40
           GRAVELED                 2.50       .00      4.55      1.82      3.51       .00       .00       .00       .00       .00      3.66
           ALL WEATHER               .00       .00      1.69       .11      1.18       .00       .00       .00       .00       .00      1.23
           DRY WEATHER              2.00       .00       .96       .32      1.22       .00       .00       .00       .00       .00       .94
           SEASONAL                  .25      1.00       .33       .29       .07       .00       .00       .00       .00       .00       .27
           CROSS-COUNTRY             .00       .38       .28       .14       .26       .00       .00       .00       .00       .00       .25

Row A - HARVEST AND TRANSPORT COST
          PER TON               $ 11.44   $ 11.70   $ 12.49   $ 13.09   $ 13.60   $   .00   $   .00   $   .00   $   .00   $   .00

       SAWTIMBER VOL (TONS)         1177      2354     31784      8240     20012         0         0         0         0         0     63567
         ACCUMULATIVE VOL           1177      3531     35315     43555     63567     63567     63567     63567     63567     63567

       PULPWOOD VOL (TONS)           562      1125     15190      3938      9564         0         0         0         0         0     30379
         ACCUMULATIVE VOL            562      1687     16877     20815     30379     30379     30379     30379     30379     30379

       ROUGH & ROTTEN (TONS)          65       131      1769       458      1114         0         0         0         0         0      3537
         ACCUMULATIVE VOL             65       196      1965      2423      3537      3537      3537      3537      3537      3537

       TOPS AND LIMBS (TONS)         788      1577     21290      5519     13404         0         0         0         0         0     42578
         ACCUMULATIVE VOL            788      2365     23655     29174     42578     42578     42578     42578     42578     42578

Row B-1-- TOTAL TONS-3 PRODUCTS     1415      2833     38249      9915     24082         0         0         0         0         0
    B-2---- TOTAL ACC TONS          1415      4248     42497     52412     76494     76494     76494     76494     76494     76494
     C-1   TOTAL COST-3 PRODUCTS $ 16187  $  33146  $ 477730  $ 129787  $ 327515  $      0  $      0  $      0  $      0  $      0
     C-2     TOTAL ACC COST      $ 16187  $  49333  $ 527063  $ 656850  $ 984365  $ 984365  $ 984365  $ 984365  $ 984365  $ 984365
     C-3-----ACC COST/TON        $ 11.44  $  11.61  $  12.40  $  12.53  $  12.87  $  12.87  $  12.87  $  12.87  $  12.87  $  12.87

       SAWLOG VOLUMES NOT INCLUDED  -  THE SAWLOGS HAVE BEEN SORTED OUT AT THE CHIPPER
```

Figure 6.—*Example of harvest and transport cost output.*

One plot representing 20 acres and 1,415 tons is 16.50 miles from the mill, 27 plots representing 555 acres and 38,249 tons are 52.67 miles from the mill. These 1,415 tons and 38,249 tons are harvestable and transportable to the mill at an average cost of $11.44 and $12.49 per ton, respectively.

Supply Curve Construction

Marginal and average delivered cost curves can be constructed from the harvest and transport cost tables for practically any combination of (a) type/site index, (b) proportion of sawtimber in the stand, (c) growing stock volume cut per acre, and (d) kind of harvest (clear cut, mechanized thinning, or selection cut/relogging).

Each harvest and transport cost table (fig. 6), already includes marginal and average cost calculations for the "three-product total" of pulpwood, rough and rotten, and tops and limbs. Row A shows the harvest and transport cost for the volumes found in each distance class. Row B-1 shows the individual volumes of the "three-product total" in each distance class that are deliverable at the costs shown in row A. Row B-2 shows the cumulative volumes of the "three-product total" that can be delivered **at or below** the cost shown in row A.

A marginal delivered cost curve can now be constructed by plotting row B-2 against row A (fig. 7). This curve shows **marginal cost** or the cost of delivering the last ton of any volume desired. For example, the mill would have to pay $13.60/ton (row A, 80-100 miles) to recover the last of 76,494 tons (row B-2, 80-100 miles). That is, this cost would be paid for each of the last 24,082 tons (row B-1, 80-100 miles). If only 52,412 tons are needed (row B-2, 60-80 miles), the cost of the last ton would be $13.09/ton (row A, 60-80 miles). Of course, at either level of demand, some wood would cost substantially less; the delivered cost of the first 1,415 tons would be $11.44/ton.

A more useful measure of supply is the **average cost.** That is, what price must be paid on the average to recover any desired amount? This is more useful because it is the average cost that will be compared to average revenue earned by the firm. Average cost is

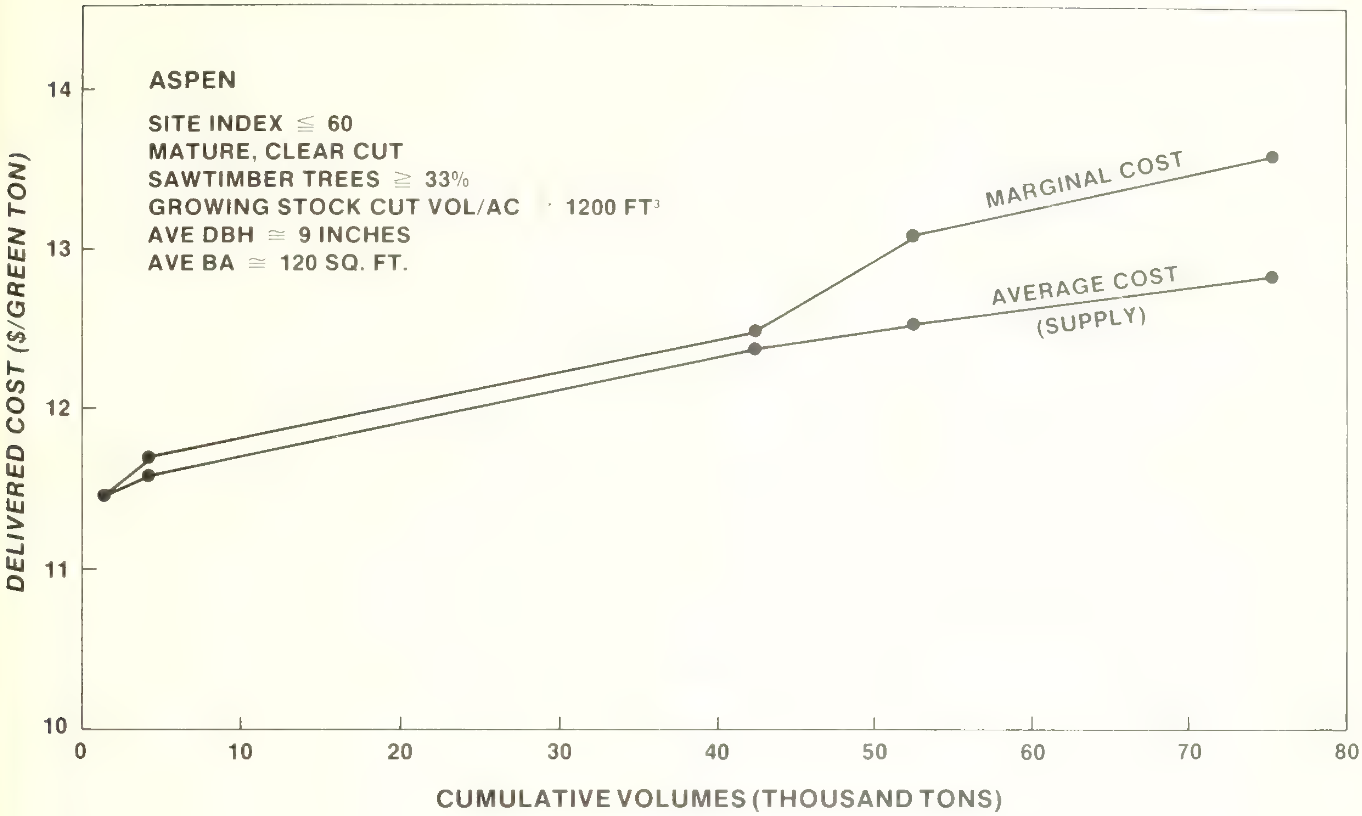


Figure 7.—*Example of marginal and average delivered cost curves.*

shown in row C-3. For any distance class, it is the cumulative cost of the "three-product total" (row C-2) divided by the cumulative tonnage (row B-2). This curve is plotted in figure 7 along with marginal cost. Row C-3 in every harvest and transport cost table shows the average cost of the cumulative volumes up to each specific distance class.

In the results section to follow, the average cost curves are called **supply curves** because they represent the average cost of meeting a specific demand for wood. Figure 7 shows the supply of timber from all the aspen stands in Mead's timbershed 1 with a site index ≤ 60 and with the other following characteristics:

a. mature stand clearcut,
b. sawtimber trees as a percent of growing stock trees ≥ 33 percent,
c. growing stock cut volumes/acre ≥ 1,200 cubic feet,
d. average d.b.h. ≅ 9,
e. average d.b.h. ≅ 120 ft.^{2}.

The harvest cost portion of delivered cost for this harvest opportunity is $5.36 per ton, and was derived in the following way: Because a clear cut was recommended, table 3 (Harvest system selections-clear cuts) was examined for the stand averaging 9 inches d.b.h. and 120 square feet basal area. A harvest cost of $4.70/ton was indicated. However, this cost assumed that all the trees weighed 55 pounds per cubic feet and it was multiplied by the ratio of assumed tree weights to actual tree weights for the aspen type.

$\$4.70/\text{ton} \times (55\ \text{lbs./ft.}^3 \div 48.20\ \text{lbs./ft.}^3) = \$5.36/\text{ton}$

The harvest cost portion of each table is the same in each distance class, but of course, transport costs increase from left to right. Similar harvest and transport cost tables were prepared for each of the 164 harvest opportunities.

Generally, individual havest and transport cost tables are not based on enough data to be significant. Therefore, most of the supply curves used in the analysis are aggregates of several tables.

Estimating Stumpage Costs

The supply curves do not include stumpage cost because of the wide variation among owners and the complexity of the calculations (which often include volume per acre, accessibility, wood quality, road construction costs, and size of area). Therefore, anyone who wishes to use the delivered cost curves should add his own estimate for stumpage.

However, for the approximate comparisons of supply and demand to follow, we estimated an average stumpage cost for the combined volumes of roundwood and residues by species groupings. Residues, including rough and rotten trees and tops, branches, and saplings, were valued at less than the minimum price now paid for mixed hardwood roundwood, as estimated in the Wisconsin Forest Products Price Review (1977).

Species	Estimated stumpage price, all products	
	$/cord	$/ton
Pine	9.14	3.97 at 2.3 tons/cord
Other softwoods	4.82	2.01 at 2.4 tons/cord
Aspen	4.00	1.67 at 2.4 tons/cord
Mixed hardwoods	2.15	0.77 at 2.8 tons/cord

Since mixed hardwood stumpage was valued at about $0.77/ton, we assumed that all categories now classed as residues would be worth no more than $0.50/ton.

Next, we used the following ratios of residues to roundwood for the species groups found in Michigan's Upper Peninsula:

Species groups	Ratio: Residue volume/ Roundwood volume
Pine	0.64
Other softwood	.67
Aspen	.66
Mixed hardwoods	.78

That is, for pine, if a stand has 1 ton of roundwood per acre, it has 0.64 tons of rough, rotten, branches, tops, and saplings.

Finally, using (1) the average roundwood stumpage price for each species group, (2) the assumed residue price of $0.50/ton, and (3) the roundwood/residue ratios above, we determined a combined roundwood and residue weighted stumpage cost/ton. For example:

1 ton of pine roundwood at $3.97/ton =	$3.97
+ .64 tons of pine residue at $ .50/ton =	.32
	$4.29

$4.29/1.64 tons = $2.62/ton

This resulted in the following tabulation for each species group:

Species group	Weighted stumpage cost (roundwood and residue $/ton)
Pine	$2.62
Other softwoods	1.41
Aspen	1.20
Mixed hardwoods	0.60
Overall average	$1.04

The last step was the calculation of an overall average, weighted by the proportion of similar species groups found in the managed harvest for Michigan's Upper Peninsula.

Mill Demand for Fiber and Fuel

This study assumed that the entire demand for wood fiber and wood fuel of 10 of the 21 mills in the region would be met from the regions forest resource (fig. 2). Four steps were required.

First, interviews were conducted at each of the 10 mills to determine mill process and technology; wood procurement program; energy requirements, sources, and current levels of energy independence; internal steam, steam-electric, and hydro-electric facilities; and current unused residues.

Second, a brief engineering analysis for each mill estimated the opportunities (and costs) to achieve complete energy independence by either converting existing boilers or constructing new ones.

Third, current and projected prices were determined for the major fossil fuels as well as for purchased electricity.

Fourth, using current and projected fuel prices and the costs of each conversion or new construction opportunity, the price advantage of wood over existing fuels that just balanced capital costs was established. This advantage was then subtracted from each mill's existing fuel costs to establish the highest price that each mill could afford to pay for wood fuel.

RESULTS

Mead Corporation, Escanaba, Michigan

Supply of wood fiber and fuel

The combined area of Mead's seven timbersheds in Michigan's Upper Peninsula and northeastern Wisconsin is 8.9 million acres, of which 7.7 million acres are classed as commercial forest land. This is distributed as follows:

Timbershed	Total land area	Commercial forest
	(acres)	
1 Escanaba mill	5,023,600	4,338,900
2 Champion	494,600	458,200
3 Gulliver	778,100	665,400
4 L'Anse	760,100	671,700
5 Newberry	614,100	550,900
6 Shingleton	275,400	241,600
7 Trout Lake	997,600	790,500
	8,943,400	7,717,200

Almost 3.5 million of the above acres are in public ownership, divided equally between State and National Forests. These acres have not been reserved for single use and presumably can be harvested as the timber matures. Two million acres are owned by forest industry. Roughly 33 percent of this area is in softwood types, 22 percent is in aspen and paper birch, and 37 percent is in northern hardwoods. Because over 50 percent of the area and inventory is in timbershed 1, the analysis will focus on this timbershed.

Managed harvest recommendations for Mead's timbershed 1 call for the annual harvest of 146,000 acres of all types, yielding over 7.4 million tons of all products (table 6). This total in timbershed 1 includes more than 1.4 million tons of saw logs assumed to be sorted during chipping or removed before relogging. The remaining saw log volumes are considered insufficient per acre to warrant separation, and are to be chipped with the remaining stand. Thus, for timbershed 1, 6 million tons of wood, not including most saw logs, are deliverable at an average cost of $14.37/ton not including stumpage cost (fig. 8). Over one-half, or 3 million tons are available from rough and rotten trees and tops and branches. These tonnages are shown by type groupings below:

Type	Volume (tons, less most sawtimber)	Maximum average delivered cost ($/ton less stumpage cost)
Pine	287,000	13.57
Other softwood	1,086,000	13.12
Aspen	1,662,000	13.71
Northern hardwoods	1,979,000	16.18
Other hardwoods	952,000	13.44
All Types	5,966,000	14.37

If all material included in the managed harvest estimates is harvested, cost per ton will average $14.37. If less material is desired, the average price will decrease assuming that a mill can avoid stands with high harvest and transport costs. For example, for all types in timbershed 1, if only half the material is needed, average price will drop to $11.33.

Although the preponderance of the northern hardwood type is clear, its average delivered costs are higher than the overall average cost by almost $2/ton. However, if only half this type were harvested, 1 million tons could be delivered at an average cost of $12.30/ton, a considerable decrease from $16.18/ton.

No timber removal data are available for Mead's timbersheds. However, the latest survey of removals for Michigan shows that in 1972, 101 million cubic feet of growing stock was harvested in the Upper Peninsula. This volume converts roughly to 3 million tons of all species. But recall that growing stock does not include rough and rotten trees, branches, tops, nor saplings. From ratios of merchantable roundwood to residues determined in this study, we know that roughly 0.7 tons of residue are generated for every ton of roundwood. Applying this ratio to growing-stock removals results in total removals of growing stock plus residues of nearly 5 million tons/year of all species in the Upper Peninsula.

Without a breakdown by type we can make no precise comparison with managed harvest data, but in timbershed 1 alone our calculations show that 7.4 million tons of wood and wood residues should be harvested each year. And this timbershed contains only 60 percent of Upper Michigan's commercial forest land.

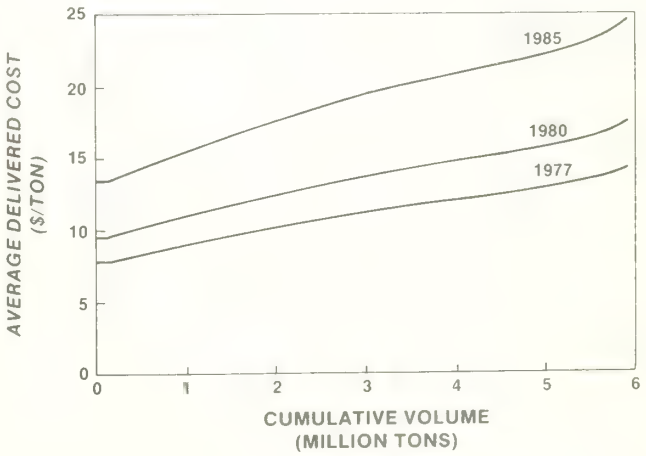


Figure 8.—*Supply curve for Mead Timbershed 1, all forest types.*

Table 6.—*Managed harvest by fuel/product classes, Mead timbershed 1*
(In green tons)

Type/Site Index	Saw logs	Pulpwood	Rough and rotten	Tops, branches, saplings	Total	Acres
Jack pine <60	59,573	50,038	4,353	54,231	168,195	7,640
Jack pine ≥60	6,453	4,747	578	5,746	17,524	390
Red pine	50,104	12,691	8,961	44,939	116,695	5,120
White pine	37,983	11,182	1,710	21,907	72,782	1,200
Balsam fir	191,914	192,076	18,098	230,881	632,929	8,170
White spruce	31,919	22,482	2,636	30,927	87,964	4,570
Black spruce <40	9,485	25,393	133	23,269	58,280	3,940
Black spruce ≥40	19,035	12,865	1,024	18,496	51,420	860
Tamarack	4,743	11,832	44	12,033	28,652	1,760
Northern white-cedar	137,236	84,473	23,354	139,035	384,098	5,430
Aspen <60	213,850	434,052	28,448	373,311	1,049,661	29,080
Aspen ≥60	224,991	288,434	35,393	337,396	886,214	14,840
Paper birch <60	24,230	92,096	10,627	74,656	201,609	4,520
Paper birch ≥60	6,509	29,593	10,639	29,627	76,368	1,910
Elm-ash-cottonwood	145,209	114,455	40,420	200,572	500,656	10,680
Oak-hickory <60	58,103	144,719	5,032	142,930	350,784	4,780
Oak-hickory ≥60	5,066	6,091	738	7,456	19,351	140
Maple-birch-beech <45	371,874	364,014	79,909	501,439	1,317,236	18,670
Maple-birch-beech ≥45	451,064	315,633	94,633	528,326	1,389,656	14,460
Nonstocked	0	289	4,515	2,263	7,067	8,070
TOTAL	2,049,341	2,217,155	371,245	2,779,440	7,417,141	146,230

Demand for wood fiber and fuel

The mill energy study showed that Mead now uses 887,000 tons of wood annually, about 100,000 tons of which goes to meet approximately 7 percent of its own energy needs (table 7). An additional 36 percent of Mead's energy requirements are met by black liquor burning and hydroelectricity. Total energy independence would require the additional purchase of about 1 million tons of wood fuel, bringing total wood use to about 1.9 million tons.

Energy independence for Mead, or for any other existing plant, could rarely be achieved in one step. A preliminary engineering analysis made for the Mead mill shows the opportunities for reaching self-sufficiency (table 8).

One question remains: Is there enough wood and wood fuel to satisfy these needs at a price Mead can afford?

Supply and demand

Although Mead does not get all its wood from timbershed 1, we have used this timbershed to illustrate the point that Mead has an abundance of wood at affordable prices. The following exercise will bear this out. On the horizontal axis of figure 8, locate Mead's demand in 1980, the time at which total energy independence could be achieved: 1.9 million tons for all purposes (fuel and pulp). Draw a vertical line from this point on the horizontal axis to the 1980 supply curve. Then run horizontally to the average delivered price less stumpage on the vertical axis: $12.50/ton. To this add the average stumpage value for all species, calculated earlier: $1.04 + $12.50 = $13.54/ton. This indicates that timbershed 1 can provide 1.9 million tons each year at an average delivered cost per ton including stumpage of $13.54, given the assumptions made in the analysis.

Table 7.—*Wood fuel requirements for the ten study mills*

	I	II	III	IV	V	VI	VII	VIII	IX	X
BILLION BTU's REQUIRED PER YEAR										
Total	9,688	1,108	5,445	631	3,355	2,402	1,290	6,575	1,362	4,885
Current wood-fired	837	20	0	262	257	209	0	79	157	1,000
New wood-fired	8,851	1,088	5,445	369	3,098	2,193	1,290	6,496	1,205	3,885
WOOD FUEL REQUIRED (Thousand tons per year)										
Total	1,140	130	641	74	395	283	152	774	160	575
Current wood use	99	2	0	31	30	25	0	9	18	118
New wood	1,041	128	641	43	365	258	152	765	142	457
HIGHEST AFFORDABLE WOOD FUEL PRICE (Dollars per million BTU's)										
1977	.77	1.51	.81	1.70	1.79	1.03	1.03	1.39	1.06	1.34
1980	1.66	2.03	1.02	2.52	2.19	1.49	1.47	1.89	1.76	1.77
1985	2.78	2.84	1.46	3.91	3.07	2.34	2.41	2.93	2.91	2.63
(Dollars per green ton)										
1977	6.12	12.84	6.88	14.45	15.22	8.76	8.76	11.82	9.01	11.39
1980	14.11	17.26	8.67	21.42	18.62	12.66	12.50	16.06	14.96	15.04
1985	26.63	24.14	12.41	33.24	26.10	19.89	20.48	24.90	24.74	22.36

Table 8.—*Opportunities for reaching self-sufficiency at the Mead Mill*

Step	Cap. cost (\$–10^6)	Annual saving (\$–10^6)	Increase in energy (Percent)	Energy independence required	Additional fuel wood (ton/yr.)
Present wood energy use			—	43	
Modify an existing boiler	.3	4.2	7	50	75,000
Convert a boiler	1.4	.6	10	60	113,000
Replace a boiler	15.3	6.0	34	94	769,000
Replace direct heating	2.0	.6	6	100	77,000
				TOTAL	1,034,000

From the mill energy study, the maximum average price Mead would be able to pay in 1980 was estimated at $14.11/ton based on projected price increases in fossil fuels (table 7). Thus, by 1980, timbershed 1 could meet Mead's entire demand well within the projected cost limit. It must be emphasized that this price will meet not only Mead's fuel requirements, but its fiber needs as well—and with no loss of raw material to the sawmill industry.

Other fuel/product opportunities

The fiber available from some forest types, especially northern hardwoods, would cost significantly more than that from others. We have prepared three other supply curves to explain why, and to demonstrate some other facets of the analysis.

The first shows the supply of wood and wood residues (minus most sawtimber) that resulted from mechanized thinning (fig. 9). This harvest technique was applied to overstocked, uneven-aged types for which average stand diameter was less than 9 inches; it was also applied to all overstocked, even-aged types. Because of small tree size, full-tree skidding is not too damaging and a strip cut can remove the excess basal area (Biltonen *et al.* 1976).

This curve shows that despite the fairly large tonnages (over 420,000 tons/year), mechanized thinning is expensive. To harvest all thinnings would require a 1977 price, not including stumpage, of close to $13.80/ton, and a 1980 price of $15.81. The large volumes and high recovery costs suggest further study of ways to reduce the cost of mechanized thinning. Perhaps the development of specialized equipment could be justified if the market for fuel and fiber were larger.

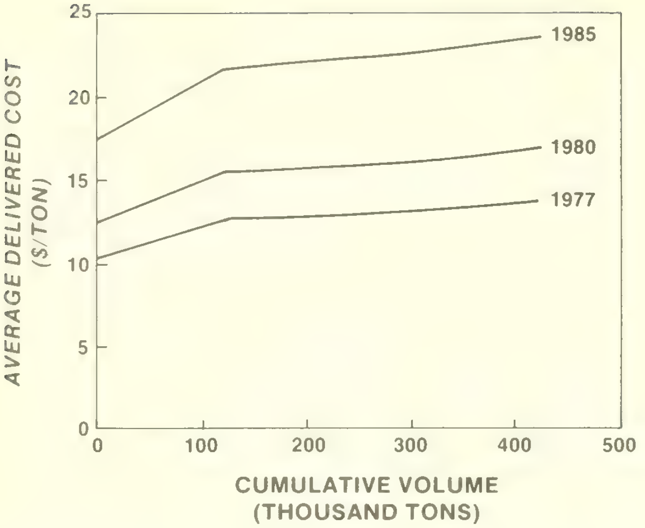


Figure 9.—*Supply curve for Mead Timbershed 1, thinnings from all forest types.*

The next curve shows the supply of chips when saw logs are bucked and sorted before chipping (fig. 10). This material resulted from both thinnings and clearcuttings, and overlaps material contained in the thinning supply curve. Figure 10 illustrates a significant point: 1.6 million tons left after sorting can be recovered, at an average cost of $12.33/ton. Thus, a huge volume of material is available for fuel or fiber at a low price, and over 1 million tons of saw logs are saved from the chipper. We need to develop efficient ways to carry out saw log sorting and field chipping operations.

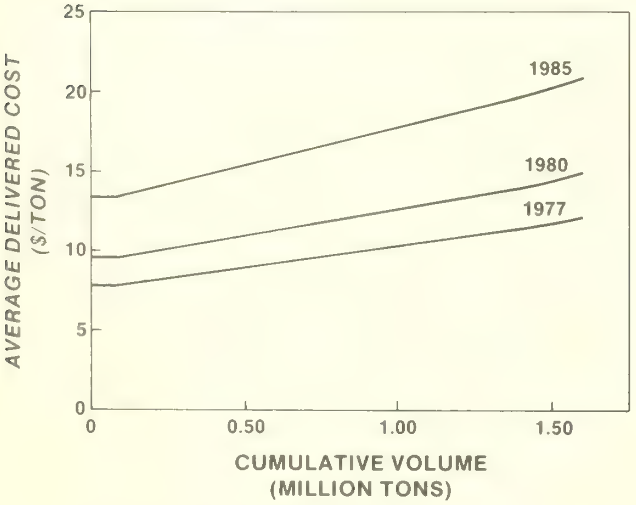


Figure 10.—*Supply curve for Mead Timbershed 1, remaining volume after saw log sorting.*

Another supply curve represents the cost of relogging large sawtimber stands in which full-tree skidding is not recommended (fig. 11). The trees with large crowns in these stands would cause unacceptable damage to future crop trees if skidded whole to the landing. We have assumed that all saw logs will be removed in separate, short-log operations. The large tops and the other trees to be removed could then be harvested with the topwood harvester, grapple skidders, and conventional chipping at the landing.

This opportunity is large, but also expensive. The supply curve shows that 712,000 tons are deliverable at an average price of $20.30/ton in 1977 and $23.24/ton in 1980, not including stumpage. For the time being at least, much of this wood is out of Mead's price range. But here, as with thinning, the need for research and development of cheaper ways to recover this material is obvious.

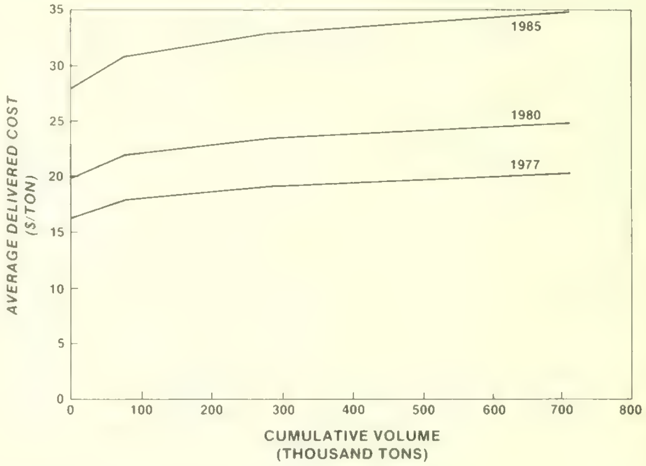


Figure 11.—*Supply curve for Mead Timbershed 1, relogging opportunities.*

Ten-mill Study Area—Northern Wisconsin and Upper Michigan

Managed harvest area and volumes

Earlier survey reports for northern Wisconsin and Upper Michigan show more than 18 million acres of commercial forest land equally distributed between the two States. Total inventory of growing stock approaches 15 billion cubic feet, and this volume converts roughly to 700 million green tons, including residue. Of the total area, 10.5 million acres, or 58 percent, is in two types: northern hardwoods and aspen. Volumes are similarly distributed—close to 60 percent of the volume is found in the northern hardwood and aspen types.

Estimates of managed harvest levels for the two States show that about 300,000 acres containing close to 19.5 million tons including residue could be harvested from each (tables 9 and 10). However, there are some differences in the distribution of managed harvest by type: northern Wisconsin has a recommended harvest for aspen of 5.4 million tons including residues, compared with 3.2 million for Upper Michigan. But northern Wisconsin has a recommended harvest of only 5.5 million tons of northern hardwoods, compared with 10.3 million tons for Upper Michigan. Northern Wisconsin also has more oak-hickory and elm-ash-cottonwood than Upper Michigan, 4.4 million tons to 1.9 million tons.

Three more supply curves were constructed for the regional study area: (1) northern Wisconsin, all types, (2) Upper Michigan, all types, and (3) both regions, all types (figs. 12, 13, and 14).

In northern Wisconsin, 15.9 million tons of fiber and fuel wood (most sawtimber not included) can be delivered at an average cost of $14.42/ton in 1977 and $16.51/ton in 1980, not including stumpage cost. For Michigan, a similar comparison shows 14.5 million tons at an average delivered cost of $13.62/ton in 1977 and $15.59/ton in 1980. For both regions combined, 30.5 million tons are deliverable at an average cost of $14.05/ton in 1977 and $16.07/ton in 1980. Again, stumpage costs have not been included in any of these comparisons, and the tonnages do not include most of the saw logs, which were assumed to be recovered during saw log sorting or prior to relogging.

Regional demand

The 10 pulp and paper mills in the study area now use 2.44 million tons of wood, 13.6 percent or 332,000 tons of which goes to meet their own energy needs. If all study mills were able to achieve energy independence, a total of 6.43 million tons would be required, 4.32 million tons of which would be used as wood fuel.

The opportunities for achieving full energy independence vary widely among mills. The brief engineering cost analysis for each mill suggested that 5 of the 10 could now justify some increased use of wood for fuel at a cost of $10/green ton or less (table 7). Further incentives may be provided by government policies affecting fuel prices, fuel availability, and investment tax credits.

By 1980 all mills except one will probably find wood fuel attractive. These nine mills presently use 2.39 million tons of wood annually. For energy independence, they would need an additional 3.35 million tons of wood annually for a total of 5.74 million tons of

Table 9.—*Managed harvest by fuel/product classes, northern Wisconsin*
(In green tons)

Type/Site Index	Saw logs	Pulpwood	Rough and rotten	Tops, branches, saplings	Total	Acres
Jack pine <60	128,842	187,696	19,400	217,789	553,727	8,440
Jack pine ⩾60	53,847	58,921	6,608	71,856	191,232	2,900
Red pine	294,403	91,440	19,777	237,435	643,055	14,430
White pine	166,537	19,258	15,665	86,113	287,573	4,450
Balsam fir	293,656	321,940	38,325	493,393	1,148,314	14,200
White spruce	5,327	10,037	1,270	12,666	29,300	1,020
Black spruce <40	8,450	14,894	1,349	58,235	82,928	2,930
Black spruce ⩾40	11,998	7,440	3,763	21,098	44,299	820
Tamarack	10,006	46,584	5,889	50,367	112,846	4,910
Northern white-cedar	60,016	51,835	9,235	82,179	203,265	3,950
Aspen <60	200,339	567,511	91,876	688,586	1,548,312	34,730
Aspen ⩾60	609,310	1,440,085	206,939	1,598,304	3,854,638	57,370
Paper birch <60	61,885	151,273	14,553	170,870	398,581	6,010
Paper birch ⩾60	81,029	186,198	41,626	210,435	519,288	9,650
Elm-ash-cottonwood	327,214	285,334	183,169	614,211	1,409,928	37,140
Oak-hickory <60	368,895	635,377	311,681	1,106,666	2,422,619	42,190
Oak-hickory ⩾60	171,688	119,823	83,655	234,606	609,772	9,670
Maple-birch-beech <45	150,045	139,834	73,566	328,954	692,399	12,980
Maple-birch-beech ⩾45	1,515,844	1,059,042	349,566	1,860,487	4,784,939	48,480
Nonstocked	4,110	3,695	27,028	39,811	74,644	18,380
TOTAL	4,523,441	5,398,217	1,504,940	8,184,061	19,610,659	334,650

Table 10.—*Managed harvest by fuel/product classes, Upper Michigan*
(In green tons)

Type/Site Index	Saw logs	Pulpwood	Rough and rotten	Tops, branches, saplings	Total	Acres
Jack pine <60	142,186	197,598	12,879	179,296	531,959	17,180
Jack pine ≥60	8,990	25,759	851	20,838	56,438	800
Red pine	162,189	79,467	25,195	167,994	434,845	15,990
White pine	88,304	28,430	3,164	51,403	171,299	2,750
Balsam fir	369,657	339,073	34,733	441,517	1,184,980	19,120
White spruce	55,195	42,527	3,416	56,763	157,901	5,350
Black spruce <40	63,451	83,309	2,779	93,884	243,423	10,290
Black spruce ≥40	51,703	27,600	3,121	46,942	129,366	2,550
Tamarack	25,881	22,641	1,817	28,100	78,439	4,150
Northern white-cedar	357,545	191,204	46,177	333,768	928,694	15,250
Aspen <60	408,320	677,383	51,848	625,087	1,762,638	47,250
Aspen ≥60	344,926	486,300	41,091	544,361	1,416,678	21,510
Paper birch <60	56,960	139,094	13,986	118,478	328,428	7,080
Paper birch ≥60	42,200	55,424	10,908	62,949	171,481	2,160
Elm-ash-cottonwood	409,768	311,565	75,899	536,308	1,333,540	26,350
Oak-hickory <60	89,464	217,625	14,597	236,978	558,664	7,970
Oak-hickory ≥60	5,066	14,181	738	16,056	36,041	590
Maple-birch-beech <45	1,806,138	1,086,079	299,053	1,936,209	5,127,479	62,790
Maple-birch-beech ≥45	1,936,779	977,994	302,873	1,921,446	5,139,092	47,960
Nonstocked	0	1,951	6,341	3,905	12,197	9,980
TOTAL	6,424,722	5,005,204	951,376	7,422,282	19,803,582	327,070

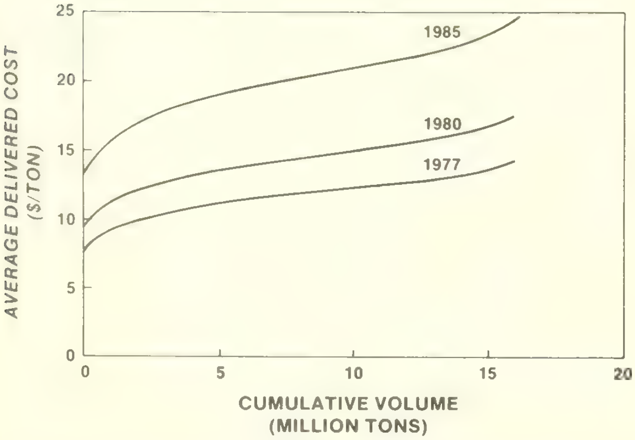


Figure 12.—*Supply curve for northern Wisconsin, all forest types.*

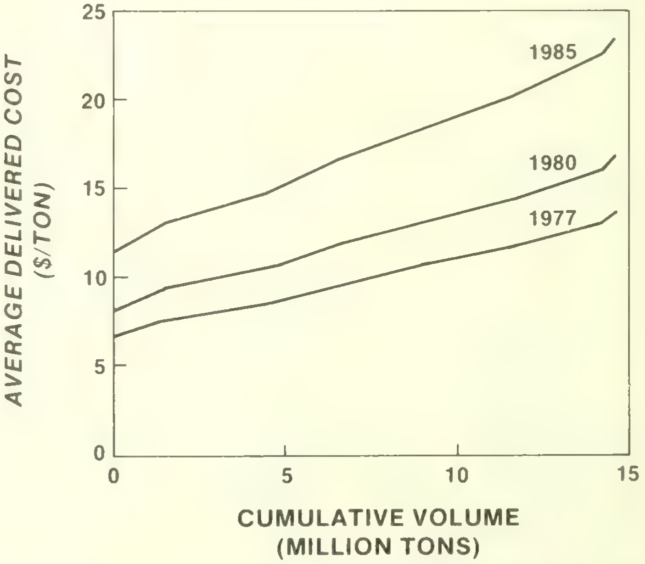


Figure 13.—*Supply curve for Upper Michigan, all forest types.*

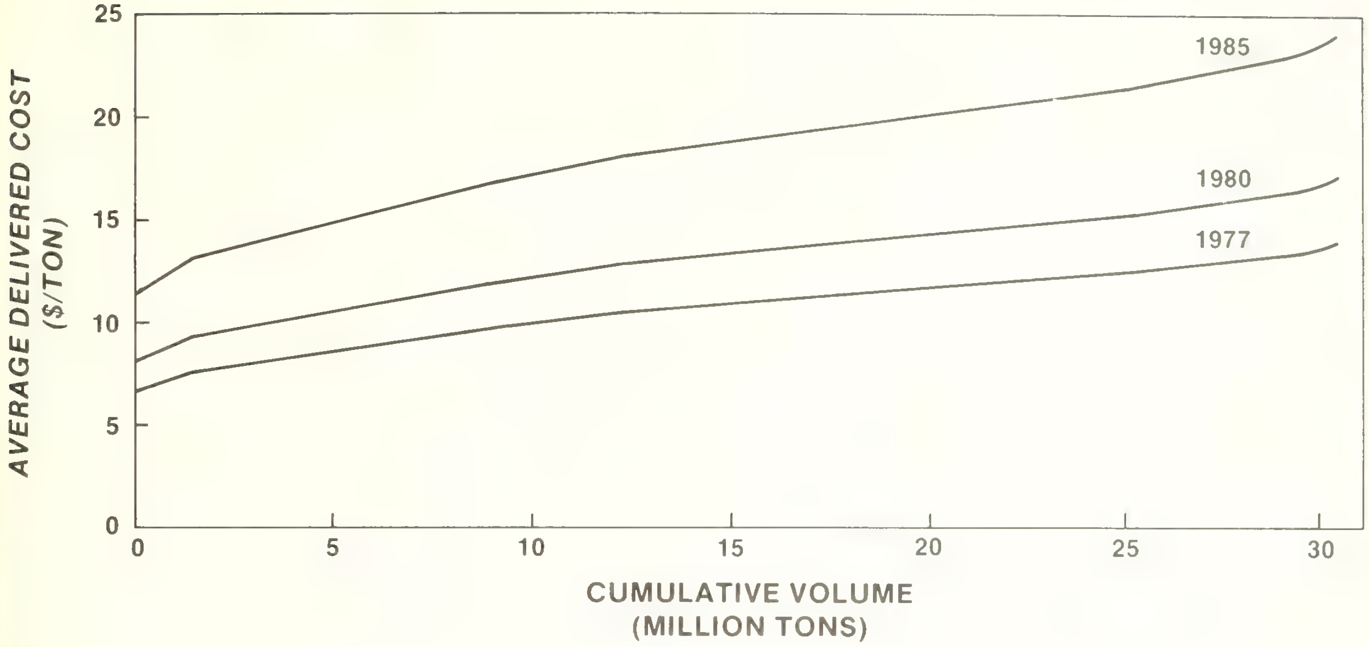


Figure 14.—*Supply curve for all regions, all forest types.*

fiber and fuel. Thus, in 1980, the increased demand of nine mills plus the existing demand of the tenth mill could equal 5.79 million tons for all needs. Given these assumptions, the following questions remain: Can the existing forest resource sustain these demands, and most important, at a price the mills can afford?

Table 7 shows maximum affordable prices that each mill can pay in 1977, in 1980, and in 1985. It seems that even in 1977 at least five mills could afford to pay more than $10/ton to achieve independence. In 1980, the demand of the 10 mills, if nine achieve independence, is estimated to be 5.8 million tons. Using the 1980 curve in figure 14, it can be seen that this 5.8 million tons of fuel and fiber can be delivered at a cost of $10.50/ton + $1.04/ton = $11.54/ton, including stumpage. This price is well below the maximum that nine of the mills can afford. And this volume is far below the 30.5 million tons of material suitable for fiber or fuel that our calculations suggest should be harvested each year.

SUMMARY

The Mead case study and the regional analysis indicate that both fuel and fiber needs can be supplied from the forest resource with significant cost savings. Mead now uses almost 900,000 green tons each year; about 100,000 tons of this provide 7 percent of its energy needs. Achieving energy independence would require an additional 1 million tons, bringing total wood use to 1.9 million tons. From a volume point of view, this projected consumption can be favorably compared to the recommended harvest of 6 million green tons from only one of Mead's seven timber sheds.

The analysis of costs in this same timbershed suggests that the 1.9 million tons could be harvested and delivered for $13.54 per green ton in 1980. This is $0.57 per ton less than the wood's equivalent fossil fuel value based on projected fossil fuel prices in 1980. Thus, achieving energy independence would result in direct energy cost savings to Mead at these same price and volume levels of at least $570,000 per year.

For the broader analysis of 10 pulp and paper mills, current wood consumption is 2.4 million green tons of which 330,000 tons go for energy. Energy self sufficiency by all 10 mills would require the added harvest of 4.0 million tons, bringing total wood use to 6.4 million tons.

Our comparison of regional supply and the specific opportunities for using more wood fuel suggests that only 9 of these 10 mills could economically achieve independence by 1980. Total wood use for this situation would be 5.8 million green tons. Again, this level must be compared to the total recommended harvest for the study region of more than 30 million green tons of fiber and fuel material.

The analysis also describes in detail several key residue opportunities that are not now being exploited: (1) thinnings from pole timber stands, and (2) tops and nonsaw log trees from selectively harvested sawtimber stands. In Mead's largest timbershed for example, these two opportunities could yield over 1 million green tons each year, over 17 percent of the total recommended harvest. However, existing harvest systems are not designed for these tasks and these harvest cost estimates are significantly higher than the costs of clearcutting. However, research and development of new equipment and methods for these improvement harvests should be able to reduce costs and permit these over-stocked stands to achieve even higher productivity and tree quality in the future.

A key factor in this analysis was the managed harvest procedure which estimated annual potential harvests based on existing forest conditions; it found some 30 million green tons suitable for either fiber or fuel or 39 million green tons if sawtimber is included. However, it must be emphasized that these estimates are in no way an upper limit on the region's forest potential. It is easily conceivable that in a regulated condition, northern Wisconsin and Upper Michigan could produce two to three times as much wood as reported here.

Closely related to the issue of increasing productivity, is a need to change residue definitions. Classifying trees as saw logs or pulpwood when they will fall down before they are needed obscures more realistic opportunities. Indeed, their use as a fuel now if no other market exists is especially appropriate. Cutting more to produce more, is not a contradiction, but is the principal means of achieving truly productive forests in the future.

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Analyzes the economic potential of achieving energy independence by 10 pulp and paper mills in northern Wisconsin and Upper Michigan. Independence would require the annual harvest of 5.79 million green tons for both fiber and fuel wood needs, compared to a recommended harvest level of 31 million green tons. Delivered wood cost projections seem well within affordable levels.

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Soil is for plants...

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SDA FOREST SERVICE
ESEARCH PAPER **NC-183**

Yield and quality of seed from YELLOW BIRCH PROGENIES

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rth Central Forest Experiment Station
rest Service, U.S. Department of Agriculture

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Seed yield in 8- and 9-year-old yellow birch varied among families and years but averaged more than 1,500 seeds per tree. Long catkins contained more seed than short ones. Seed quality was poor due to insufficient pollination and to differences among trees in flowering phenology.

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1980

YIELD AND QUALITY OF SEED FROM YELLOW BIRCH PROGENIES

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Seed production in open-grown yellow birch (*Betula alleghaniensis* Britt.) was found to begin at age 7 and to increase with age and size of the trees (Clausen 1977). Although earliness of fruiting and proportion of fruiting trees varies among and within families, the presence and abundance of catkins is mostly determined by the size of the tree crowns (Clausen 1979). However, early and abundant production of fruiting catkins will not necessarily result in a good crop of viable seeds. The purpose of this study was to determine the yield and quality of the seed produced by these young trees and possible relations of catkin size and shape to these characteristics.

METHODS

Yellow birch progenies were planted as 4-year-old seedlings in the spring of 1972 near Lake Tomahawk in Oneida County, north-central Wisconsin. The site is on Padus sandy loam and was clean-cultivated through the summer of 1975 and then mowed (Clausen 1977). Trees were planted at a spacing of 8 x 8 feet (2.4 m) and the plantation contained 155 open-pollinated families in 4-tree square plots and 4 replications (table 1). Fruiting began in the fall of 1974 but the number of fruiting trees and families was not large enough for the study until the following year. Therefore, the data presented here are for catkins and seeds produced in 1975 and 1976.

In each year, fruiting catkins were collected and allowed to dry for several weeks before length and diameter of from 1 to 20 catkins per tree were measured. Each catkin was then broken apart and the number of seeds counted and recorded. In 1975, all seeds from a tree were mixed and a sample of 100 seeds drawn for use in a germination test. Four 100-seed samples per tree were counted out from the 1976 seed crop, placed on type M film, and exposed to soft X-rays (15 kV, 1mA, 80 sec.). The radiographs were examined and the number of seeds with normal-appearing ovules, small or faintly opaque ovules (probably inviable), and empty seeds recorded. Both the 1975 and 1976 seedlots were tested for germination during the following winter by placing the seed on moist perlite in Petri dishes, which were kept under 20-hr photoperiod in a greenhouse at 24C for 30 days.

The catkin data were subjected to analysis of variance using tree means and a one-way nested classification with unequal sample sizes. Catkin diameter/length and catkin volume were calculated because the number of seeds per catkin may be related to catkin shape and volume as well as to catkin dimensions. Catkin volume was determined as that of an ellipsoid. Simple correlations based on individual catkins were calculated in order to establish possible relations between catkin size, catkin shape, number of seeds per catkin, percent filled seeds, and percent germination. Exceptions were those involving 1975 germination data where only tree averages were available. All percentage values used in the calculations were first converted by arcsin transformation.

Table 1.—*Origin of 21 yellow birch stands and number of open-pollinated families included in plantation*

Stand No.	State or Province	Origin code	Location Lat.	Location Long.	Number of families
			Degree		
3241	Nova Scotia	NS	44.6	60.5	8
3063	Nova Scotia	NS	44.1	65.8	7
3066	New Brunswick	NB	47.4	65.2	6
2998	Quebec	PQ	48.2	70.2	8
3000	Quebec	PQ	47.5	75.0	9
3004	Ontario	ON	46.7	79.6	8
3309	Ontario	ON	47.5	84.8	10
2977	Maine	ME	44.8	68.6	8
2986	New Hampshire	NH	43.5	71.4	4
2971	Massachusetts	MA	42.7	73.2	5
3312	Pennsylvania	PA	41.6	78.7	6
3299	Virginia	VA	37.8	79.1	5
2959	North Carolina	NC	35.7	82.3	4
2973	Georgia	GA	34.8	83.8	5
2983	Illinois	IL	41.9	89.4	9
2962	Wisconsin	WI	44.9	87.2	8
4340	Wisconsin	WI	45.6	88.6	8
2968	Wisconsin	WI	46.5	92.1	9
2987	Michigan	MI	47.0	88.7	10
2967	Minnesota	MN	47.8	90.2	9
2964	Minnesota	MN	44.2	94.1	9
Total					155

RESULTS

Seed Yield and Quality

Total seed yield was found to be determined by: (1) geographic origin, (2) number of seed-bearing trees per family, (3) number of fruiting catkins per tree, (4) number of seeds per catkin, and (5) climate. It may, therefore, vary greatly among and within families and from year to year.

Fruiting was poorest in yellow birch from the Maritime provinces. Trees of New Brunswick origin set no seed in either 1975 or 1976 and those from Nova Scotia stand 3063 did not fruit in 1976 (table 2). The best seed producers were generaly Wisconsin and Minnesota trees that originated within 250 miles of the plantation. Trees of northern origin (latitude 44.5° N or above) began to bear seed at an earlier age than those of southern origin (Clausen 1977). Seed yield followed a similar pattern (table 3). In both years, trees originating east of longitude 80° W averaged more catkins than western trees but had no more seeds per catkin. Geographic origin may thus have an effect on early seed yield in this species.

Fruiting trees accounted for 4 percent of the surviving trees in both 1975 and 1976. Among the seed-bearing families in 1975, the number of fruiting trees per family varied from 1 to 12 or from 2 to 20 percent of the trees (table 2). Families with few survivors had higher but atypical percentages of fruiting trees. In 1976, from 1 to 4 trees per family or from 3 to 12 percent of the trees fruited. Similarly, the number of catkins per tree ranged from 1 to 196 in 1975 and from 1 to 188 in 1976. The total number of fruiting families, trees, and catkins was greater in 1975 than in 1976, possibly due to a severe drought in 1976.

In 1975 the number of seeds per catkin averaged 139 and ranged from 30 to 297 in the 50 families. The 44 families fruiting in 1976 ranged from 9 to 306 seeds per catkin and averaged 151 (table 4). Families from different stands also showed much variation

Table 2.—*Incidence of fruiting in yellow birch trees from 21 origins in 2 years*

Stand		Fruiting in 1975			Fruiting in 1976		
No.	Origin	Families[1]	Trees per family	Catkins per tree	Families[1]	Trees per family	Catkins per tree
		Percent	*Number*		*Percent*	Number	
3241	NS	13	1	2	22	1	1
3063	NS	43	1-2	1-14	0	—	—
3066	NB	0	—	—	0	—	—
2998	PQ	25	1-2	2-60	12	1	4
3000	PQ	33	1-3	1-12	33	1	2-6
3004	ON	12	1	27	12	1	4
3309	ON	30	1	1-7	20	1	5
2977	ME	25	1-3	5-9	50	1-2	1-23
2986	NH	50	1-3	1-23	50	2	1-40
2971	MA	20	1	30	20	1	1
3312	PA	33	1	1-4	17	2	1-3
3299	VA	40	1-2	11-36	40	1	3-12
2959	NC	25	2	1-4	25	1	10
2973	GA	40	1	6-14	40	1	1-3
2983	IL	33	1-2	2-17	44	1-3	1-65
2962	WI	50	1-4	1-7	62	1-3	1-7
4340	WI	50	1-2	2-27	38	1-2	1-32
2962	WI	33	1-3	2-196	44	1-2	1-188
2987	MI	20	1-12	1-56	10	4	1-10
2967	MN	44	1-2	1-19	33	1-3	1-16
2964	MN	56	1-6	1-16	33	1-2	1-7
Total			85	1,031		65	672

[1] Fifty families fruited in 1975, 44 in 1976.

Table 3.—*Seed yield in yellow birch of northern and southern origin in 2 years*

Fruiting stands	Average number of catkins		Average number of seeds/catkin	
	1975	1976	1975	1976
11 northern	66	39	143	164
9 southern	35	28	134	132

with a range from 28 to 131 percent of the stand means in 1975 and from 8 to 178 percent in 1976. As expected, between- and within-stand variation among the individual trees was even greater (table 4), but neither stand nor family differences were statistically significant in either year. The number of seeds in individual catkins ranged from 4 to 305 in 1975 and from 3 to 399 in 1976. Variation among catkins within a tree was usually less than that among trees.

Table 4.—*Total seed yield in 1975 and 1976 seed crops of yellow birch families*

Stand		1975 families Seeds per catkin		1976 families Seeds per catkin	
No.	Origin	Mean	Range	Mean	Range
		----------	Number	----------	
3241	NS	112	112	250	250
3063	NS	121	87-165	—	—
2998	PQ	111	52-170	222	222
3000	PQ	85	30-128	196	174-219
3004	ON	190	190	180	180
3309	ON	136	106-152	84	9-160
2977	ME	159	108-209	118	45-211
2986	NH	155	129-181	120	64-175
2971	MA	244	244	59	59
3312	PA	85	59-112	110	110
3299	VA	138	113-163	164	158-170
2959	NC	148	148	171	171
2973	GA	61	45-77	125	125
2983	IL	105	69-131	137	84-189
2962	WI	173	108-297	134	108-166
4340	WI	126	63-228	163	131-222
2968	WI	152	73-220	187	119-283
2987	MI	157	135-179	98	98
2967	MN	182	142-238	177	22-306
2964	MN	156	94-295	168	124-192
Range of trees			18-297		9-314

Table 5.—*Germination of 1975 and 1976 yellow birch seed crops and filled seed percentage of 1976 seed*

Stand		1975 families		1976 families			
		Germination		Filled seeds		Germination	
No.	Origin	Mean	Range	Mean	Range	Mean	Range
		----------	----------	Percent	----------	----------	
3241	NS	10	10	0	0	0	0
3063	NS	8	4-12	—	—	—	—
2998	PQ	4	0-8	12	12	0.2	0 2
3000	PQ	3	1-6	14	0-24	9	0-17
3004	ON	19	19	11	11	8	8
3309	ON	4	2-7	17	8-26	16	6-26
2977	ME	14	8-20	21	9-27	11	4-17
2986	NH	6	0-13	10	8-12	3	2-4
2971	MA	12	12	8	8	8	8
3312	PA	4	3-4	4	4	4	4
3299	VA	5	0-9	8	6-11	5	3-8
2959	NC	2	2	0	0	0	0
2973	GA	0	0	0.3	0 3	0	0
2983	IL	24	8-38	24	11-44	1	0.4-1.3
2962	WI	13	6-23	12	22	3	7
4340	WI	7	4-9	9	8-18	8	0-16
2968	WI	10	4-16	11	0-28	9	0-23
2987	MI	11	7-14	10	10	5	5
2967	MN	11	0-18	15	2-34	5	0-14
2964	MN	12	1-19	40	24-61	18	4-34
Range of trees			0-62		0-67		0-52

In contrast to the fair to good seed yield in both years, seed quality was generally poor. Average germination percentage of the 1975 seed ranged from 0 in 5 families and 10 percent or less in 27 families up to 38 in one family (table 5). Among the individual trees it varied from 0 in 8 trees and 10 percent or less in 44 up to a maximum of 62 percent. As a result, the average germination was only 9 percent compared with 90 percent or better for mature trees in good seed years. The amount of filled seed in the 1976 seed, as determined by X-radiography, averaged only 10 percent for the 44 families and was extremely variable (table 5). Six families had only empty seed while 34 families had 30 percent or less filled seed and 4 families had more than 30 percent. Twelve trees had no filled seed, 18 had up to 10 percent, 25 had 11-30, 6 had 31-50, and 3 had more than 50 percent filled seed. In contrast, filled seed percentages exceeding 90 percent are common in natural stands in good seed years. Germination percentages were generally lower than filled seed percentages and ranged from 0 in 8 families and less than 10 percent in 26 families up to 34 percent in 1 family (table 5). The best tree had 52 percent germination, but the average for the 1976 seed crop was only 6 percent.

Catkin Characteristics and Relations to Seed Yield and Quality

On the average, catkin length and diameter were greater in 1975 than in 1976 (table 6). The smaller catkin dimensions in 1976 may be due to the drought because moisture availability affects the size of plant parts (Kozlowski 1971). Much variation among stands, families, and trees was recorded in both years but the analysis of variance showed no significant differences among seed origins or families in either year. The 1975 analysis included 74 trees of 43 families from 20 stands while the 1976 analysis included 65 trees of 43 families from 19 stands. As shown previously, the analyses of number of seeds per catkin gave similar results. The lack of significance can probably be ascribed to the fact that unequal numbers of trees per family and of families per stands were used in the analyses with the attendant reduction in degrees of freedom. Because catkin dimensions were greater in 1975 than in 1976, both the diameter/length ratio and catkin volume followed the same pattern (table 6).

Table 6.—*Characteristics of catkins collected from 8- and 9-year-old yellow birch in 1975 and 1976*

Catkin characteristic	1975 families		1976 families	
	Mean	Range	Mean	Range
Length (mm)	24.3	13.3-36.3	21.1	12.3-34.2
Diameter (mm)	15.2	10.0-24.3	10.0	5.5-14.0
Diam./length	.629	.401-.902	.484	.269-.707
Volume (cm^3)	3.23	0.75-6.85	1.27	0.32-2.72

Correlations between catkin characteristics and seed yield were higher in 1975 than in 1976. In both years, number of seeds per catkin showed the closest relation to catkin length and catkin volume (table 7). One might expect a good correlation between catkin diameter and number of seeds because catkin diameter and volume were highly correlated in both years. This was true in 1975 but not in 1976. The apparent reason is that the catkins were proportionately thinner in 1976 as evidenced by the smaller diameter/length ratio in that year (table 6) and also by the poor correlation between catkin length and diameter, which contrasts to the close relation between them in 1976 (table 7). Catkin shape, as measured by the diameter/length ratio, was unrelated to catkin volume and was a fair to poor indicator of seed yield (table 7).

Of the characteristics measured, catkin length was the best indicator of potential seed yield but not of seed quality. Catkin length was poorly correlated with percent filled seed in 1976 and with seed germination in both 1975 and 1976 (table 7). The correlation between catkin length and percent germination was closer in 1975 than in 1976 as a result of the slightly better germination in 1976. The relation between seed yield and seed quality was poor. Number of seeds was uncorrelated with both percent filled seeds and percent germination in 1976 and only poorly correlated with germination percentage in

Table 7.—*Correlations between catkin characteristics, seed yield, and seed quality for 2 years*

Variables correlated	r[1]	
	[2]1975	[3]1976
Catkin length-catkin diameter	0.668**	0.117*
Catkin length-catkin volume	.820**	.522**
Catkin diameter-catkin volume	.944**	.868**
Catkin diameter/length-catkin volume	–.253	.131
Catkin length-No. seeds/catkin	.621**	.533**
Catkin diameter-No. seeds/catkin	.529**	.254**
Catkin volume-No. seeds/catkin	.574**	.422**
Catkin diameter/length-No. seeds/catkin	–.316**	–.273**
Catkin length-percent filled seeds	—	.280**
Catkin length-percent germination	.329**	.294**
No. seeds/catkin-percent filled seeds	—	–.042
No. seeds/catkin-percent germination	.271*	.041
Percent filled seeds-percent germination	—	.550**

[1] ** = significant at 0.01 level; * = significant at 0.05 level.

[2] First 8 correlations based on 237 individual catkins; last 2 on 74-tree averages

[3] First 8 correlations based on 307 individual catkins; last 5 on 155 catkins.

1975 (table 7). The correlation between percent filled seed and percent germination (0.55) was only fair, indicating that a portion of the filled seeds was not viable. Although most of the correlations are statistically significant, few of them show biologically significant relations.

DISCUSSION

These yellow birch trees were beginning to produce substantial amounts of seed by the time they were 8 and 9 years old. Total yield of an average tree was more than 1,500 seeds in both 1975 and 1976. Trees with high numbers of catkins produced correspondingly greater numbers of seeds. Seed yield will, of course, increase with time as the number of catkins per tree goes up and with further increases in the average number of seeds per catkin. In 1975, 18 percent of the trees had more than 200 seeds per catkin compared with 22 percent in 1976. Of the latter, 3 percent had more than 300 seeds per catkin.

Variation between and within families in seed yield was substantial but not statistically significant. The lack of significance appears to be due to the plant material and the nature of the data. Unequal sample sizes were used in the analyses because the number of fruiting trees per family and the number of fruiting families per stand varied so much in both years. Therefore, the degrees of freedom were reduced accordingly and even large differences were not significant.

The correlation analyses indicate that catkin length, and, to a lesser degree, catkin volume have a fairly good positive relation with number of seeds per catkin. Catkin diameter, however, appears to vary more from year to year than other catkin variables and thus is a less reliable estimator of potential seed yield.

Seed quality so far has not been as good as seed yield. Amount of filled seed was generally low, and seed germination in both years was less than 10 percent compared with percentages above 90 percent for mature yellow birch in good seed years (Clausen 1973). As a result, effective seed yield is still disappointingly low.

The poor seed quality noted in these young trees may be due to a lack of pollen. No male catkins were produced in the plantation in the spring of 1975 and of the 16 trees with male catkins in the spring of 1976 more than one-half had less than 10 catkins per tree (Clausen 1977). Thus, in both years most of the pollen had to come from the surrounding area where yellow birch is not common. Filled seed and germination percentages should improve as more trees begin to bear male catkins.

In addition, the flowering phenology of some of the trees may be a problem. Trees of southern origin flowered later and may, therefore, be out of phase with the other trees in the plantation. The lack of seed germination in the trees from Georgia and the poorly filled and poorly germinating seed of trees from North Carolina stand 2959 and Virginia stand 3299 suggest that these trees flower too late to be pollinated by trees of northern origin. On the other hand, the Wisconsin and Minnesota trees flower in synchrony with local pollen shed, and therefore, produced more and better seed.

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Dimension yields from short logs of low-quality hardwood trees

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DIMENSION YIELDS FROM SHORT LOGS OF LOW-QUALITY HARDWOOD TREES

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As it becomes increasingly more difficult to obtain large sawtimber size logs for high-valued hardwoods, sawmills must look for alternative raw material sources. In the last decade researchers have suggested utilizing smaller diameter trees and shorter logs that are usually used only for pulp chips or fuel wood to make dimension cuttings for furniture parts (Bingham and Schroeder 1976a, 1976b, 1976c, 1977, Dunmire *et al.* 1972, Reynolds and Schroeder 1977). Before a manufacturer can choose among chips, fuelwood, or solid wood as a final product for small diameter short logs, the expected yield of the product must be determined. The amount of chips or fuelwood can be evaluated by volume or weight, but more sophisticated methods are required to determine yield of solid wood dimension cuttings.

A large quantity of material for short logs or bolts exists in the forest. About 87 percent of the commercial hardwood timber in the Eastern United States is in trees less than 21 inches in diameter (USDA Forest Service 1978). Additionally, thinning or pulpwood cuts are often intermediate parts of the forest management plan. Smaller diameter logs and logging residue represent a considerable quantity of material unsuitable for standard lumber. This material can be cut into short lengths for dimension cuttings. Although character marks are prevalent in the smaller logging residue, researchers have demonstrated that sound, character-marked cuttings can be manufactured from short logs or bolts (Cooper and Schlesinger 1974, Dunmire *et al.* 1972). In addition, the demand for character-marked hardwoods in furniture is increasing (Anonymous 1976). Thus, short logs contain a variety of material suitable for furniture.

A method of estimating dimension stock yields from standard graded 4/4 lumber has been described (Englerth 1969, Schumann and Englerth 1967a, 1967b, Schumann 1971). Nomographs were used to determine hard maple and black walnut yields for particular cutting bills. Comparisons were made between grades so that the most economical grade or mix of grades could be found. And Landt (1974a, 1974b, 1974c, 1974d) developed volume tables for predicting clear one-side (C1S) cuttings from small diameter short bolts of several species. A similar study on yellow-poplar by Cooper and Schlesinger (1974) predicted clear two-sides (C2S) and character-marked (CM) as well as C1S cuttings. However, the data were not in a form that could be easily converted to number of cuttings of a particular size per unit board feet.

The purpose of this paper is to put in a nomograph form the dimension cutting yields of aspen, soft maple, black cherry, yellow-poplar, and black walnut from logs 1.9 to 6.7 feet long and from 5 to 18 inches in diameter. This information may provide the furniture manufacturer or dimension plant manager a useful tool in selecting the most economical grade mix for a particular cutting bill.

METHOD OF DATA COLLECTION

Bolt material was removed from selected trees in stand improvement cuts or from residue remaining after logging on several sites from Wisconsin to Pennsylvania (table 1). The bolts were bucked from short tree sections and ranged in size from 1.9 to 6.7 feet in length and from 5 to 18 inches in diameter.

Table 1.— *Basic information on bolt material*

				Bolt			
			Total	Diameter		Length	
Species	Location	Bolts	volume	Mean	Range	Mean	Range
		No.	*Board feet*	*Inches*		*Feet*	
Aspen	Wisconsin[1]	199	1,796	7.7	5.5-14.5	4.0	2.0-6.3
Soft maple	Southern Illinois	302	3,721	8.0	5.5-14.0	4.6	2.0-6.4
Black cherry[2]	Pennsylvania West Virginia	775	6,998	7.5	5.0-18.0	3.9	1.9-6.4
Yellow-poplar	Southern Illinois	351	4,241	7.7	5.5-16.5	4.7	2.0-6.7
Black walnut	Southern Illinois	200	1,621	6.8	5.5-12.0	4.5	2.1-6.4

[1] Each location represents one stand of trees. The results of this study only apply to the site from which the logs were cut.

[2] Black cherry material came from two stands each in a different location. This is not meant to be taken as a sample from the population of black cherry sites but just a combining of two sets of data.

Bolt length was limited only by external defects or sweep exceeding 1 inch in 2 feet of length. The bolts were scaled by the International ¼-inch Rule—diameters were measured to the nearest ¼ inch and lengths to the nearest 1 inch. Bolt grades were recorded using a grading system similar to the method described by Redman and Willard (1957). The bolt distributions, representative of residue material, are skewed toward the large end for diameter, length, and grade.

METHOD OF CUTTING FLITCHES

The bolts were "live-sawn" into 1 ⅛-inch-thick rough unedged flitches on a portable bolter saw. Live-sawing consisted of slabbing one side of the bolt—the poorest side or the concave side of bolts with sweep—turning the bolt flat side down, and sawing the rest of the bolt without additional turning. The flitches were then air- and kiln-dried to a moisture content of 8 percent.

DIMENSION CUTTINGS

The dried flitches, which had been skip-dressed to 15/16-inch thick, were diagramed to determine the dimension cuttings. The dimension cuttings were of three grades: C2S, which had two faces clear of knots and defects; C1S, which had one clear face and sound defects on the second face; and CM, which had sound defects on both faces. To determine maximum yields the boards were diagramed three separate times—first for the longest cuttings of grade C2S, then for the longest cuttings of grade C1S or better, and finally for the longest cuttings of grade CM or better. Because of the higher value of a long cutting, the longest and widest cuttings were diagramed first. Priority was established by the formula $L^2 \times W$, where L was length and W was width of the cutting. Cuttings ranged from 1 to 6 inches wide and from 12 to 72 inches long.

DATA SUMMARY

The cuttings for each species and cutting grade for bolts 2 feet and longer (2-foot minimum) were summarized on the computer to yield the number of cuttings and total surface area by cutting length and width classes. A similar summary was made disregarding bolts shorter than 4 feet (4-foot minimum). The classes ran from 1 to 6 inches, in increments of ½ inch, for width, and from 12 to 72 inches, in increments of 6 inches, for length. The surface area recovered in cuttings is reported as the total surface area of all cuttings represented as a percentage of the total surface area possible, as predicted by the International ¼-inch Rule (table 2). The small differences in surface area recovered among the cutting grades for each species is in part due to the priority established

Table 2.—*Surface area recovered in cuttings by species, cutting grade, and minimum bolt length*

Species	Cutting grade	Two-foot (minimum length)	Four-foot (minimum length)
		Percent	
Aspen	C2S	68	69
	C1S	69	69
	CM	69	70
Soft maple	C2S	64	65
	C1S	65	66
	CM	67	67
Black cherry	C2S	56	58
	C1S	57	58
	CM	57	59
Yellow-poplar	C2S	58	58
	C1S	58	59
	CM	59	59
Black walnut	C2S	62	62
	C1S	62	63
	CM	63	63

for longer cuttings ($L^2 \times W$). The expected increase in surface area yield by allowing character marks on one of two faces was minimal because of the method of prioritizing cuttings (i.e., an increase in length was often accompanied by a decrease in width and an increase in waste). Also, the estimated yields are conservative because of the $L^2 \times W$ prioritizing.

The summarized number of cuttings for each length and width class was then entered into a computer program designed to determine the dimension cutting yield charts for 1-inch-wide material and yield adjustment values for material greater than 1 inch wide (figs. 1-14). Several yield charts were found to be nearly identical. In these cases one yield chart and width adjustment chart is reported and can be used to determine yield for several cutting grades and/or minimum bolt lengths without substantial loss in accuracy.

USING THE CHARTS

Length

The predicted percent yield of the longest desired cutting and subsequent shorter cuttings can be obtained from the charts given the length of the longest cutting required. To use the chart, first locate the maximum cutting length required on the right-hand side of the chart. The percent yield, in surface area of a 1-inch-wide cutting, is found by moving horizontally to the left until the point of intersection with the percent yield scale on the far left. This is the percent yield of the longest 1-inch-wide cutting. To find the percent yield of the second longest cutting, begin at the point on the right corresponding to the maximum cutting length and proceed vertically to the intersection with the line corresponding to the length of the second cutting. Now move horizontally to the percent yield scale. The percent yield of the second longest cutting, given the removal of the longest cutting, is obtained by subtracting the percent yield for the longest cutting from the percent yield for the second longest cutting. Other yields are obtained in a similar fashion always beginning at the point on the right corresponding to the maximum cutting length, proceeding vertically to the line corresponding to the next desired length, and then moving horizontally to the percent yield scale. The percent yield for each new length is found by subtracting the unadjusted percent yield of the previous cutting length from the percent yield of the new cutting length.

For example, if the cutting bill called for black walnut, C2S, 4-foot minimum bolt length, 1-inch-wide cuttings of lengths 48, 24, and 12 inches, the yield of 48-inch cuttings would be 14 percent (fig. 15). For 24-inch cuttings, the yield would be 22 percent (36 percent-14 percent), and the yield of 12-inch cuttings would be 15 percent (51 percent-36 percent). The total yield of all cuttings would be 51 percent (which is also the accumulated percentage of the shortest length) or 510 square feet of surface area per 1,000 board feet of bolts, scaled according to the International ¼-inch Rule.

Width Adjustments

To determine the percent yield of cuttings other than 1-inch-wide, a correction multiplier chart is given. The percent yield for cuttings greater than 1 inch are found by locating the length of the desired cutting at the base of the correction multiplier chart. Then move vertically to the intersection with the line for the needed width and then horizontally to the correction multiplier scale. Multiply the correction multiplier by the percent yield for a 1-inch-wide cutting of the required length to obtain the percent yield for the needed width.

For example, given a cutting bill as before, but with a width requirement of 2.5 inches for 48-inch cuttings, 3 inches for 24-inch cuttings, and 2 inches for 12-inch cuttings, take the percent yield before subtraction for previous lengths and multiply it by the width correction multiplier of the length needed (fig. 16, table 3). Now the yield of 48-inch cuttings is 9 percent— the original yield of 14 percent times the correction multiplier for a 2.5-inch-wide 48-inch-long cutting of 0.62. For the 3-inch-wide 24-inch cutting, the yield is now 7 percent— the original 36 percent times the correction of 0.43 and finally minus 9 percent for the 48-inch cuttings already removed. Similarly, the yield for the 2-inch-wide 12-inch cuttings is 26 percent— 51 percent times 0.82 minus 16 for the 48- and 24-inch cuttings already removed. The total yield of all desired cuttings is 42 percent or 42 square feet per 1,000 board feet, as scaled by the International ¼-inch Rule.

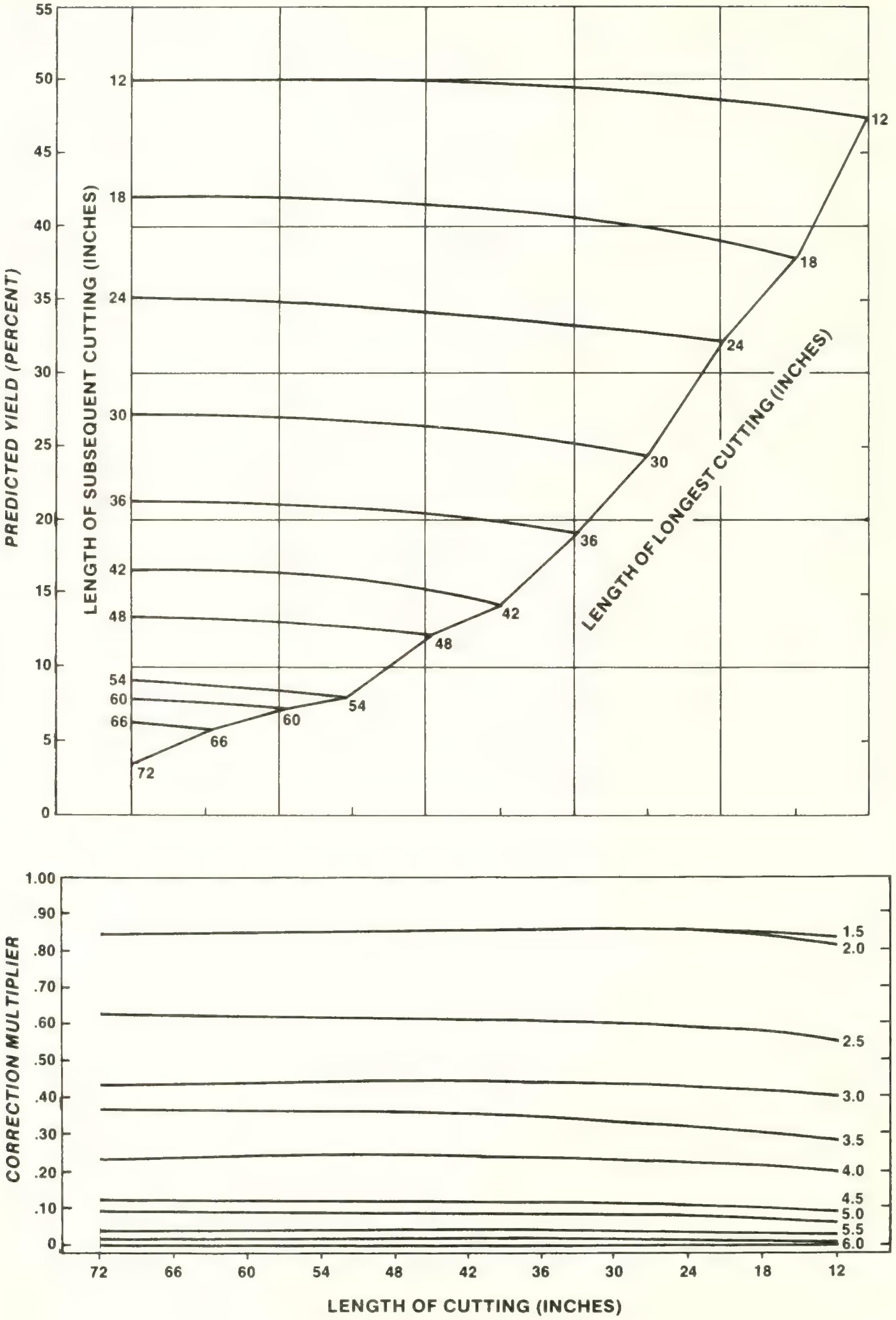


Figure 1.—*Yield prediction of 1-inch-wide cuttings with width corrections for black walnut C2S—2-foot minimum.*

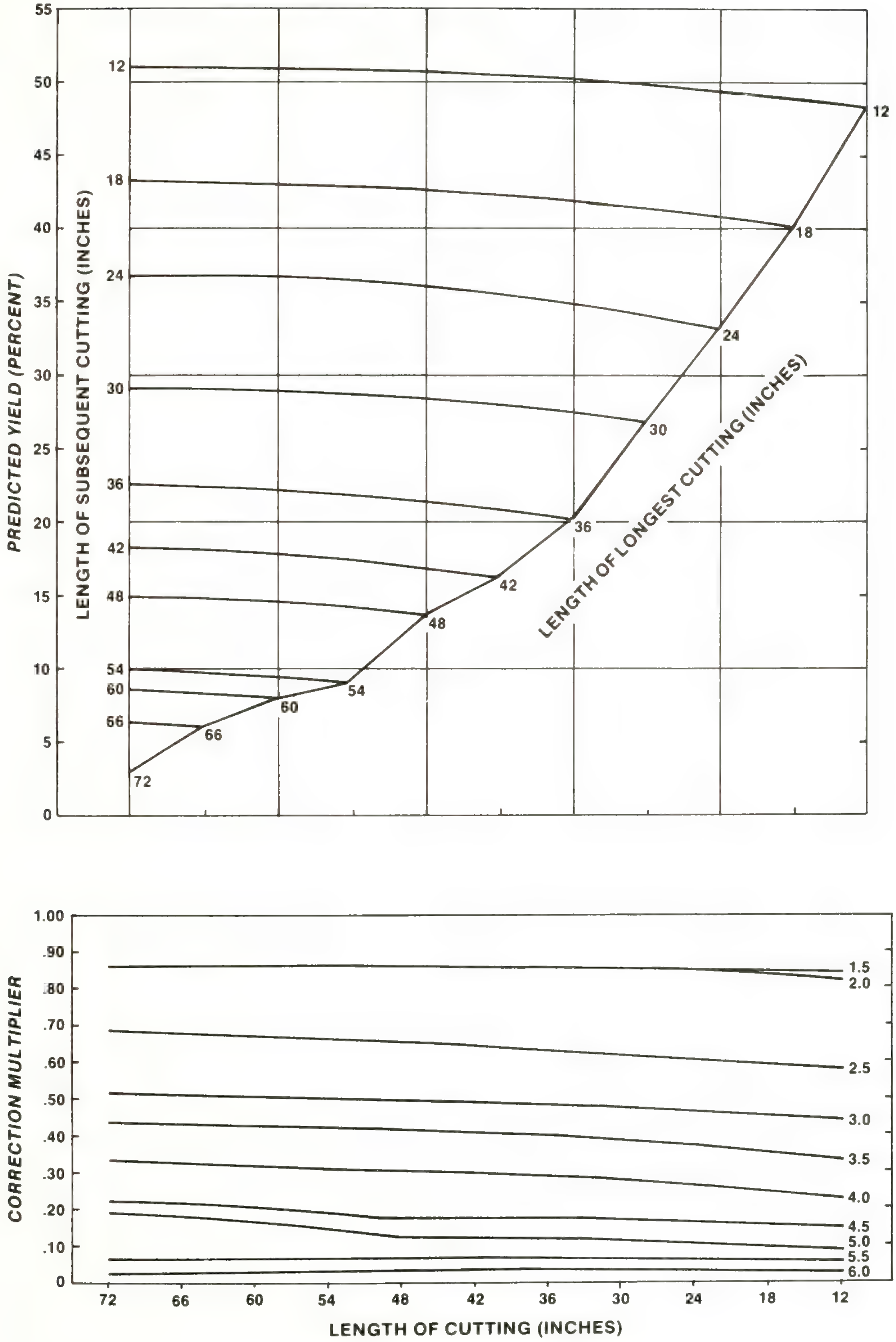


Figure 2.—*Yield prediction of 1-inch-wide cuttings with width corrections for black walnut C1S—2-foot minimum.*

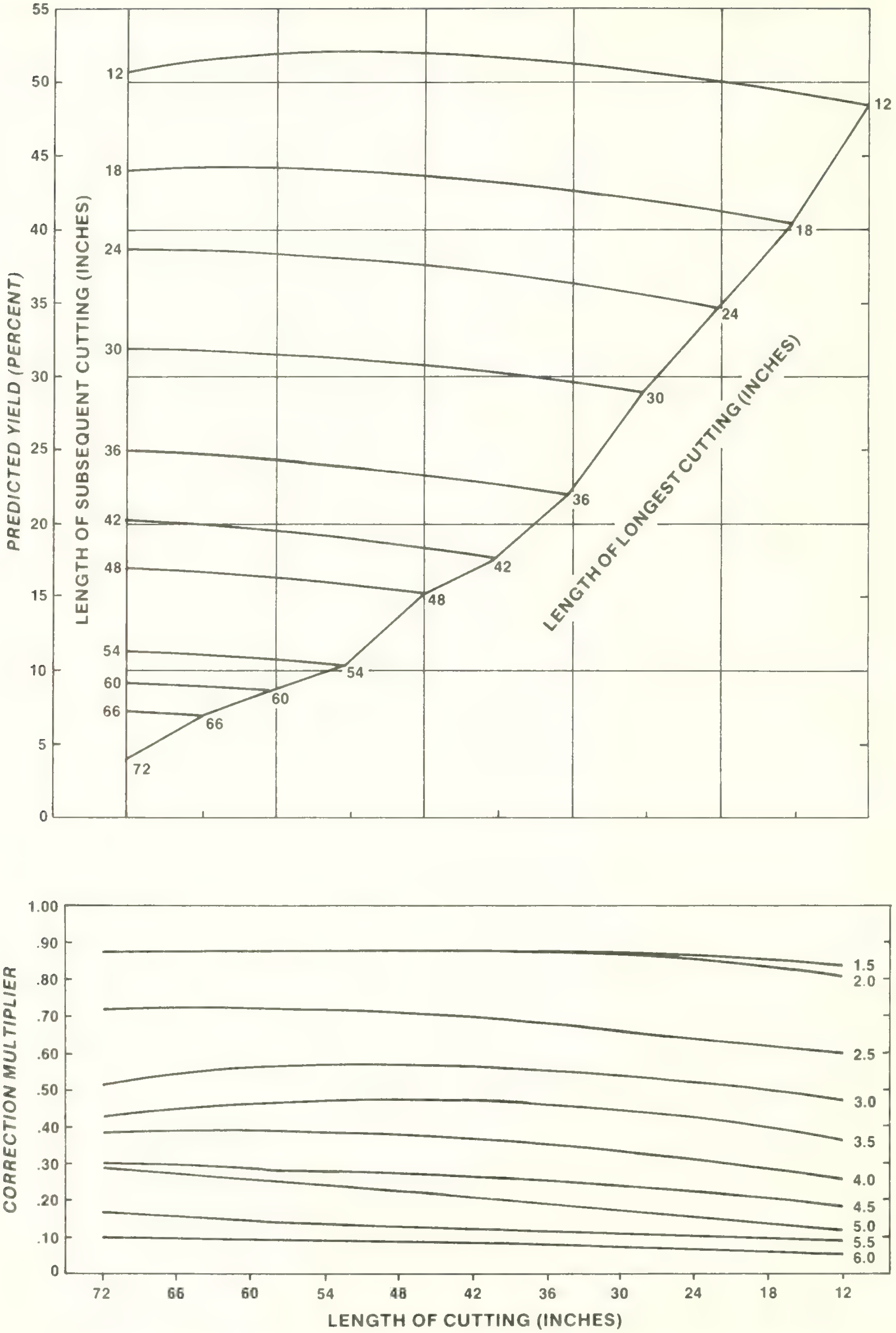


Figure 3.—*Yield prediction of 1-inch-wide cuttings with width corrections for black walnut CM—2-foot minimum.*

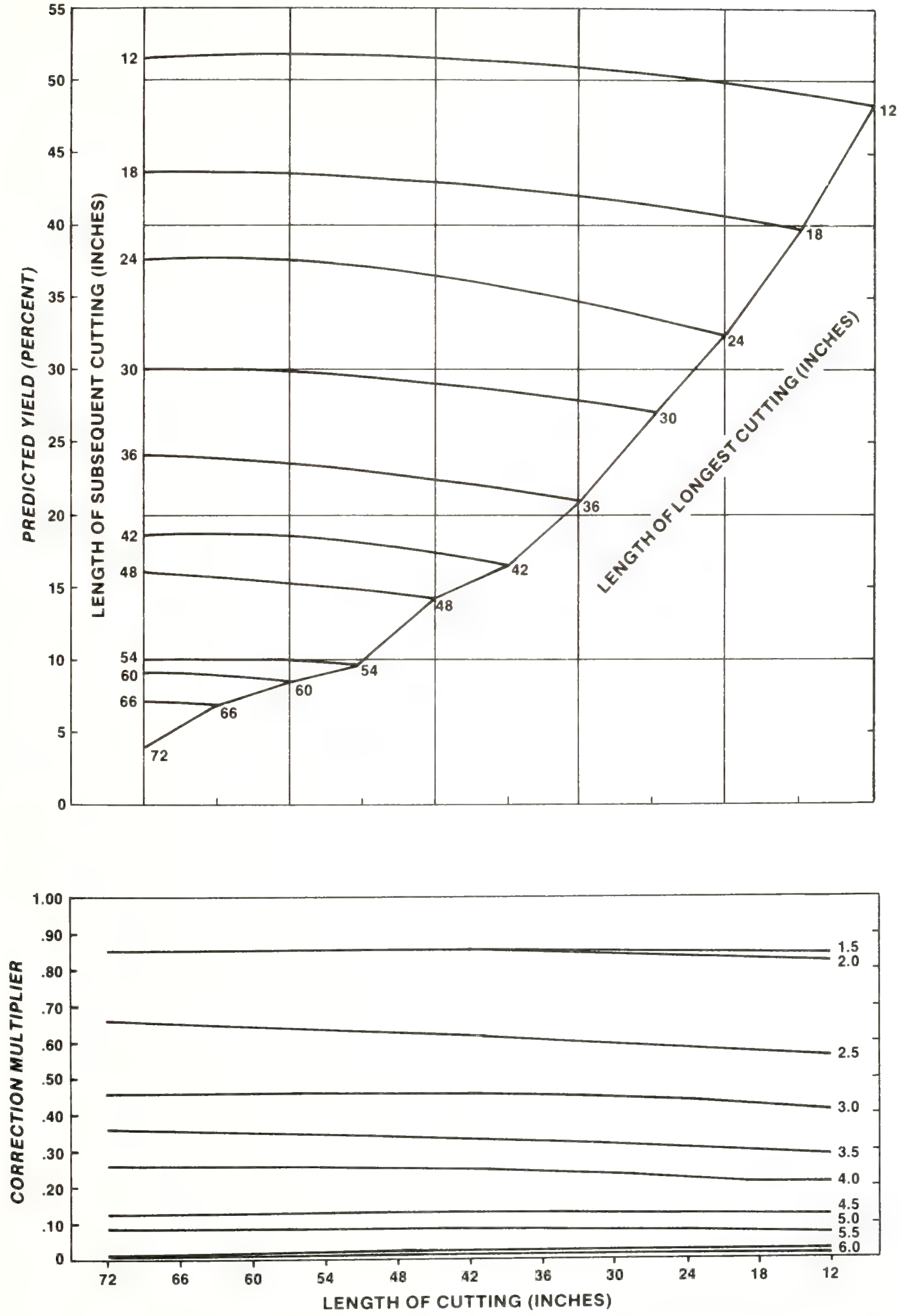


Figure 4.—*Yield prediction of 1-inch-wide cuttings with width corrections for black walnut C2S—4-foot minimum.*

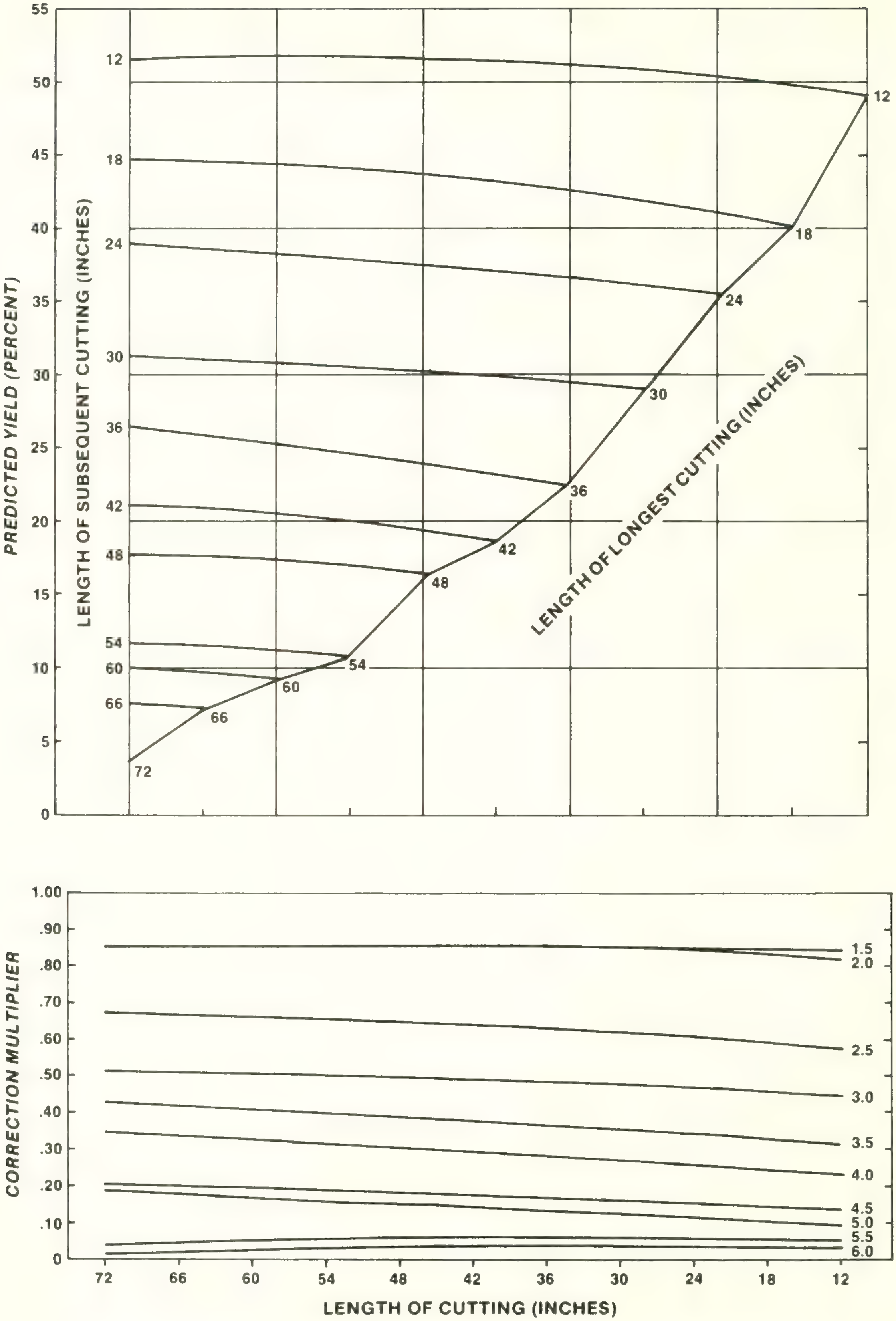


Figure 5.—*Yield prediction of 1-inch-wide cuttings with width corrections for black walnut C1S—4-foot minimum.*

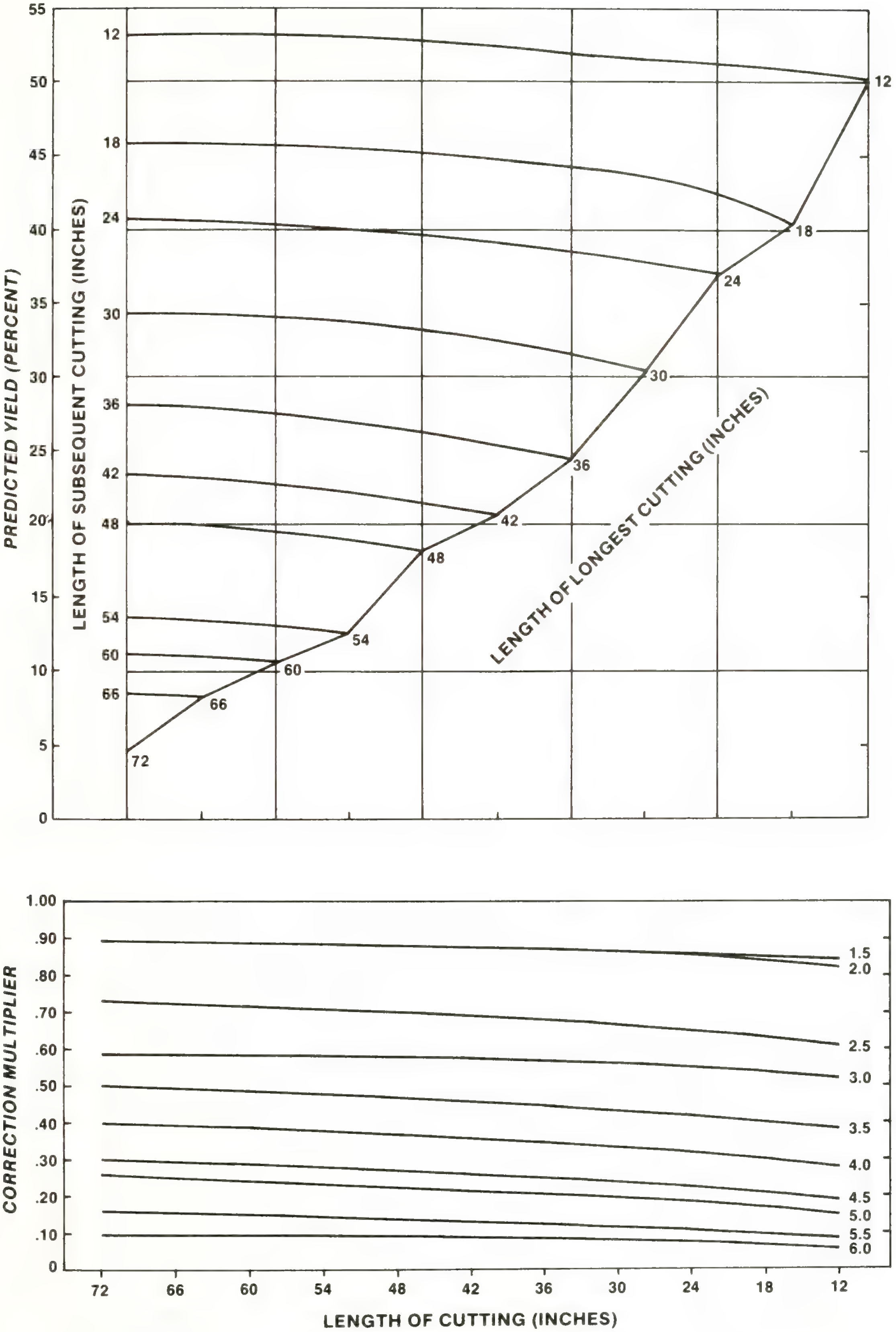


Figure 6.—*Yield prediction of 1-inch-wide cuttings with width corrections for black walnut CM—4-foot minimum.*

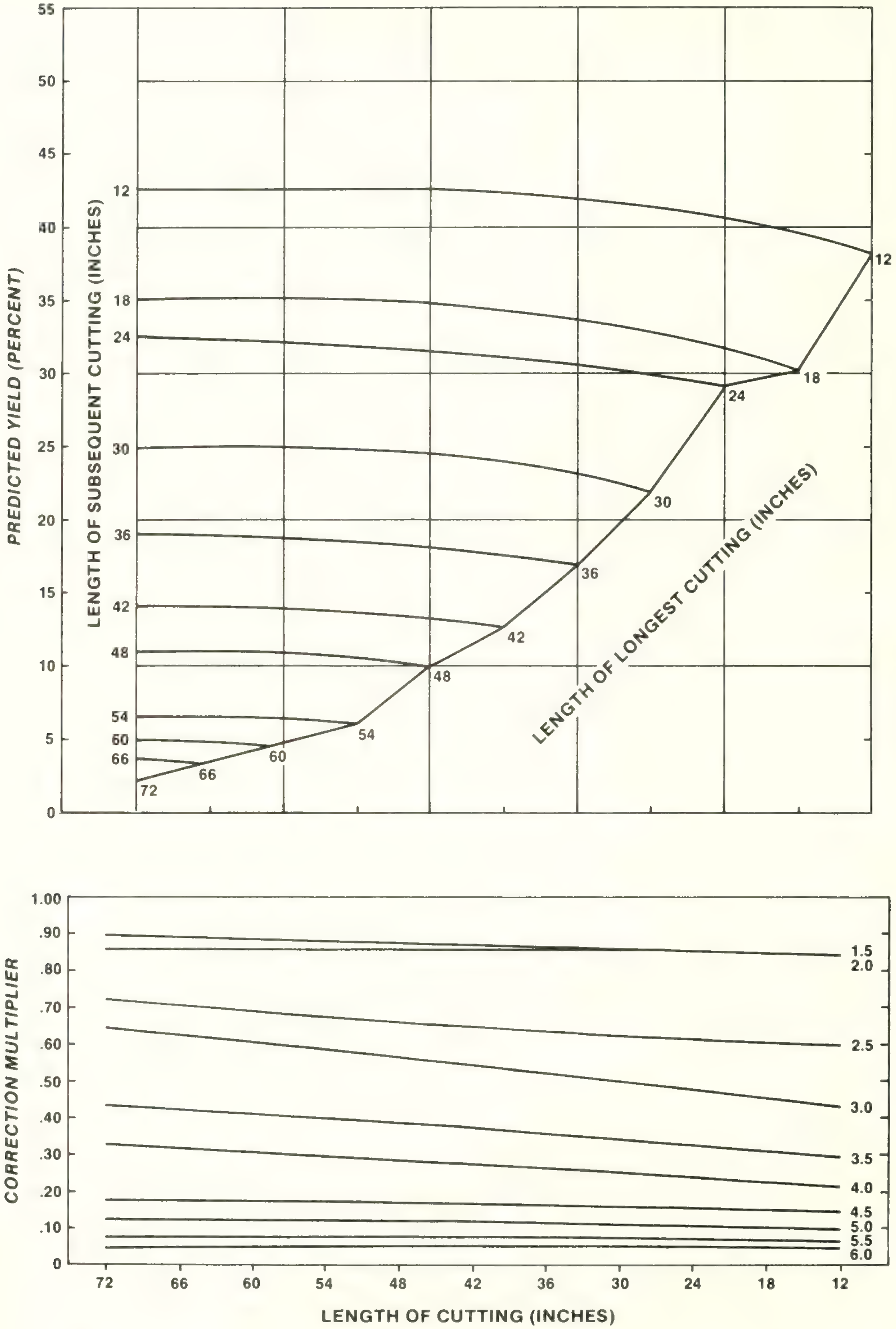
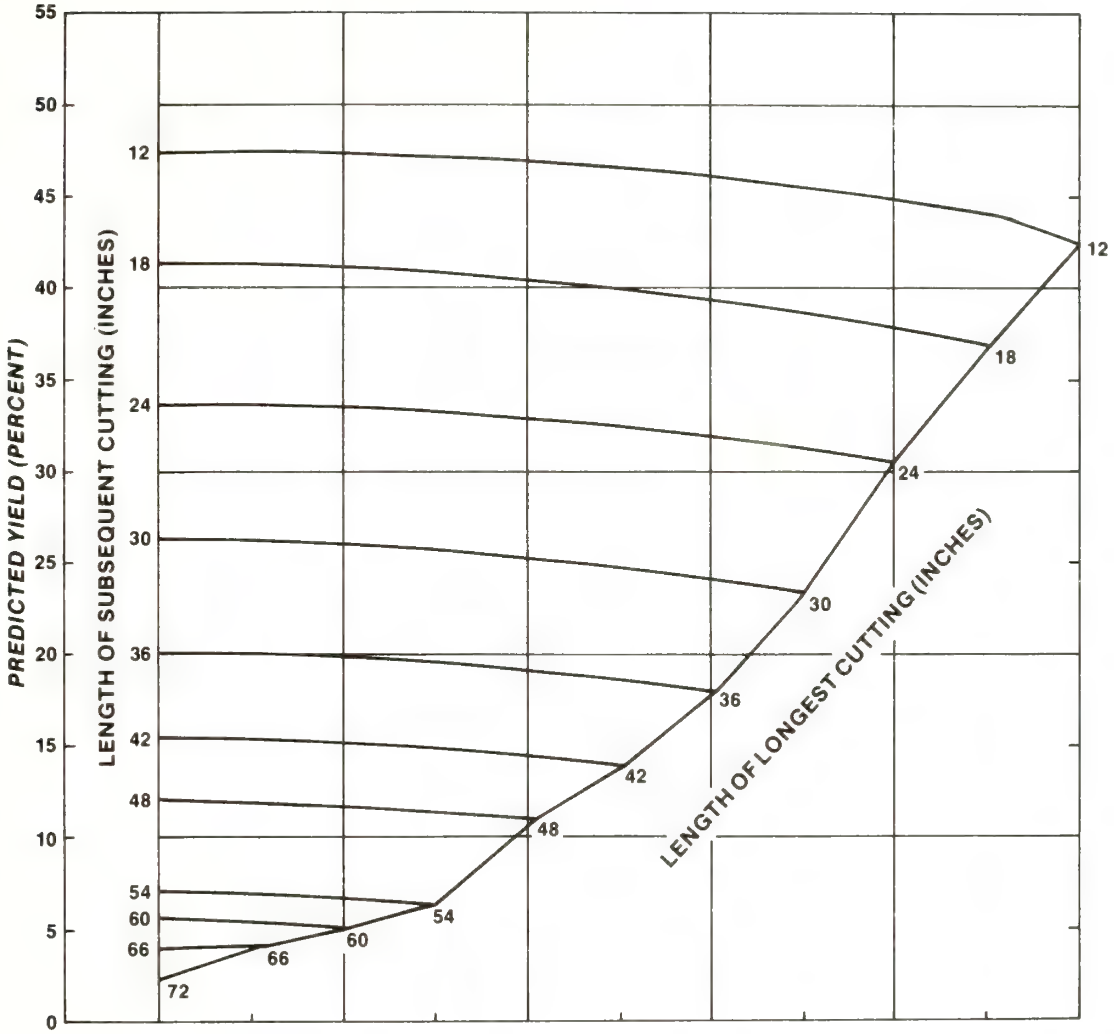


Figure 7.—*Yield prediction of 1-inch-wide cuttings with width corrections for black cherry C2S—2- and 4-foot minimum.*



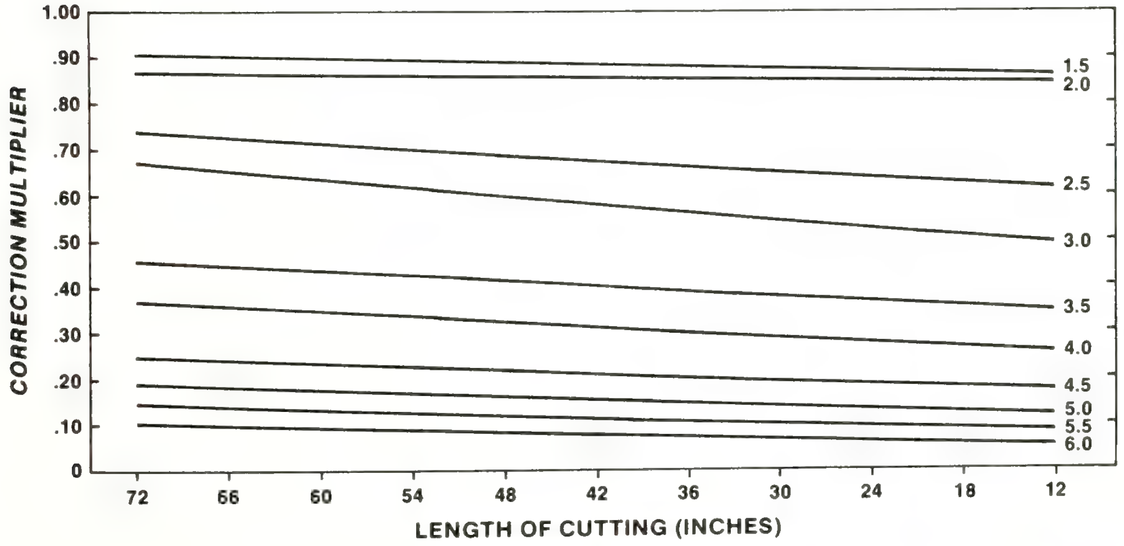


Figure 8.—*Yield prediction of 1-inch-wide cuttings with width corrections for black cherry C1S—2- and 4-foot minimum.*

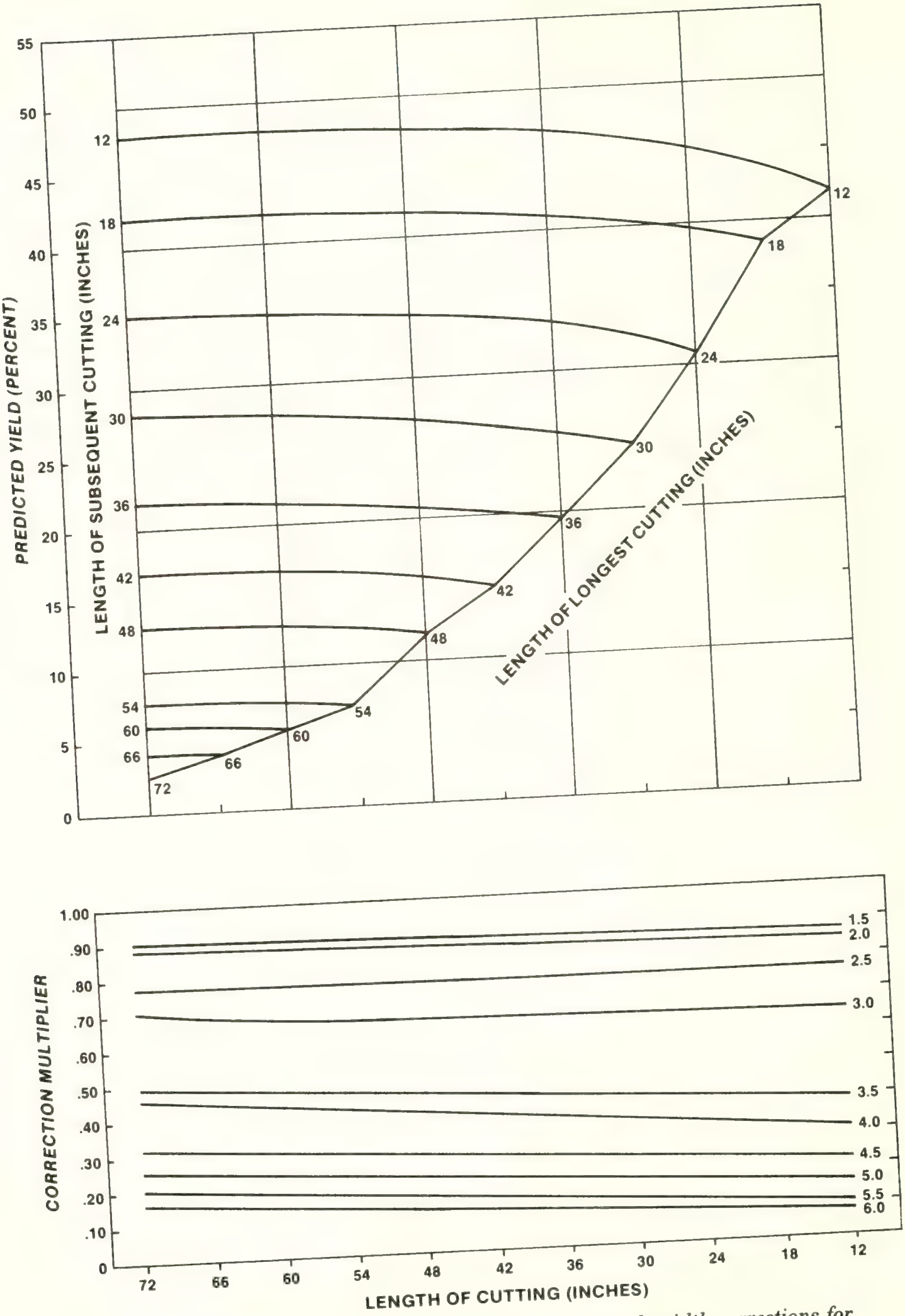


Figure 9.—*Yield prediction of 1-inch-wide cuttings with width corrections for black cherry CM—2- and 4-foot minimum.*

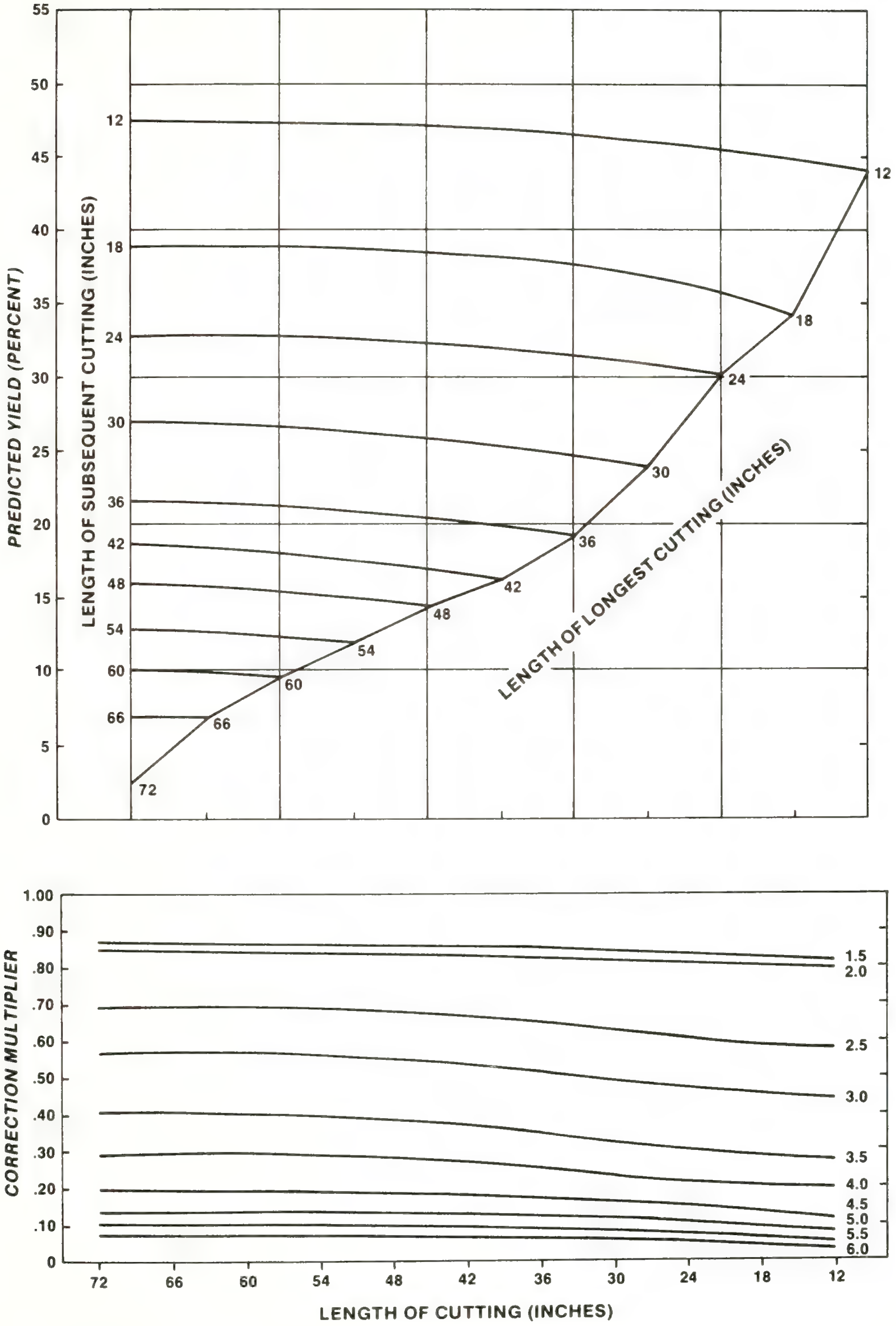


Figure 10.—*Yield prediction of 1-inch-wide cuttings with width corrections for yellow-poplar C2S—2- and 4-foot minimum.*

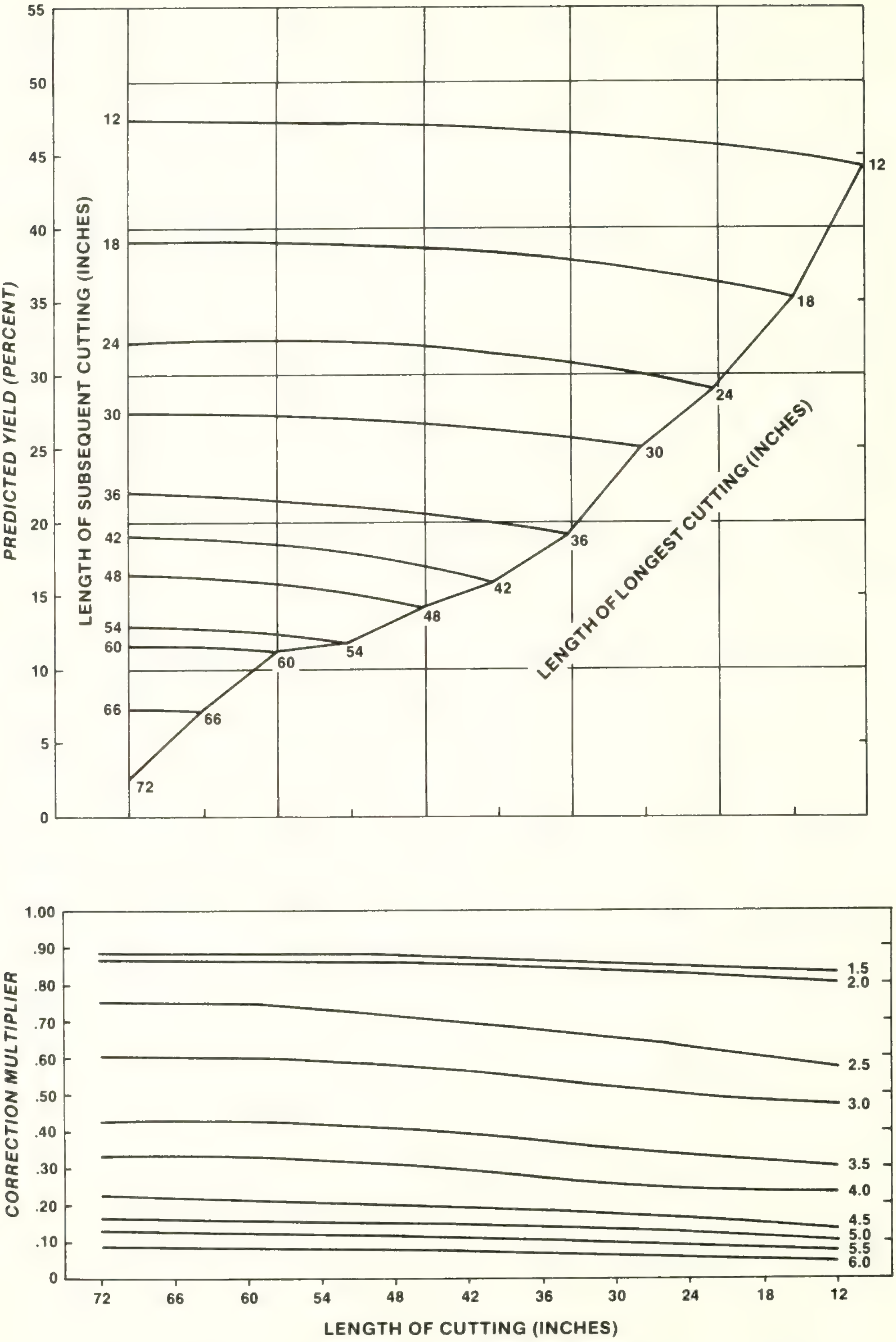


Figure 11.—*Yield prediction of 1-inch-wide cuttings with width corrections for yellow-poplar C1S—2- and 4-foot minimum.*

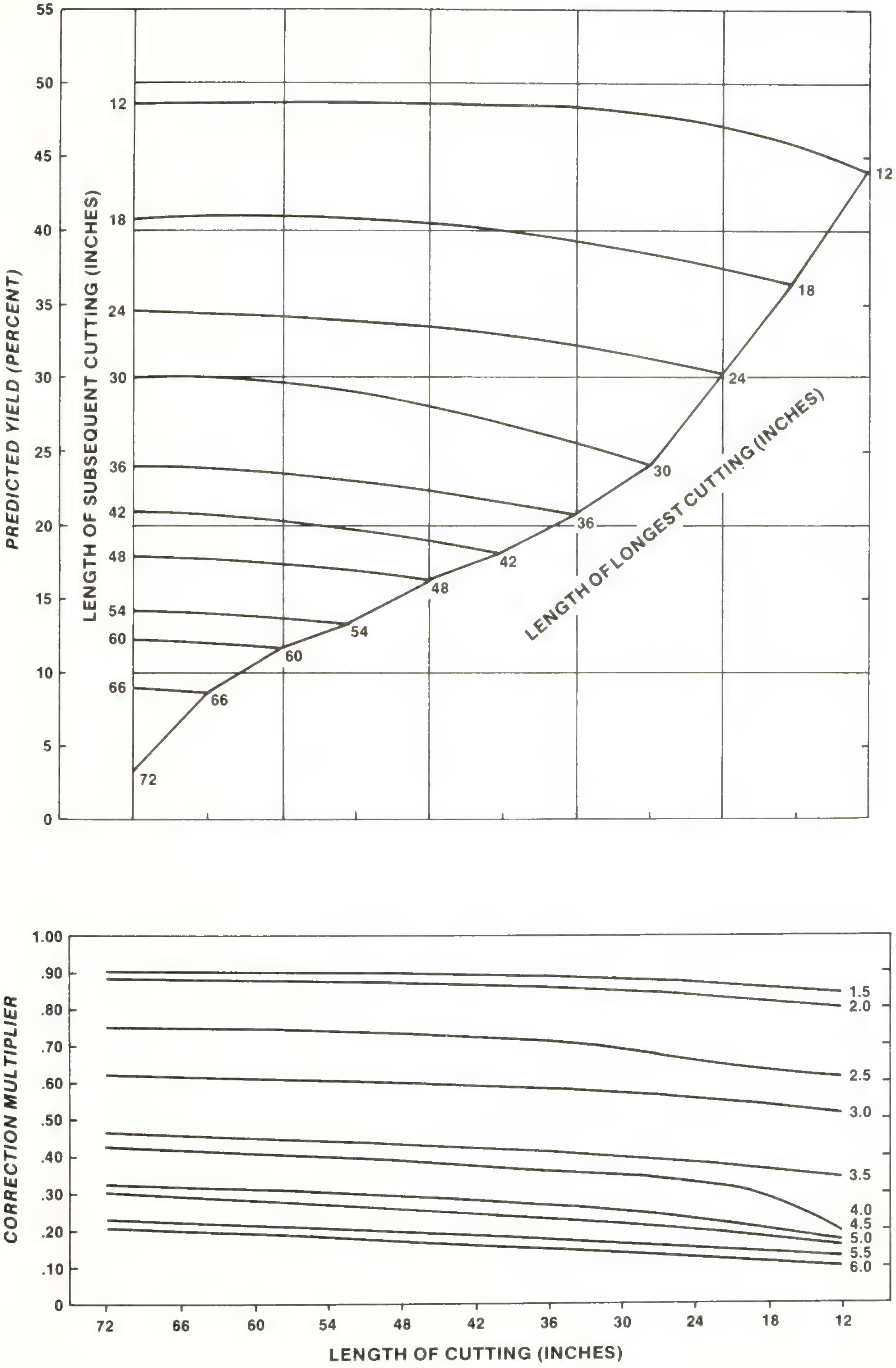


Figure 12.—*Yield prediction of 1-inch-wide cuttings with width corrections for yellow-poplar CM—2- and 4-foot minimum.*

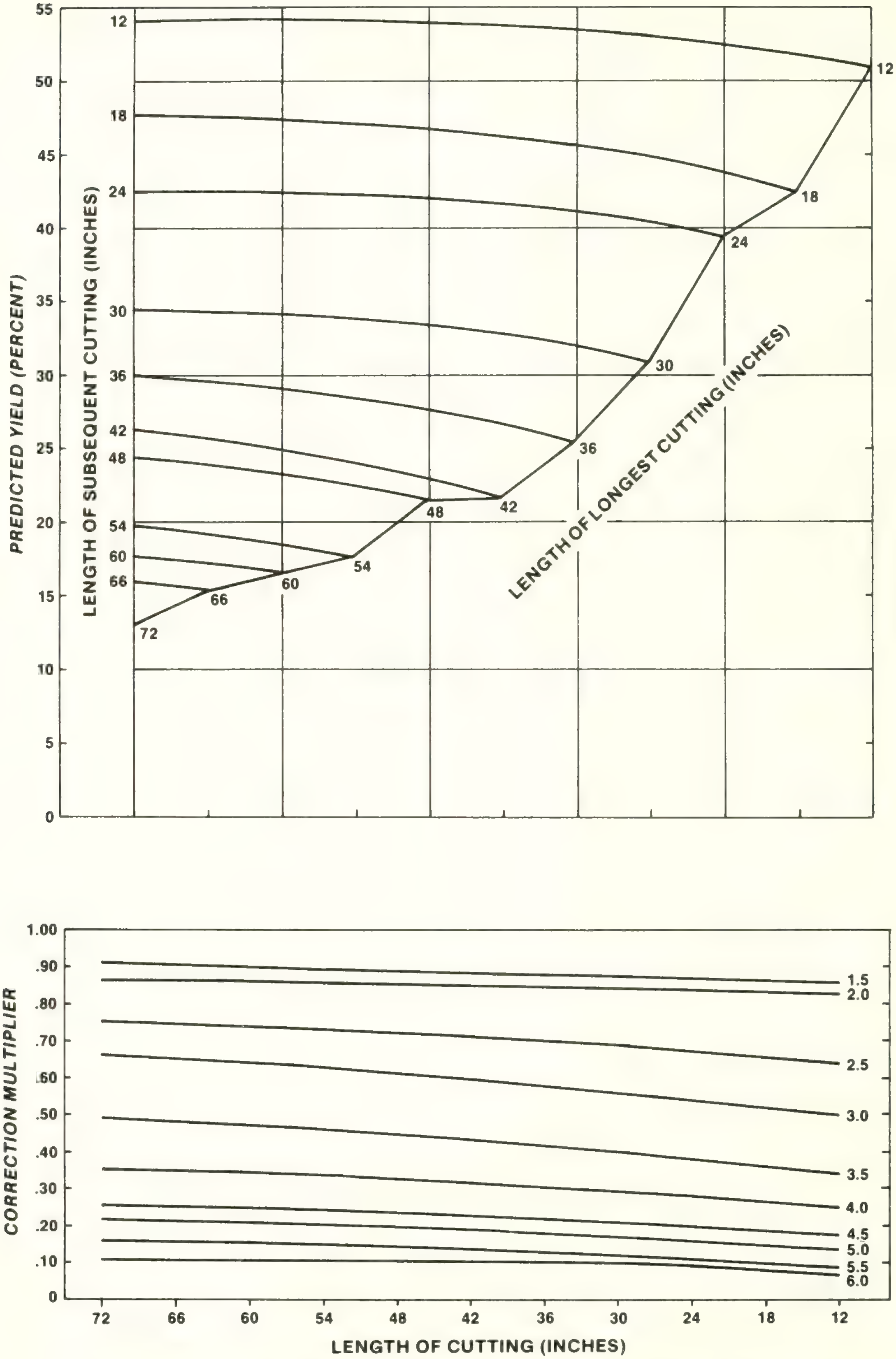


Figure 13.—*Yield prediction of 1-inch-wide cuttings with width corrections for soft maple C1S, C2S, and CM—2- and 4-foot minimum.*

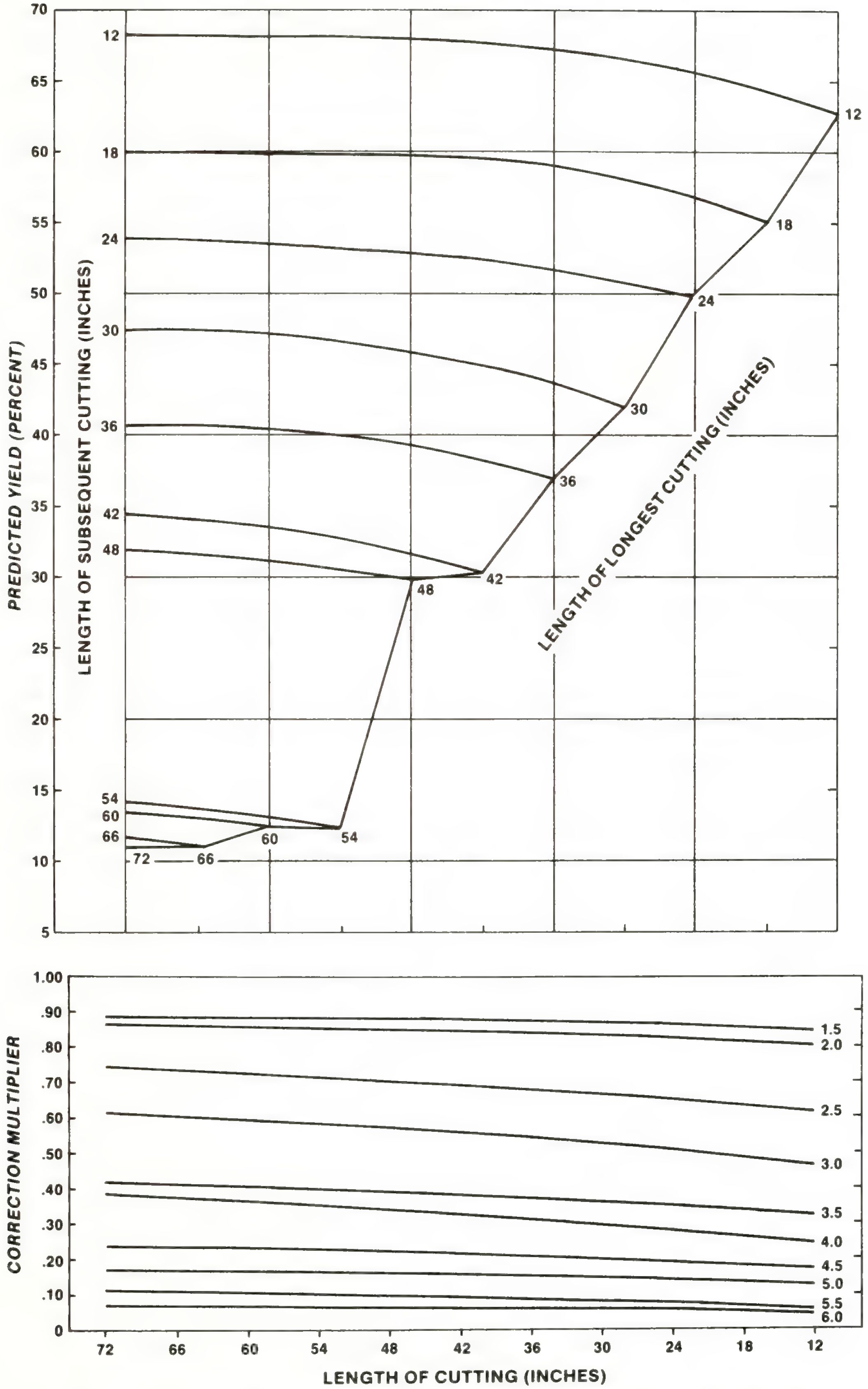


Figure 14.—*Yield prediction of 1-inch-wide cuttings with width corrections for aspen C1S, C2S, and CM—2- and 4-foot minimum.*

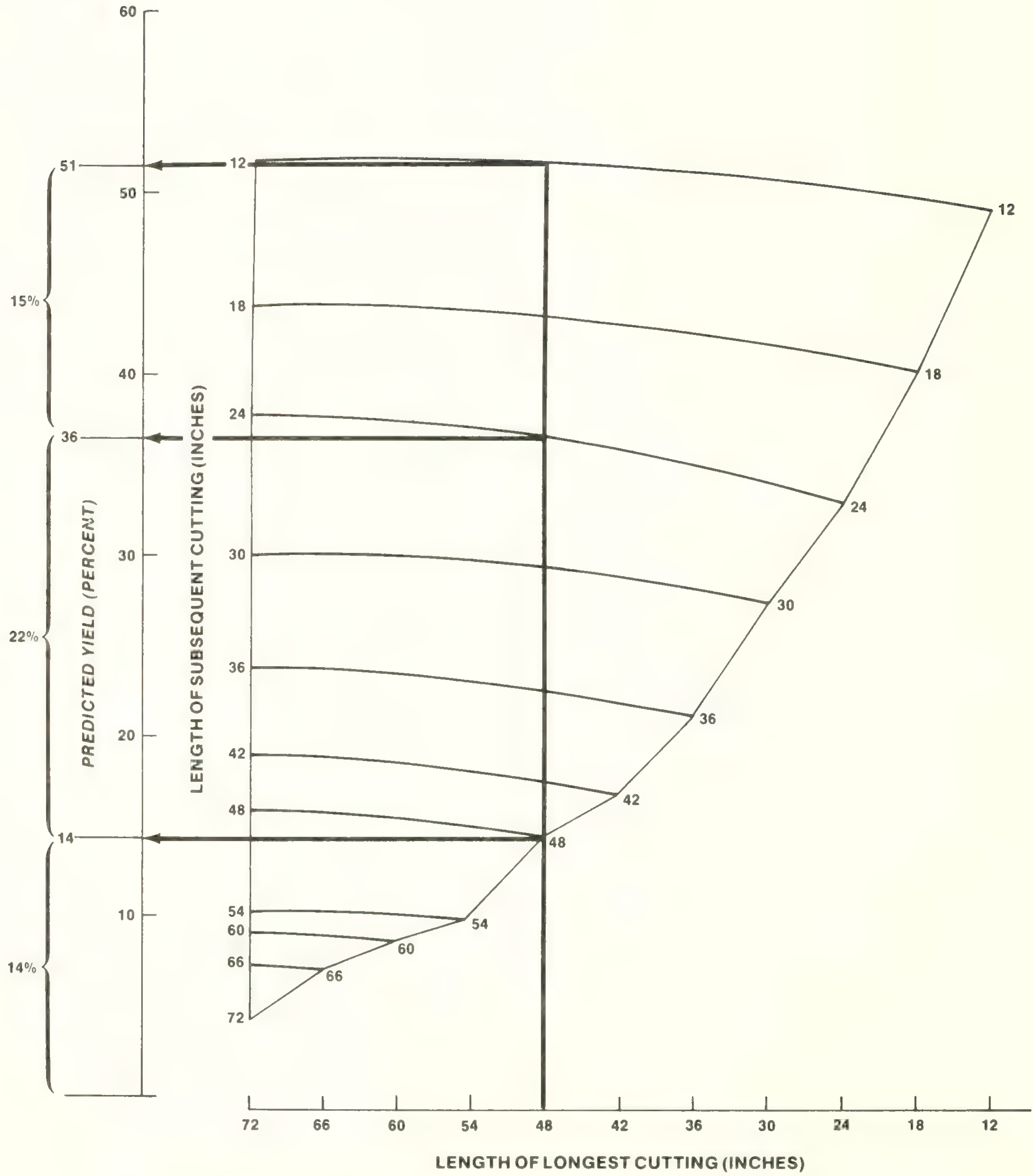


Figure 15.—*Example for using the percent yield charts: black walnut C2S—4-foot minimum.*

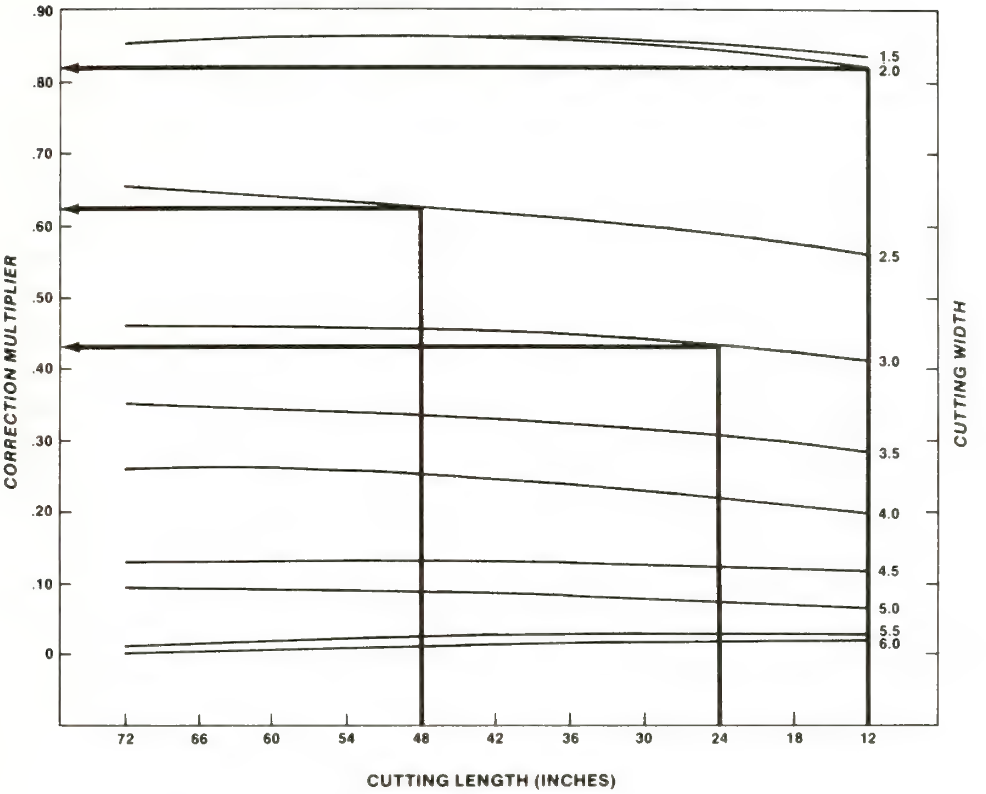


Figure 16.—*Example for using the width adjustment chart: black walnut C2S—4-foot minimum.*

Table 3.—*Example for obtaining percent yields for cuttings of various widths from black walnut, C2S lumber, and 4-foot minimum logs*

Cutting size		Yield of 1-inch-wide boards	Width correction multiplier	Adjusted yield	Yield given removal of previous cuttings
Length	Width				
Inches		*Percent*		*Percent*	
48	2.5	14	0.62	9	9
24	3.0	36	0.43	16	7
12	2.0	51	0.82	42	26
				Total yield	42

Conversion of Percent Yield to Number of Cuttings per Thousand Board Feet

Yields are easily converted from percents to number of cuttings per 1,000 board feet by dividing the percent yield by 100, multiplying by 1,000, and dividing by the area of the cutting surface in square feet (table 4).

Table 4.—*Number of cuttings per 1,000 board feet of three cutting sizes from black walnut, C2S lumber, and 4-foot minimum logs*

Cutting size		Surface area	Yield	Cuttings per 1,000 board feet
Length	Width			
Inches	*Inches*	*Ft^2*	*Percent*	*No.*
48	2.5	0.83	9	108
24	3.0	0.50	7	140
12	2.0	0.17	26	1,529

COMPARISON OF SHORT LOGS AND STANDARD GRADE LUMBER— YIELDS AND COSTS

Two general observations can be made comparing cutting yields from short logs to standard grade lumber: (1) overall yields are less for short logs and (2) distributions of cuttings are more heavily weighted to short and narrow pieces for short logs. For example, yields of short logs (C2S—4-foot minimum) compared to No. 2 Common lumber for black walnut show that recoveries for 1-inch-wide cuttings are similar, but recoveries from 3-inch lumber are better for No. 2 Common (table 5). For black walnut, yields from short logs are less than 15 percent for all lengths of cuttings 4 inches wide and above, whereas FAS grade lumber can yield up to 60 percent for the same product (Schumann 1971). The same is true for the other wood species of this study. Integrated sawmill-dimension plants can best use short logs for dimension lumber when the cutting bill requires narrow cuttings and a large percentage of the cuttings are short.

Table 5.—*Comparison of black walnut yields for No. 2 Common and short logs (C2S—4-foot minimum) for different width cuttings*

(In percent)

Cutting length (Inches)	1-inch width		3-inch width	
	No. 2 Common[1]	Short logs	No. 2 Common[1]	Short logs
48	14	14	7	7
24	28	22	24	9
12	11	5	13	5
Total	53	51	44	21

[1]From charts of Schumann (1971).

Because of the large differences in prices of lumber that exist depending on area of the country and time of year, estimating a price on standard grade lumber, much less on short log material, is difficult. Because black walnut is the most valuable wood type in this study, we estimated the cost of this wood for different grades to fill a specific cutting bill. We assumed the following quantity and sizes: 400 48- by 2½-inch, 400 24- by 3-inch, and 2,000 12- by 2-inch. We also assumed a cost per 1,000 board feet for FAS of $1,300, No. 1 Common $800, No. 2 Common $400, and the lumber derived from short logs $250.

After calculating lumber costs for several short log and grade combinations, we found that using entirely short log material was the most economical (table 6). Although three times as much short log lumber was required as for FAS lumber, the cost of cuttings from FAS lumber was almost twice as much. Combinations of No. 1 Common for the longer cuttings and short logs for the remainder reduced the lumber required, compared to only short logs, by more than half; but the lumber cost was still about $150 per 1,000 board feet higher.

The cost comparison example given is dependent upon particular prices. Also processing, handling, and drying costs may be larger due to the greater quantities of lumber needed to fill the cutting bill. Nevertheless the analysis demonstrates that short log material has potential economic value and that hardwood dimension producers and furniture manufacturers that produce their own raw material should consider this material when choosing the best grade mix to meet a specific cutting bill.

Table 6.—*Comparison of costs to cut 400 48- by 2½-inch, 400 24- by 3-inch, and 2,000 12- by 2-inch 4/4 black walnut cuttings from various grades and short logs*[1]

Lumber mix	Lumber required	Cost per 1,000 board feet	Total
	Board feet	*Dollars*	
Short logs for all lengths	3,774	250	944
FAS for all lengths	1,247	1,300	1,621
No. 1 Common for all lengths	1,544	800	1,235
No. 2 Common for all lengths	3,008	400	1,203
FAS for 48-inch lengths[2]	678	1,300	
Short log for remainder	913	250	1,110
No. 1 Common for 48- and 24-inch lengths[3]	1,278	800	
Short log for remainder	282	250	1,093

[1] Yields of standard grade from Schumann (1971).

[2] Includes 230 of 24-inch and 199 of 12-inch.

[3] Includes 1,348 of 12-inch.

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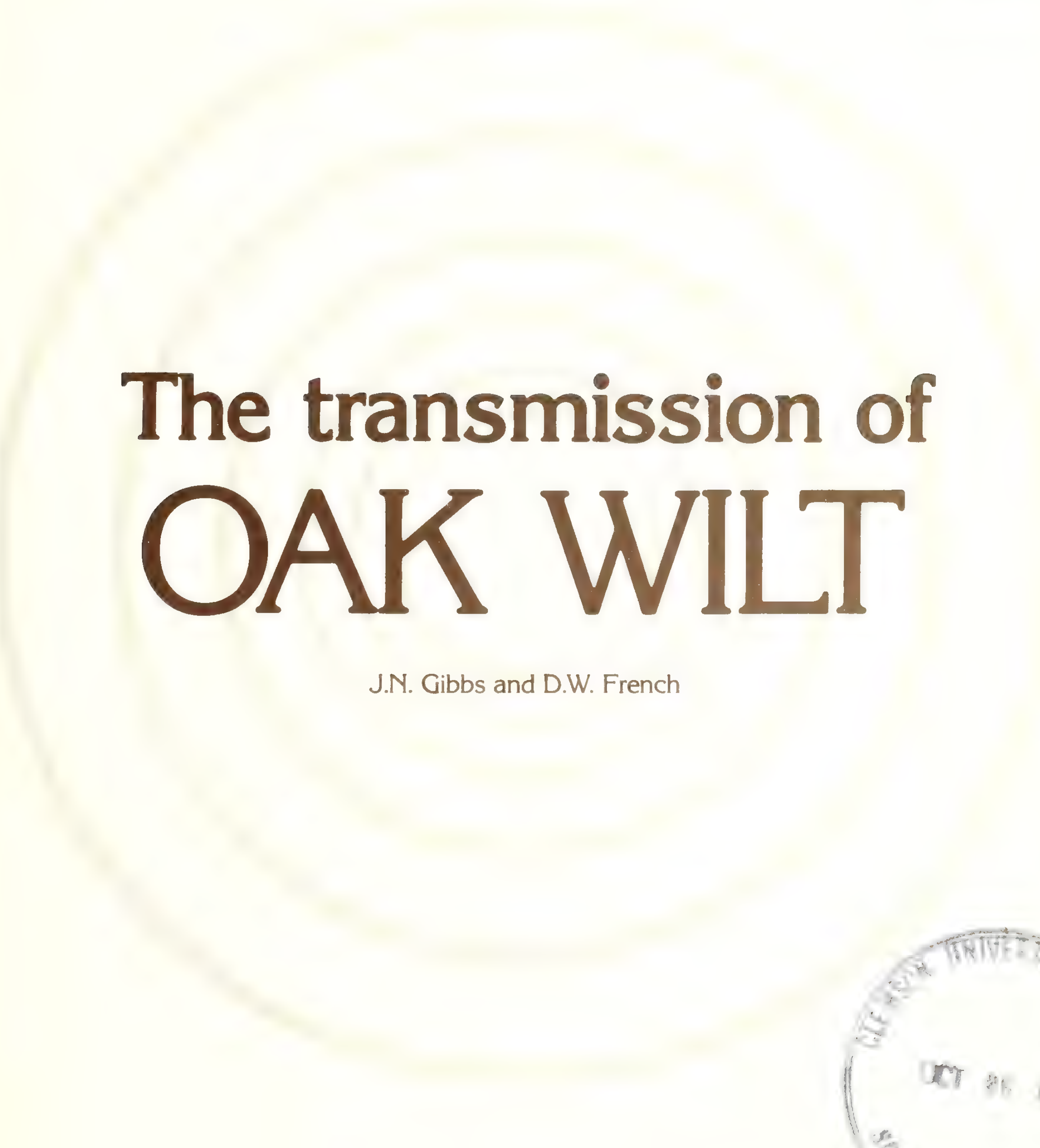

The transmission of OAK WILT

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THE TRANSMISSION OF OAK WILT

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and **D. W. French,** *Professor, Department of Plant Pathology, University of Minnesota, St. Paul, Minnesota*

Ceratocystis fagacearum (Bretz) Hunt, the cause of oak wilt, is a fungus with the potential to be one of the most destructive of all tree pathogens. Red oaks (subgenus *Erythrobalanus*) usually die within a few weeks of infection, and although white oaks (subgenus *Lepidobalanus*) are more resistant they are not immune. Trees that are diseased 1 year may recover the next but alternatively symptoms may recur. The host populations are enormous within the known range of the disease. In the eastern half of the United States the growing stock of oak amounts to 60,000 million cu. ft., or about 35 percent of the total hardwood volume. In the 20 States in which oak wilt is now known to exist, the red oak growing stock amounts to 22,000 million cu. ft., and the white oak growing stock is almost as large (U.S. Department of Agriculture, Forest Service 1965).

C. fagacearum has not caused the devastation once so greatly feared because its spread from diseased to healthy trees is slow and erratic. Three chief methods of transmission have been recognized: (1) through root grafts; (2) via sap-feeding insects such as Nitidulid beetles; and (3) via tree-wounding insects such as oak bark beetles. There is general agreement that the importance of these means of transmission varies in different parts of the oak wilt range, but in recent years little attempt has been made to evaluate all the data that have accumulated. The objective of this paper is to provide such an evaluation.

HISTORY AND SEVERITY OF THE DISEASE

Oak wilt was first described in Wisconsin in the early 1940's (Henry *et al.* 1944) but disease survey records suggest that it was present at least as early as 1912 (French and Stienstra 1975). By 1947 it was known to be the major disease of oak in the Upper Mississippi Valley. In 1950 it was recorded in Pennsylvania and by 1951 was reported from 18 States. However, in many places it was undoubtedly present for a number of years before it was recognized and identified. Thus, in Cumberland County, Pennsylvania, one disease center was probably in existence by 1935 (Craighead and Nelson 1960), and in West Virginia, True *et al.* (1951) established that it had been present for at least 5 to 10 years before it was discovered. Although the disease was subsequently recorded in Oklahoma (1958) and South Carolina (1969), its known distribution has changed little since 1951, despite the presence of apparently suitable oak popu-lations in adjacent areas (fig. 1). In some places, for example in Minnesota, it is not now known in several counties where it was present earlier (French and Bergdahl 1973).

Disease severity varies greatly and is worst within the northwest part of its range. During a 10-year period prior to 1953, the disease destroyed 4.4 percent of the oak woodland in four counties of central Wisconsin. But in four adjacent counties the loss amounted to only 0.2 percent (Anderson and Skilling 1955). Even in the worst affected parts of States such as Missouri and West Virginia, less than one tree dies of oak wilt per square mile of forest each year (Lautz and Saufley 1970, Rexrode 1977).

It should be noted that the dramatic and continuing development of the disease in parts of Minnesota and Wisconsin during the last 40 years can at least partly be explained by the presence of a relatively new, highly susceptible, host population. The dense stands of northern pin oak (*Quercus ellipsoidalis* E. J. Hill) through which infection is spreading have resulted from the vigorous coppicing habit of this species, which has enabled it to establish itself as the dominant tree after logging operations and fire destroyed the original, more diverse woodland communities.

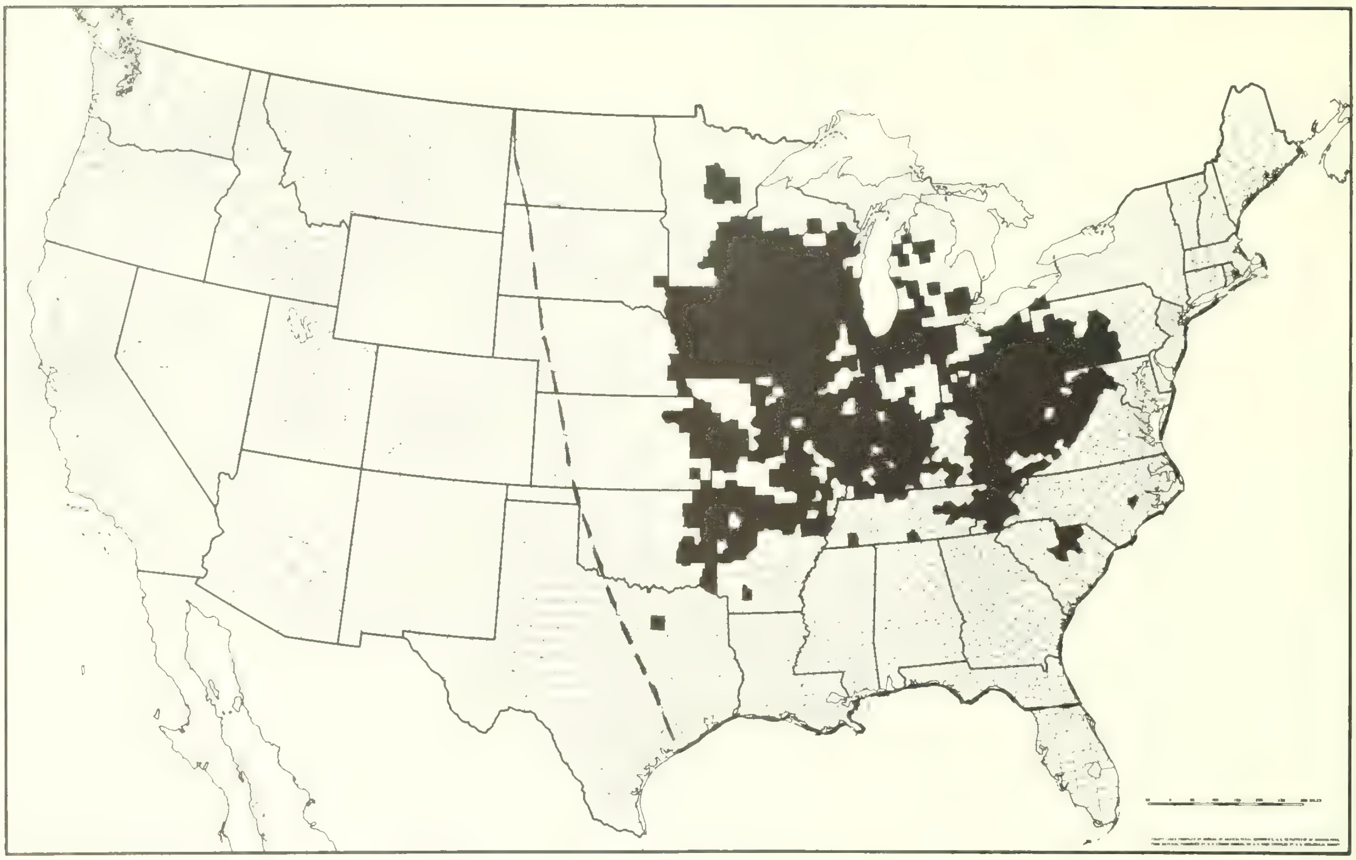

Figure 1.—*The known distribution of oak wilt as of 1978.*

All oaks and related species in the family Fagaceae that have been subjected to artificial inoculation with *C. fagacearum* have shown some susceptibility (Bretz 1955). However, as indicated earlier, the white oaks are much less susceptible than the red oaks. In one study area in northern Iowa, Young (1949) found that 55 percent of *Q. ellipsoidalis* (northern pin oak) and 53 percent of *Q. rubra* L. (red oak) had died but only 28 percent of *Q. alba* L. (white oak) and 20 percent of *Q. macrocarpa* Michx. (bur oak) had died. As might be expected, this difference in susceptibility has resulted in a change in the proportion of the two species in some areas. French and Bergdahl (1973) described an area in Sherburne County, Minnesota, in which 83 percent of the red oaks but only 11 percent of the bur oaks died from oak wilt between 1960 and 1971. This increased the percentage of bur oaks in the stand from 48 to 83.

SAPROPHYTIC EXISTENCE OF C. FAGACEARUM IN THE DYING TREE

Before discussing the various means of disease transmission it is necessary to consider the status of the pathogen within the diseased tree—the infection source. Working with naturally infected red oaks, Henry and Riker (1947) in Wisconsin and Young (1949) in northern Iowa readily isolated C. fagacearum from the xylem of roots, trunk, branches, twigs, and even leaf petioles. In the trunk Young (1949) found that the fungus was present only in the outermost sapwood layer. This pattern of distribution is not surprising. It is typical of vascular wilts of trees for the pathogen to be confined within the xylem vessels of the current annual ring until the host becomes moribund. Following the death of the tree the mycelium of *C. fagacearum* grows extensively in the xylem vessels, and the fungus penetrates the ray cells and begins to grow out toward the cambium (Struckmeyer *et al.* 1958) and also inward. In one tree studied in Missouri about 8 months after its death, Jones and Bretz (1955) recovered the fungus from the tenth annual ring. Similarly Englerth *et al.* (1956) recorded inward colonization of the sapwood in logs from diseased trees. At the cambium the fungus may form a sporulating mat characterized by a layer of mycelium and conidiophores surrounding a raised pressure "pad" or "cushion". These mats are a famous feature of oak wilt, but it is not always realized that their formation requires the pathogen to be present simultaneously in the inner bark and adjacent xylem. Inner bark colonization was nicely demonstrated by Curl (1955) who found that when bark pieces from wilted trees were placed on the forest floor, 25 percent of them produced some kind of mat. He also found several mats that had developed entirely within the bark on standing trees. Such mats were also reported by Barnett *et al.* (1952) and Fergus and Stambaugh (1957).

Because the formation of mats requires that *C. fagacearum* be present in the inner bark as well as the xylem, it follows that data on the distribution of mats on diseased trees give some information on bark colonization by the pathogen. Curl (1955) reported that in northern Illinois, mats were produced only on the trunk and large branches, and this is the common situation in other places also. However, Morris and Fergus (1952) in Pennsylvania reported that mats sometimes occurred on branches as small as 3 cm in diameter, and Engelhard (1955) in northern Iowa recorded them on 2.5 cm diameter branches. During the summer of 1977 in Minnesota, mats developed on 2-to 4-cm diameter branches on young *Q. ellipsoidalis* that died in June, following artificial inoculation with *C. fagacearum* in May. No published accounts are available from more southerly States on the presence of mats on small branches, although C. O. Rexrode[1] has observed them in West Virginia.

Data on mat formation can also provide information on the length of time during which *C. fagacearum* can survive in the dead host. The formation of a sporulating mat represents the climax of the saprophytic growth of the pathogen in that part of the tree and its replacement by other microorganisms soon follows. Shigo (1958) in West Virginia was only able to isolate *C. fagacearum* from the xylem below 2 out of 58 sporulating mats, while other fungi such as *Ceratocystis piceae* (syn. *Graphium rigidum*), *Gliocladium roseum*, and *Trichoderma lignorum* (syn. *T. viride*) were very common. In the northern part of the oak wilt range where mats are formed frequently, trees that wilt in the first half of the summer (up to mid-July) produce mats in late August or September, while those that wilt later in the summer produce mats the following spring (Curl (1955) in Illinois; Morris and Fergus (1952) in Pennsylvania; and Campbell and French (1955a) in Minnesota). In Minnesota mat formation begins on the upper part of the bole on the south side of the tree. The inner bark on the lower south side and on the north side is normally still fresh at this time although the fungus can readily be isolated from the xylem.

In the southwest of the oak wilt range, the saprophytic survival of *C. fagacearum* is probably even more limited. Mats are rarely produced on diseased trees in Missouri, Arkansas, and Ohio. This is not due to genetic differences in the *C. fagacearum* isolates involved, because isolates from these States were just as capable of producing mats on inoculated trees as isolates from Wisconsin, Illinois, and Pennsylvania (Cobb and Fergus 1964). Some light is cast on the problem by experiments in which logs cut in the summer from diseased trees in Pennsylvania and Missouri and piled in Pennsylvania produced some mats, while similar logs piled in Missouri produced none (U.S. Department of Agriculture, Forest Service 1967). It was noted that the higher air temperatures and lower relative humidities in Missouri led to a lower wood moisture content, and also that colonization by *Hypoxylon punctulatum* occurred earlier. Similarly in Arkansas, Tainter and Gubler (1973) have noticed that *Hypoxylon atropunctatum* rapidly establishes itself in the sapwood of artificially inoculated oaks, and have suggested that this fungus, together with the drying out of the branches and the high summer temperatures, greatly reduces saprophytic survival of the pathogen.

Some data on the effect of high temperatures on survival are provided by Houston *et al.* (1965). They recorded temperatures approaching 50C in the cambial region of infected northern pin oak logs exposed to the July sun for 3 days. The pathogen could not be isolated from the exposed side of the log but remained viable on the shaded side. Working with the same tree species in Minnesota, we[2] found that between

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[1] *Rexrode, C. O. Personal communication.*

[2] *Unpublished report on file at Stakman Hall, University of Minnesota, Department of Plant Pathology, St. Paul, Minnesota.*

June 21 and July 1, 1977, the percentage of xylem chips yielding *C. fagacearum* dropped from 33 to 8 on the exposed side of 2-to 5-cm diameter branches, while it remained unchanged on the shaded side.

Data on the survival of *C. fagacearum* in the xylem of standing trees come from the work of Turk (1955) who took samples at breast height from 52 northern pin oaks in Minnesota at various times after they had wilted. Within 6 months, recovery of the pathogen had dropped to 40 percent, by 9 months it was 20 percent, and by 10 months it was 0. Competition from other fungi including the sapwood colonizer *Nummularia bulliardi* and antagonism from *Trichothecium roseum* were considered important in limiting the survival of *C. fagacearum*. Merek and Fergus (1954) in Pennsylvania found that they could isolate the fungus from the trunk of diseased trees that were felled and left lying in the forest for up to 44 weeks, while in twigs it could only be isolated for 3 weeks. Recently Gibbs (1979a) examined the survival of *C. fagacearum* in small branches (1 to 10 cm in diameter) of northern pin oak in Minnesota. *C. fagacearum* survived in the xylem for only 1 to 2 months in trees that died in May or June but survived longer in trees that wilted later in the summer. *Dothiorella quercina* and *Coryneum kunzei* were the two chief antagonists of *C. fagacearum*.

Survival of the pathogen in sawn lumber has received some attention, principally because of the fear that the disease might thereby be introduced to other parts of North America or to other continents such as Europe (Gibbs 1978). Englerth *et al.* (1956) found that the frequency with which *C. fagacearum* was isolated from the wood dropped rapidly after sawing, but that the fungus could be recovered for up to 24 weeks (6 weeks as roundwood, 18 weeks as bulk-piled boards). Steaming or kiln-drying killed the pathogen. Little evidence exists linking the spread of infection with the movement of wood from diseased trees, although French and Bergdahl (1973) found an isolated outbreak of the disease in central Minnesota that might have begun from transported firewood.

From the above it would seem that within a few months in trees that die in early summer and well within a year in trees that die later, the oak wilt fungus has disappeared from the above ground parts of the tree. It is likely to survive longest on the lowest part of the north side of the trunk. As indicated above, antogonism by other fungi is one of the chief factors influencing survival of the pathogen. Additional information on this comes from the work of Shigo (1958) on trees girdled as part of the oak wilt control program in West Virginia. This treatment reduces mat formation due at least in part, to rapid colonization of the sapwood by *Hypoxylon punctulatum*.

In the roots of a diseased tree, survival of *C. fagacearum* may be more prolonged, although this seems to depend on whether the roots are grafted to those of a neighboring tree. In central Wisconsin, where root grafting is common, survival of up to 3 years has been recorded[3] and in Pennsylvania, with roots that were probably grafted, the fungus was isolated from one out of three trees that had been dead for 3 years and five out of eight trees that had been dead for 2 years (Yount 1955). Skelly (1967), also in Pennsylvania, obtained similar results. He recovered the fungus from the root systems of 52 percent of red oaks that had been dead for 1 year, 18 percent from trees dead for 2 years, and 3 percent from trees dead for 4 years. By contrast, Amos and True (1967) working with girdled trees not grafted to living trees in West Virginia, found that although the fungus could readily be isolated from roots after 1 year, it was rarely found after 2. *Armillaria mellea* rhizomorphs were commonly present on the roots after 1 year. *Umbelopsis versiformis, Trichoderma viride,* and *Pencillium* spp. were the fungi most commonly obtained from the bark, although *Gliocladium roseum* and *Dothiorella* spp. were also present. *T. viride* and *Pencillium* spp. were also commonly isolated from the wood.

Survival of the pathogen has hitherto been discussed only in relation to red oaks. In diseased white oaks the distribution of the fungus in the xylem of the current annual ring is much more restricted. And if the tree recovers, the infected ring will be buried under new wood (Parmeter *et al.* 1956). Isolation studies indicate that the pathogen survives in these buried rings for only a few years and in any event it is unlikely to constitute a significant source of inoculum. This is borne out by studies on infected but asymptomatic chestnut oak (Cobb *et al.* 1965a). If a white oak becomes infected and dies within a single season, the same events as described for red oaks could probably occur and an inoculum source could thus be created.

SEASONAL SUSCEPTIBILITY OF TREES TO INFECTION

One factor that may have some significance for all the possible means of disease transmission is the effect of season on host susceptibility. Engelhard

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[3] Kuntz, J. E. Personal communication.

(1956) in Iowa inoculated fresh stem wounds on red oaks at 4- to 5-week intervals throughout the year. Disease only occurred on trees inoculated between April 25 and August 28. Drake *et al.* (1956) in Wisconsin inoculated northern pin oak from April to September. The trees were most susceptible in early June. Many of the trees inoculated in April and May also became diseased, but symptoms did not appear as quickly. Few of the trees inoculated after summerwood had begun to form became diseased. Nair and Kuntz (1963b) found that some northern pin oak trees wilted following branch inoculations in every month from February to late November, with a peak between May and August. All wilting trees died. Trees became diseased following stem inoculations in all months of the year. With both methods trees inoculated in the dormant season showed symptoms the following June. Skelly and Merrill (1968) in Pennsylvania also found that some red oaks became diseased following stem inoculations during each month from November to March. They suggested that temperatures above freezing at the time of inoculation might be important. Nair and Kuntz (1963b) also inoculated bur oaks. The highest disease incidence following branch inoculations was from mid-May to early August. Some wilt occurred following stem inoculations in every month except December, January, and February. The highest incidence (40 to 80 percent) was from early May to early August. Cobb *et al.* (1965a) in Pennsylvania found that Chestnut oak was also most susceptible to stem inoculations in May and June.

UNDERGROUND SPREAD

Oak wilt spreads underground by the passive movement of spores of the fungus from a diseased tree to an adjacent healthy tree via the continuous xylem system that exists between root-grafted trees (fig. 2). Kuntz, Riker, and their associates in Wisconsin (Kuntz and Riker 1950, Beckman and Kuntz 1951) showed that almost all the northern pin oak within 15 m of each other in the central part of the State were grafted together. Under these circumstances root graft transmission is, not surprisingly, the main means of disease spread. In Wisconsin and parts of southern Minnesota the disease characteristically develops as a number of clearly defined disease centers which expand at the rate of about 7.5 m per year in each direction (fig. 3) (French and Bergdahl 1973).

From similar studies conducted in other States in the oak wilt range it was concluded that root grafting was less common and consequently root transmission of the disease less important. In Pennsylvania it was suggested that 20 percent of the oaks were grafted together (Craighead and Nelson 1960), in North Carolina 15 percent (Boyce 1957a), and in West Virginia 10 percent (True *et al.* 1960). In Missouri 14 percent of 175 oaks were root grafted and it was considered from inoculation studies that many of these grafts were not functional as far as transmission of the pathogen was concerned (Jones and Partridge 1961). In these four States the maximum distance between grafted trees was 10 m.

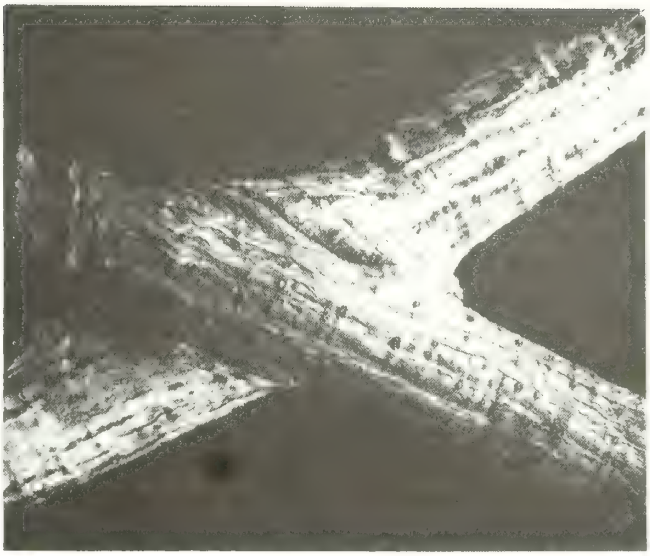
Figure 2.—*Grafted roots of northern pin oak.*


Figure 3.—*Aerial view of an infection center in northern pin oak in Minnesota. The disease is spreading through root grafts.*

A number of factors influence grafting frequency. Site factors seem to play a role because grafting frequency in northern pin oak is high in parts of southern Minnesota but is apparently low in north-central Minnesota. In Crow Wing County no root transmission occurred from inoculated to uninoculated trees although many were as close as 1.5 m (French and Schroeder 1969). Genetically controlled differences between species are also important. In that part of central Wisconsin in which virtually all the northern pin oak are grafted together, Parmeter *et al.* (1956) found that only 6 percent of the bur oaks were grafted. Jones and Partridge (1961) found that out of 29 grafts detected in Missouri, only one was between two different species (*Q. velutina* and *Q. marilandica*) so grafting between species is generally not important. However, in a situation where grafting is uncommon, interspecific grafting may comprise a significant portion of the total. Boyce (1957a) in North Carolina found that out of a total of seven grafts, three were between black oak and white oak. Similarly, Parmeter *et al.* (1956) in Wisconsin found that two of seven bur oak grafts were with northern pin oak.

Recently, work in West Virginia has placed renewed emphasis on the role of root transmission in that State. First, injections of wilting red oak trees with cacodylic acid showed that 31 percent were connected to healthy trees (Rexrode and Frame 1977), substantially more than the 10 percent suggested from earlier work in the State. Interestingly, 3 of the 12 grafts were between red and white oaks. Second, and more important, Rexrode (1978) showed that transmission via the root system might take several years to occur—4 out of 10 trees that wilted through root transmission of the fungus did not develop symptoms until 3 years after the adjacent inoculated trees had died. As Rexrode points out, such a method of disease transmission would agree with the observed distribution of the disease in northeast West Virginia where 50 percent of the wilting trees are within 15 m of previously infected trees, but where several years may elapse between the death of one tree and the appearance of symptoms in another. Such a distribution pattern is hard to explain in terms of transmission by insect vectors. Delayed root transmission may also be important in other States. In the Sinissippi Forest in Illinois, Himelick and Fox (1961) noted that 91 percent of infected trees were within 9 m of trees killed by the disease, but that the infection centers might remain dormant for several years before breaking out again. In 25 percent of the infection centers 4 or more years elapsed between the appearance of the disease in one tree and its appearance in another. Similar situations have been described in Pennsylvania (Craighead and Nelson 1960) and southern Michigan[4]. In Pennsylvania, where it was the practice to fell all healthy oaks within 15 m of a diseased tree, Yount (1955) suggested that slow movement of the fungus through grafted roots of these felled trees might explain the sporadic appearance of disease at the periphery of the cleared area several years later.

OVERLAND SPREAD

The Detection of *C. fagacearum* on Insects and Other Material

C. fagacearum is well adapted to spread by animals, and it has long been accepted that overland spread involves a vector. Yount *et al.* (1955) detected *C. fagacearum* on the bodies of insects collected from sporulating mats by plating out washings from these insects onto agar. However, *C. fagacearum* is normally overrun by other microorganisms when isolated on conventional agar media and no adequate selective medium has been devised. Therefore, most workers use the spermatization technique as described by Jewell (1956), which relies on the fact that *C. fagacearum* possesses two mating types—A and B. In this technique insects are macerated in water and then aliquots of the macerate are spread over cultures of the A and B mating types. The production of perithecia in the cultures then demonstrates the presence of viable propagules of the opposite mating type. Both ascospores and conidia can be detected in this way (Stambaugh *et al.* 1955).

Fergus *et al.* (1961) found that as few as 20 conidia could be detected by this technique. However, a number of factors must be optimum for this degree of sensitivity to be realized: (1) the composition of the medium (Bell and Fergus 1967), (2) the receptivity of the female isolates (Fergus *et al.* 1961), (3) the age of the cultures (Rexrode and Jones 1971), and (4) the temperature of incubation (Cobb *et al.* 1962). Care must be taken that sterile perithecia, which will form even in unspermatized cultures (Bell and Fergus 1967), are not regarded as evidence of fertilization. Recently Peplinski and Merrill (1974) suggested that pycnidia of *Pyrenochaeta* sp. and even synnemata of *Graphium rigidum* (syn. *Ceratocystis piceae*) developing on *C. fagacearum* cultures might have been confused with fertile perithecia. Despite these complications the technique has provided valuable data.

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[4] *Hart, J. Personal communication.*

Transmission by sap-feeding insects

The discovery of sporulating mats of *C. fagacearum* excited an immediate interest in their function. It was quickly realized that the fruity odor attracted insects and that these gained access to the mats at points where the central pressure pad had cracked the bark. Particularly abundant were Nitidulid beetles (fig. 4). Leach *et al.* (1952) showed that these insects could act as agents of fertilization for *C. fagacearum*, transporting conidia of type A to mats of type B, and vice versa. Perithecia then developed on the mat. In rare cases, if a mixed thallus of A and B mating types was present in a single tree (Hepting *et al.* 1952), perithecia might be formed before the bark cracked open to expose the mat. Perithecia are not produced on all mats—Curl (1955) found perithecia on 90 out of 393 mats in Illinois, Morris and Fergus (1952) found perithecia on only 1 tree out of many examined in Pennsylvania, and Shigo (1958) found them on only 19 out of 164 mats collected in West Virginia.

Clearly the mats could serve as abundant reservoirs of inoculum, initially in the form of conidia and later as ascospores. Knowledge that the Nitidulids (sap-feeding insects) were attracted to the mats indicated that they might act as vectors if they migrated from mats to wounds on healthy trees. In May 1953 Dorsey *et al.* in West Virginia placed Nitidulids that had been artificially contaminated with *C. fagacearum* in wounds on healthy oaks. Five out of six of the trees developed symptoms. In the same year in Iowa, Norris (1953) caged Nitidulids, freshly collected from mats, on wounds on red oaks and obtained infection in every case.

Figure 4.—*Nitidulids feeding on a mat of* Ceratocystis fagacearum *on a dead tree.*

In 1954 infection of wounds via Nitidulids was also reported from Illinois, Pennsylvania, and Wisconsin, but success rates were much lower. In Illinois Himelick *et al.* (1954) used naturally contaminated insects and obtained infection in 1 out of 36 trees wounded between April 22 and May 22. In Pennsylvania Thompson *et al.* (1955) working with field-collected insects subsequently placed on mats producing ascospores, only obtained infection in 1 out of 175 trees wounded between April 19 and June 15. In the work of McMullen *et al.* (1955a) in Wisconsin, field-collected beetles were exposed overnight to mats or laboratory cultures. Infection was obtained in 15 out of 52 trees wounded between May 1 and June 19.

Many of these experiments were highly artificial. Indeed it has been suggested that glass marbles rolled on a sporulating mat and then placed in fresh wounds might also act as "vectors". Consequently, subsequent research was devoted to a more detailed examination of the inoculum source, behavior of the Nitidulids, and the infection court.

Inoculum source.—Following the discovery of mats in Illinois, reports of their occurrence on wilt-killed red oaks quickly came in from many States. By contrast, there have been few reports for white oaks. Parmeter *et al.* (1956) did not find any mats on hundreds of inoculated bur-oaks in Wisconsin. However, in May 1954 Engelhard (1955) found 42 matlike structures on an inoculated bur oak in northern Iowa. Some consisted of both mycelium and pad; others of pad only. They were difficult to locate because of the furrowed or flaky nature of the bark. Nair and Kuntz (1963a) also described minute mats on the trunks and branches of inoculated bur oaks in Wisconsin. The mats sporulated profusely and sap-feeding beetles were found on them. In November 1965 numerous oak wilt mats were observed on a recently killed 12-inch d.b.h. white oak in West Virginia. Thirty of these had apparently formed pads that had cracked the bark (Cones 1967).

Data on the proportion of wilted red oaks producing mats are available from several workers. In northeastern West Virginia about 25 percent of the trees produced mats, whereas in the southern part of the State the percentage was around 80, (Rexrode and Frame 1973[1], Rexrode 1977). By contrast, mats are rarely formed in Missouri and Ohio (Donley 1959). T. W. Jones[2] indicated a figure of only 5percent for Missouri. Particularly important are data on mat production during the crucial period of peak host susceptibility between April and July or late June. In northern Illinois, Curl (1955) found that 22 out of 28 trees wilting between June and August produced mats the following spring. In North Carolina, Boyce (1954) reported that 12 out of 22 trees infected in the summer of 1952 produced mats the following spring. In Minnesota, Campbell and French (1955a) established that spring mat production occurred principally on trees wilting in August. Jeresek (1976) found that in 1972, 19 percent of oaks wilting in August and early September produced mats the following spring and in 1973 the figure was 26 percent. In Pennsylvania, Cobb *et al.* (1965a) found that spring mat production occurred principally on trees that had been inoculated in July and that had developed symptoms a few weeks later.

The seasonal pattern of mat formation, with peaks in spring and autumn, has been related to temperature—both high and low temperatures are unfavorable. In Minnesota mean weekly temperatures of 50°F (10C) are optimum for mat formation although they survive longer at cooler temperatures (Campbell and French 1955a). A high sapwood moisture content is also considered important (Campbell and French 1955b). Boyce (1957b) thought that high rainfall during autumn might influence the production of spring mats on felled trees.

There is no evidence that the nature of the inoculum is critical. Himelick *et al.* (1954) wondered if the low level of infection in their experiments might be because they were using an endoconidia inoculum while Dorsey *et al.* (1953) and Norris (1953) had used beetles that could also have been carrying ascospores. However, in other experiments a low degree of infection has been obtained with ascospores (Thompson *et al.* 1955) and a higher level with endoconidia (McMullen *et al.* 1955a).

It is possible that the Nitidulids are contaminated with inoculum from sources other than the sporulating mats. In Pennsylvania, Craighead and Nelson (1960) suggested that sporulation might occur in infected but symptomless chestnut oak but Cobb *et al.* (1965b) found no evidence for this. However, they did show that sporulation could occur in wounds on diseased red oak that were close to the point of mat production.

Vector behavior.—The biology of the Nitidulids was studied first in West Virginia (Dorsey and Leach 1956) and in Iowa (Norris 1956). Subsequent studies included those of McMullen *et al.* (1960) in Wisconsin and Skalbeck (1976) in Minnesota. The time of peak abundance varies with each species but is usually in the spring. Dorsey and Leach (1956) considered mean weekly temperatures of about 50°F (10C) to be optimum for Nitidulid activity. The circumstances under which Nitidulids leave the sporulating mats and fly to wounds on healthy trees have long been the subject of discussion. In Pennsylvania Morris *et al.* (1955) found that Nitidulids remained on the mats until the latter deteriorated or dried up. When migration did occur it was more often from mat to mat than from mat to wound. They concluded that "unless mats at the right stage of decline are available at the time the wounds are made or shortly thereafter, infection through these wounds is improbable". McMullen *et al.* (1960) concurred with this. They discovered that the largest numbers of insects were found on wounds made in mid-June and that this coincided with cessation of mat production and the deterioration of the existing mats in the area. The highest percentage of wilting (about 20 percent) also occurred in trees wounded at this time.

Little information is available on other sap-feeding animals that might be vectors but a number of possible candidates are discussed by Craighead and Nelson (1960).

The infection court.—Evidence that wounding leads to infection is a vital part of the case for Nitidulids as vectors. In Pennsylvania, Guyton (1952) noted an association between wilt and wounds blazed to mark a future logging road, and Jeffrey (1953) reported many instances of wilt associated with pruning, climbing-iron damage, and logging wounds. Infections only occurred when the wounds were made between late April and early June, the period of spring wood formation in Pennsylvania. In northern Iowa, Norris (1955) observed that when a tree some distance from other wilted trees became diseased, a conspicuous wound was almost always present on the trunk or major limbs. Frequently the wilt symptoms were restricted to that part of the tree distal to the wound. (This last may not be relevant because symptom expression usually begins in the distal part of a branch.) In Wisconsin, McMullen *et al.* (1955a) reported that 26 trees wounded in June became diseased in July. Further evidence was provided by Kuntz and Drake (1957) who reported that 19 percent of 109 oaks pruned in mid-June became diseased, and that the removal of stump sprouts in May and June led to 27 percent of the remaining stems becoming infected. In Minnesota, D. W. French[2] has shown from evidence collected during a 20-year-period that overland infection is closely associated with tree wounding in late May or early June. He noted that trunk wounds such as those made by climbing irons, appeared to be more important infection courts than pruning wounds.

Experiments involving deliberate wounding have confirmed that wounds made in May and June are most likely to lead to infection. In Pennsylvania, Craighead *et al.* (1953) reported that eight trees wounded in May were diseased in July and that larvae of Nitidulids and Diptera were abundant in the wounds of these trees. In Iowa, Norris (1955) found that disease occurred in 31 of 122 trees wounded between April 24 and June 22. Only 2 of 217 control trees died and these had been wounded by rodents. Similar results were obtained in Wisconsin with 11 out of 60 trees wounded between May 15 and June 18 becoming diseased (McMullen *et al.* 1955a, 1960). Recently Jeresek (1976) provided similar data for Minnesota. In 1974, 19 out of 82 trees wounded between May 19 and June 9 became diseased and in 1975, 6 out of 30 trees wounded between May 26 and June 9 became diseased. Trees on which the wounds were painted immediately did not become diseased, nor did any unwounded control trees.

The rate of wound infection seems to vary from year to year. Nair and Kuntz (1963) wounded 15 bur oaks and 20 Northern pin oaks at weekly intervals from May to August each year from 1960 to 1962. In the first 2 years no trees were infected but in 1962 10 bur oaks and 28 pin oaks became diseased. These trees were all wounded between May 21 and June 11.

There is only one report of wound infection that does not fit the seasonal pattern. In Pennsylvania, 21 of 101 red oaks pruned during the winter of 1957, wilted the following summer (Craighead and Nelson 1960).

Only one experiment has been described on the effect of wounding on infection from outside the northern part of the oak wilt range. In Missouri Buchanan (1960) found that oak wilt developed only in trees wounded between April 19 and April 26—7 out of 100 trees wounded during this period became diseased.

The possible importance of the condition of the wound and its location have received some attention. Clean cut or "bruise" wounds seem to be equally attractive to Nitidulids (Morris *et al.* 1955) and, as long as they reach the xylem, equally suitable for infection. Cobb *et al.* (1965a) showed that wound location could be important for red and Chestnut oak; less infection occurred following inoculation of branch wounds than trunk wounds. Wound age also has an important effect. Kuntz and Drake (1957) in Wisconsin inoculated 10- to 30-cm diameter northern pin oaks at various intervals after wounding. They obtained 100 percent infection the first 4 days but no infection after 8 days. Natural infection occurred only within 24 hours of wounding. Morris *et al.* (1955) and Cobb *et al.* (1965a) found that wounds in red oak in Pennsylvania were not suitable as infection courts after 3 days. On bur oak, Nair and Kuntz (1963a) reported that they could only obtain infection for 24 hours after wounding, and on Chestnut oak, Cobb *et al.* (1965a) found a progressive reduction in susceptibility, with no infection after the fifth day. The reduction in wound susceptibility with time may be due in part to the formation of wound tyloses or the accumulation of phenolic compounds, as suggested by Cobb *et al.* (1965a). However, the colonization of the wound surface by other microorganisms is also important. Gibbs (1980b) showed that if *Ceratocystis piceae* (syn. *Graphium rigidum*), one of the fungi most commonly associated with wounds on healthy oak (Shigo 1958), was introduced to a fresh wound 24 hours prior to its inoculation with *C. fagacearum*, no infection resulted. However such a wound remained fully susceptible in the absence of *C. piceae*. In nature *C. piceae* is probably brought to the wounds by insects (Jewell 1956).

It has long been thought that moisture in the wound has an important influence on natural infection (Himelick *et al.* 1954). It could affect both the transfer of spores from the insect to the xylem surface and also the germination and development of the fungus. Such moisture is probably most readily available in early summer when the vascular cambium is at its most active stage and many cells are in the process of differentiation. Rain water may also be important. In the experiments of McMullen *et al.* (1955a, 1960) in which Nitidulids were caged over drill holes, there was some evidence for a correlation between rainfall during the first 3 days after wounding and infection. The "fermenting sap" sometimes present in older wounds and regarded as highly attractive to Nitidulids (Morris *et al.* 1955) is almost certainly not an aid to infection. Its formation is associated with the activity of other microorganisms, the presence of which is likely to prevent the establishment of *C. fagacearum*.

As with other wilt pathogens the number of spores introduced to the wound is not of great importance. Cobb *et al.* (1965a) found no great difference in the incidence of infection in trees inoculated with spore doses of between 10^3 and 10^6.

Transmission by Tree-wounding Animals

Oak bark beetles

The oak bark beetles *Pseudopityophthorus* spp. were among the first insects suspected as vectors of the disease. These minute beetles breed in wilt-killed trees and feed on the twigs of healthy oak (fig. 5). Using artificially contaminated beetles Griswold and Bart (1954) obtained infection in 2 out of 6 oak seedlings and Donley (1959) obtained infection in 14 out of 135 seedlings. Attempts to achieve infection by caging field-collected beetles on young oaks were largely unsuccessful, however. In Pennsylvania Craighead and others[2] caged beetles from oak wilt trees on healthy saplings each year from 1954 to 1957. As many as 300 beetles were placed in some cages but no disease resulted. Buchanan (1958) in Missouri was a little more successful. He obtained oak wilt in 2 out of 204 red oak seedlings fed on by beetles that had emerged in spring from trees that had become diseased the previous year. (About 140,000 beetles were involved in these tests.) With these results it is not surprising that in their review of oak wilt, True *et al.* (1960) did not consider the bark beetles to be of great importance in the transmission of the disease. More recently, however, the oak bark beetles have received much more attention. The main reason for this renewed interest has been the opinion that mat production in the south and west of the oak wilt range, is too rare an event to explain the observed incidence of the disease. In view of this change of emphasis, the relevant data on the biology of the oak bark beetles, and of the evidence for their role as vectors, are reviewed in some detail.

Figure 5.—Pseudopityophthorus pruinosus *feeding on scarlet oak (photograph courtesy of C. O. Rexrode).*

The beetles and their life cycles.—*Pseudopityophthorus* spp. are present throughout and far beyond the range of oak wilt. The two key species are *P. minutissimus* and *P. pruinosus.* The former appears to have a more northerly distribution and is the only species recorded in Wisconsin. The two species are, however, similar in behavior and research workers often have not differentiated between them. There are at least two generations per year as far north as the Lake States (McMullen *et al.* 1955b). In Ohio, all the stages successfully overwinter except the pupae (Rexrode 1969). In Wisconsin, however, the larger larvae are the only winter-resistant stage, and emerge as adults in May (McMullen *et al.* 1955b).

Breeding and feeding habits.—Pseudopityophthorus spp. most commonly breed in oak, although other hosts have been recorded. Interestingly, McMullen *et al.* (1955b) in Wisconsin found that *P. minutissimus* was common in trees of the red oak group but was not found in white or bur oak. Breeding normally takes place in stems or branches from 1- to 10-cm diameter, although it has been recorded in a 42-cm diameter tree in West Virginia (Rexrode *et al.* 1965). The proportion of oak-wilted trees that are successfully colonized ranges from near 0 to 50 percent. It seems to be at its highest in Missouri where most of the diseased black and scarlet oaks (*Q. velutina* and *Q. coccinea*) were attacked (Buchanan 1956) and where successful breeding occurred in 45 out of 87 wilted trees (Rexrode and Jones 1972). In West Virginia, attack in the main stem occurred in 8 of 27 trees in 1961 and 4 of 30 trees in 1962 (Rexrode *et al.* 1965). Studies of trees that had been dead for several years suggested that these figures were above average. Attack on small branches occurred in half the trees in both years. In 1967 in Ohio Rexrode (1967) found only 3 out of 27 trees to be attacked, and colonization was light and restricted to the branches. In Minnesota, although small low branches on healthy trees almost invariably become colonized when they die from "shading", attack on the crowns of oak-wilted trees is usually light and concentrated on branches from 2 to 5 cm in diameter (Gibbs 1980a). From the observations in Minnesota, and earlier in Missouri (Buchanan 1956) and Wisconsin (McMullen *et al.* 1955b) it seems that *Pseudopityophthorus* spp. are best adapted for the colonization of slowly dying branches. Attacks on diseased trees before defoliation has occurred are normally abortive (Rexrode and Jones 1970) presumably because host resistance is too high. After defoliation, branches quickly become unsuitable for breeding, probably because the tissues dry out rapidly and the bark is colonized by fungi such as *Dothiorella quercina* and *Coryneum kunzei* (Gibbs 1980a).

Although it is clear that the bark beetles do not take full advantage of the death of trees through oak wilt, many can emerge from a single tree. In Ohio, Donley (1959) found that an average of 11,400 Scolytids (virtually all *Pseudopityophthorus* spp.) emerged in spring from a 15-cm diameter diseased black oak.

The feeding habits of the oak bark beetles on healthy trees were first investigated by Griswold and Neiswander (1953) and Griswold and Bart (1954). They concluded that *Pseudopityophthorus* spp. commonly made deep feeding wounds in the crotches, leaf axils, bud axils, and immature acorn axils of both red and white oaks. Rexrode and Jones (1970) reported that fresh feeding wounds could readily be found from mid-April onwards in Missouri, Ohio, and West Virginia. Feeding was primarily in the top branches of dominant trees and occurred mainly at the node between the previous year's and the current year's growth. The beetles bored through the bark, cambium, and xylem to the center of the twig. Rexrode and Jones found that such wounds acted as infection courts when they were inoculated with a spore suspension of *C. fagacearum*.

Bark beetles and *C. fagacearum*.—The first evidence that bark beetles could carry *C. fagacearum* was provided by Buchanan (1956) who obtained some infection when large numbers of bark beetles from oak wilt trees were macerated in water and placed on wounds of healthy trees. Stambaugh *et al.* (1955) reported that between 0.7 and 7 percent of the *Pseudopityophthorus* beetles emerging in June and July from trees that had wilted earlier that year were contaminated with *C. fagacearum*. In Missouri Berry and Bretz (1966), also working on a *Pseudopityophthorus* generation that emerged during midsummer, found that beetles from 9 out of 12 trees were carrying *C. fagacearum*. As many as 30 percent of the beetles were contaminated from some of the trees. In general the mating type of the fungus on the beetles was the same as that from the xylem of the trees from which they emerged. A few beetles were carrying the other mating type, however, and both mating types were found on beetles from five of the nine trees. Several studies have shown that both mating types are rarely found together in the xylem of an infected tree (Boyce and Garren 1953, Barnett and Staley 1953). Therefore, some of the *C. fagacearum* present on the emerging beetles was probably introduced to the branches by the parent beetles when they entered to breed. This is known to occur in elms infected with *Ceratocystis ulmi* (Lea 1977).

Beetles emerging during the latter half of the summer are not likely to act as vectors. Host susceptibility is low and late summer feeding is concentrated on the petioles of the leaves of the current shoots which provide a less favorable avenue for infection than spring feeding wounds[1]. With these considerations in mind Rexrode and Jones (1971) examined beetles that emerged in early spring from the small branches of trees that had wilted the previous July. They recorded *C. fagacearum* on beetles from 8 of 17 trees from Missouri and 7 of 15 trees from West Virginia. The percentage of contaminated beetles from all the trees together was between 0.4 and 2.5. They also reported that the fungus was present on three immature stages of the beetle—larvae, pupae, and tenerals —and also in the frass. No sporulating mats were found on any of the branches and attempts to isolate the fungus from the branches during the time of beetle emergence were unsuccessful.

Parent beetles might also be transmitters of the disease in the spring. They may make a gallery system in a diseased tree, emerge to feed on twigs of healthy trees, and then breed again in a healthy tree. Rexrode *et al.* (1965) found that between 0.5 and 5 percent of 440 parent adults re-emerging from the stems of wilted trees in West Virginia were carrying *C. fagacearum*. They suggested that the beetles ingested the fungus from the xylem vessels while making the galleries. It is also possible, however, that they were already contaminated when they entered the trees and retained the fungus on or in their bodies while there.

Extensive microscopic examination of beetle galleries by J. G. Leach and others (see Rexrode *et al.* 1965) have failed to reveal mycelium or spores of *C. fagacearum,* and the mechanism whereby the beetles become contaminated with the pathogen is not clear. Both inner bark and outer xylem are possible sources because early larval stages develop principally within the bark and later larval stages scar the xylem. If the inoculum comes principally from the strain of the fungus that kills the tree, the xylem is the more likely source because *C. fagacearum* rarely invades the inner bark of small branches (Gibbs 1980a). Nothing is known about situations in which the fungus might be introduced to gallery systems by beetles entering to breed. By analogy with Dutch elm disease, development of the pathogen in either bark or xylem seems possible.

Other tree-wounding insects

Although the oak bark beetles have received the most attention, they are not the only possible vectors among the tree-wounding insects. The other chief candidates include the flat-headed borers *(Buprestidae)* such as the two-lined chestnut borer *(Agrilus bilineatus)* (Rexrode 1968). Young adults emerge from the trunks of wilted trees and then feed on twigs and leaves of healthy trees. Although the necessary period of at least a year for larval development would be expected to reduce greatly the number of adults carrying *C. fagacearum,* Stambaugh *et al.* (1955) found that between 4 and 20 percent of a sample of 128 insects were contaminated with the fungus. However, Craighead *et al.*[2] did not achieve infection when 200 field-collected beetles were caged on small trees. Himelick and Curl (1958) also obtained negative results, even though beetles they used had been exposed to cultures of *C. fagacearum*. The flat-headed apple tree borer, *Chrysobothris femorata,* has similar habits and Himelick and Curl (1958) and Donley (1959) achieved some infection of seedlings with artificially contaminated insects of this species.

Donley (1959) found that artificially contaminated adults of the round-headed borer *Urographis fasciatus* infected 16 of 135 oak seedlings. It is interesting to note that these results are almost identical to those obtained by him for *P. minutisimus,* although the number of *U. fasciatus* adults used per cage was only one-third of the number of oak bark beetles. Whether *U. fasciatus* ever carries the pathogen in nature, however, has not been determined.

With a life cycle that may be as short as 6 weeks, the Ambrosia beetles might be expected to carry the pathogen frequently, and consequently they have been studied in some detail. *Xyleborus* spp. and *Xyloterinus politus* were found emerging through oak wilt mats, and, not surprisingly, many of them were contaminated with *C. fagacearum* (Stambaugh *et al.* 1955). Stambaugh *et al.* (1955) also found that between 2 and 10 percent of 100 adults of *X. politus* from the sapwood of wilted trees were carrying the pathogen, and Skelly (1966) found the pathogen on various Ambrosia beetles from the roots of wilted trees. However, it has recently been concluded that these insects do not act as vectors, some species because they do not attack healthy trees and others, in particular *X. politus,* because they are no longer carrying the fungus by the time their tunnels reach the xylem (Wertz *et al.* 1971).

The only quantitative data about the relative abundance of these insects are those obtained by Donley (1959) in Ohio from artificially inoculated 15-cm diameter black oak. He found that about 230 Buprestids and 150 Cerambycids (round-headed borers) emerged from each tree, but that these were out-numbered by the Scolytids (99 percent *Pseudopityophthorus* spp.) 50 to 1 and 75 to 1, respectively. Together with the other data presented here, this is enough to indicate that the oak bark beetles have good claim to be regarded as the most likely of the tree-wounding insects to spread infection.

Squirrels and other animals

In the north-central States, squirrels commonly feed on sporulating mats and consequently, have been suspected of transmitting the disease (Himelick *et al.* 1953). Transmission by squirrels has been reported under artificial conditions (Himelick and Curl 1955) but there is little reason to think that these animals are natural vectors (True *et al.* 1960). It has been postulated that birds might act as vectors, becoming contaminated while feeding on insects that inhabit the sporulating mats. There is no evidence for this (Tiffany *et al.* 1954, True *et al.* 1960), however, the downy and hairy woodpeckers (*Dendrocopus* spp.) might merit further investigation because they have been reported to make peck marks on healthy trees.

INFORMATION FROM RESEARCH ON CONTROL

Experiments on disease control are potentially a good source of information on the mechanisms of disease spread. Early control work in central Wisconsin in which roots were severed by mechanical or chemical means provided strong supporting evidence for the importance of root graft transmission. Also, the prompt application of tree paints to wounds provided evidence for the importance of those wounds as infection courts (Kuntz and Drake 1957). Other work has given more equivocal results, particularly because any one treatment may influence several possible mechanisms of spread. In the large-scale experiments carried out in West Virginia between 1970 and 1972, Rexrode and Frame (1973) found that felling wilted trees reduced bark beetle breeding by half and the production of fall sporulating mats almost to zero. Deep girdling to the heartwood, as carried out in the West Virginia control program, had no effect on beetle breeding but did reduce fall mat production by about 75 percent. However, 2 years of these treatments had no effect on the incidence of new infection centers.

A later series of experiments involved the injection of cacodylic acid, which was more effective than felling both in reducing beetle breeding and mat production (Rexrode 1977). During the 4 years of the study, the number of new infection centers was 13 percent less in the treated than the untreated plots. In the last 2 years of the study, the reduction in new centers in the treated plots was 26 percent. There was a similar reduction in the number of 'breakover centers' (newly infected trees within 15 m of a previously diseased tree) but part of the effect here might have been due to a lower frequency of root transmission.

INFORMATION FROM THE DISTRIBUTION OF THE DISEASE

Until now, little consideration has been given to the geographical distribution of oak wilt in the United States and, in particular, to its static nature and clearly defined boundaries. Some of these boundaries can be readily explained. The western limits of the disease coincide with the original prairie/forest boundary beyond which few large populations of red oak exist. A reasonable explanation of the sharply defined southern boundary in Arkansas can be found in terms of the effects of high temperature and competing fungi on the saprophytic survival of the pathogen in diseased trees (Tainter and Gubler 1973). Other boundaries cannot be so readily explained. In Minnesota and Wisconsin the disease has a distinct northern limit, which is not marked by any obvious difference in host population, climate, or soil. The same is true of the distribution of the disease in the East. True *et al.* (1960) produced a map showing those parts of the Appalachians in which oak wilt was concentrated. The same woodland types, physiographic characteristics, and shallow soils are found to the northeast and the southwest of this affected area and True *et al.* expected the disease to spread into these areas. No such spread has occurred. This is demonstrated in a striking way in Pennsylvania where the disease has a particularly abrupt eastern boundary (Craighead and Nelson 1960). Theoretically studies conducted on either side of these transition zones should provide useful evidence on mechanisms of disease transmission.

CONCLUSIONS

Through much of the oak wilt range, transmission of the disease via root grafts is responsible for most of the mortality. This is particularly evident in parts of Minnesota and Wisconsin where infection centers enlarge steadily through the summer. It may also be true in Illinois, Pennsylvania, and West Virginia. The frequency of root grafts is lower in these States than it is further west but it seems that root transmission best explains the facts that (1) a high proportion of wilting trees are within a few meters of ones previously killed by the fungus and (2) several years may elapse between the death of one tree and the appearance of symtoms in another.

In these five States most overland spread can be explained in terms of transmission by Nitidulids. In Minnesota and Wisconsin, sporulating mats are commonly found on diseased trees in spring, and for both these States and for Pennsylvania there is a wealth of evidence to show that disease commonly appears in trees that were wounded in the spring (May-June). The fact that many wounded trees escape infection is explicable in terms of factors influencing the movement of Nitidulids, the presence of spores on Nitidulids and the condition of the wound surface.

It does not seem to be a coincidence that the part of the oak wilt range within which infection by Nitidulids is most important, is also the area in which root transmission is most conspicuous. The abundant root transmission leads to the wilting of many trees in July and August. These trees produce mats the following spring at the time when trees are most susceptible to infection.

In the southern part of the oak wilt range, in particular in southern Ohio and Missouri, workers are less persuaded of the importance of root infection than their colleagues further north; although here, as elsewhere, many of the trees that die are within 15 m of infected ones. Natural infection of wounds has been shown to occur, but in general there is little enthusiasm for Nitidulids as vectors, chiefly because sporulating mats are so rarely produced. The oak bark beetles appear to be better equipped to act as vectors in these States than further north, principally because all development stages can survive the winter. In addition it appears that the beetles may breed in larger diameter branch and stem material. Consequently, they have a greater chance of linking up with the pathogen. The relation between the diameter of the branch used for breeding and the occurrence of *C. fagacearum* on beetles emerging from that branch is a matter meriting further investigation.

It has been nearly 40 years since oak wilt was first described in Wisconsin, and, in many parts of the United States, the disease now arouses only limited interest. It must not be forgotten, however, that the present situation could change rapidly if transmission of the disease were to become more efficient. The European oak bark beetle *Scolytus intricatus* Ratzeburg would seem equipped to be a formidable vector of *C. fagacearum* (Gibbs 1978), and care should be taken that this and other similar exotic insects do not become established in North America.

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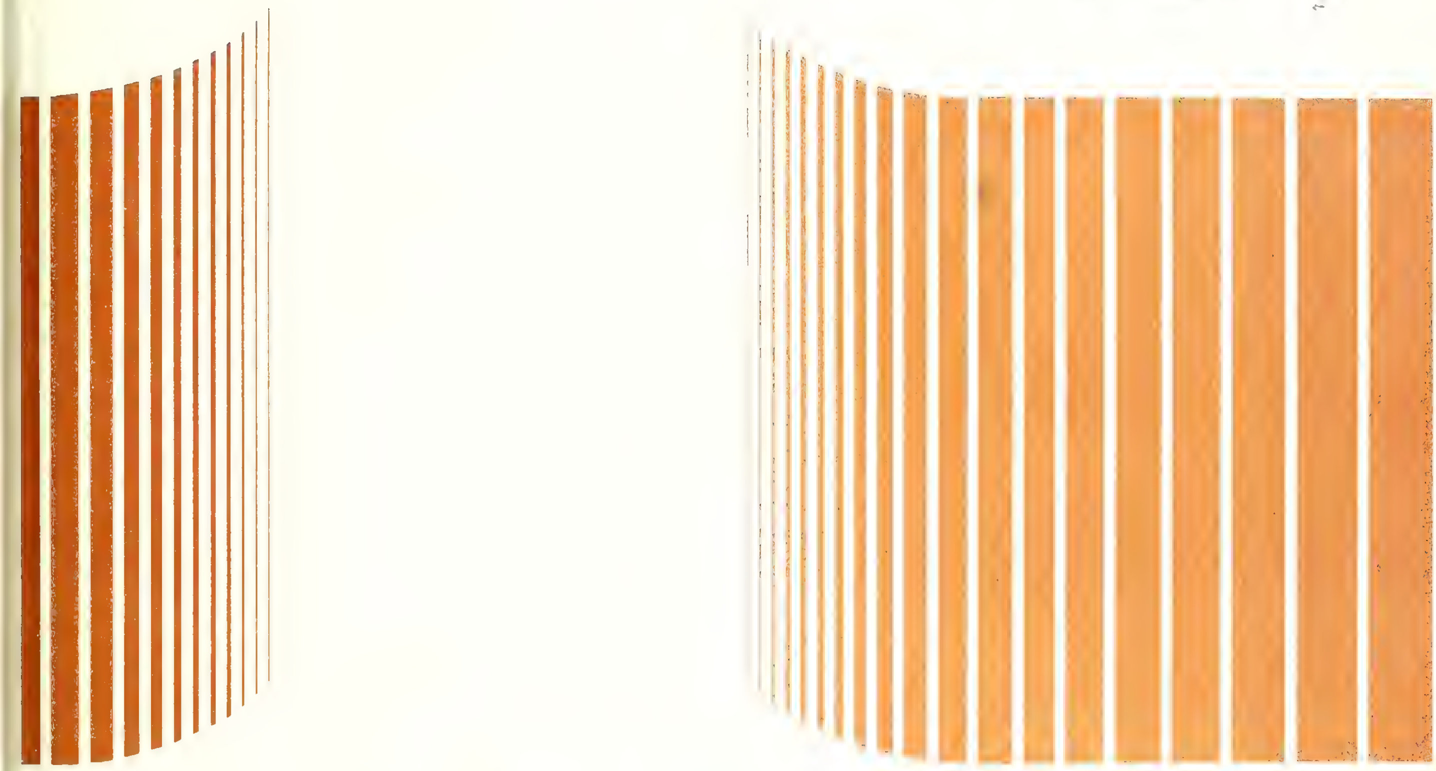

Strip clearcutting to regenerate northern hardwoods

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STRIP CLEARCUTTING TO REGENERATE NORTHERN HARDWOODS

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The Great Lakes' northern hardwood forests are a collection of various combinations of species occurring on a broad spectrum of sites, but inevitably dominated by sugar maple and/or beech. These forests have natural resilience to disturbance, and normally maintain themselves whether a single tree or an entire canopy is lost. These attributes permit use of a variety of regeneration techniques, both all-aged or even-aged.

Clearcutting has been the least successful method of regenerating northern hardwoods to date (Metzger and Tubbs 1971). Yet, a workable method of clearcutting could alleviate the problem of sugar maple and beech dominating the reproduction by improving conditions for germination and establishment of other northern hardwood species.

It is intuitively appealing to clearcut in strips rather than larger blocks, because microclimates of strips can be better manipulated to meet regeneration requirements of individual species. Northern hardwood species have better germination and seedling height growth for up to 5 years under partial shade than in the open (Logan 1965, 1966, 1973; Godman and Krefting 1960; Marquis 1966; Tubbs 1969). However, moderately shaded to open conditions usually provide the greatest increases in root and shoot weights (Logan 1965, 1966, 1973).

Varying strip width and orientation changes the timing, duration, and amount of solar radiation reaching the ground and consequently the microclimate. Berry (1964), Marquis (1965), and Brown and Merritt (1971) have shown how manipulating strips affects shadow patterns. Other factors that can be influenced are exposure to prevailing winds, cold air drainage, diurnal and seasonal periods of subfreezing temperatures, and downward penetration of winds. Manipulating strip layout can influence snow accumulation and melting on level terrain (Clausen and Mace 1972). Thus the strip microclimate could be modified to provide a more suitable germination and growth environment than that of larger block clearcuts.

A number of objectives must be met when regenerating northern hardwoods by strip clearcutting. Adequate stocking and growth of a desirable species mix are basic requirements. Also important is the potential for development of quality boles because northern hardwoods are normally managed for saw- and veneer-log production. Future bole quality is influenced early by both stand environment and reproduction characteristics. Strip clearcutting also has advantages in wildlife habitat and watershed management, requiring other criteria.

In 1959 a series of strip cutting trials was begun to compare early establishment and development of reproduction under two orientations, two widths, and with or without herbicide treatment of advance reproduction.

METHODS

Stand Conditions

The two types in the northern hardwood forest included in the trials are SAF type 25 (sugar maple-beech-yellow birch, referred to hereafter as northern hardwood) and SAF 24 (hemlock-yellow birch, referred to hereafter as hemlock-hardwood). In all, four separate stands were studied: two northern hardwood stands and one hemlock-hardwood stand on the Upper Peninsula Experimental Forest (UPEF), 15 miles southeast of Marquette, Michigan; and one hemlock-hardwood stand on the Argonne Experimental Forest (AEF), 22 miles northeast of Rhinelander, Wisconsin. All four were old-growth stands containing large, overmature trees (table 1).

Table 1.—*Density, basal area stocking and volumes of original stands in clearcutting trials on the Upper Peninsula and Argonne Experimental Forests (based on all trees 5 inches d.b.h. and larger)*

Type and stand	Density	Basal area stocking	Volumes	
	Trees/acre	*Sq.ft./acre*	*Net MBF/acre*	*Cords/acre*
Northern Hardwood:				
UPEF 1	120	120	8.8	15.6
UPEF 2	133	118	NA[1]	NA[1]
Hemlock Hardwood:				
UPEF	177	179	11.4	11.7
AEF	208	161	6.0	24.4

[1] NA = not available.

Only light salvage cuttings had been made in the several decades preceding the study.

All of the stands are on relatively level till plains. Soils on the UPEF site are usually sandy loams, free of rock; they vary from well drained to somewhat poorly drained in the northern hardwood stands, and from somewhat poorly to poorly drained in the hemlock-hardwood stand. Soils at AEF are silt loams, with numerous large stones at or near the surface; they range from moderately well drained to somewhat poorly drained. The better drained UPEF soils frequently have fragipans or in some cases bedrock within 24 inches of the surface.

Seedlings were present in all stands prior to cutting. Their development and stocking were best in the northern hardwood stands, where 75 percent of the quadrats were stocked and sugar maple dominated. The AEF hemlock-hardwood stand had the most poorly developed seedling layer, dominated by sugar maple. The advance reproduction in the UPEF hemlock-hardwood stand was a more diverse mixture of species with red maple most common, but had the poorest stocking (51 percent).

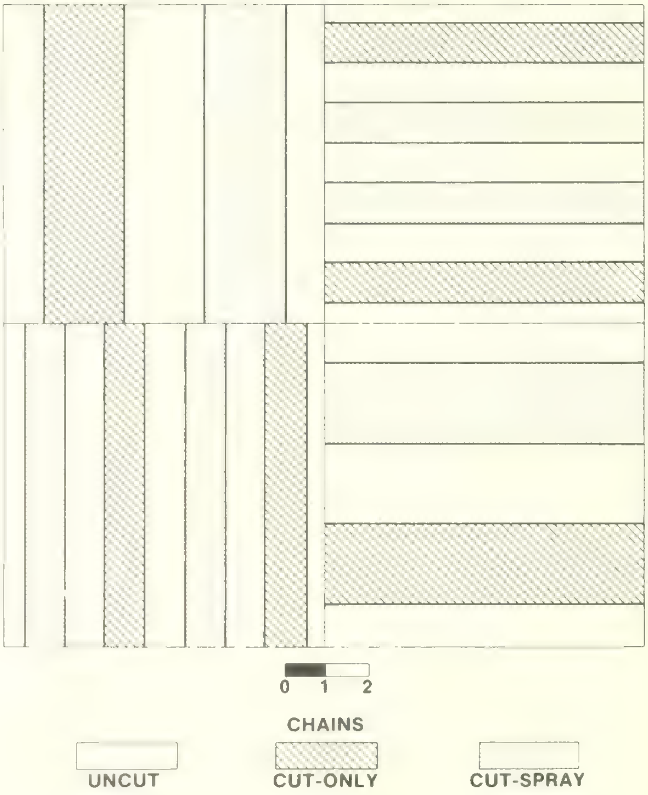

Figure 1.— *Generalized layout of clearcut strips in a UPEF stand.*

Silvicultural Treatment

At UPEF, strips were clearcut by commercial operators and were 1 or 2 chains wide by 8 chains long with the long axis oriented either east-west or north-south (fig. 1). Uncut strips of equal width alternated with the cut strips. All trees over 4 inches d.b.h. were cut and the merchantable material removed. Strips were cut in the northern hardwood stands in the winter of 1959-60 (stand 1) and in the winter of 1960-61 (stand 2). Strips in the hemlock-hardwood stand were cut the winter of 1964-65. Each winter two strips of each orientation of 2-chain width and four strips of each orientation of 1-chain width were cut.

In the AEF hemlock-hardwood stand, all strips were oriented east-west to parallel an 8-percent slope of west aspect. Because most strips exceeded 8 chains in length, the study was confined to the central 8-chain portion. Saplings were cut in addition to the larger trees. During each of the winters of 1964-65 and 1965-66 two 2-chain and four 1-chain-wide strips were cut.

Herbicides were used to eliminate advance reproduction on half of the strips in each combination of widths and orientations. They were sprayed the summer following logging. Northern hardwood stands were treated with 2,4,5-T in a water-oil carrier at 8 and 4 lbs. of herbicide in 100 gals. of carrier in stands 1 and 2, respectively. Tordon 101 (Picloram and 2,4-D) was used in the hemlock-hardwood stands at a strength of 2.5 lbs. per 100 gals. of water. Herbicides were applied until they dripped from the foliage.

Stumps in the UPEF sprayed strips were also treated separately with a stronger solution of herbicide in an oil carrier. Northern hardwood stand 1 was treated with 2,4,5-T at 20 lbs. per 100 gals., stand 2 with a mixture of 2,4,5-T and 2,4-D at 30 lbs. per 100 gals., and the hemlock-hardwoods with 2,4,5-T at 16 lbs. per 100 gals.

Survey Procedures

Reproduction on uncut and cut-only strips was first measured one or two seasons after cutting; a second measurement was made six or seven seasons after cutting. Reproduction on cut-sprayed strips was measured the first or second season after spraying and again in the fifth or sixth season. Seedlings were recorded by species, height class, density class, and origin (seedling or sprout); the species and height class of the tallest or dominant stem was also determined. Quarter-milacre quadrats spaced at 10-link intervals on transects crossing the strip perpendicular to the long axis were used. Between five and nine transects per strip were run. The second survey of hemlock-hardwood strips used actual counts of reproduction instead of density classes and assessed the dominant stem on milacre and ninetieth-acre quadrats. Each milacre quadrat was centered over a quarter-milacre quadrat. Three ninetieth-acre quadrats were installed per chain of transect. The large quadrats sampled reproduction that had the best opportunity of becoming one of approximately 90 final crop trees per acre.

RESULTS

Stand Establishment

Cut-only strips were generally well stocked with reproduction 6 or 7 years after cutting. In the three UPEF stands, each cut-only strip had more than 17,000 stems per acre (table 2), and 73 percent or more of the quarter-milacre quadrats contained at least one tree (table 3). The cut-only AEF hemlock-hardwood strips were not as well stocked. They averaged 9,000 seedlings per acre and 60-percent stocking of the quadrats.

Reproduction on cut-sprayed strips was much more variable. Best results were obtained in UPEF northern hardwood stand 1 and in the UPEF hemlock-hardwood stand. Each had in excess of 25,000 seedlings per acre and 66 percent stocking of reproduction on quadrats 6 years after spraying (tables 2 and 3). Northern hardwood stand 2 at UPEF averaged only 9,000 stems per acre and 63 percent stocking. The herbicide-treated AEF strips had the poorest reproduction, averaging only 4,000 stems per acre and 30 percent stocking.

Neither strip width nor orientation consistently led to increased reproduction (tables 2 and 3). Much of the variation within stands was due to factors unrelated to strip layout, such as soil moisture, original overstory, and advance reproduction.

Desirable hardwoods—sugar maple, red maple, yellow birch, beech, white ash, and basswood—of seedling or seedling-sprout origin occurred on an average of 95 percent of the quarter-milacre quadrats that were stocked with any species or form of tree reproduction at UPEF. Again, the cut-sprayed strips of northern hardwood stand 2 were the exception; the proportion of stocked quadrats with a desirable hardwood declined to an average of 72 percent on the 2-chain-wide strips. Somewhat poorer results also occurred at AEF, where 87 and 57 percent of the stocked quadrats had desirable hardwoods on the cut-only and cut-sprayed strips, respectively.

Effects of advance reproduction

Regeneration success on cut-only strips depended on the presence of large advance reproduction. Stocking percentages 6 to 7 years after cutting were positively correlated ($r^2 = .70$) with the percent of quadrats stocked with advance reproduction over 4 feet tall at the time of cutting. All successfully regenerated cut-only strips originally had more than 9 percent of their quadrats stocked with reproduction over 4 feet tall.

Table 2.—*Number of seedlings per acre, by cutting treatment and strip width and orientation*[1], *5 to 7 years after strip clearcutting on the Upper Peninsula and Argonne Experimental Forests*

(In thousands of seedlings per acre)

Type and stand	Cut-only					Cut-sprayed					Uncut				
	1-NS	1-EW	2-NS	2-EW	Mean	1-NS	1-EW	2-NS	2-EW	Mean	1-NS	1-EW	2-NS	2-EW	Mean
Northern Hardwood:[2]															
UPEF 1	26.3	28.0	28.3	27.9	27.6	40.8	29.1	35.5	25.3	32.7	29.1	24.2	21.4	17.2	23.0
UPEF 2	25.9	17.5	30.1	35.5	27.3	8.7	11.2	7.8	9.8	9.4	21.7	20.7	28.6	22.9	23.5
Hemlock-Hardwood:[3]															
UPEF	26.1	27.7	34.5	22.3	27.7	31.5	30.9	50.9	32.0	36.3	16.5	19.4	13.3	19.6	17.2
AEF	—	9.8	—	8.4	9.1	—	4.7	—	3.4	4.0	—	26.2	—	19.6	21.5

[1] 1-NS = 1 chain wide, oriented north-south, etc.

[2] Estimates are "minimum populations" because counts for each species, size-class terminated at five on each quadrat.

[3] Estimates are based on counts of all seedlings on quadrats.

Table 3.—*Quarter-milacre quadrats stocked with one or more seedlings by cutting treatment and strip width and orientation*[1], *5 to 7 years after strip clearcutting on the Upper Peninsula and Argonne Experimental Forests*

(In percent)

Type and stand	Cut-only					Cut-sprayed					Uncut				
	1-NS	1-EW	2-NS	2-EW	Mean	1-NS	1-EW	2-NS	2-EW	Mean	1-NS	1-EW	2-NS	2-EW	Mean
Northern Hardwood:															
UPEF 1	89	91	95	99	93	99	91	96	89	94	96	95	91	85	92
UPEF 2	79	73	89	91	83	62	59	63	66	62	86	78	90	79	83
Hemlock-Hardwood:															
UPEF	81	81	91	77	82	66	87	83	88	81	71	62	56	76	66
AEF	—	59	—	60	60	—	30	—	30	30	—	88	—	78	81

[1] 1-NS = 1 chain wide oriented north-south, etc.

Other related parameters, such as desirable hardwood stocking 6 to 7 years after cutting, stocking of advance reproduction over 2 feet tall, and numbers of advance reproduction instead of stocking percentages, yielded significant correlations but reduced coefficients of determination. The initial stocking of all sizes of advance reproduction was poorly correlated with stocking 6 to 7 years later ($r^2 = .10$).

Stump sprouting

Stump sprouts were limited to the cut-only strips because spraying effectively minimized them. Most species sprouted to some degree, but only red maple did so prolifically. Red maple sprouts were not well distributed, yet due to their rapid growth and large number per stump they occupied much growing space and readily overtopped other reproduction. They were most abundant on UPEF hemlock-hardwood cut-only strips, where they made up 6 percent of the dominants on milacre quadrats and 21 percent of the dominants on ninetieth-acre quadrats.

Time of establishment

Seedling age data showed most yellow birch and red maple seedlings originated after spraying in the UPEF hemlock-hardwood stand (93 percent of the birch and 85 percent of the maple). Establishment continued over 4 years following spraying. In the first season a third of both species became established. Birch establishment peaked the second year with half the birch seedlings becoming established then. Twenty percent of the maple seedlings became established in each of the next 2 years.

Effects on quality

The degree of crown competition within northern hardwood stands affects development of stem quality. Thus, two factors affecting crown competition were considered: variation in height and distance to nearest competitor (tree at least two-thirds as tall) for the dominant tree on the ninetieth-acre quadrat. Cutting only trees larger than 4 inches d.b.h. in the hemlock-hardwoods at UPEF resulted in more variation in height among dominants than at AEF, where trees over 2 inches d.b.h. were cut (table 4). Spraying at UPEF did not reduce this variability because a number of conifer and larger hardwood saplings were unaffected by the herbicide. Spraying at AEF, however, created more variation in height than occurred on the cut-only strips. The majority of dominants on cut-only strips had a competitor within a distance not exceeding the dominant's crown diameter. On cut-sprayed strips, half or fewer of the dominants had a competitor within this distance.

Stand Development

Reproduction developed best in the cut-only strips in both stands and in the cut-sprayed strips in stand 1 in the northern hardwoods at UPEF. There were substantial increases in quadrats stocked with reproduction over 4 feet tall through the first 6 to 7 years after cutting (table 5). The hemlock-hardwood stands did not develop as well, particularly at AEF. All the UPEF hemlock-hardwood strips had the potential to improve, however, because many quadrats had gained seedlings between 2 and 4 feet tall. The AEF strips had the poorest prospects for improvement.

Poor development of reproduction as a stand at AEF and on cut-sprayed strips in UPEF stand 2 was not due to poor growth rates of the surviving trees, but due to loss of existing stocking and poor establishment of new reproduction. Growth rates on these units (0.71 feet/year) were comparable to the overall average (0.73 feet/year). Height growth was calculated as the difference between the two surveys in the weighted averages of class midpoints for the tallest seedling per quadrat.

Neither strip width nor orientation affected reproduction growth rates (table 6). Differences were usually caused by other factors, often the proportion of fast-growing pioneer species present.

Additional support for the conclusion that strip width did not affect height growth came from analyzing reproduction height across the strips for individual species. Heights did not improve with distance from the timbered edge, although the opposite impression was apparent in the field, since the taller pioneer species— quaking aspen, paper birch, and pin cherry— were more abundant in the central portion of the strip.

Species Composition

Cut-only strips

Strip clearcutting in the northern hardwood type had little effect on species composition in the regenerated stand. Composition on cut strips was very similar to that on adjacent uncut strips (table 7). Sugar maple comprised most of this reproduction and its preponderance reduced species diversity of the reproduction below that of the original overstory.

Table 4.—*Characteristics of dominant trees on ninetieth-acre quadrats in hemlock-hardwood clearcut strips at the Upper Peninsula and Argonne Experimental Forests, 5 to 6 years after treatment*

Stand and treatment	Height			Dominants with competitor[1]	Mean distance to competitor	Mean crown diameter of dominant
	Mean	Range	Coefficient of variation			
	Feet	*Feet*	*Percent*	*Percent*	*Feet*	*Feet*
UPEF:						
Cut-only	18.6	4-67	59	63	6.7	7.2
Cut-sprayed	11.4	4-46	58	50	6.1	4.3
AEF:						
Cut-only	10.2	4-15	24	75	3.7	4.3
Cut-sprayed	7.2	3-17	36	42	5.7	2.5

[1] Percent of quadrats where dominant tree has a competitor (tree at least ⅔ height of dominant) not more than dominant crown diameter away.

Table 5.—*Height of tallest reproduction stem on quarter milacre quadrats by cutting method and year after clearcutting or spraying on the Upper Peninsula and Argonne Experimental Forests*

(In percent of quadrats stocked)

Type and stand	Year	Cut-only			Cut-sprayed		
		Nonstocked & 0-2′	2-4′	4′ +	Nonstocked & 0-2′	2-4′	4′ +
Northern hardwood:							
UPEF 1	1-2	64	22	14	96	2	3
	6-7	15	16	69	15	29	55
UPEF 2	1-2	66	25	9	96	2	2
	5-6	25	17	58	65	21	15
Hemlock-hardwood:							
UPEF	2	77	14	10	98	2	<1
	6	32	30	38	30	45	25
AEF	1-2	91	8	1	98	1	1
	5-6	50	16	34	76	12	12

Table 6.—*Average annual height growth*[1] *of dominant reproduction in the 4- to 5-year period following treatment by strip width and orientation*[2] *on the Upper Peninsula and Argonne Experimental Forests*

(In feet per year)

Type and stand	Cut-only									Cut-sprayed								
					Means									Means				
	1NS	1EW	2NS	2EW	1	2	NS	EW	All	1NS	1EW	2NS	2EW	1	2	NS	EW	All
Northern hardwoods:																		
UPEF 1	0.67	0.79	0.66	0.69	0.73	0.68	0.66	0.74	0.70	0.88	0.73	0.93	0.60	0.81	0.77	0.90	0.67	0.79
UPEF 2	.75	.84	.94	.86	.79	.90	.85	.85	.85	.44	.53	.74	.74	.48	.74	.59	.64	.61
Hemlock-hardwoods:																		
UPEF	.42	.66	.55	.62	.54	.58	.49	.64	.56	.65	.79	.80	.86	.73	.84	.74	.83	.78
AEF	—	.74	—	.74	—	—	—	—	.74	—	1.09	—	.47	—	—	—	—	.79

[1] See text for method of derivation

[2] Strip width: 1 = 1 chain wide, 2 = 2 chains wide; orientation: NS = north-south, EW = east-west.

Table 7.—*Comparison between species composition of the original stand and of the reproduction 5 to 7 years after strip clearcutting on the Upper Peninsula and Argonne Experimental Forests*

	Original stand: ≥ 5 inches d.b.h.		Regenerated stand: ≥ 6 inches tall				
			Percent of number of seedlings			Percent of dominant stems	
Species	Percent of basal area	Percent of numbers	Leave	Cut-only	Cut-spray	Cut-only	Cut-spray
NORTHERN HARDWOOD-UPEF Stand 1							
Sugar maple	50	43	74	66	60	51	44
Red maple	3	5	7	10	3	13	4
Yellow birch	14	10	6	16	33	17	47
Other hardwoods[1]	25	35	13	8	3	18	5
Conifers	8	7	1	1	1	1	0
NORTHERN HARDWOOD-UPEF Stand 2							
Sugar maple	63	61	86	88	64	76	57
Red maple	1	(2)	1	1	2	1	2
Yellow birch	20	13	5	6	12	7	9
Other hardwoods[1]	13	19	8	6	22	15	32
Conifers	3	7	1	1	1	1	1
HEMLOCK HARDWOOD-UPEF							
Sugar maple	3	4	10	10	1	9	1
Red maple	22	28	37	52	6	51	15
Yellow birch	22	24	45	31	84	21	39
Other desirable hardwoods	1	2	1	1	1	2	1
Pioneer hardwoods	0	0	1	1	9	4	41
Conifers	53	42	6	5	1	14	3
HEMLOCK HARDWOOD-AEF							
Sugar maple	16	14	78	56	13	37	18
Red maple	5	5	9	11	5	19	9
Yellow birch	21	14	9	12	28	8	13
Other desirable hardwoods	6	7	1	3	1	3	1
Pioneer hardwoods	1	(2)	1	13	53	32	57
Conifers	52	60	1	4	1	1	2

[1] Includes pioneer hardwood species, other desirable hardwood species, and ironwood.

[2] Less than 1 percent.

Sugar maple's importance in the new stand may decline, allowing diversity to increase over time if the composition of the new stand shifts toward that of seedlings dominating the quadrats. Even so, the new stand will probably not reach the diversity of the parent stand. Offsetting the decline of sugar maple would be one or more species of the group of other hardwoods (beech, ironwood, quaking aspen, black ash, basswood, and American elm), which as a group make up a larger proportion of dominants than of all reproduction. Conifers made up a minor proportion of the new stand and probably will continue to do so. Red maple and yellow birch reproduction was inconsistent; these species were more abundant than in the original overstory and the uncut strip reproduction in stand 1, but were about the same or declining in relation to these populations in stand 2. The net effect was that no important changes occurred in these two species due to strip cutting.

The hemlock-hardwood stands at both UPEF and AEF underwent considerable change in character as hemlock-dominated overstories were replaced by hardwood-dominated reproduction. The change was not solely due to cutting, since the uncut and cut-only strips were more comparable to each other than to the original overstory (table 7). These stands would have probably reverted to hardwoods naturally, through attrition of overmature conifers over time and poor regeneration of hemlock.

Sugar maple became the most common reproduction species on both uncut and cut-only strips in the AEF hemlock-hardwood stands. However, cutting reduced the proportion of sugar maple compared to the uncut strips, while increasing the proportion of pioneer species (quaking aspen, paper birch, and pin cherry). This trend may continue, since the amounts of sugar maple and pioneer hardwood dominants were almost equal.

On the UPEF hemlock-hardwood cut strips, red maple became the most common species and should remain so. It benefitted from cutting, as did the pioneer species, while most other species remained unchanged or declined in relative abundance. These strips had the only significant amount of hemlock advance reproduction. Because it was well developed, it was often dominant.

Cut-sprayed strips

Spraying herbicides in combination with cutting was only partially effective in creating desired changes in species composition of the reproduction. Sugar maple, although relatively less abundant on cut-sprayed than on cut or uncut strips in all four stands, still comprised about the same proportion of the new stand as it did in the original overstory (table 7).

The proportion of yellow birch increased after spraying in all four stands, but real increases in numbers and stocking were attained in only two. In northern hardwood stand 1, yellow birch became the leading dominant, with over 10,000 seedlings per acre. It was also the most abundant species in the UPEF hemlock-hardwood stand, where its 30,000 seedlings per acre made up 84 percent of the reproduction, but only 39 percent of the dominants. Higher proportions of yellow birch in the other two stands were caused by fewer stems of other species rather than by a gain in birch numbers. In these two stands, yellow birch numbers and stocking percentages were similar on cut-sprayed, cut-only, and uncut strips.

Establishment of pioneer hardwood species (mostly quaking aspen, but including pin cherry and paper birch) was highly variable following spraying. They were a minor component of the reproduction in only the UPEF northern hardwood stand 1. In the remaining stands they ranked either first or second in abundance and proportion of dominants (table 7). In both hemlock-hardwood stands they were the most common dominants.

Red maple was the only other species present in significant amounts in the cut-sprayed strips. It was relatively less abundant than in the other strips, but it remained at levels comparable with its position in the original overstories.

Effect of strip design

Changing strip width and orientation had little effect on the performance of desired species. Sugar maple was the only desired hardwood species to respond to changes in strip layout, but this occurred only in the cut-only strips of one stand. In this case sugar maple stocking was 12 percent greater on 1-chain than 2-chain strips and 9 percent greater on north-south than east-west strips. The pioneer species generally exhibited the opposite behavior, being better stocked on the more exposed cut-sprayed strips and AEF cut-only strips. Overall, pioneer hardwoods in the 2-chain strips averaged 12 percent and the east-west strips 5 percent better stocking than in the 1-chain and north-south strips, respectively. These trends would probably have been better expressed if other factors affecting seedling establishment had been more uniform throughout each stand.

Effects of parent stand and site

Species composition of reproduction was related to the composition of the original overstory and site factors, especially on the cut-only strips. The abundance of either sugar or red maple in the reproduction was positively correlated to its abundance in the overstory, but often negatively correlated to the abundance of the opposite species (table 8). Abundance of beech or hemlock in the overstory and red maple in the reproduction were positively correlated, while the opposite was often true for sugar maple in the reproduction. Yellow birch reproduction responded similarly to red maple reproduction, being positively associated with overstory red maple but negatively with sugar maple. Abundance is the same as the ecologists' importance value for a species; it represents the mean of relative density and relative stocking for a reproduction species and the mean of relative density and relative basal area for each overstory species.

There were fewer significant relations between reproduction and original overstory species in the cut-sprayed than in the cut-only strips (table 8). In northern hardwood stands, yellow birch reproduction was associated with overstory red maple, beech, and hemlock, but along with quaking aspen and pin

Table 8.—*Correlation coefficients for occurrence of species in reproduction and in overstory by strips, or segments of strips (see text for method of computing coefficients)*

Reproduction species	Cut-only strips					Cut-sprayed strips				
	Overstory species									
	Sugar maple	Red maple	Yellow birch	Hemlock	Beech	Sugar maple	Red maple	Yellow birch	Hemlock	Beech
NORTHERN HARDWOOD-UPEF STANDS 1 & 2										
Sugar maple	71[1]	–89[2]	38	–91[2]	–77[1]	32	–61	33	–53	–40
Red maple	–77[1]	96[2]	–24	91[2]	74[1]	–46	24	–16	16	77[1]
Yellow birch	–53	76[1]	–28	70	65	–79[1]	87[2]	–29	88[2]	86[2]
HEMLOCK HARDWOOD-UPEF										
Sugar maple	87[1]	–37	72	–64		87[1]	–14	39	–29	
Red maple	–31	90[2]	18	–29		85[1]	–31	32	–17	
Yellow birch	–41	–43	–46	57		47	37	52	–51	
Quaking aspen	–52	–32	–38	60		–85[2]	–6	–46	38	
HEMLOCK HARDWOOD-AEF										
Sugar maple	78[2]	–41[1]	–4	–58[2]		27	5	–12	–21	
Red maple	–41[1]	52[2]	19	20		–1	8	27	14	
Yellow birch	–55[2]	34	0	40		13	–4	–5	–2	
Quaking aspen	–25	–18	–10	33		–6	–17	–6	–2	
Pin cherry	–55[2]	13	–2	44[1]		–51[1]	11	8	51[1]	

[1] Correlation coefficient of 95 percent acceptance.

[2] Correlation coefficient of 99 percent acceptance.

cherry it was negatively related to overstory sugar maple.

Soil moisture gradients within the stips also affected species composition. Sugar maple was most abundant on mesic sites, and red maple on somewhat poorly drained sites; yellow birch was slightly more common on somewhat poorly drained than on better drained sites.

Lesser vegetation

A dense layer of shrubs, herbs, and grasses followed cutting and cutting-spraying, initially dominating reproduction on many hemlock-hardwood strips (fig. 2). A similar vegetation survey was not made in northern hardwood stands. By the fifth to the seventh year, reproduction dominated the lesser vegetation in most stands, yet this lesser vegetation remained an important component of the total plant cover. The cut-sprayed strips at AEF and UPEF stand 2 continued to be dominated by lesser vegetation on the majority of quadrats even after 5 years.

Raspberry was the most common shrub on mesic sites. Wetter sites had a mixture of shrubs, usually with mountain maple an important component. Other species of shrubs and small trees occurring in the strips were pin cherry, red-berried elder, blackberry, beaked hazel, and willow. Sedge-grass communities proliferated after spraying on wetter sites and on many of the AEF strips.

DISCUSSION

These trials demonstrated the great potential of strip clearcutting for re-establishing well-stocked stands of high-value hardwoods. Simultaneously, the poor results obtained served as a reminder that misapplication of the method can result in failure (Metzger and Tubbs 1971). Obviously, strip clearcutting must be very carefully prescribed and used. The inconsistent results of these trials provide some leads toward improving our understanding of where and under what conditions the method is likely to succeed.

Most strips in these trials had the potential to produce a fiber crop, in that the numbers and distribution of stems within the strips appear adequate to assure utilization of the site. Stocking on several of the cut-sprayed strips, however, was low, with much

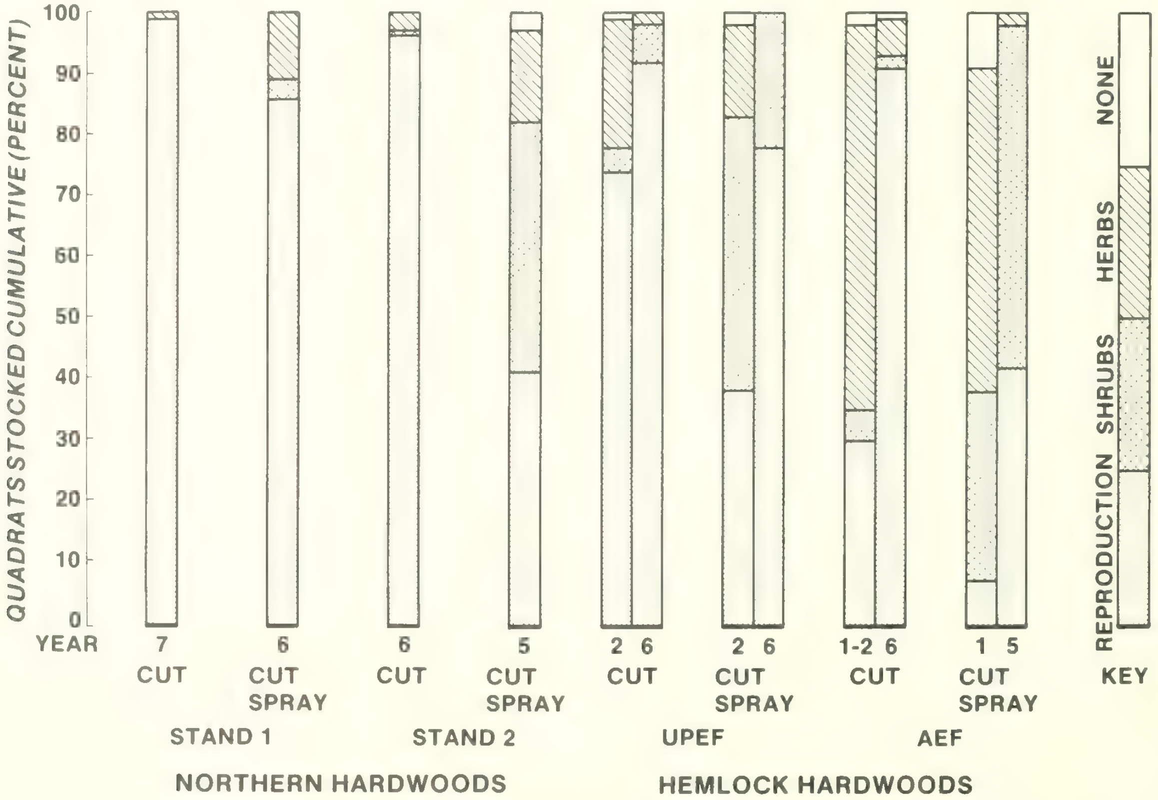

Figure 2.— *Form of vegetation dominating quadrats on clearcut strips on the Upper Peninsula and Argonne Experimental Forest.*

reproduction subordinate to lesser vegetation. In these cases, the well-established shrub and grass-sedge communities appeared likely to continue domination of sizeable areas for some time (Levy 1970, Metzger and Tubbs 1971).

The good distribution of desirable hardwoods in competitve positions on all strips at UPEF except the cut-sprayed strips in stand 2 create the potential for producing saw and veneer logs as well as fiber. The outlook for developing high-quality boles in these stands is not as readily apparent, but depends on maintaining high levels of crown competition to reduce branch and fork caused bole defects (Godman and Books 1971). Achieving both vertical and horizontal competition among crowns requires well-spaced reproduction of uniform height in recently reproduced stands. Cutting to a 5-inch d.b.h. limit at UPEF left many potential wolf trees and considerable variation in height, even after spraying. Had the stands been weeded, residual density and distribution should have resulted in crown closure, thus promoting higher stem quality. However, until research provides minimum stocking standards in relation to potential stem quality, the impact of stocking on quality can only be speculated upon.

Poorer stocking and competitive positions of desirable hardwoods in the AEF cut-only strips and UPEF cut-sprayed strips of stand 2 make the prospects of obtaining high-quality yields very marginal. Furthermore, these stands' crown structure, needed to promote stem quality, is not anticipated to develop for some time. Cut-sprayed strips at AEF are so severely understocked that there is no question of their failure.

One frequently cited advantage of clearcutting is its potential to increase species diversity of regenerated stands. On the contrary, these clearcutting trials without supplemental treatment reduced diversity. Clearcutting released reproduction established before cutting, whose superior competitive position prevented establishment of any significant amounts of new reproduction that could have increased diversity. Sugar maple was usually the most abundant species of advance reproduction, but beech, red maple, and hemlock were important in a few situations. The use of herbicides also failed to increase species diversity, although the advance regeneration was effectively eliminated or set back. Single species tended to dominate the regenerated stand, although the species varied from stand to stand depending on seed availability and site conditions.

This study did not identify an optimum width or orientation for strips, since little of the variation in results could be associated with strip layout. Ringger and Stearns' (1972) microclimatic data for AEF openings suggest why stocking differences for many species are slight between 1- and 2-chain strips. A number of microclimatic parameters remain relatively constant until opening diameters exceed twice the height of the border trees, then change abruptly. In these trials, the ratio of strip width to border tree height was less than 2. Larger openings increase the risk of lower temperatures for longer periods and increase the drought stress brought about by a combination of longer durations of high temperatures, higher wind speeds, and increased direct solar radiation. There is considerable uncertainty about the successful establishment of key species in wider strips, and added trials are warranted.

When advance reproduction was released by strip clearcutting, its success in the new stand depended on its ability to withstand major changes in light, heat, moisture, and competition. If the reproduction can withstand release, the size of area released apparently has little effect. Wider cut-only strips might be successful, because composition in these trials resembled that in larger clearcuts in Canada (Winget 1968, Boivin 1971) and in northeastern United States (Nyland and Irish 1971, Richards and Farnsworth 1971).

Reproduction height proved to be a good measure of its capability of withstanding overstory removal in the strips as well as in shelterwoods (Jacobs 1974). Site and climatic conditions also affect the outcome, so no single minimum stocking standard for widespread use is advisable. This study's results would apply to sites with low plant moisture stress similar to UPEF; a minimum of 15-percent stocking (a 50-percent safety factor has been added) of advance reproduction over 4 feet tall is recommended in such cases. In situations with relatively high potential moisture stress, Jacobs' (1974) recommendations developed for shelterwood release at AEF would be more appropriate (5,000 well distributed 2- to 4-foot-tall seedlings per acre). When these levels are not attainable, an alternative cutting method should be used; if an even-aged stand is desired, a shelterwood to promote further development of advance reproduction before final release is necessary (Godman and Tubbs 1973).

Species composition of the overstory and soil drainage had a greater influence on composition of reproduction on cut-only strips than did cutting or strip design. Sugar maple reproduction was most aggressive under its own canopy and on moderately well-drained to well-drained sites. On sites with less than well-drained soils, where red maple, yellow birch or hemlock were abundant in the overstory, reproduction of red maple and yellow birch increased in relative abundance or became the dominant species. These results are generally contrary to the hypotheses of Fox (1977) and Forcier (1975) that different species tend to replace overstory species in climax forests.

Successful regeneration from seed on the herbicide-treated cut strips depended on an adequate seed supply, elimination of advance reproduction, and a favorable environment. The importance of seed supply was indicated by the successful establishment of reproduction following bumper crops of sugar maple and yellow birch seed. Conversely, reproduction establishment declined drastically after crop failure or poor crops. It is also important that the seed is available the first season after spraying. Bumper crops of yellow birch occurred 2 and 3 years after spraying, but did not contribute measurably to the new stand. Rapid develpment of competing vegetation probably limited the chances of later seedling establishment.

Herbicide spraying proved to be especially beneficial to the establishment of yellow birch in two stands by successfully eliminating the advance reproduction. Sugar maple rebounded after spraying in the northern hardwood stands and became an important component of the reproduction again. Also benefitting from spraying were the pioneer species—quaking aspen, paper birch, and pin cherry. The pioneer species' abundance on the strips was probably less than what would be more commonly expected. This was partially due to the lack of pioneer species in the original stand (except for one paper birch per acre on the AEF), which meant there was no vegetative reproduction or seed available from adjacent uncut strips. There also would have been little seed available in the litter layer, because these stands had been undisturbed for 200 or more years (Graber and Thompson 1978). The source of seed was, therefore, in areas away from the strips, and in 2 of the 3 years of establishment at AEF, seed crops of quaking aspen and paper birch were failures (Godman and Mattson 1976). Pioneer species' increased abundance on the wider or more open strips suggests that these species would be favored by even larger strips.

Establishment of many other desirable species was hampered by too few trees, poor seed crops, or low seed mobility. For some, additional silvicultural practices may be needed. Basswood at AEF is an excellent example. Its reproduction was lacking despite good stocking in the overstory and plentiful seed. Supplemental treatments may be needed to overcome seed dormancy and to provide protection from decay and rodent predation (Godman and Mattson 1976).

Adequate dispersal of seed from the uncut border was no problem on the 1- and 2-chain-wide strips used. Benzie (1959) found high numbers of seeds from sugar maple and yellow birch up to 5 chains from their sources.

The generally poorer regeneration at AEF suggests the environmental differences between AEF and UPEF are important and should be considered in any future applications of strip clearcutting. A combination of factors leads to increased moisture stress at AEF. The climate at AEF is more continental than at UPEF, which is in close proximity to Lake Superior. Also contributing to greater stress at AEF are a boulder layer near the soil surface that reduces moisture-holding capacity, and the westerly aspect of the strips which may have increased evapotranspiration at the site. The other extreme, excessive soil moisture, caused reproduction failures of certain small areas at UPEF. Areas of high water tables throughout the growing season regenerated poorly.

Successful strip clearcutting trials at UPEF were comparable in many respects to shelterwood (Tubbs and Metzger 1969) and seed tree (Godman and Krefting 1960) trials also conducted there. These trials all became fully stocked after cutting and sugar maple stocking did not vary greatly among the different cutting methods. Yellow birch establishment on the successfully regenerated sprayed strips exceeded the results obtained in shelterwood trials with either seedbed scarification or seedbed scarification plus herbicide treatment (Tubbs and Metzger 1969).

Results of strip clearcutting in the hemlock-hardwood stand at AEF were similar to those from an earlier study of strip and block clearcutting in immature northern hardwood stands there (Metzger and Tubbs 1971). Reproduction in both trials was marginal to unacceptable. Stocking often declined when the stand was heavily disturbed—that is, when larger areas were cut, when cutting diameter limits were lowered, or when strips were sprayed. Desired shifts in species composition were not obtained.

Browse yields from shrubs and reproduction on clearcut strips at AEF reached 500 pounds per acre 7 years after cutting (Stearns 1969). Other benefits to wildlife from strip cutting are the interspersion of various stand structures, creation of edges and the increase in important food and cover species absent in mature northern hardwood stands.

SUMMARY

Strip clearcutting with or without supplemental treatments is a workable silvicultural option for even-aged management of northern hardwoods. It is not a technique that can be applied indiscriminately, because an error in application can result in long-term loss or reduction of tree cover and development of a community of lesser vegetation. Each situation requires careful evaluation, and strip clearcutting should be used only when it is the logical means to achieve management objectives.

Strip clearcutting to release advance reproduction should only be done when the stocking of reproduction capable of withstanding exposure is adequate. Guidelines for stocking should be more conservative on sites subject to greater moisture stress. This method does not allow significant manipulation of species composition in the regenerated stand.

Strip clearcutting combined with herbicide treatment should be even more judiciously prescribed and is subject to more constraints. Our experience revealed that treatments must effectively eliminate the advance reproduction and seed must be available. Experience shows that at least good or better seed crops of yellow birch, sugar maple, and red maple are needed to restock clearcut areas. Good crops of other species, except the pioneer hardwoods, did not successfully establish them. Soil moisture availability at the site influences regeneration results but our limited data do not warrant specific recommendations regarding soil moisture and stocking levels.

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COMMON AND SCIENTIFIC NAMES OF TREES AND SHRUBS MENTIONED

Ash, black	*Fraxinus nigra* Marsh.
white	*Fraxinus americana* L.
Aspen, quaking	*Populus tremuloides* Michx.
Basswood	*Tilia americana* L.
Beech	*Fagus grandifolia* Ehrh.
Birch, paper	*Betula papyrifera* Marsh.
yellow	*Betula alleghaniensis* Britton
Blackberry	*Rubus* (subgen. *eubatus* Focke)
Cherry, pin	*Prunus pensylvanica* L. f.
Elder, red-berried	*Sambucus pubens* Michx.
Elm, American	*Ulmus americana* L.
Hazel, beaked	*Corylus cornuta* Marsh.
Hemlock, eastern	*Tsuga canadensis* (L.) Carr
Ironwood	*Ostrya virginiana* (Mill) K. Koch
Maple, mountain	*Acer spicatum* Lam.
red	*Acer rubrum* L.
sugar	*Acer saccharum* Marsh.
Raspberry	*Rubus idaeus* L.
Willow	*Salix* spp. L.

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Metzger, Frederick T.

1980. Strip clearcutting to regenerate northern hardwoods. U.S. Department of Agriculture Forest Service, Research Paper NC-186, 14 p. U.S. Department of Agriculture Forest Service, North Central Forest Experiment Station, St. Paul, Minnesota.

Describes results of strip clearcutting trials in mature northern hardwood and hemlock-hardwood stands in the Lake States. Two strip widths and orientations were tested, with and without herbicide treatment of the advance regeneration. Establishment, growth, and species composition of the regeneration were assessed.

KEY WORDS: Sugar maple, yellow birch, red maple, eastern hemlock, even-aged silvicultural systems, herbicides, Michigan, Wisconsin.

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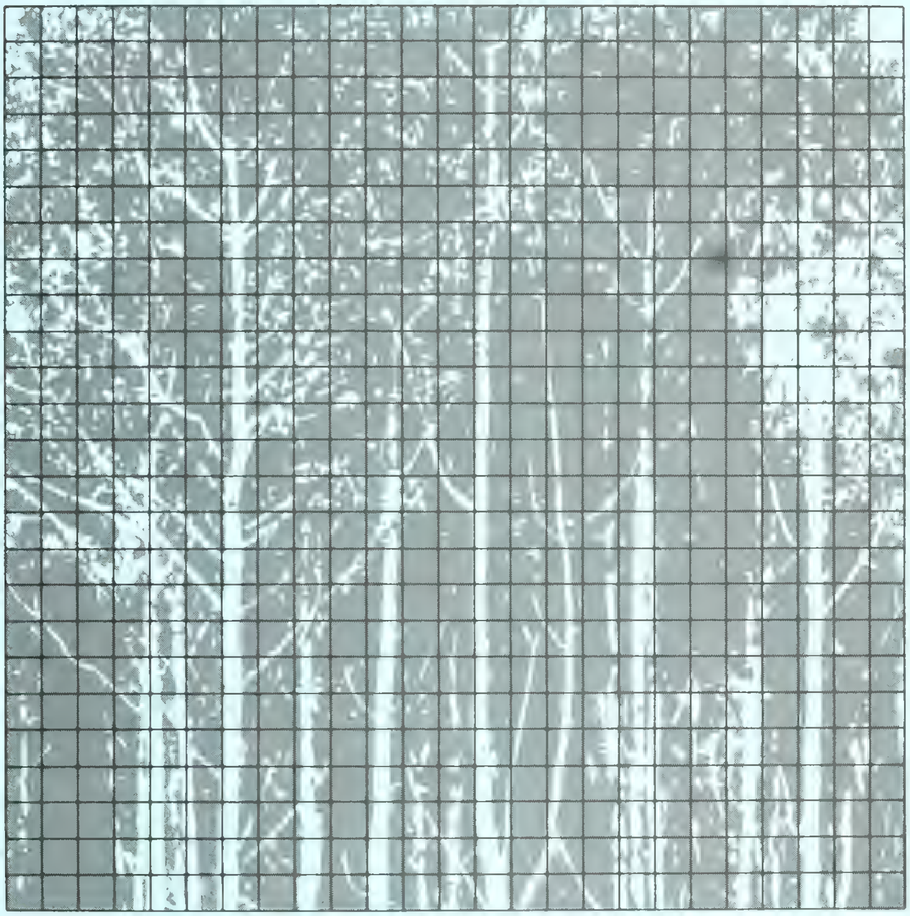

Evaluating stocking in **upland hardwood forests** using metric measurements

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EVALUATING STOCKING IN UPLAND HARDWOOD FORESTS USING METRIC MEASUREMENTS

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Stocking standards have been established for upland hardwood stands. The standards define the range of stocking within which the amount of space available for tree growth is fully utilized. The methods used to develop the stocking standards (Gingrich 1964, 1967) and the use of these standards in making stand prescriptions have been published (Roach and Gingrich 1968, Sander 1977) and have been widely adopted for field use.

Stocking is related to basal area per acre, number of trees per acre, and diameter of the tree of average basal area. These relations have been depicted in the form of a stocking chart (fig. 1). However, the data needed to interpret stocking percent and average tree diameter are based on measurements made in the English system.

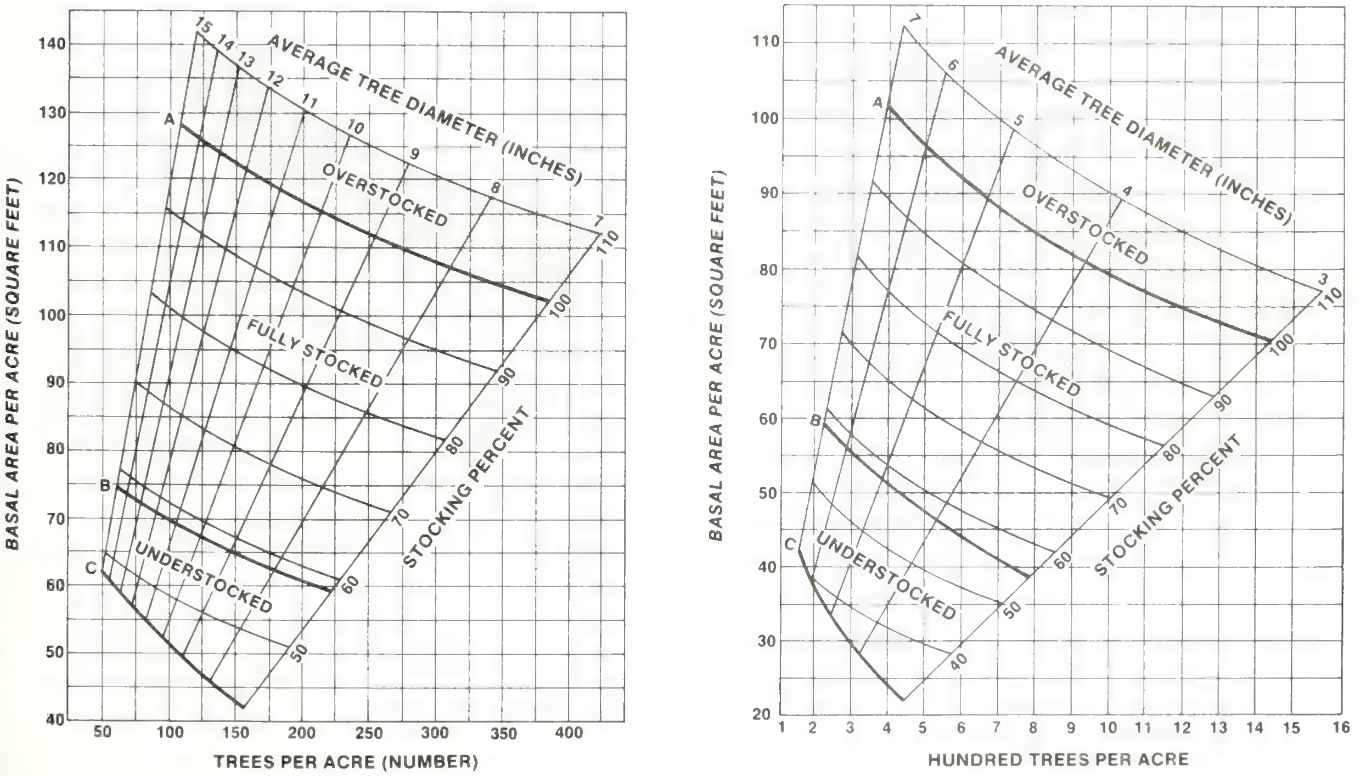

Figure 1.—*Relations of basal area, number of trees, and average tree diameter to stocking percent for upland hardwood forests of average uniformity. Tree diameter range 7-15 inches (left), 3-7 inches (right). The area between curves A and B indicates the range of stocking where trees can fully utilize the growing space. Curve C shows the lower limit of stocking necessary to reach the B level in 10 years on average sites. (Average tree diameter is the diameter of the tree of average basal area.) (From Gingrich 1967).*

The purpose of this paper is to provide the information necessary to evaluate stocking when measurements have been made in the metric system and to provide some pertinent conversion factors.

EVALUATING STOCKING

The basic data needed to evaluate stand stocking are basal area and tree count. Stocking percent and average stand diameter are determined from figure 2 using these two data items. Basal area and the number of trees can be estimated by using the method suggested by Roach and Gingrich (1968) but modified to accomodate metric measurements.

BASAL AREA

The use of an angle gage or wedge prism makes the determination of basal area in the field by the point sample technique easy and quick. The 10-factor gage has proved well suited for use with the central hardwoods and is widely used in this type. The approximate metric equivalent of the 10-factor gage (ft^2/A) is the 2-factor gage (m^2/ha). This gage is calibrated in square meters per hectare, so each tree tallied at a point contributes 2 square meters per hectare to the estimate of basal area per hectare. The metric equivalents of other basal area factors (BAFs) are given in table 1.

Table 1.— *Basal area factor (BAF) conversions*

BAF	BAF	BAF	BAF
ft^2/a	*m^2/ha*	*ft^2/a*	*m^2/ha*
5	1.15	1	4.36
10	2.30	2	8.71
15	3.44	3	13.07
20	4.59	4	17.42
25	5.75	5	21.78
30	6.89	7	30.49

TREE COUNT

A tree count can be made on a plot of fixed radius whose center is coincident with the point of the point sample. Normally a 1/20th-acre plot is recommended for the tree count in the English system. In the metric system, a 1/50th hectare plot whose radius is 7.98 meters approximates 1/20th acre. Trees lying within plot boundaries are counted and the total multiplied by 50 in order to put the number of trees counted on a per hectare basis. Thus, the number of trees in the metric system is expressed as the number of trees per hectare.

An alternative method for obtaining the tree count is to use the conversion factors for the number of trees per hectare based upon the sizes of trees tallied using

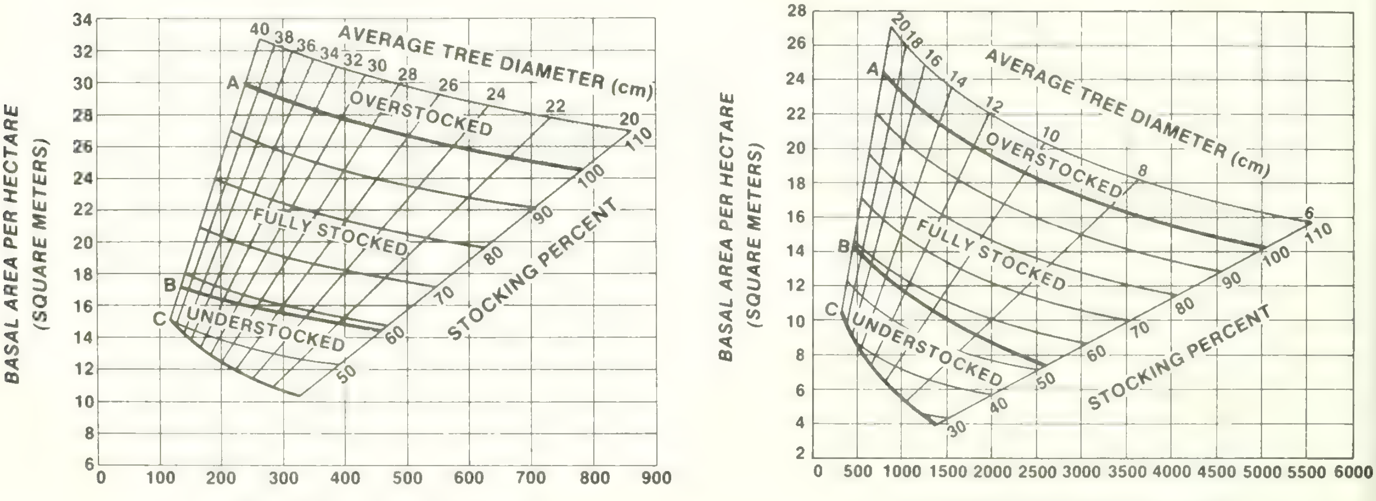

Figure 2.— *Relation of basal area, number of trees, and average tree diameter in metric units to stocking percentage for upland central hardwoods. Tree diameter range 20-40 cm (a), and 6-20 cm (b). The area between curves A and B on both charts indicates the range of stocking where trees can fully utilize the growing space. Curve C shows the lower limit of stocking necessary to reach the B level in 10 years on average sites. (Average tree diameter is the diameter of the tree of average basal area.)*

the angle gage. The per hectare conversion factors for BAF 2 (m^2/ha) are given in the tabulation below.[1]

Diameter (cm)	Number of trees
2	6366
6	707
10	255
14	130
18	79
22	53
26	38
30	28
34	22
38	18
42	14
46	12
50	10.2
54	8.7
58	7.6
62	6.6
66	5.8
70	5.2
74	4.7
78	4.2

If two 18 cm, two 30 cm, four 50 cm, and two 62 cm trees were tallied at a point, then $2 \times 79 + 2 \times 28 + 4 \times 10.2 + 2 \times 6.6 = 268$ trees/ha (the basal area would be 2×10 trees $= 20$ m^2/ha).

THE TALLY

A tally such as proposed by Roach and Gingrich (1968; fig. 22, p. 24) can be modified for use with metric measurements. A 2-factor prism is used to estimate basal area in square meters per hectare (m^2/ha) at 10 point samples and the number of trees per hectare is estimated by tree counts on 1/50th-hectare plots. An example of a tally using metric measurements is presented in table 2. Stocking percent and average stand diameter are determined from figure 2 using the estimates of basal area and number of trees obtained from the data collected in table 2.

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[1] *The tabulation is based on the following equation: Per-hectare conversion factor* $= BAF/(7.85398 \times 10^{-5}D^2)$ *where* $BAF = 2$.

Table 2.— *Sample tally sheet*

Sample point number	Basal area tally: Mature Timber	Sawtimber AGS[1]	Sawtimber UGS[2]	Poletimber AGS	Poletimber UGS	Small trees AGS	Small trees UGS	Cull	Tree count: No. trees per 1/50-hectare plot
1		2	1	2	2			1	10
2		6		3	2		1		13
3		1	2	5	1			2	10
4		3	1	2	4		1		9
5		6		1		1		2	11
6		2	2	2	1		2		12
7		4		1	3		1		10
8		3	2		2	2		2	9
9		5	1	1	3	1	2	1	14
10		2	1	3	2		1		12
Total	0	34	10	20	20	4	8	8	110
Per ha[3]		6.8	2.0	4.0	4.0	.8	1.6	1.6	110 × 5 = 550

Basal area: AGS 11.6 Total 20.8
Number of trees/ha: 550
Stocking percent: 83
Average tree diameter: 22 cm

[1] Acceptable Growing Stock.

[2] Unacceptable Growing Stock.

[3] Obtained by multiplying 2 times total and dividing by 10 (number of points), e.g., $2 \times 34 = 68$ $68/10 = 6.8$. General formula is $\frac{\text{BAF x tree count}}{\text{No. of points}}$.

STOCKING PERCENT PARAMETER CONVERSIONS

Parameter estimates made from data collected in either the English or metric system can be converted to the other system using the conversion factors presented on page xx.

Example 1. Metric to English
Given:
Percent stocking = 85
Number of trees/hectare = 530
Basal area, square meters per hectare = 22
Average tree diameter, cm = 23.0
English equivalent:
Percent stocking = 85
Number of trees/acre = 0.4047 × 530 = 214
Basal area, square feet per acre = 4.356 × 22 = 96
Average tree diameter, inches = 0.3937 × 23.0 = 9.1

Example 2. English to Metric
Given:
Percent stocking = 90
Number of trees per acre = 275
Basal area, square feet per acre = 96
Average tree diameter, inches = 8.0
Metric equivalent:
Percent stocking = 90
Number of trees per hectare = 2.471 × 275 = 680
Basal area, square meters per hectare = 0.22957 × 96 = 22
Average tree diameter, cm = 2.54 × 8.0 = 20.3

English-Metric Conversion Factors

Metric to English:

Basal area per acre (sq. ft.) = 4.356 × basal area per hectare (m^2)
Trees per acre = 0.4047 × trees per hectare
Average tree diameter (inches) = 0.3937 × average tree diameter (cm)
Tree basal area (sq. ft.) = .0008454 × d.b.h.^{2} (cm)
Square feet = 10.764 × square meters
Feet = 0.3048 × meters
Acres = 2.471 × hectares

English to Metric:

Basal area per hectare (sq. meters) = 0.22957 × basal area per acre (ft.^{2})
Trees per hectare = 2.471 × trees per acre
Average tree diameter (cm) = 2.54 × average tree diameter (in.)
Tree basal area (sq. meters) = .0005067 × d.b.h.^{2} (in.)
Square meters = 0.0929 × square feet
Meters = 3.28 × feet
Hectares = 0.4047 × acres

TREE AREA EQUATION

Gingrich's (1967) original tree area equation used to compute the stocking-density criteria expressed tree area in terms of mil-acres. This equation has the form:

Tree area (mil-acres) = $aN + b\Sigma D + c\Sigma D^2$, where N = number of trees per acre and D = tree diameter in inches. Solving this equation (given the appropriate constants a, b, and c) for $N = 1$ and D = any given diameter, defines the minimum tree area requirements for that size tree. Thus a stand having 1,000 mil-acres of tree area per acre was considered to be 100 percent stocked (A-Level).

In the metric system tree area is expressed in ares. One are equals 100 square meters and therefore 100 ares equals one hectare (10,000 square meters). A stand having 100 ares of tree area per hectare is considered to be 100 percent stocked. N is the number of trees per hectare and D is measured in centimeters. The metric stocking equation is:

Tree area (ares) = $(-2.0518N + 2.7053\,\Sigma D + 0.19884\,\Sigma D^2)/1000$. (Stocking percent)

Minimum tree area requirements expressed in ares (stocking percent) for individual trees of varying diameters are given in the tabulation below. The metric equation expressing the maximum amount of area that trees can use (B-Level) is:

Tree area (ares) = $(7.0820 + 3.2662\,\Sigma D + 0.37636\,\Sigma D^2)/1000$.

D.b.h. (cm)	Tree area (ares)	D.b.h. (cm)	Tree area (ares)
6	0.0213	40	0.4243
8	0.0323	42	0.4623
10	0.0449	44	0.5019
12	0.0590	46	0.5431
14	0.0748	48	0.5859
16	0.0921	50	0.6303
18	0.1111	52	0.6763
20	0.1316	54	0.7239
22	0.1537	56	0.7730
24	0.1774	58	0.8238
26	0.2027	60	0.8761
28	0.2296	62	0.9300
30	0.2581	64	0.9855
32	0.2881	66	1.0427
34	0.3198	68	1.1013
36	0.3530	70	1.1616
38	0.3879	72	1.2235

SUMMARY

In an effort to carry out our Nation's commitment to adopt the metric standard, this publication makes available information necessary to evaluate stocking in upland hardwood forests when stocking variables are based on metric measurements. Metric-English conversions are presented so that comparisons can be made between stocking variables obtained using either measurement system.

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Rogers, Robert.
1980. Evaluating stocking in upland hardwood forests using metric measurements. U.S. Department of Agriculture Forest Service, Research Paper NC-187, 5 p. U.S. Department of Agriculture Forest Service, North Central Forest Experiment Station, St. Paul, Minnesota.

Allows stocking percent in upland forests as developed by Gingrich (1964, 1967) to be calculated when tree and stand variables are measured in the metric system.

KEY WORDS: Metric stocking percent, metric stocking conversion factors, metric tree area equation, tree area requirements, and oak-hickory forests.

Help save the birds, animals and flowers.

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Predicted yields from selected cutting prescriptions in northern Minnesota

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PREDICTED YIELDS FROM SELECTED CUTTING PRESCRIPTIONS IN NORTHERN MINNESOTA

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As demand for forest products grows, it will become increasingly important to use forest resources efficiently. In Minnesota, the commercial forest area decreased 11 percent between 1962 and 1977, yet existing forest industries are expanding and new wood-using industries are entering the State. This increase in demand for timber coupled with a shrinking commercial forest land base, emphasizes the need for improved utilization of Minnesota's timber resources.

By calculating predicted yields from selected cutting prescriptions, we identified deficiencies or surpluses in the forest resource. The two sets of cutting prescriptions used in this report should not be construed as management goals, but rather as sideboards defining a range of future yields, using current Minnesota forest conditions as a base. Predicted yields resulting from the prescriptions are only one facet of the total resource picture; they should be used in conjunction with other resource information in planning for the future.

METHODS

The first step involved in calculating predicted yields was specifying cutting prescriptions. We considered two prescriptions, each defined by a set of rotation ages for 14 Minnesota forest types (table 1). The long rotation age option is a prescription based on criteria established jointly by representatives from Minnesota forest industries and the Minnesota Department of Natural Resources. The rotation ages used in this prescription approximate current harvest practices, where the final product (sawtimber or pulpwood) depends on the forest type and site quality (specified by site index ranges). The short rotation age option uses current empirical yields to select rotation age at the age of maximum total volume yield. The final product from this prescription is primarily poletimber (see Appendix).

For both prescriptions, an area control algorithm was used to calculate the number of acres cut in each forest type and site index range. The number of acres cut was set so that an even distribution of area among age classes would be achieved in each forest type by the end of one rotation. Harvest areas were calculated for the decade 1977-1986; after 1986, the areas must be recalculated to account for changes in stand characteristics and the commercial forest land base.

Plot data from the 1977 Minnesota Forest Inventory were then used in a modified version of the Tree Growth Projection System of the Forest Resources Evaluation Program (FREP).[1] The System "grew" each plot for 5 years and then scanned data from each commercial forest plot, selected plots that met the cutting prescription criteria, and calculated the area and volume represented by the plot. Since yields are estimated for a 10-year period, it was necessary to project each plot 5 years as an estimate of average growth on all harvest plots for the decade.

The System assigns the highest cutting priority to overmature stands (fig. 1). In some forest types, there are large areas of stands too young to harvest. Some of these stands were "harvested" before rotation age

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[1] *U.S. Department of Agriculture, Forest Service. 1979. A generalized forest growth projection system applied to the Lake States region. U.S. Department of Agriculture Forest Service, General Technical Report NC-49, 96 p. U.S. Department of Agriculture Forest Service, North Central Forest Experiment Station, St. Paul, Minnesota.*

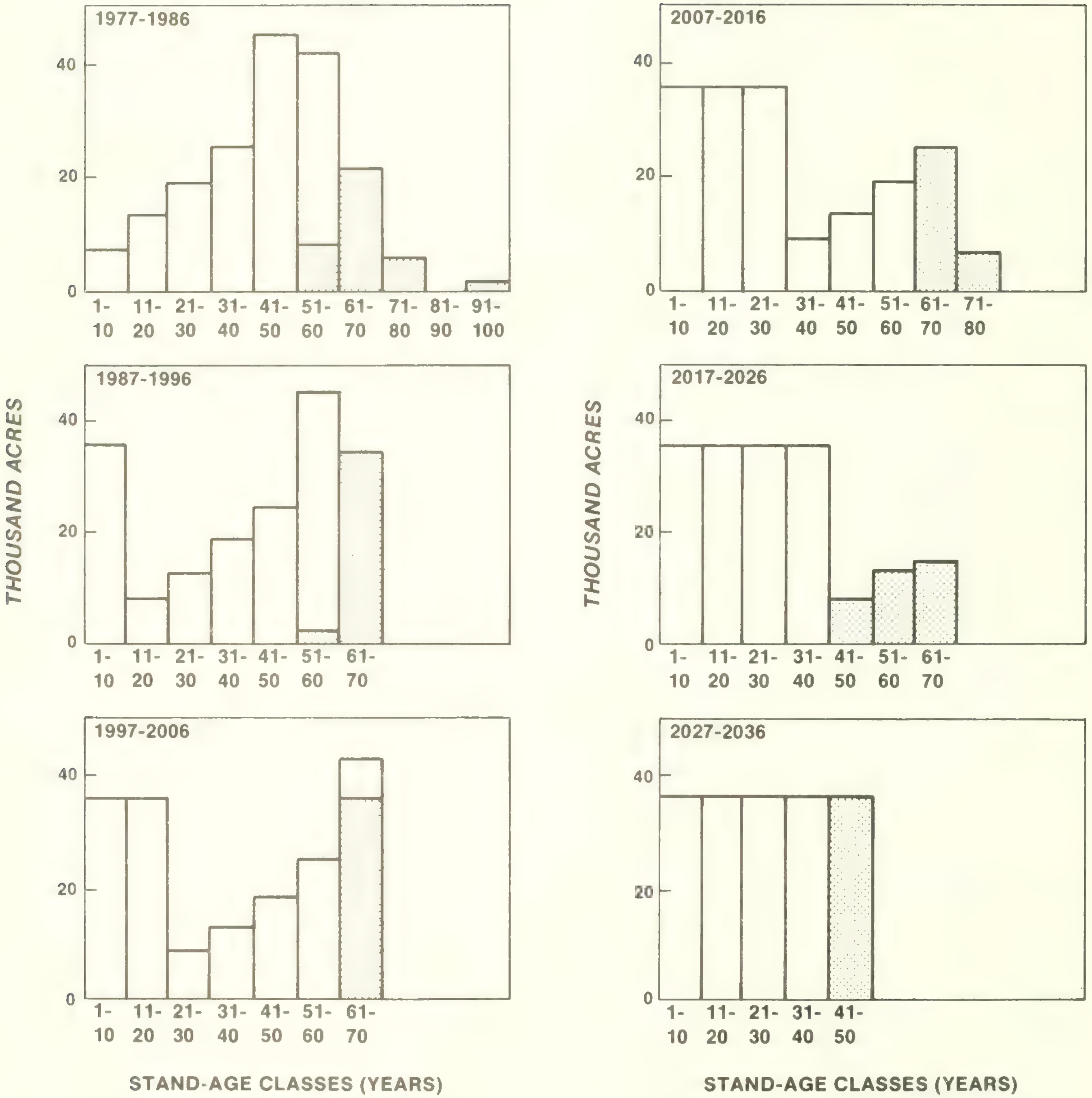

Figure 1.—*Example of the progression of the area control program to even area distribution among stand-age classes for a 50-year rotation by decades. Shaded portions show area cut per decade.*

to bring about an even area distribution among age classes by the end of one rotation. The number of acres harvested in an age class cannot be directly compared to the number of acres in the age class as reported in the 1977 Forest Inventory of Minnesota. Because plots were grown for 5 years before harvest, a shift in commercial land between age classes resulted.

ASSUMPTIONS

Calculations of yields from selected cutting prescriptions are based on these assumptions: (1) the area of commercial forest land will remain stable for the decade 1977-1986; (2) the current mix of area by forest type will remain stable—i.e., no stand conversion will occur; and (3) all timber is available for harvest and a ready market exists for all species and products. The method does not account for possible economic, social, political, or silvicultural constraints on timber removals.

FINDINGS

Predicted yields from selected cutting prescriptions are presented for the Aspen-Birch and the Northern Pine Forest Survey Units, referred to here as the northern Minnesota region (fig. 2). Data from the 1977 Minnesota Forest Inventory show that these two Units contain 82 percent of the State's commercial forest land. Of the 11.2 million acres of commercial forest land in these Units, 62 percent is in public ownership. The State of Minnesota owns the largest portion of the commercial forest land base, 2.4 million acres. Growing-stock volume in the region totals 9.5 billion cubic feet. The region has 98 percent of the State's softwood growing-stock volume. In 1976, growing-stock removals totaled 150.7 million cubic feet, 78 percent of the State total.

Predicted Yields and Area Harvested—Long Rotation Age Option

Between 1977 and 1986, 1.9 million acres of commercial forest land in northern Minnesota can be harvested, according to long rotation age criteria (table 2). The harvest acreage is equally divided between the Aspen-Birch Unit and the Northern Pine Unit, with each having approximately 1.0 million acres available for harvest over the decade (tables 3 and 4). Of the 11.2 million acres of commercial forest land in the region, 2 percent would be cut annually under this harvest plan.

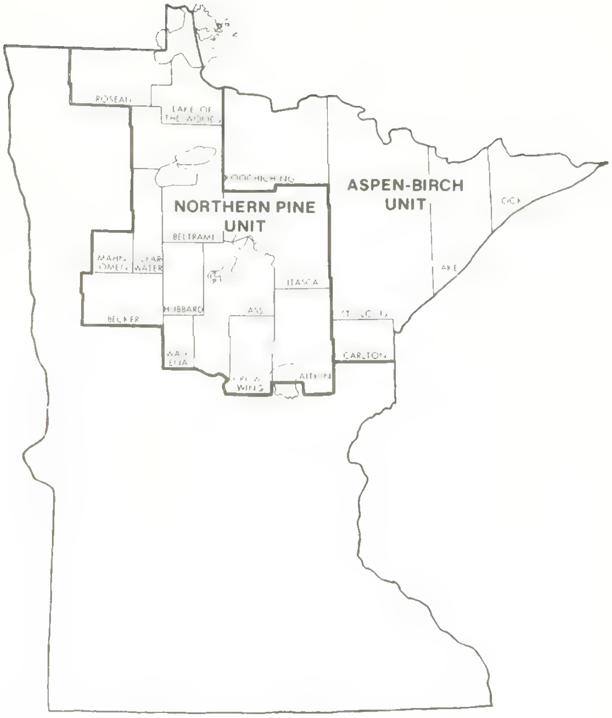

Figure 2.—*Northern Minnesota region.*

The aspen forest type accounts for 49 percent of the harvest acreage, and the paper birch, balsam fir, and jack pine forest types cover an additional 25 percent. Although the distribution of harvest acreage among forest types differs slightly between the Survey Units, aspen makes up the largest portion of the harvest acreage in both—45 percent in the Aspen-Birch Unit, 52 percent in the Northern Pine Unit. In the Aspen-Birch Unit, balsam fir accounts for 13 percent of the harvest acreage, while in the Northern Pine Unit the type accounts for 5 percent. Black spruce occurs on 7 percent of the harvest acreage in the Aspen-Birch Unit, but on only 2 percent in the Northern Pine Unit.

In most forest types, distribution of harvest acreage among age classes is concentrated in overmature stands (tables 5-7). As the System works toward establishing an even distribution among age classes for each forest type by the end of one rotation, it cuts an equal number of acres every year. During this process, overmature stands are assigned the highest cutting priority. For example, the rotation age of low site index jack pine is 50 years, yet during the decade

1977-1986, 52 percent of the jack pine harvest acreage would be over 70 years old. In low site index aspen, all the harvest acreage would be at least 10 years past rotation age.

A different problem arises in forest types where young stands dominate large areas. In the case of high site index red pine with a rotation age of 120 years, all of the acreage harvested in the decade 1977-1986 would be in stands less than 120 years of age. Again, this is necessary to achieve an equal area distribution among all classes by the end of one rotation.

Harvest volume under long rotation age criteria would total 279.5 million cubic feet annually (table 8). Of this total, 253.9 million cubic feet are growing stock and 25.6 million cubic feet are cull. Although harvest acreage is evenly divided between the Aspen-Birch Unit and the Northern Pine Unit, the greatest harvest volume would occur in the Aspen-Birch Unit (tables 9 and 10). This discrepancy is due to differences in the volume per acre on commercial forest land between the two Units. The average growing-stock volume per acre on commercial forest land harvested in the Aspen-Birch Unit is 1,621 cubic feet, while in the Northern Pine Unit the volume per acre on commercial forest land harvested is 1,117 cubic feet.

Hardwood species comprise 65 percent of the harvest volume. Aspen accounts for 36 percent of the growing-stock harvest, the largest percentage of any species. The softwood species accounting for the most harvest volume is balsam fir, with 8 percent of total harvest.

A large portion of the harvest volume of many species is found in the aspen forest type (tables 11-13). Of the 5.4 million cubic feet of white pine harvest volume, 55 percent is in the aspen type; only 12 percent is in the white pine type. Over one-third of the total softwood harvest volume is in aspen stands. The dominance of the aspen type in the hardwood harvest volume would be expected—nearly three-quarters of the hardwood harvest volume is found in the type.

The hardwood annual harvest is fairly evenly divided between poletimber and sawtimber. The annual harvest of hardwood poletimber would total 83.8 million cubic feet, while the annual harvest of hardwood sawtimber would total 82.1 million cubic feet. Softwood annual harvest is composed primarily of sawtimber, which accounts for 62 percent of the softwood growing-stock harvest.

Predicted Yields and Area Harvested—Short Rotation Age Option

In changing harvest criteria from a long rotation age option to a short rotation age option (or from sawtimber to poletimber harvest ages), the area of commercial forest land available for harvest over the decade increases from 1.9 million acres to 2.5 million acres (table 2). Under short rotation age criteria, timber would be harvested on 254,700 acres annually. Harvest acreage remains fairly evenly divided between the Aspen-Birch Unit and the Northern Pine Unit (tables 3 and 4).

As in the long rotation age option, the largest portion (50 percent) of the harvest acreage is in the aspen forest type. Paper birch, balsam fir, and black spruce types account for an additional 23 percent of the harvest acreage. The 1.3 million acres of aspen that would be harvested during the decade under the short rotation age option are 42 percent more than the acreage that would be harvested under the long rotation age option. Black spruce harvest acreage would increase 68 percent under short rotation age harvest criteria. Harvest acreages in the northern white-cedar and oak forest types would more than double.

Although a large portion of the harvest acreage in the short rotation age option remains concentrated in overmature stands, additional younger aged stands would also be harvested (tables 5-7). For example, in the aspen forest type, 904,000 acres would be harvested during the decade under long rotation age criteria, all in stands over 50 years old. Under short rotation age criteria, an additional 2,900 acres would be cut in the 61-70 age class, 357,800 acres in the 51-60 years age class and 18,000 acres in the 41-50 years age class, for a total of 1.3 million acres.

Harvest volume under short rotation age criteria would total 372.7 million cubic feet annually—337.3 million cubic feet in growing-stock trees, and 35.4 million cubic feet in cull (table 8). Harvest volumes under the short rotation age option are about 33 percent higher than volumes under the high rotation age option. Differences between Survey Units in the growing-stock volume per acre on commercial forest land harvested result in more volume being harvested in the Aspen-Birch Unit than in the Northern Pine Unit (tables 9 and 10). Harvest volume in the Aspen-Birch Unit would total 188.7 million cubic feet (1,526 cubic feet per acre) and in the Northern Pine

Unit it would total 148.6 million cubic feet (1,134 cubic feet per acre).

Of the 337.3 million cubic feet of growing-stock harvest volume, 65 percent is hardwood (primarily aspen), and 35 percent is softwood. The 123.5 million cubic feet of aspen harvested is 37 percent of the total harvest and 56 percent of the hardwood harvest. Under short rotation age criteria, aspen harvest volume alone is greater than the total softwood harvest volume. Balsam fir accounts for the largest portion of the softwood harvest volume (28.5 million cubic feet), and jack pine and black spruce harvest volumes are 20.2 million and 20.9 million cubic feet, respectively.

The aspen forest type, which is important in supplying softwood as well as hardwood harvest volume, contains 59 percent of total growing-stock harvest volume (tables 11-13). Fifty percent of the white pine, 49 percent of the balsam fir, and 60 percent of the white spruce harvest volumes are found in the aspen forest type.

Most of the increase in harvest volume resulting from the change in harvest criteria from long rotation age to short rotation age occurs in poletimber stands. Harvest volumes under short rotation age criteria are fairly evenly divided between sawtimber and poletimber stands; however the harvest volumes of species in the two size classes vary widely. Most of the softwood harvest volumes are concentrated in sawtimber trees—95 percent of both the red pine and white pine harvest volume is in sawtimber stands. Three softwood species—balsam fir, black spruce, and tamarack—have the majority of their harvest volumes in pole-timber stands. Hardwood species are evenly divided between those with a majority of their volume in poletimber and those with a majority in sawtimber stands.

DISCUSSION

This study indicates that, under the assumptions specified above, the supply of timber from Minnesota's commercial forest land would be much higher than current timber removals (fig. 3). Under the long and short rotation cutting prescriptions considered, average annual growing-stock removals for the decade would be from 69 percent to 124 percent higher than the 1976 growing-stock removals (tables 14-16).[2] In reality, however, these yields may never be realized for the following reasons: (1) the objectives of some landowners may be incompatible with timber production, (2) edaphic, topographic, or hydrologic characteristics of some sites may make it impossible to harvest timber, (3) some areas may be inaccessible, (4) markets may not exist for the products or species harvested. By using their knowledge of the local resource and other inventory data, forest managers and planners can temper the findings of this report to fit the circumstances of their areas.

Hardwood Removals Would More than Double Between 1977 and 1986

Opportunities for increasing hardwood removals are greater than those for increasing softwood removals. Under the long rotation age option, average annual hardwood removals over the decade would be 165.9 million cubic feet—nearly twice the 1976 removals of 83.4 million cubic feet. The annual removals under low rotation age criteria would be 220.9 million cubic feet, 137.5 million cubic feet higher than the 1976 removals. For every hardwood species, empirical yields from harvests are higher than 1976 removals.

The distribution of hardwood removals volume among species is different under both cutting prescriptions from that in the 1976 harvest (fig. 4). Aspen will continue to provide the largest portion of hardwood removals volume; however, the relative importance of aspen in supplying harvest volume will decline. In 1976, aspen removals were 79 percent of total hardwood removals, while under the cutting prescriptions outlined here, aspen will contribute an average of 55 percent of harvest volume. The importance of paper birch, balsam poplar and ash will increase under these cutting prescriptions.

Softwood Removals Would Increase More than 38 Percent

Under long rotation age criteria, softwood annual removals would total 88.0 million cubic feet—20.7 million cubic feet higher than the 67.3 million cubic feet of softwood growing-stock removals in 1976. The difference between 1976 removals and predicted

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[2] *Removals resulting from the transfer of commercial forest land to productive-reserved forest land are not included.*

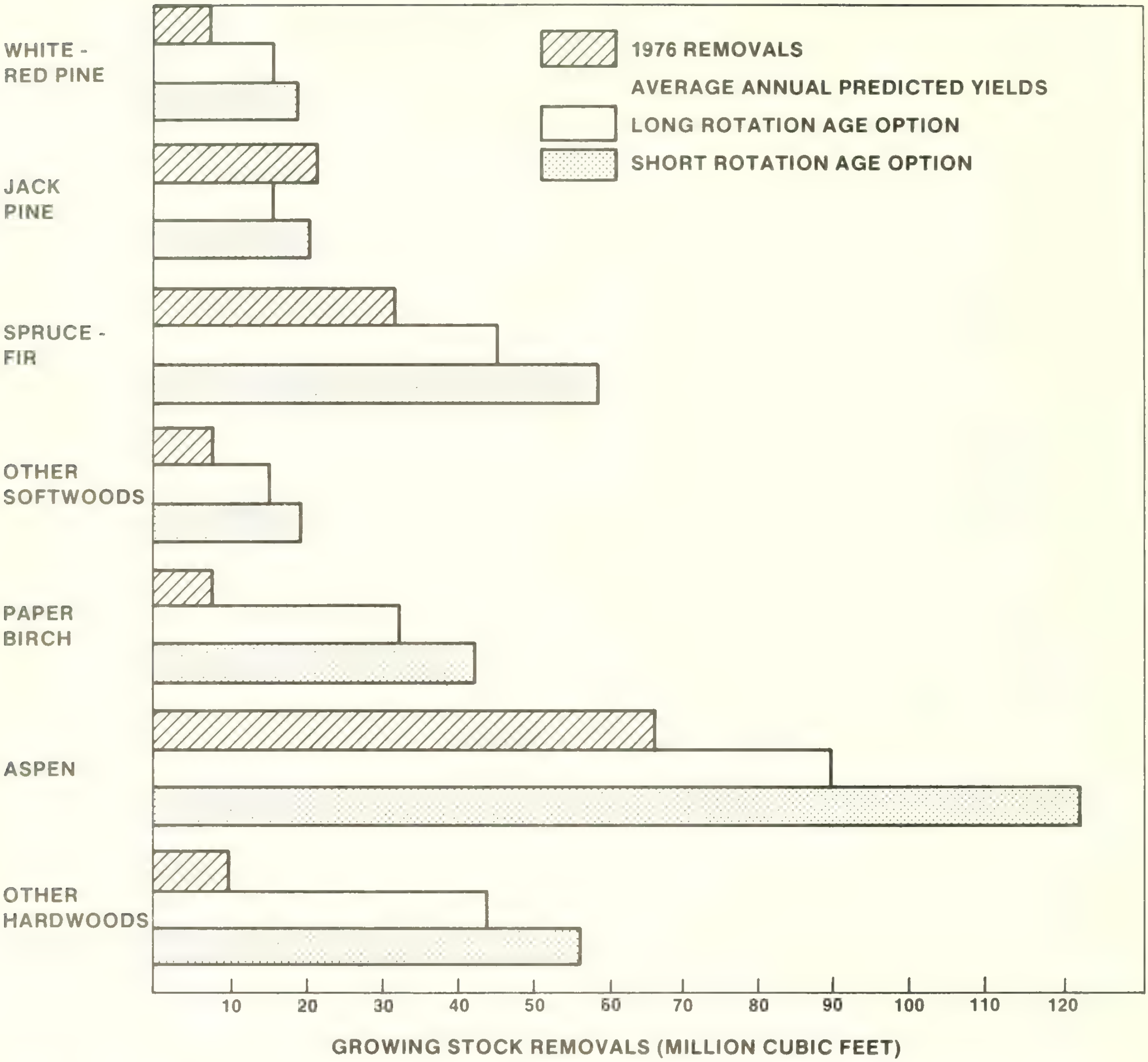

Figure 3.—*1976 growing-stock removals and average annual predicted yields from selected cutting prescriptions, by species groups, northern Minnesota.*

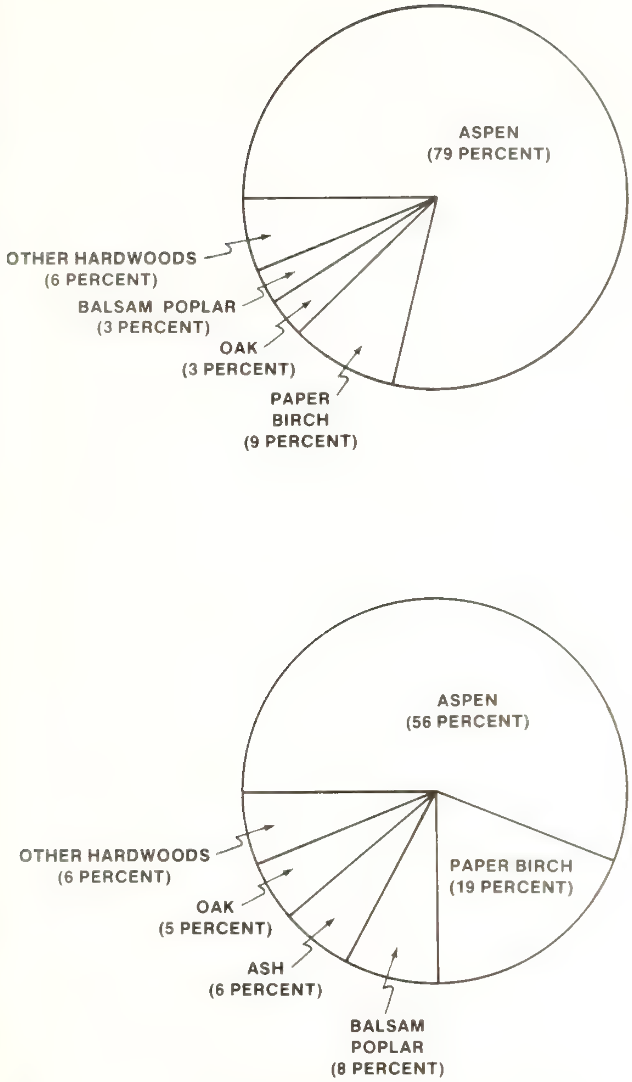

Figure 4.—*(a) 1976 hardwood growing-stock removals by species and (b) average annual predicted yields under short-rotation-age criteria, northern Minnesota.*

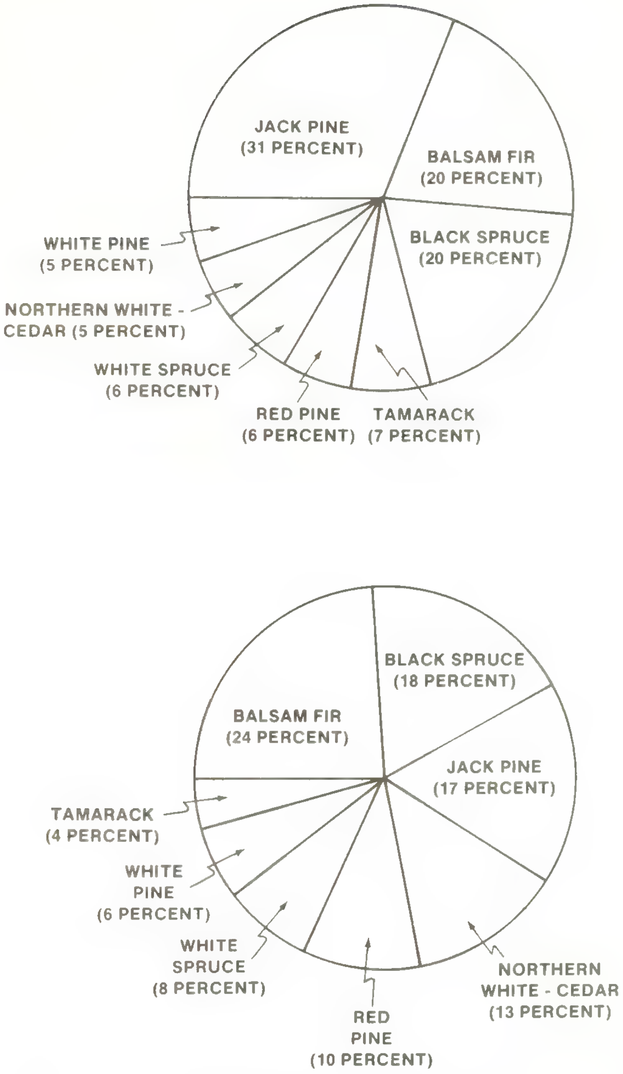

Figure 5.—*(a) 1976 softwood growing-stock removals by species and (b) average annual predicted yields under short-rotation-age criteria, northern Minnesota.*

harvest volume is even greater under short rotation age criteria, where removals would be 116.5 million cubic feet.

Opportunities exist for increased removals from all softwood species, with the exception of tamarack and jack pine. Under both sets of harvest prescriptions, tamarack removals in 1976 exceed predicted harvest yields. The 1976 level of tamarack removals cannot be maintained if the objectives of the cutting prescriptions are to be achieved. Jack pine yields from the long and short rotation age criteria fall below the level of removals in 1976.

Softwood removals are more evenly distributed among species under the harvest prescriptions than they were in the 1976 removals. Jack pine, balsam fir, and black spruce will continue to contribute the bulk of softwood removals, but their percentages will decline during the decade as removals of the other species increase (fig. 5).

Aspen-Birch Unit has Greatest Potential

Under the harvest prescriptions, the Aspen-Birch Unit will supply a greater proportion of total removals than it did in 1976. Growing-stock removals in northern Minnesota in 1976 were fairly evenly divided between the Aspen-Birch Unit and the Northern Pine Unit. Under the cutting prescriptions, the

Aspen-Birch Unit will contribute approximately 57 percent of harvest volume.

Predicted yields from cutting prescriptions range from 103.2 million cubic feet to 186.7 million cubic feet higher than 1976 removals. Most of this increase in removals volume would be in the Aspen-Birch Unit. The Unit would account for 69 percent of the increase in the long rotation age option, and 60 percent of the increase in the short rotation age option. Softwood yields are concentrated in the Aspen-Birch Unit.

The Northern Pine Unit plays an increasingly important role in supplying harvest volume of some species under the cutting prescriptions. For example, in 1976, jack pine removals were evenly divided between the two northern Survey Units; under the prescriptions, the Northern Pine Unit would supply a majority of the jack pine harvest volume.

Table 1.--Site index and rotation age by forest type for long and short rotation age cutting prescriptions, northern Minnesota, 1977-1986

	Long rotation age option		Short rotation age option	
Forest type	Site index	Rotation age	Site index	Rotation age
		years		years
Jack pine	0-60	50	all	40
	61+	60		
Red pine	0-55	100	all	75
	56+	120		
White pine	0-55	100	all	75
	56+	120		
Balsam fir	all	50	all	45
White spruce	all	80	all	65
Black spruce	0-40	120	all	60
	41+	90		
Northern white-cedar	all	100	all	85
Tamarack	0-40	120	all	45
	41+	90		
Oak	0-55	100	all	40
	56+	80		
Elm-ash-cottonwood	0-55	70	all	50
	56+	90		
Maple-basswood	all	90[1]	all	90[1]
Aspen	0-65	40	all	35
	66+	60		
Paper birch	0-65	40	all	35
	66+	60		
Balsam poplar	0-65	40	all	40
	66+	60		

[1] Tubbs, Carl H. 1977. Manager's handbook for northern hardwoods in the North Central States. U.S. Department of Agriculture Forest Service, General Technical Report NC-29, 29 p. U.S Department of Agriculture Forest Service, North Central Forest Experiment Station, St. Paul, Minnesota (applied to stands over age 90).

Table 2.-- Average annual predicted yields from selected cutting prescriptions by forest type and tree class, northern Minnesota, 1977-1986

Forest type	Harvest area	Number growing-stock trees harvested	Total volume	Pole-timber volume	Saw-timber volume	Short-log volume	Other cull volume[1]
	Thousand acres	Thousand trees	. . . . Thousand cubic feet				
LONG ROTATION AGE OPTION							
Jack pine	9.2	1,593	14,933	4,207	9,870	696	160
Red pine	2.2	377	4,963	814	3,969	93	87
White pine	0.5	69	1,262	172	965	100	25
Balsam fir	16.5	2,634	16,488	8,294	7,002	923	269
White spruce	1.0	104	1,240	127	1,049	43	21
Black spruce	8.4	2,442	8,960	6,504	2,230	61	165
Northern white-cedar	4.6	1,044	4,738	1,208	2,950	324	256
Tamarack	4.1	760	3,281	2,050	1,001	72	158
Oak-hickory	2.8	361	3,128	950	1,825	284	69
Elm-ash-cottonwood	7.3	1,121	7,825	3,037	3,697	559	532
Maple-basswood	7.4	139	1,903	558	11	977	357
Aspen	90.4	16,473	166,916	71,455	80,291	9,126	6,044
Paper birch	20.9	3,607	30,603	13,562	14,136	1,882	1,023
Balsam poplar	10.7	1,366	13,227	4,747	7,213	760	507
All types	186.0	32,090	279,467	117,685	136,209	15,900	9,673
SHORT ROTATION AGE OPTION							
Jack pine	12.2	2,570	21,165	7,614	12,553	765	233
Red pine	3.2	405	5,896	626	5,113	113	44
White pine	0.7	85	1,703	128	1,424	135	16
Balsam fir	18.4	3,066	19,837	9,601	8,680	1,194	362
White spruce	1.2	216	1,628	399	1,165	43	21
Black spruce	14.0	4,117	13,570	10,529	2,703	57	281
Northern white-cedar	10.0	2,163	9,972	2,589	6,124	790	469
Tamarack	5.1	1,046	3,600	2,601	738	60	201
Oak-hickory	6.3	855	6,631	2,195	3,713	559	164
Elm-ash-cottonwood	10.9	1,651	11,801	4,956	5,423	719	703
Maple-basswood	7.4	139	1,903	558	11	977	357
Aspen	128.3	22,362	222,925	97,175	103,515	13,115	9,120
Paper birch	25.6	4,854	37,420	18,626	15,383	2,127	1,284
Balsam poplar	11.4	1,442	14,633	5,236	7,979	815	603
All types	254.7	44,971	372,684	162,833	174,524	21,469	13,858

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[1] Rough and rotten cull.

Table 3.-- Average annual predicted yields from selected cutting prescriptions by forest type and tree class, Aspen-Birch Unit, Minnesota, 1977-1986

Forest type	Harvest area	Number growing-stock trees harvested	Total volume	Pole-timber volume	Saw-timber volume	Short-log volume	Other cull volume[1]
LONG ROTATION AGE OPTION							
	Thousand acres	Thousand trees	. . . . Thousand cubic feet				
Jack pine	3.1	525	5,539	1,698	3,307	495	39
Red pine	1.2	274	3,043	630	2,334	32	47
White pine	0.3	29	605	78	415	97	15
Balsam fir	12.2	2,045	13,797	6,685	6,099	825	188
White spruce	0.8	68	902	78	792	32	0
Black spruce	6.0	1,739	7,046	5,010	1,865	61	110
Northern white-cedar	3.1	620	3,042	687	1,983	238	134
Tamarack	1.6	235	1,228	632	492	46	58
Oak-hickory	0.1	12	94	50	36	8	0
Elm-ash-cottonwood	3.4	504	3,335	1,485	1,540	188	122
Maple-basswood	2.2	27	553	133	11	294	115
Aspen	40.9	9,501	95,114	44,577	45,520	3,102	1,915
Paper birch	12.2	2,025	18,490	8,150	8,535	1,252	553
Balsam poplar	4.5	623	6,370	2,395	3,257	431	287
All types	91.6	18,227	159,158	72,288	76,186	7,101	3,583
SHORT ROTATION AGE OPTION							
Jack pine	4.0	1,057	8,512	3,787	4,227	458	40
Red pine	1.6	277	2,981	395	2,580	6	0
White pine	0.4	39	795	90	569	125	11
Balsam fir	13.6	2,436	16,908	7,880	7,665	1,084	279
White spruce	0.9	163	1,198	329	837	32	0
Black spruce	9.9	2,961	10,239	7,992	2,033	41	173
Northern white-cedar	6.8	1,411	6,755	1,697	4,299	498	261
Tamarack	1.9	347	1,299	835	382	29	53
Oak-hickory	0.1	27	239	120	93	26	0
Elm-ash-cottonwood	4.9	816	5,463	2,541	2,422	279	221
Maple-basswood	2.2	27	553	133	11	294	115
Aspen	57.5	12,089	117,826	56,127	54,537	4,267	2,895
Paper birch	14.8	3,013	22,779	11,986	8,960	1,290	543
Balsam poplar	5.1	721	6,977	2,757	3,446	463	311
All types	123.7	25,384	202,524	96,669	92,061	8,892	4,902

[1] Rough and rotten cull.

Table 4.-- Average annual predicted yields from selected cutting prescriptions by forest type and tree class, Northern Pine Unit, Minnesota, 1977-1986

LONG ROTATION AGE OPTION

Forest type	Harvest area	Number growing-stock trees harvested	Total volume	Pole-timber volume	Saw-timber volume	Short-log volume	Other cull volume[1]
	Thousand acres	Thousand trees	. . . . Thousand cubic feet				
Jack pine	6.1	1,068	9,394	2,509	6,563	201	121
Red pine	1.0	103	1,920	184	1,635	61	40
White pine	0.2	40	657	94	550	3	10
Balsam fir	4.3	589	2,691	1,609	903	98	81
White spruce	0.2	36	338	49	257	11	21
Black spruce	2.4	703	1,914	1,494	365	0	55
Northern white-cedar	1.5	424	1,696	521	967	86	122
Tamarack	2.5	525	2,053	1,418	509	26	100
Oak-hickory	2.7	349	3,034	900	1,789	276	69
Elm-ash-cottonwood	3.9	617	4,490	1,552	2,157	371	410
Maple-basswood	5.2	112	1,350	425	0	683	242
Aspen	49.5	6,972	71,802	26,878	34,771	6,024	4,129
Paper birch	8.7	1,582	12,113	5,412	5,601	630	470
Balsam poplar	6.2	743	6,857	2,352	3,956	329	220
All types	94.4	13,863	120,309	45,397	60,023	8,799	6,090
SHORT ROTATION AGE OPTION							
Jack pine	8.2	1,513	12,653	3,827	8,326	307	193
Red pine	1.6	128	2,915	231	2,533	107	44
White pine	0.3	46	908	38	855	10	5
Balsam fir	4.8	630	2,929	1,721	1,015	110	83
White spruce	0.3	53	430	70	328	11	21
Black spruce	4.2	1,156	3,331	2,537	670	16	108
Northern white-cedar	3.2	752	3,217	892	1,825	292	208
Tamarack	3.2	699	2,301	1,766	356	31	148
Oak-hickory	6.2	828	6,392	2,075	3,620	533	164
Elm-ash-cottonwood	6.0	835	6,338	2,415	3,001	440	482
Maple-basswood	5.2	112	1,350	425	0	683	242
Aspen	70.8	10,273	105,099	41,048	48,978	8,848	6,225
Paper birch	10.8	1,841	14,641	6,640	6,423	837	741
Balsam poplar	6.3	721	7,656	2,479	4,533	352	292
All types	131.1	19,587	170,160	66,164	82,463	12,577	8,956

[1] Rough and rotten cull.

Table 5.--Ten-year harvest area from selected cutting prescriptions by forest type, site index class, and stand-age class, northern Minnesota, 1977-1986

(In thousand acres)

LONG ROTATION AGE OPTION

Forest type	Site index class	Total	Stand-age class (years)									
			1-40	41-50	51-60	61-70	71-80	81-90	91-100	101-120	121-140	141+
Jack pine	0-60	64.1	0	0	7.8	22.9	7.4	12.4	11.8	1.8	0	0
	61+	27.9	0	0	20.1	7.8	0	0	0	0	0	0
Red pine	0-55	8.9	0	0	0	0	0	4.4	2.0	2.5	0	0
	56+	13.4	0	0	2.2	2.1	0	1.1	8.0	0	0	0
White pine	0-55	3.7	0	0	0	0	0	0	1.6	2.1	0	0
	56+	1.6	0	0	0	0	0	0	1.6	0	0	0
Balsam fir	All	165.1	0	0	27.5	80.3	35.8	9.7	9.2	2.6	0	0
White spruce	All	10.0	0	0	0	2.5	1.2	2.4	2.8	1.1	0	0
Black spruce	0-40	54.4	0	0	0	0	0	8.7	21.1	12.5	12.1	0
	41+	29.0	0	0	0	1.8	8.4	9.5	7.8	1.5	0	0
Northern white-cedar	All	46.3	0	0	0	0	0	0	0	0	43.3	3.0
Tamarack	0-40	20.9	0	0	0	0	0	0	0	2.9	16.8	1.2
	41+	20.0	0	0	0	1.9	3.1	0	0.7	9.8	4.5	0
Oak-hickory	0-55	17.2	0	0.3	0	0	0	1.4	9.6	5.9	0	0
	56+	10.4	0	0	0.4	4.4	2.8	1.4	0	1.4	0	0
Elm-ash-cottonwood	0-55	55.9	0	0	0	0	0	0	17.9	25.8	12.2	0
	56+	16.9	0	0	0	0	0	1.7	7.9	3.4	3.9	0
Maple-basswood	All	73.7	0	0	0	0	0	0	24.5	20.5	28.7	0
Aspen	0-65	504.9	0	0	177.9	209.5	80.9	26.9	5.3	3.0	1.4	0
	66+	399.1	0	0	229.5	104.4	32.9	21.8	9.1	1.4	0	0
Paper birch	0-65	179.3	0	0	0	71.9	61.7	34.9	5.5	5.3	0	0
	66+	29.3	0	0	1.1	18.0	6.3	1.2	2.7	0	0	0
Balsam poplar	0-65	76.6	0	1.9	26.1	24.4	20.1	2.8	1.3	0	0	0
	66+	30.4	0	0	10.4	12.2	5.1	2.7	0	0	0	0
All types		1,859.0	0	2.2	503.0	564.1	265.7	143.0	150.4	103.5	122.9	4.2
SHORT ROTATION AGE OPTION												
Jack pine	All	122.2	0	0	47.5	41.3	7.4	12.4	11.8	1.8	0	0
Red pine	All	32.4	0	0	0	0	0	14.3	15.6	2.5	0	0
White pine	All	7.2	0	0	0	0	0	0	2.8	4.4	0	0
Balsam fir	All	183.8	0	0	41.3	85.2	35.8	9.7	9.2	2.6	0	0
White spruce	All	12.3	0	0	1.7	3.0	1.2	2.4	2.9	1.1	0	0
Black spruce	All	140.1	0	0	0	4.5	14.1	45.2	50.2	14.0	12.1	0
Northern white-cedar	All	99.7	0	0	0	0	0	0	0.5	30.2	66.0	3.0
Tamarack	All	51.2	0	0	0	0	0	1.0	1.4	23.8	23.8	1.2
Oak-hickory	All	63.3	0	0	1.3	12.8	25.3	7.0	9.6	7.3	0	0
Elm-ash-cottonwood	All	108.4	0	0	0	0	0	21.6	41.6	29.1	16.1	0
Maple-basswood	All	73.7	0	0	0	0	0	0	24.5	20.5	28.7	0
Aspen	All	1,282.9	0	18.0	765.2	316.8	114.0	48.8	14.3	4.4	1.4	0
Paper birch	All	256.1	0	0	28.1	110.3	68.1	36.1	8.2	5.3	0	0
Balsam poplar	All	114.0	0	1.9	39.9	37.5	27.8	5.5	1.4	0	0	0
All types		2,547.3	0	19.9	925.0	611.4	293.7	204.0	194.0	147.0	148.1	4.2

Table 6.--Ten-year harvest area from selected cutting prescriptions by forest type, site index class, and stand-age class, Aspen-Birch Unit, Minnesota, 1977-1986

(In thousand acres)

Forest type	Site index class	Total	Stand-age class (years)									
			1-40	41-50	51-60	61-70	71-80	81-90	91-100	101-120	121-140	141+
LONG ROTATION AGE OPTION												
Jack pine	0-60	28.1	0	0	0	2.2	1.0	12.4	10.7	1.8	0	0
	61+	3.1	0	0	2.0	1.1	0	0	0	0	0	0
Red pine	0-55	6.4	0	0	0	0	0	4.4	0.9	1.1	0	0
	56+	5.4	0	0	2.2	2.1	0	1.1	0	0	0	0
White pine	0-55	2.7	0	0	0	0	0	0	1.6	1.1	0	0
	56+	0.3	0	0	0	0	0	0	0.3	0	0	0
Balsam fir	ALL	121.7	0	0	27.5	50.8	24.9	8.1	9.2	1.2	0	0
White spruce	ALL	7.6	0	0	0	1.3	1.2	1.2	2.8	1.1	0	0
Black spruce	0-40	37.2	0	0	0	0	0	0	17.1	10.9	9.2	0
	41+	22.6	0	0	0	0	6.9	7.9	7.8	0	0	0
Northern white-cedar	ALL	30.9	0	0	0	0	0	0	0	0	30.9	0
Tamarack	0-40	7.8	0	0	0	0	0	0	0	2.9	3.7	1.2
	41+	7.7	0	0	0	1.9	3.1	0	0	1.4	1.3	0
Oak-hickory	0-55	0.3	0	0.3	0	0	0	0	0	0	0	0
	56+	0.4	0	0	0.4	0	0	0	0	0	0	0
Elm-ash-cottonwood	0-55	29.5	0	0	0	0	0	0	10.5	12.3	6.7	0
	56+	4.3	0	0	0	0	0	1.7	0	0	2.6	0
Maple-basswood	ALL	21.9	0	0	0	0	0	0	0	12.9	9.0	0
Aspen	0-65	267.3	0	0	88.7	111.8	46.0	16.8	2.7	1.3	0	0
	66+	141.4	0	0	72.4	38.5	15.8	9.7	5.0	0	0	0
Paper birch	0-65	107.5	0	0	0	34.6	45.3	23.9	2.4	1.3	0	0
	66+	13.9	0	0	1.1	6.6	4.9	0	1.3	0	0	0
Balsam poplar	0-65	30.9	0	0	7.1	11.1	8.6	2.8	1.3	0	0	0
	66+	13.6	0	0	4.3	4.2	3.8	1.3	0	0	0	0
All types		912.5	0	0.3	205.7	266.2	161.5	91.3	73.6	49.3	63.4	1.2
SHORT ROTATION AGE OPTION												
Jack pine	All	39.8	0	0	0	13.9	1.0	12.4	10.7	1.8	0	0
Red pine	All	16.3	0	0	0	0	0	14.3	0.9	1.1	0	0
White pine	All	3.9	0	0	0	0	0	0	2.8	1.1	0	0
Balsam fir	All	135.6	0	0	41.3	50.9	24.9	8.1	9.2	1.2	0	0
White spruce	All	9.4	0	0	1.7	1.3	1.2	1.2	2.9	1.1	0	0
Black spruce	All	98.6	0	0	0	0	5.9	26.4	46.2	10.9	9.2	0
Northern white-cedar	All	67.7	0	0	0	0	0	0	0.5	25.8	41.4	0
Tamarack	All	19.1	0	0	0	0	0	1.0	1.4	10.5	5.0	1.2
Oak-hickory	All	1.3	0	0	1.3	0	0	0	0	0	0	0
Elm-ash-cottonwood	All	48.9	0	0	0	0	0	8.1	19.3	12.2	9.3	0
Maple-basswood	All	21.9	0	0	0	0	0	0	0	12.9	9.0	0
Aspen	All	574.5	0	0	324.1	153.1	61.8	26.5	7.7	1.3	0	0
Paper birch	All	147.8	0	0	10.6	58.0	50.3	23.9	3.7	1.3	0	0
Balsam poplar	All	51.4	0	0	18.3	15.2	12.4	4.1	1.4	0	0	0
All types		1,236.2	0	0	397.3	292.4	157.5	126.0	106.7	81.2	73.9	1.2

Table 7.--Ten-year harvest area from selected cutting prescriptions by forest type, site index class, and stand-age class, Northern Pine Unit, Minnesota, 1977-1986

(In thousand acres)

LONG ROTATION AGE OPTION

Forest type	Site index class	Total	Stand-age class (years)									
			1-40	41-50	51-60	61-70	71-80	81-90	91-100	101-120	121-140	141+
Jack pine	0-60	36.0	0	0	7.8	20.7	6.4	0	1.1	0	0	0
	61+	24.8	0	0	18.1	6.7	0	0	0	0	0	0
Red pine	0-55	2.5	0	0	0	0	0	0	1.1	1.4	0	0
	56+	8.0	0	0	0	0	0	0	8.0	0	0	0
White pine	0-55	1.0	0	0	0	0	0	0	0	1.0	0	0
	56+	1.3	0	0	0	0	0	0	1.3	0	0	0
Balsam fir	All	43.4	0	0	0	29.5	10.9	1.6	0	1.4	0	0
White spruce	All	2.4	0	0	0	1.2	0	1.2	0	0	0	0
Black spruce	0-40	17.2	0	0	0	0	0	8.7	4.0	1.6	2.9	0
	41+	6.4	0	0	0	1.8	1.5	1.6	0	1.5	0	0
Northern white-cedar	All	15.4	0	0	0	0	0	0	0	0	12.4	3.0
Tamarack	0-40	13.1	0	0	0	0	0	0	0	0	13.1	0
	41+	12.3	0	0	0	0	0	0	0.7	8.4	3.2	0
Oak-hickory	0-55	16.9	0	0	0	0	0	1.4	9.6	5.9	0	0
	56+	10.0	0	0	0	4.4	2.8	1.4	0	1.4	0	0
Elm-ash-cottonwood	0-55	26.4	0	0	0	0	0	0	7.4	13.5	5.5	0
	56+	12.6	0	0	0	0	0	0	7.9	3.4	1.3	0
Maple-basswood	All	51.8	0	0	0	0	0	0	24.5	7.6	19.7	0
Aspen	0-65	237.6	0	0	89.2	97.7	34.9	10.1	2.6	1.7	1.4	0
	66+	257.7	0	0	157.1	65.9	17.1	12.1	4.1	1.4	0	0
Paper birch	0-65	71.8	0	0	0	37.3	16.4	11.0	3.1	4.0	0	0
	66+	15.4	0	0	0	11.4	1.4	1.2	1.4	0	0	0
Balsam poplar	0-65	45.7	0	1.9	19.0	13.3	11.5	0	0	0	0	0
	66+	16.8	0	0	6.1	8.0	1.3	1.4	0	0	0	0
All types		946.5	0	1.9	297.3	297.9	104.2	51.7	76.8	54.2	59.5	3.0
SHORT ROTATION AGE OPTION												
Jack pine	All	82.4	0	0	47.5	27.4	6.4	0	1.1	0	0	0
Red pine	All	16.1	0	0	0	0	0	0	14.7	1.4	0	0
White pine	All	3.3	0	0	0	0	0	0	0	3.3	0	0
Balsam fir	All	48.2	0	0	0	34.3	10.9	1.6	0	1.4	0	0
White spruce	All	2.9	0	0	0	1.7	0	1.2	0	0	0	0
Black spruce	All	41.5	0	0	0	4.5	8.2	18.8	4.0	3.1	2.9	0
Northern white-cedar	All	32.0	0	0	0	0	0	0	0	4.4	24.6	3.0
Tamarack	All	32.1	0	0	0	0	0	0	0	13.3	18.8	0
Oak-hickory	All	62.0	0	0	0	12.8	25.3	7.0	9.6	7.3	0	0
Elm-ash-cottonwood	All	59.5	0	0	0	0	0	13.5	22.3	16.9	6.8	0
Maple-basswood	All	51.8	0	0	0	0	0	0	24.5	7.6	19.7	0
Aspen	All	708.4	0	18.0	441.1	163.7	52.2	22.3	6.6	3.1	1.4	0
Paper birch	All	108.3	0	0	17.5	52.3	17.8	12.2	4.5	4.0	0	0
Balsam poplar	All	62.6	0	1.9	21.6	22.3	15.4	1.4	0	0	0	0
All types		1,311.1	0	19.9	527.7	319.0	136.2	78.0	87.3	65.8	74.2	3.0

Table 8.--Average annual predicted yields from selected cutting prescriptions by species group and tree class, northern Minnesota, 1977-1986

Species group	Growing stock			Cull			Sawtimber
	Total	Pole-timber	Saw-timber	Total	Shortlog	Other [1]	Saw-timber
	. . . . Thousand cubic feet					. . . .	Thousand board feet [2]
LONG ROTATION AGE OPTION							
SOFTWOODS:							
White pine	5,444	107	5,337	195	172	23	36,267
Red pine	9,404	595	8,809	58	44	14	53,498
Jack pine	14,083	2,842	11,241	480	338	142	57,737
White spruce	8,099	2,314	5,785	64	48	16	27,239
Black spruce	15,924	10,166	5,758	177	20	157	26,569
Balsam fir	21,464	13,022	8,442	612	259	353	39,201
Tamarack	3,778	2,255	1,523	302	97	205	6,586
Northern white-cedar	9,787	2,554	7,233	1,613	1,237	376	39,587
Other softwoods	0	0	0	0	0	0	0
Total	87,983	33,855	54,128	3,501	2,215	1,286	286,684
HARDWOODS:							
White oak	2,616	1,206	1,410	235	142	93	7,337
Select red oak	4,686	1,730	2,956	583	416	167	14,781
Other red oak	0	0	0	0	0	0	0
Hickory	16	8	8	0	0	0	41
Yellow birch	140	56	84	116	87	29	392
Hard maple	1,327	991	336	1,102	735	367	1,925
Soft maple	1,337	942	395	661	288	373	1,938
Ash	11,360	7,354	4,006	710	265	445	22,874
Balsam poplar	15,493	7,141	8,352	890	505	385	43,021
Paper birch	32,070	23,591	8,479	2,963	1,356	1,607	43,791
Bigtooth aspen	4,109	1,866	2,243	616	392	224	10,627
Quaking aspen	86,253	36,593	49,660	13,330	8,971	4,359	265,170
Basswood	2,428	1,344	1,084	346	168	178	5,410
Elm	4,027	981	3,046	447	355	92	17,172
Select hardwoods	28	6	22	12	0	12	108
Other hardwoods	21	21	0	27	5	22	0
Noncommercial species	0	0	0	58	0	58	0
Total	165,911	83,830	82,081	22,096	13,685	8,411	434,587
All species	253,894	117,685	136,209	25,597	15,900	9,697	721,271
SHORT ROTATION AGE OPTION							
SOFTWOODS:							
White pine	6,978	346	6,632	230	202	28	44,928
Red pine	11,317	542	10,775	70	62	8	66,228
Jack pine	20,183	5,522	14,661	664	484	180	75,472
White spruce	9,343	2,726	6,617	81	48	33	31,348
Black spruce	20,887	14,518	6,369	252	21	231	29,537
Balsam fir	28,469	17,323	11,146	808	394	414	51,479
Tamarack	4,332	2,863	1,469	406	115	291	6,338
Northern white-cedar	14,964	3,727	11,237	2,390	1,817	573	61,891
Other softwoods	23	23	0	3	0	3	0
Total	116,496	47,590	68,906	4,904	3,143	1,761	367,221
HARDWOODS:							
White oak	3,944	1,852	2,092	410	254	156	10,872
Select red oak	7,415	3,020	4,395	880	645	235	22,032
Other red oak	78	67	11	3	0	3	54
Hickory	16	8	8	0	0	0	41
Yellow birch	206	63	143	139	102	37	701
Hard maple	1,783	1,358	425	1,211	770	441	2,430
Soft maple	1,838	1,295	543	844	338	506	2,676
Ash	14,003	9,155	4,848	877	323	554	27,792
Balsam poplar	17,607	8,386	9,221	1,150	619	531	47,548
Paper birch	41,822	31,425	10,397	4,226	1,909	2,317	53,937
Bigtooth aspen	5,921	2,935	2,986	774	466	308	14,075
Quaking aspen	117,574	52,181	65,393	18,757	12,197	6,560	349,142
Basswood	3,657	2,225	1,432	505	243	262	7,091
Elm	4,922	1,226	3,696	565	454	111	20,648
Select hardwoods	40	12	28	18	0	18	140
Other hardwoods	35	35	0	28	6	22	0
Noncommercial species	0	0	0	69	0	69	0
Total	220,861	115,243	105,618	30,456	18,326	12,130	559,179
All species	337,357	162,833	174,524	35,360	21,469	13,891	926,400

[1] Rough and rotten cull.

[2] International 1/4-inch rule.

Table 9.--Average annual predicted yields from selected cutting prescriptions by species group and tree class, Aspen-Birch Unit, Minnesota, 1977-1986

LONG ROTATION AGE OPTION

Species group	Growing stock Total	Growing stock Pole-timber	Growing stock Saw-timber	Cull Total	Cull Shortlog	Cull Other[1]	Saw-timber
	. . . . Thousand cubic feet					. . . .	Thousand board feet [2]
SOFTWOODS:							
White pine	3,690	54	3,636	101	84	17	26,092
Red pine	4,383	388	3,995	27	13	14	26,805
Jack pine	4,671	713	3,958	122	87	35	21,366
White spruce	6,875	2,124	4,751	53	43	10	21,775
Black spruce	13,049	7,948	5,101	108	6	102	23,890
Balsam fir	14,876	9,555	5,321	452	219	233	26,097
Tamarack	1,562	891	671	141	42	99	2,441
Northern white-cedar	5,760	1,405	4,355	887	734	153	25,448
Other softwoods	0	0	0	0	0	0	0
Total	54,866	23,078	31,788	1,891	1,228	663	173,914
HARDWOODS:							
White oak	101	12	89	22	10	12	369
Select red oak	123	50	73	13	11	2	353
Other red oak	0	0	0	0	0	0	0
Hickory	0	0	0	0	0	0	0
Yellow birch	102	25	77	67	57	10	355
Hard maple	343	287	56	328	212	116	355
Soft maple	579	393	186	372	163	209	907
Ash	7,120	4,526	2,594	214	89	125	15,740
Balsam poplar	10,133	5,007	5,126	587	386	201	26,814
Paper birch	19,887	15,295	4,592	1,504	853	651	24,507
Bigtooth aspen	542	226	316	67	38	29	1,692
Quaking aspen	52,775	22,987	29,788	5,403	3,880	1,523	161,787
Basswood	272	120	152	49	37	12	800
Elm	1,631	282	1,349	166	137	29	7,784
Select hardwoods	0	0	0	0	0	0	0
Other hardwoods	0	0	0	1	0	1	0
Noncommercial species	0	0	0	24	0	24	0
Total	93,608	49,210	44,398	8,817	5,873	2,944	241,463
All species	148,474	72,288	76,186	10,708	7,101	3,607	415,377

SHORT ROTATION AGE OPTION

Species group	Growing stock Total	Growing stock Pole-timber	Growing stock Saw-timber	Cull Total	Cull Shortlog	Cull Other[1]	Saw-timber
SOFTWOODS:							
White pine	4,595	275	4,320	83	69	14	31,462
Red pine	4,444	288	4,156	25	23	2	29,221
Jack pine	7,205	2,202	5,003	122	80	42	27,396
White spruce	7,713	2,477	5,236	65	43	22	24,037
Black spruce	16,665	11,235	5,430	168	15	153	25,681
Balsam fir	19,335	12,645	6,690	597	303	294	32,822
Tamarack	1,748	1,102	646	168	52	116	2,319
Northern white-cedar	9,437	2,162	7,275	1,334	1,076	258	42,501
Other softwoods	0	0	0	0	0	0	0
Total	71,142	32,386	38,756	2,562	1,661	901	215,439
HARDWOODS:							
White oak	98	31	67	21	9	12	319
Select red oak	270	121	149	36	29	7	783
Other red oak	0	0	0	0	0	0	0
Hickory	0	0	0	0	0	0	0
Yellow birch	168	32	136	92	72	20	664
Hard maple	461	405	56	341	224	117	355
Soft maple	773	556	217	473	196	277	1,081
Ash	8,799	5,671	3,128	293	102	191	19,113
Balsam poplar	11,269	5,727	5,542	702	454	248	28,986
Paper birch	25,711	19,986	5,725	2,009	1,179	830	30,723
Bigtooth aspen	995	580	415	103	54	49	2,225
Quaking aspen	66,790	30,516	36,274	6,930	4,722	2,208	196,831
Basswood	427	282	145	49	37	12	754
Elm	1,827	376	1,451	181	152	29	8,379
Select hardwoods	0	0	0	0	0	0	0
Other hardwoods	0	0	0	2	1	1	0
Noncommercial species	0	0	0	33	0	33	0
Total	117,588	64,283	53,305	11,265	7,231	4,034	290,213
All species	188,730	96,669	92,061	13,827	8,892	4,935	505,652

[1] Rough and rotten cull.

[2] International 1/4-inch rule.

Table 10.--Average annual predicted yields from selected cutting prescriptions by species group and tree class, Northern Pine Unit, Minnesota, 1977-1986

LONG ROTATION AGE OPTION

	Growing stock			Cull			
Species Group	Total	Pole-timber	Saw-timber	Total	Shortlog	Other[1]	Saw-timber
	Thousand cubic feet						Thousand board feet[2]
SOFTWOODS:							
White pine	1,754	53	1,701	94	88	6	10,175
Red pine	5,021	207	4,814	31	31	0	26,693
Jack pine	9,412	2,129	7,283	358	251	107	36,371
White spruce	1,224	190	1,034	11	5	6	5,464
Black spruce	2,875	2,218	657	69	14	55	2,679
Balsam fir	6,588	3,467	3,121	160	40	120	13,104
Tamarack	2,216	1,364	852	161	55	106	4,145
Northern white-cedar	4,027	1,149	2,878	726	503	223	14,139
Other softwoods	0	0	0	0	0	0	0
Total	33,117	10,777	22,340	1,610	987	623	112,770
HARDWOODS:							
White oak	2,515	1,194	1,321	213	132	81	6,968
Select red oak	4,563	1,680	2,883	570	405	165	14,428
Other red oak	0	0	0	0	0	0	0
Hickory	16	8	8	0	0	0	41
Yellow birch	38	31	7	49	30	19	37
Hard maple	984	704	280	774	523	251	1,570
Soft maple	758	549	209	289	125	164	1,031
Ash	4,240	2,828	1,412	496	176	320	7,134
Balsam poplar	5,360	2,134	3,226	303	119	184	16,207
Paper birch	12,183	8,296	3,887	1,459	503	956	19,284
Bigtooth aspen	3,567	1,640	1,927	549	354	195	8,935
Quaking aspen	33,478	13,606	19,872	7,927	5,091	2,836	103,383
Basswood	2,156	1,224	932	297	131	166	4,610
Elm	2,396	699	1,697	281	218	63	9,388
Select hardwoods	28	6	22	12	0	12	108
Other hardwoods	21	21	0	26	5	21	0
Noncommercial species	0	0	0	34	0	34	0
Total	72,303	34,620	37,683	13,279	7,812	5,467	193,124
All species	105,420	45,397	60,023	14,889	8,799	6,090	305,894
SHORT ROTATION AGE OPTION							
SOFTWOODS:							
White pine	2,383	71	2,312	147	133	14	13,466
Red pine	6,873	254	6,619	45	39	6	37,007
Jack pine	12,978	3,320	9,658	542	404	138	48,076
White spruce	1,630	249	1,381	16	5	11	7,311
Black spruce	4,222	3,283	939	84	6	78	3,856
Balsam fir	9,134	4,678	4,456	211	91	120	18,657
Tamarack	2,584	1,761	823	238	63	175	4,019
Northern white-cedar	5,527	1,565	3,962	1,056	741	315	19,390
Other softwoods	23	23	0	3	0	3	0
Total	45,354	15,204	30,150	2,342	1,482	860	151,782
HARDWOODS:							
White oak	3,846	1,821	2,025	389	245	144	10,553
Select red oak	7,145	2,899	4,246	844	616	228	21,249
Other red oak	78	67	11	3	0	3	54
Hickory	16	8	8	0	0	0	41
Yellow birch	38	31	7	47	30	17	37
Hard maple	1,322	953	369	870	546	324	2,075
Soft maple	1,065	739	326	371	142	229	1,595
Ash	5,204	3,484	1,720	584	221	363	8,679
Balsam poplar	6,338	2,659	3,679	448	165	283	18,562
Paper birch	16,111	11,439	4,672	2,217	730	1,487	23,214
Bigtooth aspen	4,926	2,355	2,571	671	412	259	11,850
Quaking aspen	50,784	21,665	29,119	11,827	7,475	4,352	152,311
Basswood	3,230	1,943	1,287	456	206	250	6,337
Elm	3,095	850	2,245	384	302	82	12,269
Select hardwoods	40	12	28	18	0	18	140
Other hardwoods	35	35	0	26	5	21	0
Noncommercial species	0	0	0	36	0	36	0
Total	103,273	50,960	52,313	19,191	11,095	8,096	268,966
All species	148,627	66,164	82,463	21,533	12,577	8,956	420,748

[1] Rough and rotten cull.

[2] International 1/4-inch rule.

Table 11.--Average annual predicted yields of growing-stock from selected cutting prescriptions by species group and forest type, northern Minnesota, 1977-1986

(In thousand cubic feet)

LONG ROTATION AGE OPTION

Species group	Total	Jack pine	Red pine	White pine	Balsam fir	White spruce	Black spruce	Northern white-cedar	Tamarack	Oak-hickory	Elm-ash-cottonwood	Maple-basswood	Aspen	Paper birch	Balsam poplar
SOFTWOODS:															
White pine	5,444	48	616	672	427	63	119	40	0	21	0	0	2,990	431	17
Red pine	9,404	563	3,554	140	226	28	63	25	0	143	0	0	3,254	1,408	0
Jack pine	14,083	10,161	10	0	137	2	143	0	16	0	0	0	3,407	188	19
White spruce	8,099	37	15	111	1,287	598	107	23	0	6	64	0	4,769	884	198
Black spruce	15,924	1,229	71	0	2,606	1	7,186	135	306	0	11	0	4,129	167	83
Balsam fir	21,464	119	200	111	5,715	102	203	68	31	11	484	55	10,038	2,999	1,328
Tamarack	3,778	0	0	0	282	1	350	83	2,572	0	7	0	171	0	312
Northern white-cedar	9,787	0	18	0	1,072	107	289	3,368	85	0	1,427	0	1,990	999	432
Other softwoods	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	87,983	12,157	4,484	1,034	11,752	902	8,460	3,742	3,010	181	1,993	55	30,748	7,076	2,389
HARDWOODS:															
White oak	2,616	5	0	0	0	3	0	0	0	561	30	39	1,781	157	40
Select red oak	4,686	26	0	0	0	0	0	0	0	1,252	0	6	2,914	432	56
Other red oak	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hickory	16	0	0	0	0	0	0	0	0	0	0	0	0	16	0
Yellow birch	140	0	0	0	0	0	0	24	0	0	8	0	20	65	23
Hard maple	1,327	0	0	0	29	0	0	0	0	20	0	107	810	310	51
Soft maple	1,337	0	0	2	206	0	0	0	0	46	148	14	737	184	0
Ash	11,360	0	0	0	238	0	25	205	5	55	2,941	170	5,550	1,099	1,072
Balsam poplar	15,493	34	0	0	771	1	12	11	14	6	87	6	8,545	421	5,585
Paper birch	32,070	668	73	101	1,303	206	144	169	16	143	368	65	14,904	13,124	786
Bigtooth aspen	4,109	69	44	0	0	0	6	0	0	64	57	0	3,731	118	20
Quaking aspen	86,253	1,089	182	0	978	64	76	0	6	265	119	19	78,197	3,834	1,424
Basswood	2,428	4	0	0	8	0	0	0	0	133	121	28	1,626	414	94
Elm	4,027	9	0	0	11	0	11	7	0	44	862	60	2,155	448	420
Select hardwood	28	0	0	0	0	0	0	0	0	0	0	0	28	0	0
Other hardwoods	21	16	0	0	0	0	0	0	0	5	0	0	0	0	0
Total	165,911	1,920	299	103	3,544	274	274	416	41	2,594	4,741	514	120,998	20,622	9,571
All species	253,894	14,077	4,783	1,137	15,296	1,176	8,734	4,158	3,051	2,775	6,734	569	151,746	27,698	11,960
SHORT ROTATION AGE OPTION															
SOFTWOODS:															
White pine	6,978	48	959	787	427	76	38	100	0	128	63	0	3,472	844	36
Red pine	11,317	891	3,951	461	226	28	82	25	0	212	0	0	3,887	1,554	0
Jack pine	20,183	14,776	229	0	137	26	221	0	16	180	15	0	4,377	187	19
White spruce	9,343	62	15	138	1,288	835	185	73	0	6	78	0	5,620	894	149
Black spruce	20,887	1,599	0	0	2,713	20	10,815	463	401	0	18	0	4,573	210	75
Balsam fir	28,469	163	174	96	7,074	144	408	193	35	9	861	55	14,040	3,512	1,705
Tamarack	4,332	0	0	0	282	10	642	126	2,663	9	7	0	281	0	312
Northern white-cedar	14,964	0	0	0	1,647	107	395	6,834	159	0	1,968	0	2,281	1,011	562
Other softwoods	23	0	0	0	0	0	23	0	0	0	0	0	0	0	0
Total	116,496	17,539	5,328	1,482	13,794	1,246	12,809	7,814	3,274	544	3,010	55	38,531	8,212	2,858
HARDWOODS:															
White oak	3,944	8	0	0	0	3	0	0	0	1,258	91	39	2,249	246	50
Select red oak	7,415	43	0	0	0	0	0	0	0	2,516	0	6	4,146	636	68
Other red oak	78	0	0	0	0	0	0	0	0	0	0	0	78	0	0
Hickory	16	0	0	0	0	0	0	0	0	0	0	0	0	16	0
Yellow birch	206	0	0	0	0	0	0	24	0	0	72	0	20	66	24
Hard maple	1,783	0	0	0	29	0	0	0	0	19	0	107	1,228	339	61
Soft maple	1,838	0	0	0	206	0	0	0	0	71	160	14	1,163	219	5
Ash	14,003	0	0	0	255	0	8	272	5	89	4,557	170	6,477	1,149	1,021
Balsam poplar	17,607	40	0	0	775	12	12	36	14	6	154	6	10,000	459	6,093
Paper birch	41,822	723	119	70	2,052	213	244	483	40	389	497	65	19,736	16,355	836
Bigtooth aspen	5,921	103	81	0	0	0	6	0	0	104	57	0	5,362	188	20
Quaking aspen	117,574	1,682	211	0	1,135	90	142	71	6	609	337	19	106,605	5,074	1,593
Basswood	3,657	4	0	0	24	0	0	0	0	222	204	28	2,469	591	115
Elm	4,922	9	0	0	11	0	11	13	0	64	1,240	60	2,584	459	471
Select hardwood	40	0	0	0	0	0	0	0	0	12	0	0	28	0	0
Other hardwoods	35	16	0	0	0	0	0	0	0	5	0	0	14	0	0
Total	220,861	2,628	411	70	4,487	318	423	899	65	5,364	7,369	514	162,159	25,797	10,357
All species	337,357	20,167	5,739	1,552	18,281	1,564	13,232	8,713	3,339	5,908	10,379	569	200,690	34,009	13,215

Table 12.--Average annual predicted yields of growing-stock from selected cutting prescriptions by species group and forest type, Aspen-Birch Unit, Minnesota, 1977-1986

(In thousand cubic feet)

Species group	Total	Jack pine	Red pine	White pine	Balsam fir	White spruce	Black spruce	Northern white-cedar	Tamarack	Oak-hickory	Elm-ash-cottonwood	Maple-basswood	Aspen	Paper birch	Balsam poplar
LONG ROTATION AGE OPTION															
SOFTWOODS:															
White pine	3,690	31	411	269	427	0	119	39	0	0	0	0	2,290	104	0
Red pine	4,383	15	2,246	0	208	0	63	25	0	0	0	0	1,074	752	0
Jack pine	4,671	2,316	10	0	137	0	143	0	0	0	0	0	2,036	29	0
White spruce	6,875	22	15	111	1,243	518	107	14	0	0	64	0	3,972	737	72
Black spruce	13,049	1,218	71	0	1,815	0	5,602	86	68	0	0	0	3,980	134	75
Balsam fir	14,876	29	48	75	5,023	54	143	62	31	2	323	23	6,526	1,785	752
Tamarack	1,562	0	0	0	282	0	274	23	939	0	0	0	12	0	32
Northern white-cedar	5,760	0	18	0	584	83	212	2,031	71	0	352	0	1,775	476	158
Other softwoods	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	54,866	3,631	2,819	455	9,719	655	6,663	2,280	1,109	2	739	23	21,665	4,017	1,089
HARDWOODS:															
White oak	101	0	0	0	0	0	0	0	0	8	30	0	51	12	0
Select red oak	123	0	0	0	0	0	0	0	0	55	0	0	23	0	45
Other red oak	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hickory	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Yellow birch	102	0	0	0	0	0	0	24	0	0	8	0	10	37	23
Hard maple	343	0	0	0	29	0	0	0	0	0	0	37	72	179	26
Soft maple	579	0	0	2	191	0	0	0	0	0	22	0	250	114	0
Ash	7,120	0	0	0	112	0	17	188	5	5	1,451	22	4,301	478	541
Balsam poplar	10,133	0	0	0	699	0	12	11	0	6	54	0	6,402	252	2,697
Paper birch	19,887	515	0	36	1,168	175	101	160	10	0	153	24	8,933	8,258	354
Bigtooth aspen	542	0	0	0	0	0	6	0	0	0	0	0	516	14	6
Quaking aspen	52,775	859	145	0	858	40	76	0	0	8	110	19	46,844	3,184	632
Basswood	272	0	0	0	8	0	0	0	0	0	49	0	103	71	41
Elm	1,631	0	0	0	0	0	0	7	0	2	409	19	927	69	198
Select hardwoods	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Other hardwoods	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	93,608	1,374	145	38	3,065	215	212	390	15	84	2,286	121	68,432	12,668	4,563
All species	148,474	5,005	2,964	493	12,784	870	6,875	2,670	1,124	86	3,025	144	90,097	16,685	5,652
SHORT ROTATION AGE OPTION															
SOFTWOODS:															
White pine	4,595	31	627	379	427	13	38	99	0	0	63	0	2,511	396	11
Red pine	4,444	175	1,900	0	208	0	82	25	0	0	0	0	1,302	752	0
Jack pine	7,205	4,387	229	0	137	0	189	0	0	0	15	0	2,219	29	0
White spruce	7,713	22	15	138	1,244	732	185	63	0	0	78	0	4,416	748	72
Black spruce	16,665	1,534	0	0	1,818	9	8,174	406	139	0	7	0	4,326	177	75
Balsam fir	19,335	29	24	96	6,305	81	344	157	35	0	353	23	8,820	2,297	771
Tamarack	1,748	0	0	0	282	0	449	39	934	0	0	0	12	0	32
Northern white-cedar	9,437	0	0	0	1,153	83	205	4,512	76	0	569	0	2,066	488	285
Other softwoods	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	71,142	6,178	2,795	613	11,574	918	9,666	5,301	1,184	0	1,085	23	25,672	4,887	1,246
HARDWOODS:															
White oak	98	0	0	0	0	0	0	0	0	0	0	0	63	35	0
Select red oak	270	0	0	0	0	0	0	0	0	185	0	0	23	16	46
Other red oak	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hickory	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Yellow birch	168	0	0	0	0	0	0	24	0	0	72	0	10	38	24
Hard maple	461	0	0	0	29	0	0	0	0	0	0	37	189	179	27
Soft maple	773	0	0	0	191	0	0	0	0	0	34	0	417	126	5
Ash	8,799	0	0	0	112	0	0	203	5	0	2,662	22	4,705	528	562
Balsam poplar	11,269	0	0	0	699	0	12	32	0	0	121	0	7,138	270	2,997
Paper birch	25,711	478	0	46	1,917	182	199	376	28	0	251	24	11,246	10,559	405
Bigtooth aspen	995	0	0	0	0	0	6	0	0	0	0	0	969	14	6
Quaking aspen	66,790	1,358	180	0	1,015	66	142	53	0	28	208	19	58,950	4,125	646
Basswood	427	0	0	0	8	0	0	0	0	0	28	0	250	100	41
Elm	1,827	0	0	0	0	0	0	7	0	0	502	19	1,032	69	198
Select hardwoods	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Other hardwoods	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	117,588	1,836	180	46	3,971	248	359	695	33	213	3,878	121	84,992	16,059	4,957
All species	188,730	8,014	2,975	659	15,545	1,166	10,025	5,996	1,217	213	4,963	144	110,664	20,946	6,203

Table 13.--Average annual predicted yields of growing-stock from selected cutting prescriptions by species group and forest type, Northern Pine Unit, Minnesota, 1977-1986

(In thousand cubic feet)

LONG ROTATION AGE OPTION

Species group	Total	Jack pine	Red pine	White pine	White spruce	Black spruce	Balsam fir	Tamarack	Northern white-cedar	Oak-hickory	Elm-ash-cottonwood	Maple-basswood	Aspen	Paper birch	Balsam poplar
SOFTWOODS:															
White pine	1,754	17	205	403	63	0	0	0	1	21	0	0	700	327	17
Red pine	5,021	548	1,308	140	28	0	18	0	0	143	0	0	2,180	656	0
Jack pine	9,412	7,845	0	0	2	0	0	16	0	0	0	0	1,371	159	19
White spruce	1,224	15	0	0	80	0	44	0	9	6	0	0	797	147	126
Black spruce	2,875	11	0	0	1	1,584	791	238	49	0	11	0	149	33	8
Balsam fir	6,588	90	152	36	48	60	692	0	6	9	161	32	3,512	1,214	576
Tamarack	2,216	0	0	0	1	76	0	1,633	60	0	7	0	159	0	280
Northern white-cedar	4,027	0	0	0	24	77	488	14	1,337	0	1,075	0	215	523	274
Other softwoods	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	33,117	8,526	1,665	579	247	1,797	2,033	1,901	1,462	179	1,254	32	9,083	3,059	1,300
HARDWOODS:															
White oak	2,515	5	0	0	3	0	0	0	0	553	0	39	1,730	145	40
Select red oak	4,563	26	0	0	0	0	0	0	0	1,197	0	6	2,891	432	11
Other red oak	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hickory	16	0	0	0	0	0	0	0	0	0	0	0	0	16	0
Yellow birch	38	0	0	0	0	0	0	0	0	0	0	0	10	28	0
Hard maple	984	0	0	0	0	0	0	0	0	20	0	70	738	131	25
Soft maple	758	0	0	0	0	0	15	0	0	46	126	14	487	70	0
Ash	4,240	0	0	0	0	8	126	0	17	50	1,490	148	1,249	621	531
Balsam poplar	5,360	34	0	0	1	0	72	14	0	0	33	6	2,143	169	2,888
Paper birch	12,183	153	73	65	31	43	135	6	9	143	215	41	5,971	4,866	432
Bigtooth aspen	3,567	69	44	0	0	0	0	0	0	64	57	0	3,215	104	14
Quaking aspen	33,478	230	37	0	24	0	120	6	0	257	9	0	31,353	650	792
Basswood	2,156	4	0	0	0	0	0	0	0	133	72	28	1,523	343	53
Elm	2,396	9	0	0	0	11	11	0	0	42	453	41	1,228	379	222
Select hardwoods	28	0	0	0	0	0	0	0	0	0	0	0	28	0	0
Other hardwoods	21	16	0	0	0	0	0	0	0	5	0	0	0	0	0
Total	72,303	546	154	65	59	62	479	26	26	2,510	2,455	393	52,566	7,954	5,008
All species	105,420	9,072	1,819	644	306	1,859	2,512	1,927	1,488	2,689	3,709	425	61,649	11,013	6,308
SHORT ROTATION AGE OPTION															
SOFTWOODS:															
White pine	2,383	17	332	408	63	0	0	0	1	128	0	0	961	448	25
Red pine	6,873	716	2,051	461	28	0	18	0	0	212	0	0	2,585	802	0
Jack pine	12,978	10,389	0	0	26	32	0	16	0	180	0	0	2,158	158	19
White spruce	1,630	40	0	0	103	0	44	0	10	6	0	0	1,204	146	77
Black spruce	4,222	65	0	0	11	2,641	895	262	57	0	11	0	247	33	0
Balsam fir	9,134	134	150	0	63	64	769	0	36	9	508	32	5,220	1,215	934
Tamarack	2,584	0	0	0	10	193	0	1,729	87	9	7	0	269	0	280
Northern white-cedar	5,527	0	0	0	24	190	494	83	2,322	0	1,399	0	215	523	277
Other softwoods	23	0	0	0	0	23	0	0	0	0	0	0	0	0	0
Total	45,354	11,361	2,533	869	328	3,143	2,220	2,090	2,513	544	1,925	32	12,859	3,325	1,612
HARDWOODS:															
White oak	3,846	8	0	0	3	0	0	0	0	1,258	91	39	2,186	211	50
Select red oak	7,145	43	0	0	0	0	0	0	0	2,331	0	6	4,123	620	22
Other red oak	78	0	0	0	0	0	0	0	0	0	0	0	78	0	0
Hickory	16	0	0	0	0	0	0	0	0	0	0	0	0	16	0
Yellow birch	38	0	0	0	0	0	0	0	0	0	0	0	10	28	0
Hard maple	1,322	0	0	0	0	0	0	0	0	19	0	70	1,039	160	34
Soft maple	1,065	0	0	0	0	0	15	0	0	71	126	14	746	93	0
Ash	5,204	0	0	0	0	8	143	0	69	89	1,895	148	1,772	621	459
Balsam poplar	6,338	40	0	0	12	0	76	14	4	6	33	6	2,862	189	3,096
Paper birch	16,111	245	119	24	31	45	135	12	107	389	246	41	8,490	5,796	431
Bigtooth aspen	4,926	103	81	0	0	0	0	0	0	104	57	0	4,393	174	14
Quaking aspen	50,784	324	31	0	24	0	120	6	18	581	129	0	47,655	949	947
Basswood	3,230	4	0	0	0	0	16	0	0	222	176	28	2,219	491	74
Elm	3,095	9	0	0	0	11	11	0	6	64	738	41	1,552	390	273
Select hardwoods	40	0	0	0	0	0	0	0	0	12	0	0	28	0	0
Other hardwoods	35	16	0	0	0	0	0	0	0	5	0	0	14	0	0
Total	103,273	792	231	24	70	64	516	32	204	5,151	3,491	393	77,167	9,738	5,400
All species	148,627	12,153	2,764	893	398	3,207	2,736	2,122	2,717	5,695	5,416	425	90,026	13,063	7,012

Table 14.--Growing-stock removals for 1976[1] and average annual predicted yields from selected cutting prescriptions for 1977-1986 by species, northern Minnesota

(In thousand cubic feet)

Species group	1976 Growing-stock removals	Predicted yields from selected cutting prescriptions: Long rotation age option	Predicted yields from selected cutting prescriptions: Short rotation age option
SOFTWOODS:			
White pine	2,724	5,444	6,978
Red pine	4,025	9,404	11,317
Jack pine	20,977	14,083	20,183
White spruce	4,153	8,099	9,343
Black spruce	13,733	15,924	20,887
Balsam fir	13,768	21,464	28,469
Tamarack	4,629	3,778	4,332
Northern white-cedar	3,296	9,787	14,964
Other softwoods	0	0	23
Total	67,305	87,983	116,496
HARDWOODS:			
White oak	605	2,616	3,944
Select red oak	2,101	4,686	7,415
Other red oak	0	0	78
Hickory	5	16	16
Yellow birch	11	140	206
Hard maple	347	1,327	1,783
Soft maple	346	1,337	1,838
Ash	1,539	11,360	14,003
Balsam poplar	2,499	15,493	17,607
Paper birch	7,793	32,070	41,822
Bigtooth aspen	2,867	4,109	5,921
Quaking aspen	63,126	86,253	117,574
Basswood	853	2,428	3,657
Elm	1,257	4,027	4,922
Select hardwoods	0	28	40
Other hardwoods	22	21	35
Noncommercial species	0	0	0
Total	83,371	165,911	220,861
All species	150,676	253,894	337,357

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[1] 1976 Growing-stock removals are trend removals for the period 1962 to 1976.

Table 15.--Growing-stock removals for 1976[1] and average annual predicted yields from selected cutting prescriptions for 1977-1986 by species, Aspen-Birch Unit, Minnesota

(In thousand cubic feet)

Species group	1976 Growing-stock removals	Predicted yields from selected cutting prescriptions	
		Long rotation age option	Short rotation age option
SOFTWOODS:			
White pine	1,711	3,690	4,595
Red pine	1,485	4,383	4,444
Jack pine	10,718	4,671	7,205
White spruce	2,888	6,875	7,713
Black spruce	10,275	13,049	16,665
Balsam fir	7,728	14,876	19,335
Tamarack	2,503	1,562	1,748
Northern white-cedar	1,495	5,760	9,437
Other softwoods	0	0	0
Total	38,803	54,866	71,142
HARDWOODS:			
White oak	10	101	98
Select red oak	113	123	270
Other red oak	0	0	0
Hickory	0	0	0
Yellow birch	3	102	168
Hard maple	28	343	461
Soft maple	77	579	773
Ash	302	7,120	8,799
Balsam poplar	1,044	10,133	11,269
Paper birch	3,253	19,887	25,711
Bigtooth aspen	665	542	995
Quaking aspen	32,686	52,775	66,790
Basswood	48	272	427
Elm	207	1,631	1,827
Select hardwoods	0	0	0
Other hardwoods	9	0	0
Noncommercial species	0	0	0
Total	38,445	93,608	117,588
All species	77,248	148,474	188,730

[1] 1976 Growing-stock removals are trend removals for the period 1962 to 1976.

Table 16.--Growing-stock removals for 1976[1] and average annual predicted yields for selected cutting prescriptions for 1977-1986 by species, Northern Pine Unit, Minnesota

(In thousand cubic feet)

Species group	1976 Growing-stock removals	Predicted yields from selected cutting prescriptions: Long rotation age option	Predicted yields from selected cutting prescriptions: Short rotation age option
SOFTWOODS:			
White pine	1,013	1,754	2,383
Red pine	2,540	5,021	6,873
Jack pine	10,259	9,412	12,978
White spruce	1,265	1,224	1,630
Black spruce	3,458	2,875	4,222
Balsam fir	6,040	6,588	9,134
Tamarack	2,126	2,216	2,584
Northern white-cedar	1,801	4,027	5,527
Other softwoods	0	0	23
Total	28,502	33,117	45,354
HARDWOODS:			
White oak	595	2,515	3,846
Select red oak	1,988	4,563	7,145
Other red oak	0	0	78
Hickory	5	16	16
Yellow birch	8	38	38
Hard maple	319	984	1,322
Soft maple	269	758	1,065
Ash	1,237	4,240	5,204
Balsam poplar	1,455	5,360	6,338
Paper birch	4,540	12,183	16,111
Bigtooth aspen	2,202	3,567	4,926
Quaking aspen	30,440	33,478	50,784
Basswood	805	2,156	3,230
Elm	1,050	2,396	3,095
Select hardwoods	0	28	40
Other hardwoods	13	21	35
Noncommercial species	0	0	0
Total	44,926	72,303	103,273
All species	73,428	105,420	148,627

[1] 1976 Growing-stock removals are trend removals for the period 1962 to 1976.

Table 17.--Average annual managed harvest growing-stock volume from harvested plots by forest type, site index class and stand-age class, northern Minnesota, 1977-1986

(In thousand cubic feet)

Forest type	Site index class	Total	Stand-age class (years) less than 41	41-50	51-60	61-70	71-80	81-90	91-100	101-120	121-140	more than 140
HIGH ROTATION AGE OPTION												
Jack pine	0-60	8,932	0	0	988	2,745	941	1,961	2,120	177	0	0
	61+	5,145	0	0	3,402	1,743	0	0	0	0	0	0
Red pine	0-55	1,622	0	0	0	0	0	893	442	287	0	0
	56+	3,161	0	0	1,050	374	0	326	1,411	0	0	0
White pine	0-55	742	0	0	0	0	0	0	357	385	0	0
	56+	395	0	0	0	0	0	0	395	0	0	0
White spruce	All	1,176	0	0	0	327	120	294	327	108	0	0
Black spruce	0-40	4,780	0	0	0	0	0	779	2,182	783	1,036	0
	41+	3,954	0	0	0	206	1,153	1,603	911	81	0	0
Balsam fir	All	15,296	0	0	4,149	5,742	3,234	988	935	248	0	0
Tamarack	0-40	1,128	0	0	0	0	0	0	0	220	861	47
	41+	1,923	0	0	0	224	165	0	104	970	460	0
Northern white-cedar	All	4,158	0	0	0	0	0	0	0	0	3,901	257
Oak	0-55	1,213	0	23	0	0	0	84	790	316	0	0
	56+	1,562	0	0	63	594	431	156	0	318	0	0
Elm-ash-cottonwood	0-55	5,030	0	0	0	0	0	0	1,593	2,133	1,304	0
	56+	1,704	0	0	0	0	0	331	236	526	611	0
Maple-basswood	All	569	0	0	0	0	0	0	221	77	271	0
Aspen	0-65	76,758	0	0	31,256	29,397	11,369	3,797	647	154	138	0
	66+	74,988	0	0	42,097	20,025	6,431	4,699	1,541	195	0	0
Paper birch	0-65	22,154	0	0	0	7,555	7,899	5,338	655	707	0	0
	66+	5,544	0	0	253	2,546	1,796	268	681	0	0	0
Balsam poplar	0-65	7,056	0	117	2,265	2,365	1,669	469	171	0	0	0
	66+	4,904	0	0	1,394	2,110	851	549	0	0	0	0
All types		253,894	0	140	86,917	75,953	36,059	22,535	15,719	7,685	8,582	304
LOW ROTATION AGE OPTION												
Jack pine	All	20,167	0	0	7,062	7,906	941	1,961	2,120	177	0	0
Red pine	All	5,739	0	0	0	0	0	2,654	2,798	287	0	0
White pine	All	1,552	0	0	0	0	0	0	544	1,008	0	0
White spruce	All	1,564	0	0	296	419	120	294	327	108	0	0
Black spruce	All	13,232	0	0	0	490	1,158	4,487	5,196	865	1,036	0
Balsam fir	All	18,281	0	0	6,910	5,966	3,234	988	935	248	0	0
Tamarack	All	3,339	0	0	0	0	0	34	66	1,710	1,482	47
Northern white-cedar	All	8,713	0	0	0	0	0	0	71	2,469	5,916	257
Oak	All	5,908	0	0	213	1,391	2,368	509	790	637	0	0
Elm-ash-cottonwood	All	10,379	0	0	0	0	0	2,039	3,753	2,661	1,926	0
Maple-basswood	All	569	0	0	0	0	0	0	221	77	271	0
Aspen	All	200,690	0	2,726	119,189	49,769	17,834	8,503	2,182	349	138	0
Paper birch	All	34,009	0	0	4,466	12,186	9,702	5,611	1,337	707	0	0
Balsam poplar	All	13,215	0	188	4,825	4,481	2,527	1,023	171	0	0	0
All types		337,357	0	2,914	142,961	82,608	37,884	28,103	20,511	11,303	10,769	304

Table 18.--Average annual managed harvest growing-stock volume from harvested plots by forest type, site index class, and stand-age class, Aspen-Birch Unit, Minnesota, 1977-1986

(In thousand cubic feet)

Forest type	Site index class	Total	Stand-age class (years)									
			less than 41	41-50	51-60	61-70	71-80	81-90	91-100	101-120	121-140	more than 140
HIGH ROTATION AGE OPTION												
Jack pine	0-60	4,438	0	0	0	168	145	1,961	1,987	177	0	0
	61+	567	0	0	409	158	0	0	0	0	0	0
Red pine	0-55	1,214	0	0	0	0	0	893	205	116	0	0
	56+	1,750	0	0	1,050	374	0	326	0	0	0	0
White pine	0-55	472	0	0	0	0	0	0	357	115	0	0
	56+	21	0	0	0	0	0	0	21	0	0	0
White spruce	All	870	0	0	0	174	120	141	327	108	0	0
Black spruce	0-40	3,509	0	0	0	0	0	0	1,921	690	898	0
	41+	3,366	0	0	0	0	1,105	1,350	911	0	0	0
Balsam fir	All	12,784	0	0	4,149	4,918	1,805	800	935	177	0	0
Tamarack	0-40	488	0	0	0	0	0	0	0	220	221	47
	41+	636	0	0	0	224	165	0	0	128	119	0
Northern white-cedar	All	2,670	0	0	0	0	0	0	0	0	2,670	0
Oak	0-55	23	0	23	0	0	0	0	0	0	0	0
	56+	63	0	0	63	0	0	0	0	0	0	0
Elm-ash-cottonwood	0-55	2,288	0	0	0	0	0	0	623	919	746	0
	56+	737	0	0	0	0	0	331	0	0	406	0
Maple-basswood	All	144	0	0	0	0	0	0	0	73	71	0
Aspen	0-65	53,220	0	0	22,096	19,840	7,800	2,952	442	90	0	0
	66+	36,877	0	0	19,379	9,947	3,979	2,865	707	0	0	0
Paper birch	0-65	13,707	0	0	0	3,331	5,950	3,907	348	171	0	0
	66+	2,978	0	0	253	779	1,594	0	352	0	0	0
Balsam poplar	0-65	3,088	0	0	585	1,081	782	469	171	0	0	0
	66+	2,564	0	0	555	1,037	741	231	0	0	0	0
All types		148,474	0	23	48,539	42,031	24,186	16,226	9,307	2,984	5,131	47
LOW ROTATION AGE OPTION												
Jack pine	All	8,014	0	0	0	3,744	145	1,961	1,987	177	0	0
Red pine	All	2,975	0	0	0	0	0	2,654	205	116	0	0
White pine	All	659	0	0	0	0	0	0	544	115	0	0
White spruce	All	1,166	0	0	296	174	120	141	327	108	0	0
Black spruce	All	10,025	0	0	0	0	625	2,877	4,935	690	898	0
Balsam fir	All	15,545	0	0	6,910	4,918	1,805	800	935	177	0	0
Tamarack	All	1,217	0	0	0	0	0	34	66	731	339	47
Northern white-cedar	All	5,996	0	0	0	0	0	0	71	2,212	3,713	0
Oak	All	213	0	0	213	0	0	0	0	0	0	0
Elm-ash-cottonwood	All	4,963	0	0	0	0	0	1,071	1,812	919	1,161	0
Maple-basswood	All	144	0	0	0	0	0	0	0	73	71	0
Aspen	All	110,664	0	0	61,701	30,134	11,779	5,817	1,143	90	0	0
Paper birch	All	20,946	0	0	2,953	5,666	7,549	3,907	700	171	0	0
Balsam poplar	All	6,203	0	0	1,674	2,124	1,529	705	171	0	0	0
All types		188,730	0	0	73,747	46,760	23,552	19,967	12,896	5,579	6,182	47

Table 19.--Average annual managed harvest growing-stock volume from harvested plots by forest type, site index class, and stand-age class, Northern Pine Unit, Minnesota, 1977-1986

(In thousand cubic feet)

Forest type	Site index class	Total	Stand-age class (years)									
			less than 41	41-50	51-60	61-70	71-80	81-90	91-100	101-120	121-140	more than 140
HIGH ROTATION AGE OPTION												
Jack pine	0-60	4,494	0	0	988	2,577	796	0	133	0	0	0
	61+	4,578	0	0	2,993	1,585	0	0	0	0	0	0
Red pine	0-55	408	0	0	0	0	0	0	237	171	0	0
	56+	1,411	0	0	0	0	0	0	1,411	0	0	0
White pine	0-55	270	0	0	0	0	0	0	0	270	0	0
	56+	374	0	0	0	0	0	0	374	0	0	0
White spruce	All	306	0	0	0	153	0	153	0	0	0	0
Black spruce	0-40	1,271	0	0	0	0	0	779	261	93	138	0
	41+	588	0	0	0	206	48	253	0	81	0	0
Balsam fir	All	2,512	0	0	0	824	1,429	188	0	71	0	0
Tamarack	0-40	640	0	0	0	0	0	0	0	0	640	0
	41+	1,287	0	0	0	0	0	0	104	842	341	0
Northern white-cedar	All	1,488	0	0	0	0	0	0	0	0	1,231	257
Oak	0-55	1,190	0	0	0	0	0	84	790	316	0	0
	56+	1,499	0	0	0	594	431	156	0	318	0	0
Elm-ash-cottonwood	0-55	2,742	0	0	0	0	0	0	970	1,214	558	0
	56+	967	0	0	0	0	0	0	236	526	205	0
Maple-basswood	ALL	425	0	0	0	0	0	0	221	4	200	0
Aspen	0-65	23,538	0	0	9,160	9,557	3,569	845	205	64	138	0
	66+	38,111	0	0	22,718	10,078	2,452	1,834	834	195	0	0
Paper birch	0-65	8,447	0	0	0	4,224	1,949	1,431	307	536	0	0
	66+	2,566	0	0	0	1,767	202	268	329	0	0	0
Balsam poplar	0-65	3,968	0	117	1,680	1,284	887	0	0	0	0	0
	66+	2,340	0	0	839	1,073	110	318	0	0	0	0
All types		105,420	0	117	38,378	33,922	11,873	6,309	6,412	4,701	3,451	257
LOW ROTATION AGE OPTION												
Jack pine	All	12,153	0	0	7,062	4,162	796	0	133	0	0	0
Red pine	All	2,764	0	0	0	0	0	0	2,593	171	0	0
White pine	All	893	0	0	0	0	0	0	0	893	0	0
White spruce	All	398	0	0	0	245	0	153	0	0	0	0
Black spruce	All	3,207	0	0	0	490	533	1,610	261	175	138	0
Balsam fir	All	2,736	0	0	0	1,048	1,429	188	0	71	0	0
Tamarack	All	2,122	0	0	0	0	0	0	0	979	1,143	0
Northern white-cedar	All	2,717	0	0	0	0	0	0	0	257	2,203	257
Oak	All	5,695	0	0	0	1,391	2,368	509	790	637	0	0
Elm-ash-cottonwood	All	5,416	0	0	0	0	0	968	1,941	1,742	765	0
Maple-basswood	All	425	0	0	0	0	0	0	221	4	200	0
Aspen	All	90,026	0	2,726	57,488	19,635	6,055	2,686	1,039	259	138	0
Paper birch	All	13,063	0	0	1,513	6,520	2,153	1,704	637	536	0	0
Balsam poplar	All	7,012	0	188	3,151	2,357	998	318	0	0	0	0
All types		148,627	0	2,914	69,214	35,848	14,332	8,136	7,615	5,724	4,587	257

APPENDIX

Specifying Cutting Prescriptions

The level of yield from cutting prescriptions varies according to the criteria specified. Two prescriptions are considered here.[3] The long rotation age option uses harvest criteria established jointly by representatives from Minnesota forest industries and the Minnesota Department of Natural Resources (table 1). Harvest criteria for this option are based on forest type, age, and site index.

The short rotation age option is based on current stand conditions, and sets the rotation age for a species at the age of maximum total volume yield. Forest type and age are the stand characteristics considered in this option. Age of maximum total volume yield is calculated for each forest type by (1) determining the number of rotation acres in each age class per year—this is equal to the area in the forest type divided by the midpoint of the age class; (2) calculating the growing-stock volume per acre of commercial forest land for each age class—this is equal to the growing-stock volume in the age class divided by the commercial forest area in the age class; (3) determining the yield of an age class—this is equal to the rotation acres in the age class multiplied by the growing-stock volume per acre of commercial forest in the age class. The rotation age is selected from the age class where total volume yield is highest.

Definition of Terms

Land-use classes

Forest land.—Land at least 16.7 percent stocked by forest trees of any size, or formerly having such tree cover, and not currently developed for nonforest use. Includes afforested areas. The minimum forest area classified was 1 acre. Roadside, streamside, and shelterbelt strips of timber must have a crown width of at least 120 feet to qualify as forest land. Unimproved roads and trails, streams, and clearings in forest areas were classed as forest if less than 120 feet wide.

Commercial forest land.—Forest land that is producing or is capable of producing crops of industrial wood and that is not withdrawn from timber utilization by statute or adiministrative regulation. This includes areas suitable for management to grow crops of industrial wood generally of a site quality capable of producing in excess of 20 cubic feet per acre of annual growth. This includes both inaccessible and inoperable areas.

Tree class

Growing-stock trees.—All live trees of commercial species except rough and rotten trees.

Sawtimber trees.—Growing-stock trees of commercial species containing at least a 12-foot saw log or two noncontiguous saw logs, each 8 feet or longer. At least 33 percent of the gross volume of the tree must be sound wood. Softwoods must be at least 9.0 inches d.b.h. and hardwoods at least 11.0 inches.

Poletimber trees.—Growing-stock trees of commercial species at least 5.0 inches d.b.h. but smaller than sawtimber size, and of good form and vigor.

Rotten trees.—Live trees (any size) of commercial species that do not contain a merchantable 12-foot saw log or two noncontiguous 8-foot or longer saw logs, now or prospectively, because of rot (that is, when more than 50 percent of the cull volume of the tree is rotten).

Rough trees.—Live trees that do not contain at least one merchantable 12-foot saw log or two noncontiguous 8-foot or longer saw logs, now or prospectively, because of roughness and poor form, as well as all live noncommercial species.

Short-log (rough trees).—Sawtimber sized trees of commercial species that contain at least one merchantable 8- to 11-foot saw log but not a 12-foot saw log.

Other classifications

Site index.—An expression of forest site quality based on the height of a free-growing dominant or codominant tree of a representative species in the forest type at age 50.

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[3] *The Minnesota Department of Natural Resources has made an estimate of yield under a third set of cutting prescriptions.*

Stand-age.—Age of the main stand. Main stand refers to trees of the dominant forest type and stand-size class.

Forest types

A classification of forest land based upon the species forming a plurality of live-tree stocking. Major forest types in Minnesota are:

Jack pine.—Forests in which jack pine comprises a plurality of the stocking. (Common associates include eastern white pine, red pine, aspen, birch, and maple.)

Red pine.—Forests in which red pine comprises a plurality of the stocking. (Common associates include eastern white pine, jack pine, aspen, birch, and maple.)

White pine.—Forests in which eastern white pine comprises a plurality of the stocking. (Common associates include red pine, jack pine, aspen, birch, and maple.)

White spruce.—Forests in which white spruce and balsam fir comprise a plurality of the stocking, with white spruce more common. (Common associates include aspen, maple, birch, northern white-cedar, tamarack.)

Black spruce.—Forests in which swamp conifers comprise a plurality of the stocking with black spruce most common. (Common associates include tamarack and northern white-cedar.)

Balsam fir.—Forests in which balsam fir and white spruce comprise a plurality of stocking, with balsam fir more common. (Common associates include aspen, maple, birch, northern white-cedar, and tamarack.)

Tamarack.—Forests in which swamp conifers comprise a plurality of the stocking, with tamarack most common. (Common associates include black spruce and northern white-cedar.)

Northern white-cedar.—Forests in which swamp conifers comprise a plurality of the stocking, with northern white-cedar most common. (Common associates include tamarack and black spruce.)

Oak.—Forests in which northern red oak, white oak, or bur oak, singly or in combination, comprise a plurality of the stocking. (Common associates include elm, maple, and aspen.)

Elm-ash-cottonwood.—Forests in which elm, ash, cottonwood and red maple, singly or in combination, comprise a plurality of the stocking. (Common associates include basswood and balsam poplar.)

Maple-basswood.—Forests in which sugar maple, basswood, yellow birch, American elm, and red maple, singly or in combination, comprise a plurality of the stocking. (Common associates include white pine and elm.)

Aspen.—Forests in which quaking aspen or bigtooth aspen, singly or in combination, comprise a plurality of the stocking. (Common associates include balsam poplar, balsam fir, and paper birch.)

Paper birch.—Forests in which paper birch comprises a plurality of the stocking. (Common associates include maple, aspen, and balsam fir.)

Balsam poplar.—Forests in which balsam poplar comprises a plurality of the stocking. (Common associates include aspen, elm, and ash.)

Timber removals

Timber removals from growing stock.—The volume of sound wood in growing-stock trees removed annually for forest products (including roundwood products and logging residues) and for other removals. Roundwood products are logs, bolts, or other round sections cut and used from trees. Logging residues are the unused portions of cut trees plus unused trees killed by logging. Other removals are growing-stock trees removed but not utilized for products, or trees left standing but "removed" from the commercial forest land classification by land use change—examples are removals from cultural operations such as timber stand improvement work, land clearing, and changes in land use.

Metric Equivalents of Units Used in this Report

1 acre = 4,046.86 square meters or 0.405 hectare.

1,000 acres = 405 hectares.

1,000 board feet (International ¼-inch rule) = 3.48 cubic meters.

1 cubic foot = 0.0283 cubic meter.

Principal Tree Species Groups in Northern Minnesota[4]

Eastern white pine	*Pinus strobus*
Red pine	*Pinus resinosa*
Jack pine	*Pinus banksiana*
White spruce	*Picea glauca*
Black spruce	*Picea mariana*
Balsam fir	*Abies balsamea*
Tamarack	*Larix laricina*
Northern white-cedar	*Thuja occidentalis*
Other softwoods:	
Eastern redcedar	*Juniperus virginiana*
Scotch pine	*Pinus sylvestris*
White oaks:	
White oak	*Quercus alba*
Bur oak	*Quercus macrocarpa*
Select red oak:	
Northern red oak	*Quercus rubra*
Other red oaks:	
Northern pin oak	*Quercus ellipsoidalis*
Hickories:	
Butternut hickory	*Carya cordiformis*
Yellow birch	*Betula alleghaniensis*
Hard maples:	
Sugar maple	*Acer saccharum*
Soft maples:	
Red maple	*Acer rubrum*
Silver maple	*Acer saccharinum*
Ashes:	
White ash	*Fraxinus americana*
Black ash	*Fraxinus nigra*
Green ash	*Fraxinus pennsylvanica*
Balsam poplar	*Populus balsamifera*
Paper birch	*Betula papyrifera*
Aspens:	
Bigtooth aspen	*Populus grandidentata*
Quaking aspen	*Populus tremuloides*
Basswood	*Tilia americana*
Elms:	
Amercian elm	*Ulmus americana*
Slippery elm	*Ulmus rubra*
Rock elm	*Ulmus thomasii*
Select hardwoods:	
Butternut	*Juglans cinerea*
Black cherry	*Prunus serotina*
Other hardwoods:	
Boxelder	*Acer negundo*
Eastern cottonwood	*Populus deltoides*
Black willow	*Salix nigra*

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[4] *The common and scientific names are based on: Little, Elbert L., Jr. 1979. Check List of United States Trees (Native and Naturalized). U.S. Department of Agriculture, Agricultural Handbook 541, 375 p.*

☆ U.S. GOVERNMENT PRINTING OFFICE: 1980-669-277/62 REG.#6

Jakes, Pamela J., and W. Brad Smith.

1980. Predicted yields from selected cutting prescriptions in northern Minnesota. U.S. Department of Agriculture Forest Service, Research Paper NC-188, 29 p. U.S. Department of Agriculture Forest Service, North Central Forest Experiment Station, St. Paul, Minnesota.

Includes predicted yields based on two sets of cutting prescriptions in northern Minnesota. Indicates that given a specific set of assumptions, average annual growing-stock removals for the decade 1977-1986 would be from 69 percent to 124 percent higher than 1976 growing-stock removals.

KEY WORDS: Minnesota, timber removals, timber harvest.

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KEY WORDS: Minnesota, timber removals, timber harvest.

More bicycles and shoe leather...less smog.

DA FOREST SERVICE
SEARCH PAPER **NC-189**

Comparing Jack Pine Slash and Forest Floor Moisture Contents and National Fire Danger Rating System Predictions

Robert M. Loomis and William A. Main

rth Central Forest Experiment Station
est Service, U.S. Department of Agriculture

Loomis, Robert M., and William A. Main.

1980. Comparing jack pine slash and forest floor moisture contents and National Fire Danger Rating System predictions. U.S. Department of Agriculture Forest Service, Research Paper NC-189, 10 p. U.S. Department of Agriculture Forest Service, North Central Forest Experiment Station, St. Paul, Minnesota.

Relations between certain slash and forest floor moisture contents and the applicable estimated timelag fuel moistures of the National Fire Danger Rating System were investigated for 1-year-old jack pine fuel types in notheastern Minnesota and central Lower Michigan. Only approximate estimates of actual fuel moisture are possible for the relations determined, thus emphasizing the need for on-site measurements when fuel moisture may be critical.

KEY WORDS: Forest fuels, fire hazard.

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1980

COMPARING JACK PINE SLASH AND FOREST FLOOR MOISTURE CONTENTS AND NATIONAL FIRE DANGER RATING SYSTEM PREDICTIONS

Robert M. Loomis,
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and **William A. Main,**
Computer Programmer
East Lansing, Michigan

Thousands of acres of jack pine are clear-cut in the Lake States each year (fig. 1). Prescribed fire to reduce fuel amounts and prepare the site for planting or seeding frequently follows this cutting. The land manager must select the time when fuel and weather conditions will produce a fire that will accomplish the desired results and assist in planning burning operations (Deeming *et al.* 1977). The National Fire Danger Rating System (NFDRS) estimates and interprets fuel moisture, a critical variable in fire behavior. Information is limited as to the actual fuel moisture content of natural fuels in relation to NFDRS moisture content estimates. Our study reports the moisture content of specific fuels found on 1-year-old jack pine clear-cut areas in relation to NFDRS 1-hour, 10-hour, and 100-hour timelag fuel moisture content estimates.[1]

RESULTS

We found only a general relation (significant, but with much variation) between the moisture content of certain naturally occurring fuels on 1-year-old jack pine slash areas and NFDRS fuel moisture estimates. Statistically significant but low correlation exists between actual and NFDRS-estimated moisture content for Fines and 1-hour timelag fuels (fig. 2); between L-layer and 1-hour timelag fuels (fig. 3); and between F-layer and 100-hour timelag fuels (fig. 4).[2] The actual moisture content of Fines and of L-layer almost always exceeded the estimated 1-hour timelag fuel moisture. We examined each of these relations using the paired t-test. In all cases, the null hypothesis was rejected—the mean of the population differences was not zero.

THE STUDY

Two study areas were selected on the Superior National Forest in Minnesota. The previous summer, 55 cords per acre of jack pine pulpwood had been harvested by clear-cutting. The soils were well-drained loamy sands. We selected a third study area on State land near Roscommon, Michigan, where clear-cutting had removed about 15 cords per acre of jack pine pulpwood the winter preceding the summer study. This site had well-drained sandy soil.

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[1] *This study was designed by Rodney Sando (formerly with the North Central Forest Experiment Station) who was responsible for data collected in Minnesota.*

[2] *Fines consist of jack pine slash needles and twigs less than 1/4 inch in diameter aerially exposed at one foot or more above ground; L-layer consists of forest floor loose surface needles, leaves, grass, twigs, etc.; F-layer consists of the forest floor layer beneath the L-layer—the compacted decomposing organic materials still identifiable as to source.*

Figure 1.—*Thousands of acres of jack pine are clearcut in the Lake States each year.*

Actual fuel moistures were measured for Fines, for forest floor L-layer and for forest floor F-layer from fuel sample collections taken: June 9 through September 9, 1968, in Lake County, Minnesota; and June 13 through September 3, 1969, in St. Louis County, Minnesota; and June 12 through September 17, 1975, in Roscommon County, Michigan.

On-site weather instruments and records were maintained to provide data to compute NFDRS fuel moisture values. Samples were collected daily except on weekends or when fuels were wet from rainfall at collection time. We had no 10-hour timelag fuel moisture sticks so this value for the NFDRS was computed.

In Minnesota a steel sampling cutter was used to remove 2-inch diameter circular samples of forest floor materials, and in Michigan a 5-inch diameter sampling cylinder was used. Five samples of slash and 10 samples each of the forest floor layers were collected daily, 15 samples of the F-layer were collected beginning the second summer because of the variability found the first year. We determined moisture content by oven drying the samples at 105°C for about 24 hours. The observations and measurements were made during early or mid-afternoon to relate closely with time of basic fire weather observations.

Covariance analysis indicated 1968 and 1969 data should not be combined for regressions. Data for these two years (locations) came from apparently similar areas in Minnesota. Because of differences in moisture response—moisture estimate relations, a similar data set was obtained in Michigan in 1975 and each year (location) was considered separately.

DISCUSSION

The NFDRS fuel classes relate directly to dead, round wood. They relate only "roughly" to portions of the forest floor. The aerially exposed slash studied is a 1-hour timelag fuel while forest floor fuel components are not clearly defined in terms of timelag (Deeming *et al.* 1977). Sticks (½-inch pine dowels) are an excellent source of 10-hour timelag fuel moisture estimates and contributed to the 1-hour timelag fuel moisture estimate in the 1978 system. These fuel moisture sticks integrate effects of the meteorological environment including day length and cloudiness. Stick weight measurements were not available so 1-hour and 10-hour timelag fuel moistures were computed. Without stick moisture measurements, the system has an adjustment for 1-hour timelag moisture estimates based on state of weather. Temperature and relative humidity adjustments of shelter observations (4.5 feet above ground) are made to better estimate the temperature of fuels on the ground and the relative humidity at their level before computing an equilibrium moisture content.

Because 1-hour and 10-hour timelag fuel moistures are "multiples" of each other when stick moisture contents are not available, we considered only the 1-hour estimates related to the actual moisture content of Fines and the L-layer actual. However, the 10-hour timelag fuel moisture also could have been used. The L-layer probably has between a 1-hour and 10-hour timelag response. Fosberg (1971) reported the NFDRS 100-hour timelag fuel moisture estimates are inapplicable for duff and litter. This study found significant, but low correlation between the 100-hour estimates and the F-layer moisture contents. The F-layer response had slightly higher correlation with the 100-hour than with the 10-hour timelag fuel moisture estimates.

This study did not determine a timelag response value for the fuel components, but does show their relation to NFDRS timelag fuel moisture values.

The moisture content of the Fines and L-layer was almost always equal to or greater than the estimated NFDRS 1-hour timelag fuel moisture. The regression lines are distinctly above the 1-hour timelag estimates.

Similar discrepancies have been reported by others. Hough and Albini (1978) found NFDRS

(Deeming *et al.* 1972) estimates of 1-hour and 10-hour timelag fuel moisture inadequate to estimate dead fuel moisture for their palmetto-gallberry fuel model. Actual moisture content of field plot L-layer ranged from 9 to 33 percent while 1-hour estimates ranged from 5 to 11 percent and 10-hour estimates ranged from 6 to 14 percent.

The NFDRS 1-hour timelag fuel moisture predictions are unlikely to be exactly the same as those found for various naturally occurring 1-hour timelag fuels. NFDRS predictions are based on equilibrium moisture content for wood while the fuels we observed included needles, leaves, bark, and grasses in addition to wood. Investigators have shown equilibrium moisture content for such other materials to be slightly higher than for wood (Dunlap 1932, Blackmarr 1971, VanWagner 1972, Anderson *et al.* 1978).

Some interacting variables influencing moisture content are not directly considered in the national system. Forest floor and surface soil temperature and moisture gradients; fuel amounts, composition and potential equilibrium moisture contents; wind speed, aspect, slope, stability, and the radiation absorption and emission characteristics of the fuels and surrounding environment contribute to NFDRS fuel moisture value variation.

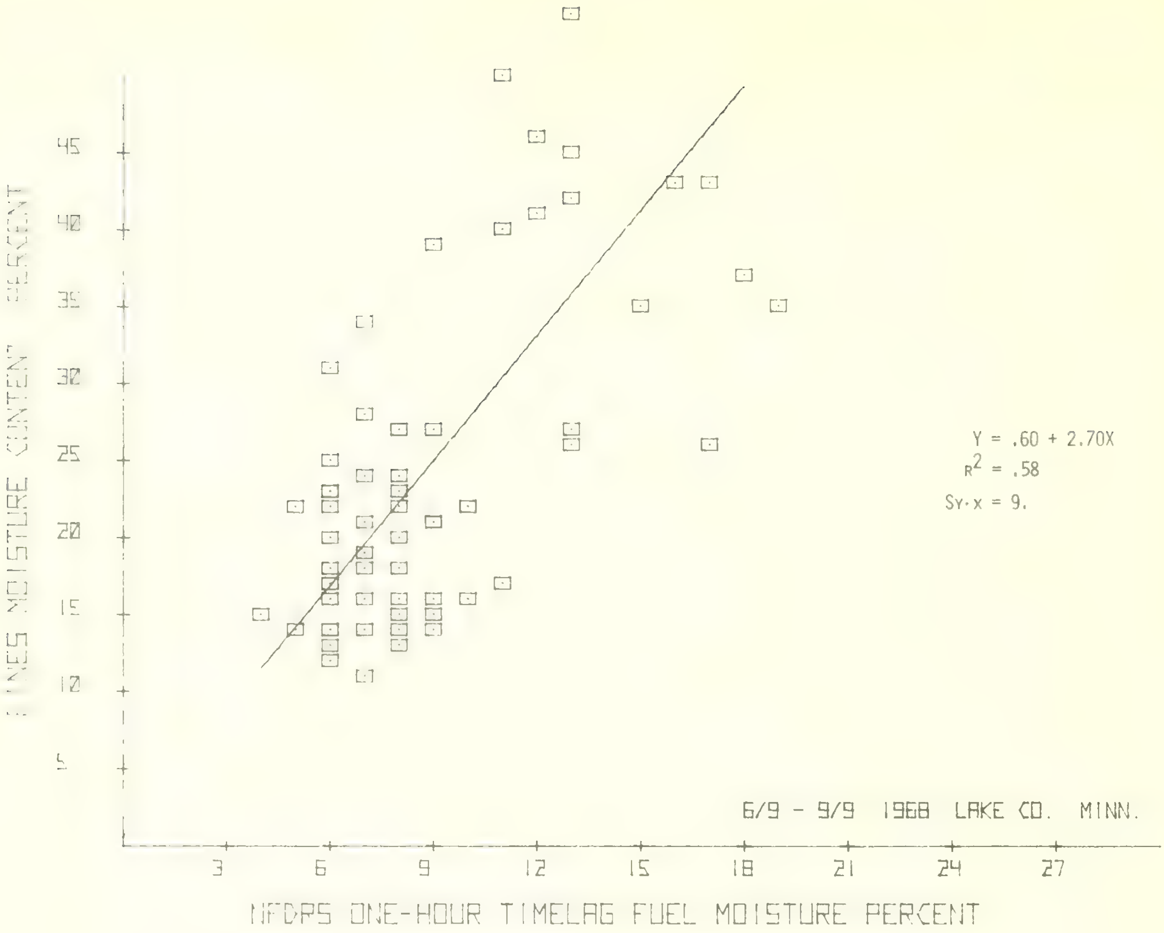
A clear division between L-layer and F-layer, and between F-layer and H-layer usually does not exist. In addition, forest floor and upper soil moisture is influenced by vegetative roots contributing to a transpirational drain. Because the Fines were the most uniform and uniformly exposed materials, they had the smallest standard errors of estimates.

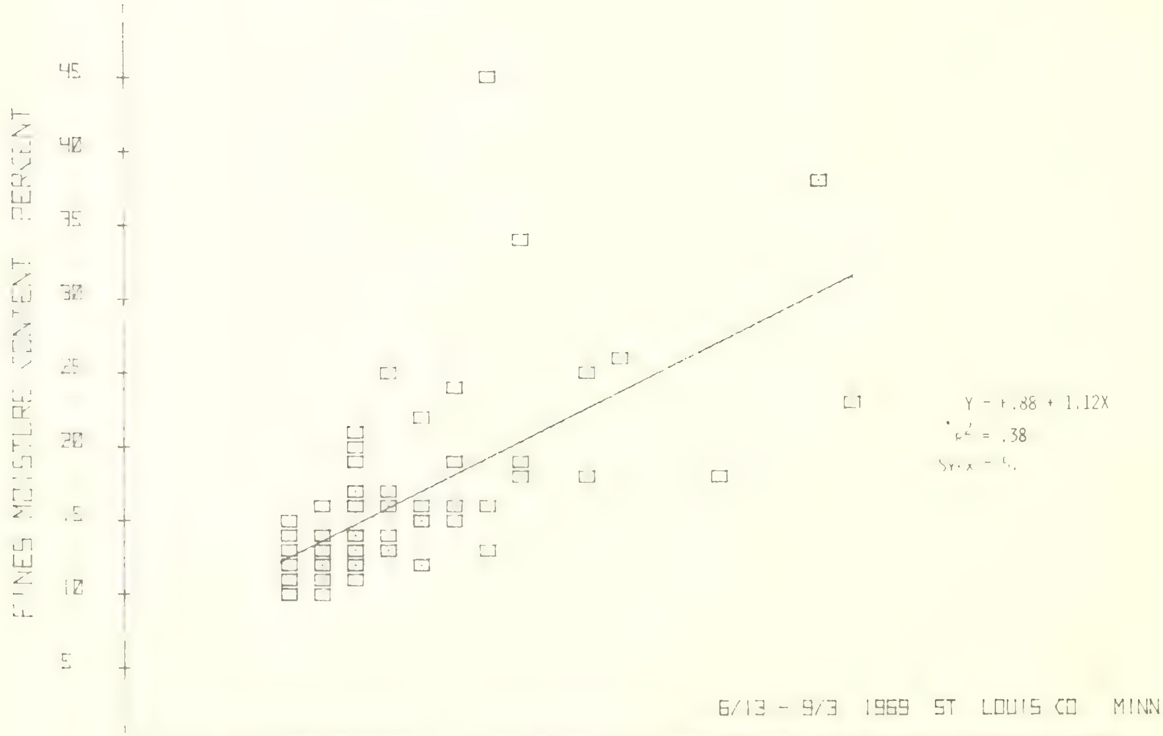
A question arises as to whether the low correlations result from natural variability or a poor relation between forest floor moisture content and NFDRS predictions. To check the data, we compared it to the Canadian Fire Weather Index (FWI) which VanWagner (1975) reports is related to forest floor moisture content. This independent comparison resulted in an r^2 (coefficient of determination) of 0.71 when the FWI Fine Fuel Moisture Code was regressed against L-layer moisture content.

These results indicate that natural variability of the data was not the underlying cause of low correlations.

SUMMARY

This study emphasized the range and variability in moisture response for various slash and forest floor fuels associated with 1-year-old jack pine slash areas in Minnesota and Michigan when the moisture values were related to NFDRS fuel moisture estimates. Our results indicate the National Fire Danger Rating System, which rates fire danger for the worst possible conditions—on south or southwesterly aspects, based on aerially exposed woody material (Deeming *et al.* 1977)—does not work well for litter and duff on the forest floor. Only approximate estimates can be made for the moisture content of Fines, L-layer, and F-layer using NFDRS estimates of the moisture content of 1-hour and 100-hour timelag fuels. These results emphasize the value of on-site fuel moisture measurements when fuel moisture content may be critical.


FINES MOISTURE CONTENT PERCENT
5
10
15
20
25
30
35
40
45
3
6
9
12
15
18
21
24
27
NFDRS ONE-HOUR TIMELAG FUEL MOISTURE PERCENT
Y = .60 + 2.70X
R² = .58
Sy·x = 9.
6/9 - 9/9 1968 LAKE CO. MINN.


FINES MOISTURE CONTENT PERCENT
5
10
15
20
25
30
35
40
45
3
6
9
12
15
18
21
24
27
NFDRS ONE-HOUR TIMELAG FUEL MOISTURE PERCENT
Y = +.88 + 1.12X
R² = .38
Sy·x = 5.
6/13 - 9/3 1969 ST LOUIS CO MINN

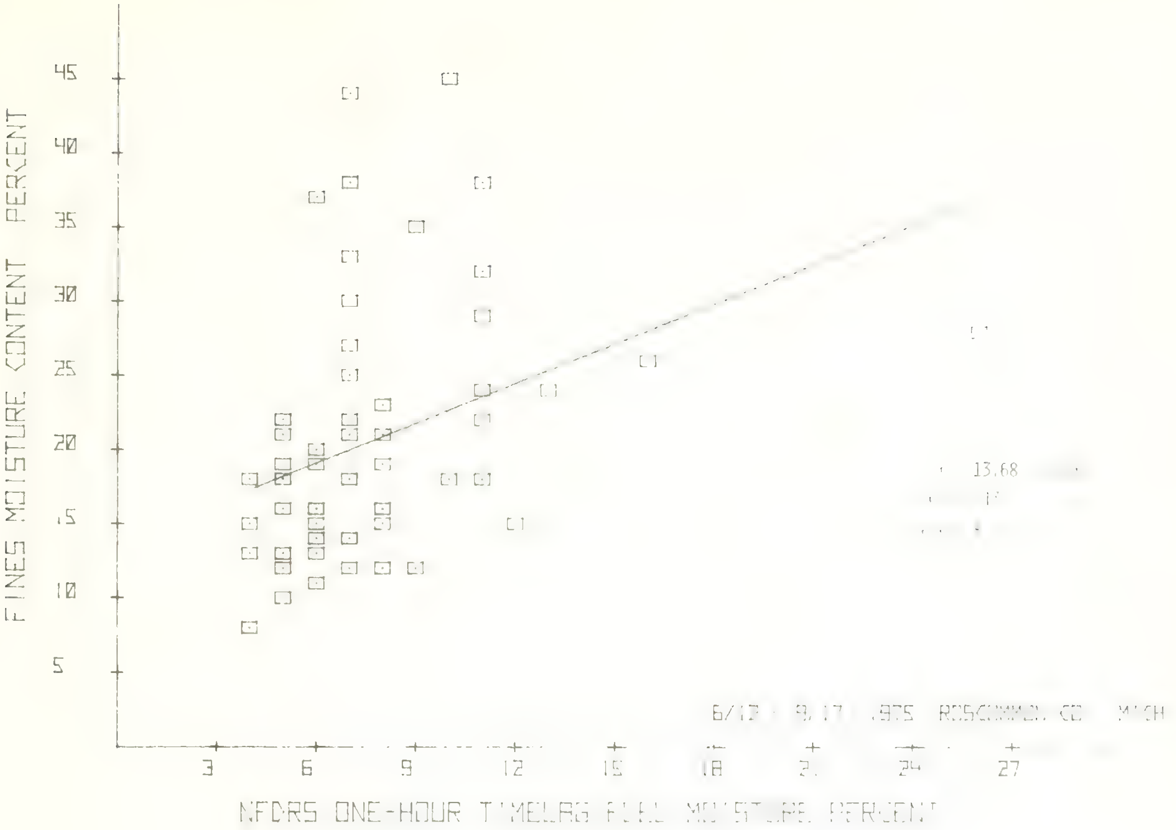
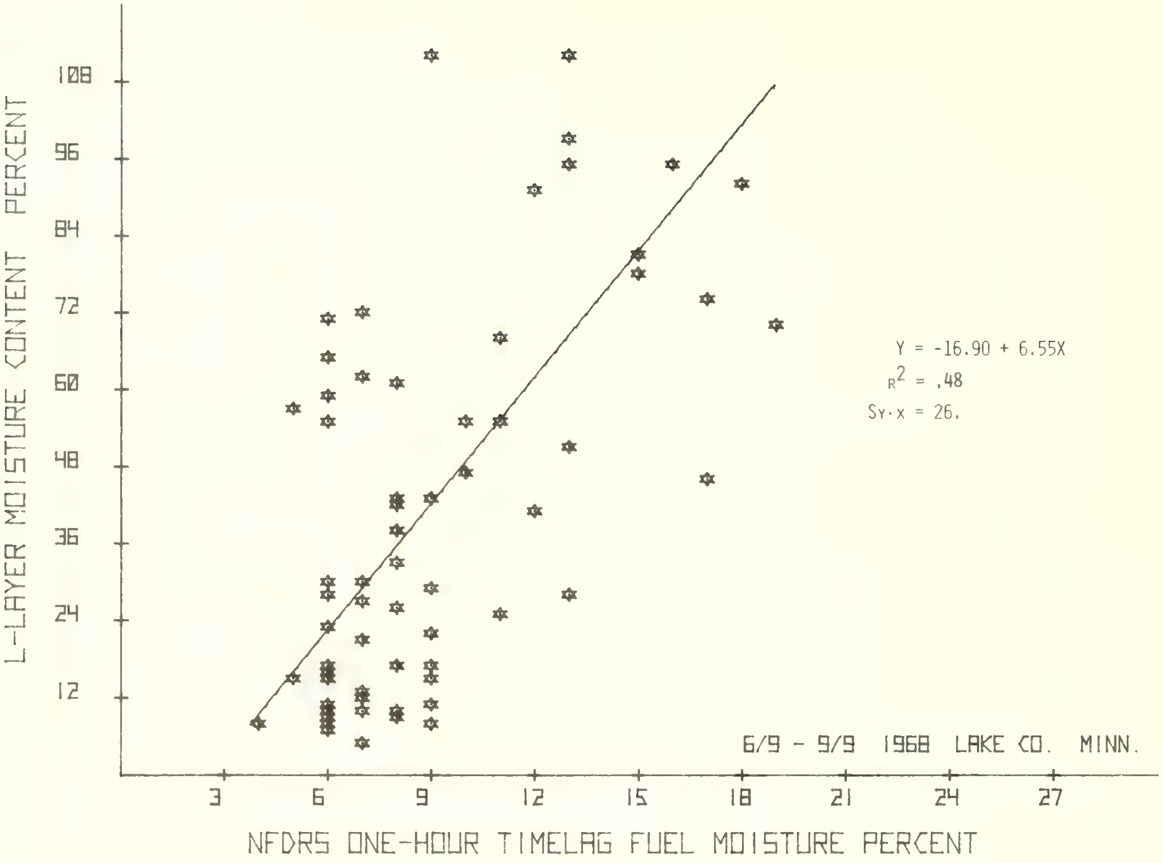
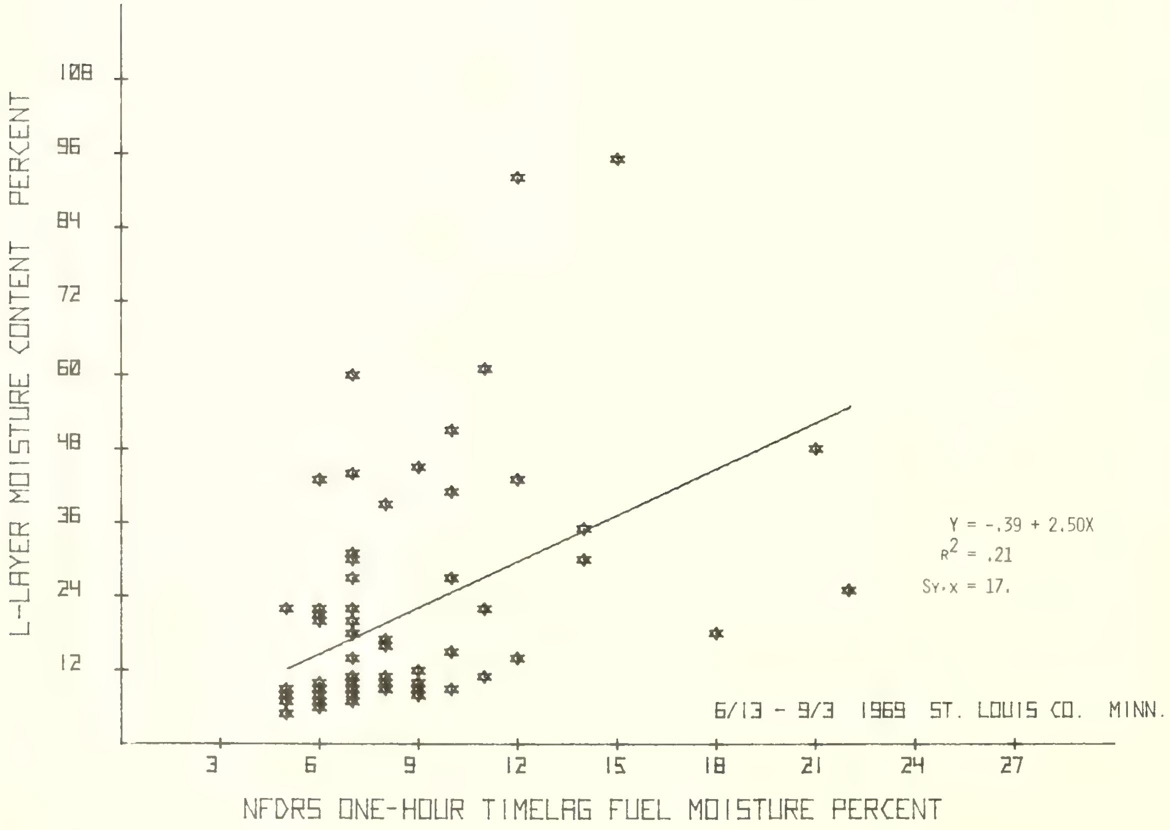


Figure 2.—*Aerially exposed (1 foot or more above ground) slash needles and twigs (equal to or less than ¼ inch in diameter), (Fines) moisture content—National Fire Danger Rating System (NFDRS) 1-hour timelag fuel moisture relations from 1-year-old jack pine slash area.*


L-LAYER MOISTURE CONTENT PERCENT
108
96
84
72
60
48
36
24
12
Y = -16.90 + 6.55X
R^2 = .48
Sy·x = 26.
6/9 - 9/9 1968 LAKE CO. MINN.
3
6
9
12
15
18
21
24
27
NFDRS ONE-HOUR TIMELAG FUEL MOISTURE PERCENT


L-LAYER MOISTURE CONTENT PERCENT
108
96
84
72
60
48
36
24
12
Y = -.39 + 2.50X
R^2 = .21
Sy·x = 17.
6/13 - 9/3 1969 ST. LOUIS CO. MINN.
3
6
9
12
15
18
21
24
27
NFDRS ONE-HOUR TIMELAG FUEL MOISTURE PERCENT

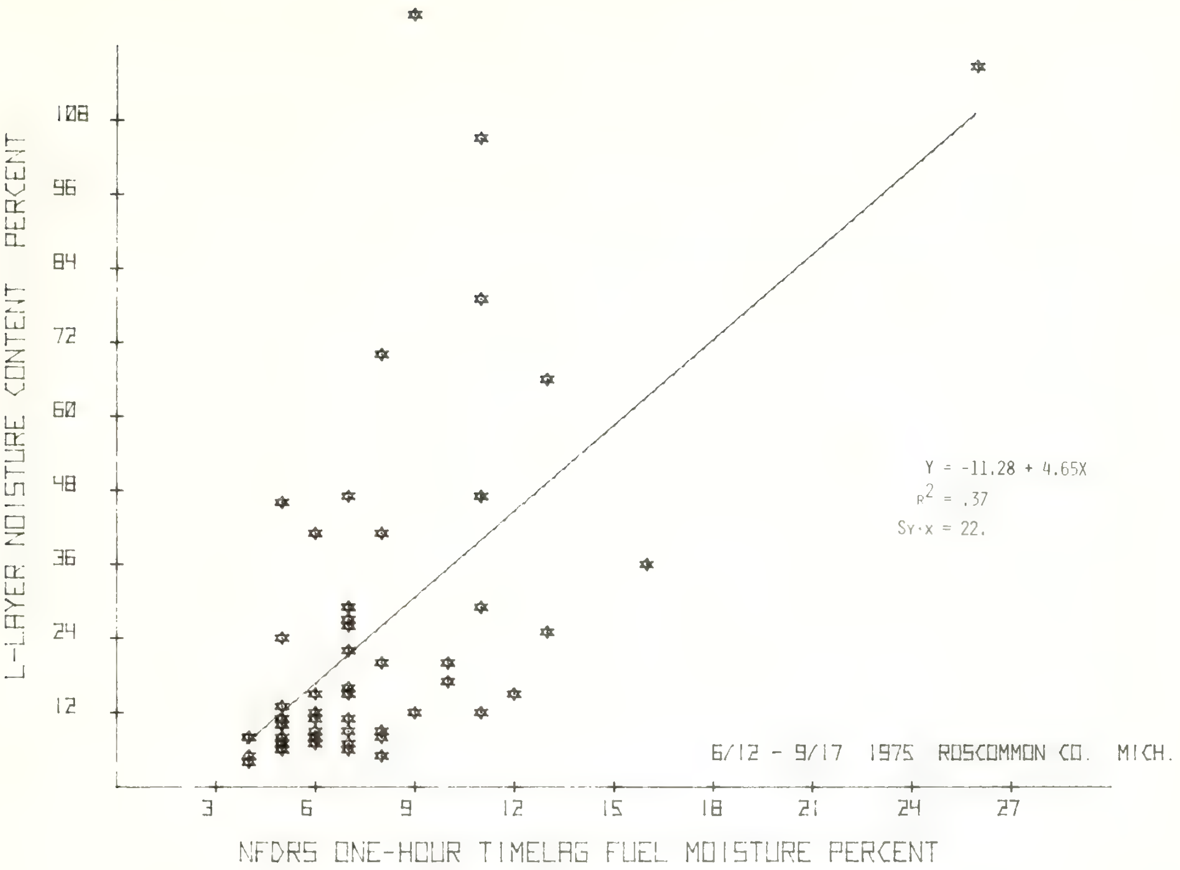
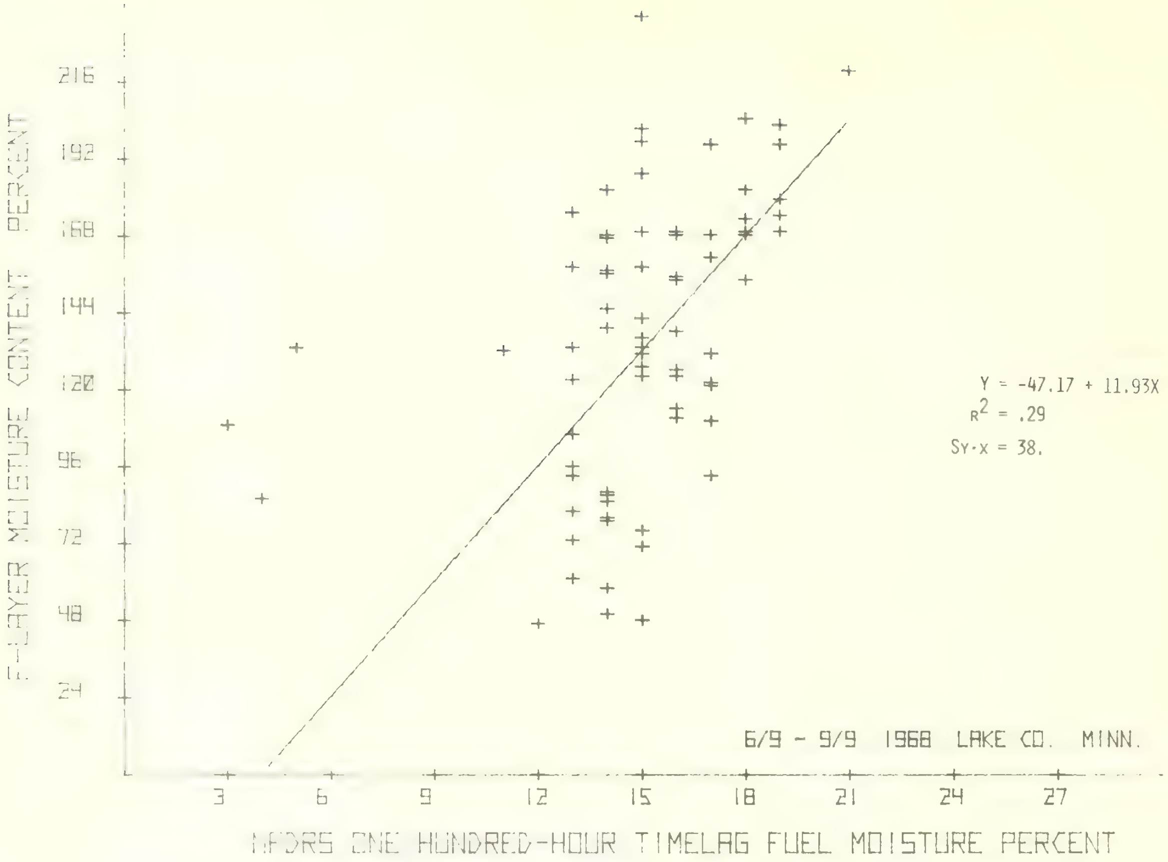
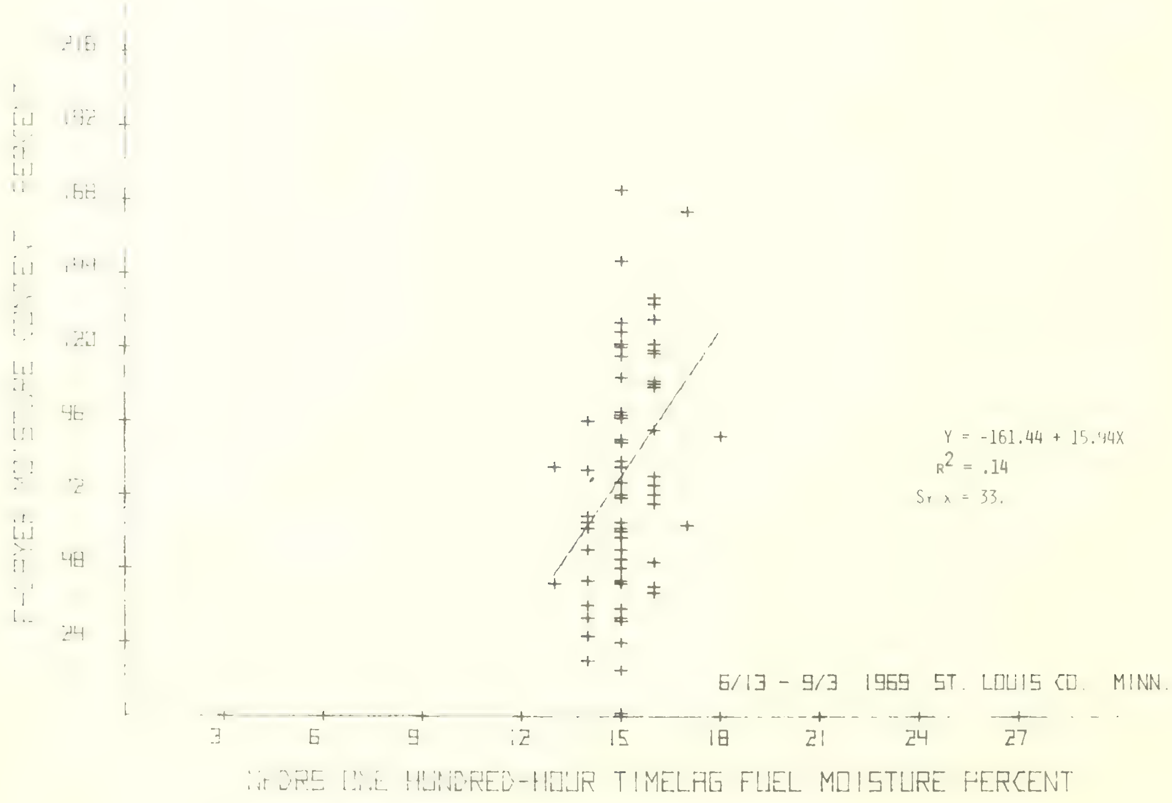


Figure 3.—*Forest floor L-layer moisture content— National Fire Danger Rating System (NFDRS) 1-hour timelag fuel moisture relations for 1-year-old jack pine slash area.*


216
192
168
144
120
96
72
48
24
F-LAYER MOISTURE CONTENT PERCENT
Y = -47.17 + 11.93X
R^2 = .29
SY·X = 38.
6/9 - 9/9 1968 LAKE CO. MINN.
3
6
9
12
15
18
21
24
27
NFDRS ONE HUNDRED-HOUR TIMELAG FUEL MOISTURE PERCENT


216
192
168
144
120
96
72
48
24
F-LAYER MOISTURE CONTENT PERCENT
Y = -161.44 + 15.94X
R^2 = .14
SY·X = 33.
6/13 - 9/3 1969 ST. LOUIS CO. MINN.
3
6
9
12
15
18
21
24
27
NFDRS ONE HUNDRED-HOUR TIMELAG FUEL MOISTURE PERCENT

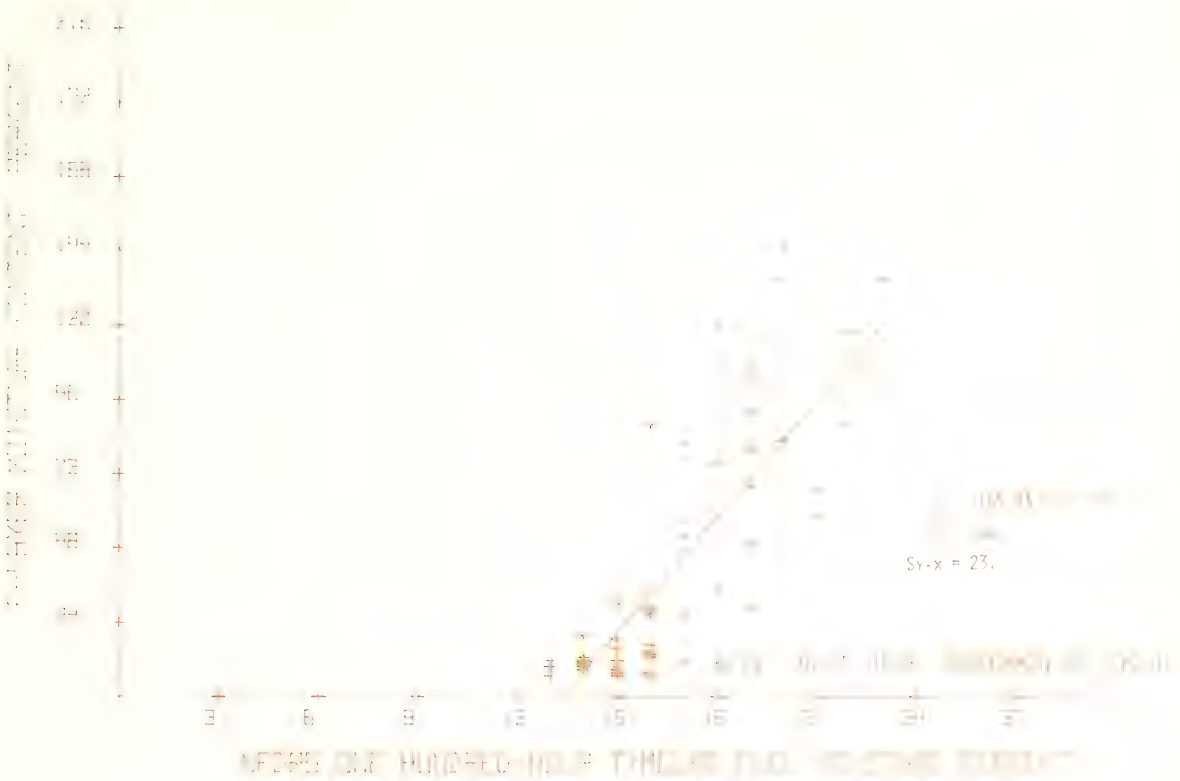


Figure 4.—*Forest floor F-layer moisture content—National Fire Danger Rating System (NFDRS) 100-hour timelag fuel moisture relations for 1-year-old jack pine slash area.*

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SDA FOREST SERVICE
ESEARCH PAPER **NC-190**

Height and diameter of tamarack seed sources in northern Wisconsin

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rest Service, U.S. Department of Agriculture

Riemenschneider, Don E., and R. M. Jeffers.

1980. Height and diameter growth of tamarack seed sources in northern Wisconsin. U.S. Department of Agriculture Forest Service, Research Paper NC-190, 6 p. U.S. Department of Agriculture Forest Service, North Central Forest Experiment Station, St. Paul, Minnesota.

Reports height and diameter growth of tamarack seed sources planted in northern Wisconsin and makes recommendations for selecting the highest-yielding sources.

KEY WORDS: *Larix laricina*, seed source test, planting recommendations.

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Manuscript approved for publication August 7, 1979

1980

HEIGHT AND DIAMETER OF TAMARACK SEED SOURCES IN NORTHERN WISCONSIN

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and **R. M. Jeffers,** *Plant Geneticist,*
(currently with the Rocky Mountain Region, Lakewood, Colorado),
Rhinelander, Wisconsin

Tamarack (*Larix laricina* (DuRoi) K. Koch) is one of the most widely distributed North American conifer species. It will grow under a wide range of climatic conditions and site characteristics and is one of the fastest growing boreal conifers on well-drained sites (Roe 1957). Although it accounts for a small proportion of pulpwood production in the Lake States (Blyth and Hahn 1974), harvesting is increasing (Johnston 1975). Recent investigations have been designed to evaluate genetic variation (Pauley 1965, Jeffers 1975, Sajdak 1970, Cech *et al.* 1977) and the potential for short rotation intensive culture (Zavitkovski and Dawson 1978).

This paper presents survival, height, and diameter data for 13- and 14-year-old trees in a seed source test of tamarack. The investigation is part of a cooperative study of rangewide variation in tamarack begun by the University of Minnesota (Pauley 1965). Earlier height and survival data have been reported by Jeffers (1975).

MATERIALS AND METHODS

Two experimental plantings were established on old field sites in north-central Wisconsin in October 1967. The planting sites and experimental design have been previously described (Jeffers 1975).

One planting consists of 24 seed sources and is located on a well-drained, high quality tamarack site in Forest County (table 1) (Jeffers 1975). The other planting is in Oneida County and includes 17 of the same seed sources. In both cases, a few seed sources were planted as 2-2 transplants but the majority were planted as 3-0 seedlings. A randomized complete block design with 10 replicates and 4-tree row plots was used at both locations.

All trees were measured in November 1977 for total height and diameter at breast height. Data were subjected to analysis of variance with plot means as entries. Variation among sources was then partitioned to determine if significant differences existed between age groups and between sources within each age group. The relation between seed source performance and the latitude and longitude of origin was examined using linear and curvilinear regression models. Relations among variables were tested by simple correlation analysis.

RESULTS

Survival

Mean survival for 13- and 14-year-old trees at the Forest County site was 76 percent and 91 percent, respectively (table 1). Most of the losses occurred in the first 2 years after planting (Jeffers 1975). Analysis of variance showed significant differences in survival between age groups and among 13-year-old sources but not among 14-year-old sources (table 2).

Mean survival for 13- and 14-year-old trees at the Oneida County site was 60 percent, which is considerably less than the survival at the Forest County site (table 1). Mortality did not drop off after 2 years like it did at the Forest County site.

Table 1.—*Origin, survival, height, and diameter of tamarack seed sources*

Age	Source no.	State or Province	County	°N Latitude	°W Longitude	Forest County			Oneida County		
						Survival	Height	D.b.h.	Survival	Height	D.b.h.
						Percent	*m*	*cm*	*Percent*	*m*	*cm*
14	3036	ME	Somerset	45.7	71.2	88	6.36	8.28			
	3019	WI	EauClaire	44.7	91.0	98	5.51	6.79	68	4.85	6.75
	3014	MN	Anoka	45.1	93.0	100	5.43	6.57	72	4.76	6.05
	3007	WI	Washburn	46.0	91.8	90	5.41	6.55			
	3038	MI	VanBuren	42.2	86.1	90	5.18	5.82	60	4.36	5.32
	3011	WI	Waukesha	43.0	88.2	82	5.16	5.67	45	4.68	5.50
					Average	91	5.51	6.61	61	4.66	5.90
13	3333	NS	Annapolis	44.8	65.0	75	5.05	5.61	80	4.86	5.89
	3319	MN	Anoka	45.2	93.1	52	5.04	5.66	42	3.63	3.96
	3266	WI	Oneida	45.8	89.2	90	4.96	5.43			
	3330	ME	Somerset	45.6	70.3	85	5.02	5.80	72	4.40	5.29
	3282	WI	LaCrosse	43.8	91.1	80	5.02	5.67	45	4.59	5.61
	3265	WI	Forest	45.8	88.9	88	4.94	5.54	58	4.13	4.50
	3323	WI	Trempaleau	44.2	91.5	80	4.89	5.18			
	3332	ONT	Oxford	43.2	80.6	62	4.81	5.69	72	4.58	5.24
	3284	MN	Itasca	47.4	93.6	85	4.76	5.14	52	4.19	5.13
	3272	MI	Alger	46.5	87.0	82	4.72	5.16			
	3283	MN	Itasca	47.5	94.1	95	4.61	4.85	65	4.10	4.57
	3320	MN	St.Louis	47.0	93.0	80	4.55	4.91	65	3.94	4.37
	3324	MAN		50.1	95.4	90	4.55	4.64	60	4.16	5.30
	3327	MI	Chippewa	46.3	84.2	55	4.55	4.99	58	4.94	6.14
	3331	MI	Houghton	47.0	88.4	78	4.40	4.69	45	3.83	4.30
	3273	MI	Alger	46.5	87.0	68	4.35	4.81	58	3.86	4.73
	3337	MI	Ingham	42.5	84.8	62	3.66	3.48			
	3332	ATA		56.6	111.2	68	3.04	3.08			
					Average	76	4.61	5.02	59	4.25	5.00
			Least significant difference			18	0.61	0.93	25	0.55	0.85

Table 2.—*Mean squares for survival, height, and diameter of tamarack seed source*

Mean square	Forest County				Oneida County			
	df	Survival	Height	Diameter	df	Survival	Height	Diameter
Among sources	23	[1]2.674	[1]3.988	[1]10.728	16	[2]2.031	[1]1.624	[1]5.862
Between age groups	1	[1]32.289	[1]36.453	[1]113.128	1	[2]0.163	[1]4.370	[1]26.888
Among 14-year-old sources	5	[2]0.670	11.984	[1]8.783	3	[2]2.300	[2]0.383	[1]4.280
Among 13-year-old sources	17	[1]1.404	[1]2.668	[1]5.276	12	[2]1.119	[1]1.706	[1]4.503
Error	205	0.678	0.482	1.130	129	1.293	0.392	0.947

[1] Significant at $P < 0.01$.

[2] Not significant.

Height

Mean height at Forest County was 5.51 m for 14-year-old trees and 4.61 m for 13-year-old trees. All components of variation between and within sources were significant (table 2). The mean of the shortest 14-year-old trees (Source 3011, Waukesha County, WI) was greater than the mean of the tallest 13-year-old trees (Source 3333, Annapolis County, Nova Scotia). The tallest trees in both age groups were from Wisconsin, central Minnesota, Maine, and Nova Scotia. However, trees from Source 3319 from Anoka County, Minnesota, have shown susceptibility to snow damage (Sajdak 1970, Jeffers 1975). The shortest trees were from Michigan, northern Minnesota, and northwestern Canada.

Mean height at Oneida County was 4.66 m for 14-year-old trees and 4.25 m for 13-year-old trees (10 percent less than at Forest County). Differences were significant between age groups and among sources of 13-year-old trees but not among sources of 14-year-old trees. The tallest 13-year-old trees were from Chippewa County, Michigan, and Annapolis County, Nova Scotia. Source 3319 from Anoka County, Minnesota, was the poorest source at Oneida County and was one of the best sources at Forest County.

Diameter

Results for this variable were similar to those for total height. The most notable difference was that the range of seed source means was greater than for height (96 percent of the mean for d.b.h. vs. 69 percent for height at Forest County and 54 percent vs. 28 percent at Oneida County). Mean d.b.h. at Forest County was 6.61 cm for 14-year-old trees and 5.02 cm for 13-year-old trees. Age groups overlapped somewhat. Fourteen-year-old trees from Source 3011 had a mean d.b.h. of 5.67 cm while 13-year-old trees from Source 3330 had a mean d.b.h. of 5.80 cm. The tallest trees also had the largest diameters.

Differences were also significant between age groups and among sources within age groups in Oneida County. Again, sources that ranked high in height also ranked high in diameter. The poorest source once more was 3319 from Anoka County, Minnesota.

Correlation and Regression Analyses

Simple correlation analysis was performed between all variables measured in this study at ages 13 and 14 and also the 8- and 9-year heights presented by Jeffers (1975) (table 3). The age-age correlation for total height was remarkably high—0.92 at the Forest County site and 0.81 at the Oneida County site. The height-diameter correlations were 0.98 at Forest County and 0.93 at Oneida County. The correlation between seed source means at different sites was 0.55 for height and 0.59 for d.b.h.

Height and diameter at the Forest County planting were significantly and negatively correlated with

Table 3.—*Simple correlations*

	1	2	3	4	5	6	7	8
Forest County								
7,8-year height								
13,14-year survival	[1,2]0.58							
13,14-year height	[1].92	[3]0.49						
13,14-year d.b.h.	[1].93	[3].45	[1]0.98					
Oneida County								
7,8-year height	[1].82	[4].42	[1].62	[1]0.85				
13,14-year survival	[4].06	[4].29	[4].22	[4].31	[4]0.39			
13,14-year height	[4].47	[4].17	[3].55	[3].56	[1].81	[4]0.45		
13,14-year d.b.h.	[3].57	[4].28	[3].58	[3].59	[1].86	[4].15	[1]0.93	
Source latitude			[1]−.54	[3]−.46			[4]−.44	[4]−0.30
Source longitude			[3]−.49	[3]−.47			[4]−.40	[4].26

[1] Significant at P < 0.01.

[2] df = 22 for Forest County; 15 for Oneida County; 15 between sources common to both locations.

[3] Significant at P < 0.05.

[4] Not significant.

latitude and longitude of the source origin. The effect of latitude is easily interpreted as a photoperiod controlled adaptation to environmental gradients, but the effect of longitude is not as easily understood. It should be noted that latitude and longitude were significantly correlated ($r = 0.56$), i.e., the collections ranged from northwestern Canada to the eastern United States, suggesting that the relation between growth and longitude of seed source may be spurious. Partial correlation analysis did not provide an answer to this question.

The effect of latitude of origin on tree height at the Forest County site was also investigated via linear regression of seed source mean height on latitude of origin for the 18 sources of 13-year-old trees. The regression ($P < 0.025$) accounted for 38 percent of the variation in height (fig. 1). There was a response gradient of 2 percent of the experiment mean per degree of latitude with trees of more northern latitudes performing poorly. An examination of raw data and standardized residuals indicated, however, that they departed from the linear model. Two sources from north and south of the planting site (3332 and 3337) were found to lie more than two standard deviations below the regression line. Although a third degree polynominal model accounted for 69 percent of the variation, the cubic independent variable was on the borderline of significance ($P < 0.10$) and the relation was not investigated further.

DISCUSSION

Seed sources of tamarack differed significantly in survival, height, and diameter at two sites in north-central Wisconsin. The presence of significant differences tended to depend on the age group of the trees and the site on which they were grown—more differences existed among seed sources on the better site and among seed sources of the younger trees. However, this may be a result of differences in precision due to the unequal numbers of sources in the two age groups.

The site with the best survival and growth was a well-drained upland site adjacent to a stand of natural tamarack (Jeffers 1975). The best trees at this location were from Wisconsin, central Minnesota, Maine, and Nova Scotia. In other cooperative tests, a source from Clare County, Michigan, was tallest

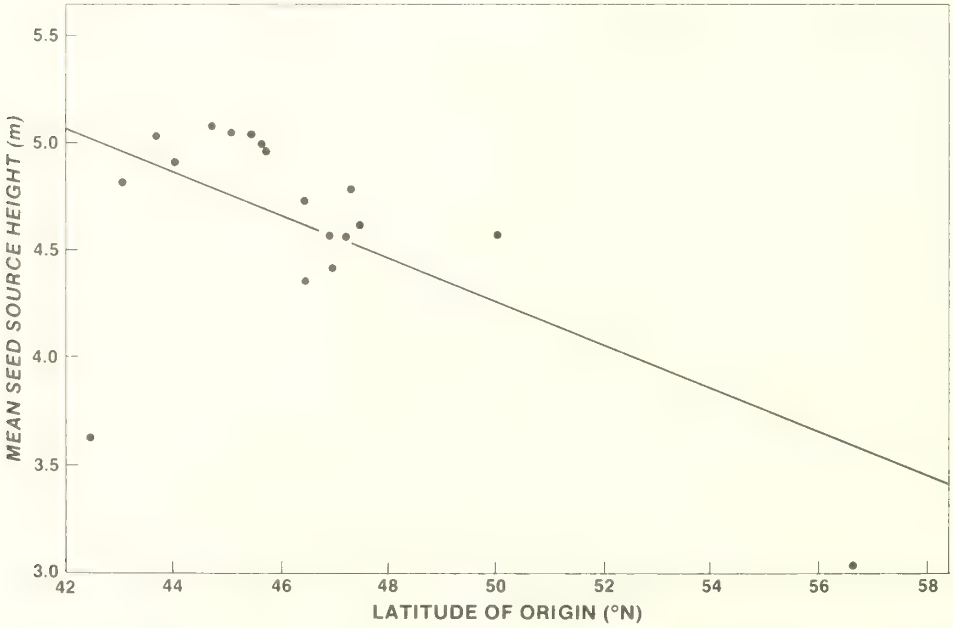

Figure 1.—*The regression of mean height on latitude of origin for 18 sources of 13-year-old tamarack. The regression equation is height = 9.43 − .10* (°N Latitude).

(Sajdak 1970, Cech *et al.* 1977). This source was not represented in the Wisconsin tests, but sources from similar latitudes (3282 and 3323) ranked high.

Due to the limited nature of the experimental population, no estimate of genotype × environment interaction was made. Some inference, however, can be made on the basis of seed source rank and correlations. The correlations between sites were 0.55 for height and 0.59 for d.b.h. ($r^2 = 0.30$ and 0.35). Although the correlations are significant ($P < 0.01$), they are not extremely high values and reflect a lack of consistent performance over the two sites. An examination of seed source means shows that sources 3319 (Anoka County, Minnesota) and 3327 (Chippewa County, Michigan) are extremely unstable in this experiment (fig. 2). The reason for this instability remains unknown however, because the two sources do behave erratically, they may not be suited to planting in north-central Wisconsin.

Due to the strong age-age and height-diameter correlations, there appears to be no reason to modify the following seed source recommendations for north-central Wisconsin (Jeffers 1975):

1. Maine, Somerset County (3036 and 3330)
2. Wisconsin, Eau Claire County (3019)
   LaCrosse County (3282)
   Oneida County (3266)
3. Nova Scotia, Annapolis County (3333)

These sources are those that grew best on the highest yeilding site and also appeared to have reasonably stable performance. Although collections from the original stands represented in this study may be the best approach to seed procurement, the curvilinear regression of mean seed source height on latitude of origin indicates that there may be a range (43.5°N to 46.0°N) where high performing genotypes can be found. However, because one of the sources that lead to the fitting of a polynominal model is present at only one location and a source with known instability (3319) is included in the latitudinal range, there may be some risk associated with such a generalization.

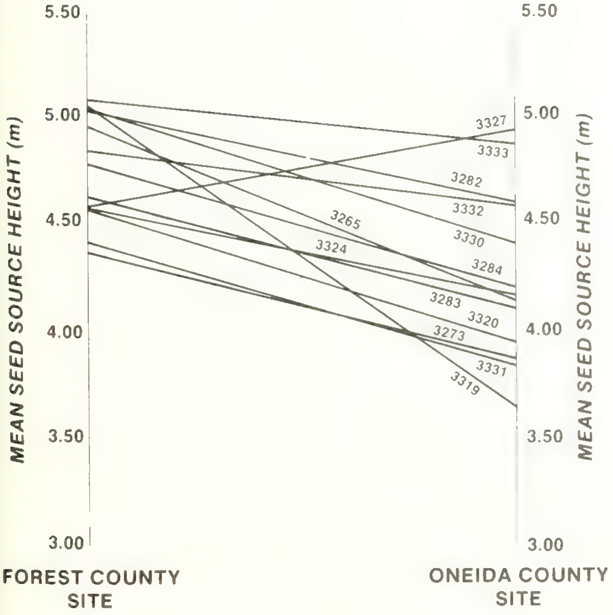

Figure 2.—*Height of 13-year-old trees from 13 sources of tamarack at two locations in northern Wisconsin.*

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USDA FOREST SERVICE
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Summary of **green weights** and **volumes** for five tree species in Michigan

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SUMMARY OF GREEN WEIGHTS AND VOLUMES FOR FIVE TREE SPECIES IN MICHIGAN

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In the past few years more and more small, whole rees, and the residue remaining from conventional ogging operations have been converted to chips for iber or fuel. As fossil fuels become scarcer, chipping rees and logging debris in the woods will probably ecome a common way to harvest much of this material vhich was previously considered unmerchantable. So, oresters and loggers increasingly need to estimate the veight of trees, boles, and logging residue.

Studies made in the western part of the Upper Peninula of Michigan in 1970 (Steinhilb and Erickson 970), 1972 (Steinhilb and Erickson 1972), and 1976 Steinhilb and Winsauer 1976) produced estimating quations, tables, and graphs for the weights and cubic oot volumes of trees, boles, and residue for aspen, pruce, balsam fir, red pine, and sugar maple. This nformation is summarized here in a condensed and nore usable form.

Definitions: the "total tree" is the entire tree above the stump, while the "bole" is the delimbed stem cut at a point 3 inches in diameter outside the bark for all species except sugar maple, where the top diameter of the bole was 4 inches outside the bark. "Residue" is all remaining portions of the tree except the stump and roots, including tops, limbs, and foliage.

In the original studies, field data were obtained from 7 aspen, 71 balsam fir, 58 white spruce, 58 red pine nd 58 pulpwood-sized and 79 saw log-sized sugar ma le trees.

FIELD PROCEDURES

Each tree was numbered and its d.b.h. recorded to ne nearest 0.1 inch and felled carefully to minimize breakage and loss of limbs. Each tree was weighed within 24 hours of felling.

All limbs were severed and the main stem lopped at its 3-inch-diameter point outside the bark (d.o.b.) except for sugar maple which was severed at 4-inch d.o.b. Taper measurements were taken on each stem outside the bark at the stump cut, at 2 feet and 4 feet above the stump and every 8 feet thereafter to the point of lopping. Total length of the tree and the bole were also measured to the nearest foot.

ANALYTIC PROCEDURE

A standard form of estimating equation for all five species was felt desirable. The equations used in the sugar maple study (Steinhilb and Winsauer 1976) were chosen because of their simplicity and the general availability of the independent variables from timber inventory.

Cubic foot volume was calculated for the whole tree and its residue from the tree weight and pound per cubic foot figures. Regression equations were developed for each species. Several other regression models were also tested to insure that the common form chosen was sufficiently accurate for all species.

RESULTS AND DISCUSSIONS

The variance in weight and volume measurements increased as the diameter of the trees increased, at a rate of approximately $(\text{d.b.h.})^4$. Therefore, the final equations were obtained from weighted regressions with a weighting factor of $(1/\text{d.b.h.})^4$ to compensate for the nonhomogenity of weights and volumes of trees, boles, and residue.

The saw log size (12 inches d.b.h. or larger) sugar maple trees were included in the analyses of tree weights and volumes but could not be used for the bole and residue equations because their bole length had been defined differently.

The similarity of the tree weight curves (Young 1976) would suggest the possibility of creating a set of general curves to predict green tree weight of any species. It also seems to imply that if d.b.h. is known, a practical estimate of green tree weight can be obtained regardless of species. Although a larger variation appears in the residue weight curves, these also indicate the possibility of a set of general curves.

GRAPHS AND EQUATIONS

	Table		Figure	
Subject	**No.**	**Page**	**No.**	**Page**
Tree weight vs. d.b.h. and tree height	1-5	3-7	1-5	14-15
Tree volume vs. d.b.h. and tree height	1-5	3-7	6-10	15-16
Bole weight vs. d.b.h. and bole length	6-10	8-12	11-15	16-17
Bole volume vs. d.b.h. and bole length	6-10	8-12	16-20	17-18
Residue weight vs. d.b.h.	11	13	21-25	19-20
Residue volume vs. d.b.h.	11	13	26-30	20-22

Tables of tree weights and volumes with 95 percent confidence limits on the mean for each species are presented in tables 1-5. Tables of bole weights and volumes with 95 percent confidence limits on the mean are presented in tables 6-10. Residue weights and volumes for all five species are presented in table 11.

Two additional graphs are included— one for tre weight for all five species based on d.b.h. (fig. 31) an one containing all five residue weight curves (fig. 32

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able 1.— *Aspen tree weight and tree volume (95 percent confidence limit on the mean)*

	Tree length (feet)											
	30		40		50		60		70		80	
.b.h.	**Weight**	**Volume**	**Weight**	**Volume**	**Weight**	**Volume**	**Weight**	**Volume**	**Weight**	**Volume**	**Weight**	**Volume**
nches	*Pounds*	*Feet*^{3}	*Pounds*	*Feet*^{3}	*Pounds*	*Feet*^{3}	*Pounds*	*Feet*^{3}	*Pounds*	*Feet*^{3}	*Pounds*	*Feet*^{3}
5	142.5	3.52	182.0	4.27	221.6	5.04	261.1	5.80	300.7	6.56	340.2	7.32
	(24.2)[1]	(.57)	(23.1)	(.61)	(22.0)	(.67)	(21.1)	(.74)	(20.2)	(.82)	(19.5)	(.91)
6	194.7	4.52	251.6	5.62	308.6	6.71	365.5	7.81	422.5	8.91	479.4	10.00
	(22.7)	(.63)	(21.3)	(.73)	(20.1)	(.84)	(19.1)	(.97)	(18.5)	(1.10)	(18.1)	(1.24)
7	256.4	5.71	333.9	7.20	411.4	8.69	488.9	10.18	566.4	11.67	643.9	13.17
	(21.2)	(.74)	(19.6)	(.90)	(18.6)	(1.07)	(18.1)	(1.26)	(18.3)	(1.46)	(19.1)	(1.66)
8	327.5	7.08	428.8	9.03	530.0	10.98	631.3	12.92	732.5	14.87	833.8	16.82
	(19.7)	(.88)	(18.4)	(1.12)	(18.1)	(1.37)	(19.0)	(1.63)	(20.7)	(1.89)	(23.3)	(2.16)
9	408.2	8.63	536.4	11.10	664.5	13.56	792.7	16.03	920.8	18.50	1,048.9	20.96
	(18.6)	(1.07)	(18.2)	(1.38)	(19.4)	(1.71)	(22.2)	(2.05)	(25.8)	(2.39)	(30.2)	(2.74)
10	498.4	10.37	656.6	13.41	814.8	16.46	973.0	19.50	1,131.2	22.55	1,289.4	25.59
	(18.1)	(1.29)	(19.3)	(1.69)	(22.7)	(2.11)	(27.5)	(2.53)	(33.1)	(2.96)	(39.2)	(3.39)
11	598.1	12.29	789.5	15.97	980.9	19.65	1,172.3	23.34	1,363.8	27.02	1,555.2	30.70
	(18.6)	(1.54)	(22.1)	(2.04)	(27.8)	(2.55)	(34.7)	(3.07)	(42.2)	(3.59)	(49.9)	(4.11)
12	707.2	14.39	935.0	18.77	1,162.8	23.16	1,390.6	27.54	1,618.5	31.93	1,846.3	36.31
	(20.2)	(1.83)	(26.3)	(2.43)	(34.3)	(3.05)	(43.2)	(3.66)	(52.6)	(4.28)	(62.1)	(4.91)
13	825.9	16.67	1,093.2	21.82	1,360.6	26.96	1,627.9	32.11	1,895.3	37.25	2,162.7	42.40
	(23.0)	(2.14)	(31.8)	(2.86)	(42.0)	(3.58)	(53.0)	(4.31)	(64.2)	(5.04)	(75.7)	(5.77)
14	954.0	19.14	1,264.1	26.10	1,574.2	31.07	1,884.2	37.04	2,194.3	43.01	2,504.4	48.98
	(26.9)	(2.48)	(38.2)	(3.32)	(50.7)	(4.16)	(63.7)	(5.01)	(77.0)	(5.86)	(90.4)	(6.71)
15	1,091.7	21.79	1,447.6	28.64	1,803.6	35.49	2,159.5	42.34	2,515.5	49.19	2,871.4	56.04
	(31.7)	(2.85)	(45.5)	(3.82)	(60.3)	(4.79)	(75.5)	(5.76)	(90.9)	(6.74)	(106.4)	(7.71)
16	1,238.8	24.62	1,643.8	32.41	2,048.8	40.21	2,453.8	48.00	2,858.7	55.80	3,263.7	63.59
	(37.2)	(3.25)	(53.6)	(4.35)	(70.8)	(5.46)	(88.2)	(6.57)	(105.8)	(7.68)	(123.6)	(8.79)
17	1,395.4	27.63	1,852.6	36.43	2,309.8	45.23	2,767.0	54.03	3,224.2	62.83	3,681.4	71.63
	(43.4)	(3.68)	(62.4)	(4.92)	(82.0)	(6.17)	(101.8)	(7.43)	(121.8)	(8.68)	(141.9)	(9.93)
18	1,561.5	30.83	2,074.1	40.70	2,586.6	50.56	3,099.2	60.43	3,611.8	70.29	4,124.3	80.16
	(50.2)	(4.13)	(71.8)	(5.53)	(94.0)	(6.93)	(116.4)	(8.34)	(138.8)	(9.74)	(161.4)	(11.15)

e numbers in parentheses give a confidence interval on the mean.

Table 2.—*White spruce tree weight and tree volume (95 percent confidence limit on the mean).*

	Tree length (feet)									
	30		40		50		60		70	
D.b.h.	**Weight**	**Volume**	**Weight**	**Volume**	**Weight**	**Volume**	**Weight**	**Volume**	**Weight**	**Volum**
Inches	*Pounds*	*Feet^3*	*Pounds*	*Feet^3*	*Pounds*	*Feet^3*	*Pounds*	*Feet^3*	*Pounds*	*Fee*
5	273.5	4.00	313.7	4.86	354.0	5.72	394.2	6.58	434.5	7.4
	(72.7)[1]	(1.10)	(69.2)	(1.05)	(65.8)	(1.00)	(62.7)	(.95)	(59.8)	(.9
6	326.6	5.14	384.6	6.38	442.5	7.62	500.5	8.85	558.4	10.0
	(68.1)	(1.03)	(63.4)	(.96)	(59.2)	(.90)	(55.6)	(.84)	(52.6)	(.8
7	389.4	6.48	468.3	8.17	547.2	9.85	626.1	11.54	705.0	13.2
	(63.1)	(.96)	(57.5)	(.87)	(53.2)	(.81)	(50.3)	(.76)	(49.1)	(.7
8	461.8	8.03	564.9	10.23	667.9	12.43	771.0	14.64	874.0	16.8
	(57.9)	(.88)	(52.4)	(.79)	(49.4)	(.75)	(49.5)	(.75)	(52.7)	(.8
9	544.0	9.78	674.4	12.57	804.8	15.36	935.2	18.15	1,065.6	20.9
	(53.3)	(.81)	(49.3)	(.75)	(50.2)	(.76)	(55.8)	(.85)	(64.9)	(.9
10	635.7	11.75	796.7	15.19	957.7	18.63	1,118.7	22.07	1,279.7	25.5
	(50.0)	(.76)	(50.0)	(.75)	(57.2)	(.87)	(69.3)	(1.05)	(84.3)	(1.2
11	737.2	13.91	932.0	18.08	1,126.8	22.24	1,321.6	26.41	1,516.4	30.5
	(49.1)	(.74)	(55.7)	(.84)	(70.0)	(1.06)	(88.4)	(1.34)	(108.9)	(1.6
12	848.2	16.29	1,080.1	21.25	1,311.9	26.20	1,543.8	31.16	1,775.6	36.1
	(51.6)	(.78)	(66.1)	(1.00)	(87.5)	(1.32)	(111.9)	(1.69)	(137.7)	(2.0
13	969.0	18.87	1,241.1	24.69	1,513.2	30.50	1,785.3	36.32	2,057.4	42.1
	(57.9)	(.88)	(80.5)	(1.22)	(108.6)	(1.64)	(138.8)	(2.10)	(170.1)	(2.5
14	1,099.4	21.66	1,415.0	28.40	1,730.5	35.15	2,046.1	41.90	2,361.6	48.6
	(67.7)	(1.02)	(98.1)	(1.49)	(132.6)	(2.01)	(168.8)	(2.56)	(205.8)	(3.1
15	1,239.5	24.65	1,601.7	32.40	1,964.0	40.14	2,326.2	47.89	2,688.5	55.6
	(80.3)	(1.22)	(118.3)	(1.79)	(159.3)	(2.41)	(201.6)	(3.05)	(244.5)	(3.7
16	1,389.2	27.85	1,801.4	36.67	2,213.5	45.48	2,625.7	54.29	3,037.8	63.
	(95.4)	(1.44)	(140.7)	(2.13)	(188.4)	(2.85)	(237.1)	(3.59)	(286.2)	(4.
17	1,548.6	31.26	2,013.9	41.21	2,479.2	51.16	2,944.5	61.10	3,409.8	71.
	(112.4)	(1.70)	(165.1)	(2.50)	(219.7)	(3.33)	(275.0)	(4.16)	(330.8)	(5.
18	1,717.6	34.88	2,239.3	46.03	2,760.9	57.18	3,282.6	68.33	3,804.2	79.
	(131.2)	(1.99)	(191.4)	(2.90)	(253.1)	(3.83)	(315.5)	(4.78)	(378.2)	(5.

[1] The numbers in parentheses give a confidence interval on the mean

ble 3.— *Red pine tree weight and tree volume (95 percent confidence limit on the mean)*

	Tree length (feet)									
	40		50		60		70		80	
.b.h.	**Weight**	**Volume**	**Weight**	**Volume**	**Weight**	**Volume**	**Weight**	**Volume**	**Weight**	**Volume**
ches	*Pounds*	*Feet^3*	*Pounds*	*Feet^3*	*Pounds*	*Feet^3*	*Pounds*	*Feet^3*	*Pounds*	*Feet^3*
5	187.5	3.59	232.5	4.34	277.6	5.09	322.6	5.84	367.7	6.59
	(18.1)[1]	(.51)	(17.0)	(.53)	(16.0)	(.55)	(15.1)	(.58)	(14.2)	(.60)
6	266.8	4.91	331.6	5.99	396.5	7.08	461.4	8.16	526.3	9.24
	(16.3)	(.55)	(14.9)	(.58)	(13.8)	(.62)	(12.8)	(.65)	(12.2)	(.69)
7	360.5	6.47	448.8	7.95	537.1	9.42	625.4	10.90	713.7	12.37
	(14.4)	(.60)	(13.0)	(.65)	(12.1)	(.70)	(11.8)	(.74)	(12.2)	(.79)
8	468.6	8.28	583.9	10.20	699.3	12.13	814.6	14.05	929.9	15.98
	(12.7)	(.66)	(11.9)	(.72)	(12.1)	(.79)	(13.5)	(.85)	(15.6)	(.92)
9	591.1	10.32	737.1	12.76	883.1	15.20	1,029.0	17.63	1,175.0	20.07
	(11.9)	(.73)	(12.5)	(.81)	(14.6)	(.89)	(17.8)	(.97)	(21.5)	(1.05)
10	728.1	12.61	908.3	15.62	1,088.5	18.62	1,268.7	21.63	1,448.9	24.64
	(12.4)	(.80)	(15.1)	(.90)	(19.2)	(1.00)	(24.1)	(1.11)	(29.2)	(1.21)
11	879.5	15.14	1,097.5	18.77	1,315.5	22.41	1,533.6	26.05	1,751.6	29.69
	(14.6)	(.89)	(19.5)	(1.01)	(25.4)	(1.13)	(31.7)	(1.26)	(38.3)	(1.38)
12	1,045.2	17.90	1,304.7	22.23	1,564.2	26.56	1,823.7	30.89	2,083.2	35.22
	(18.2)	(.98)	(25.1)	(1.13)	(32.6)	(1.28)	(40.5)	(1.42)	(48.5)	(1.57)
13	1,225.4	20.91	1,530.0	25.99	1,834.5	31.07	2,139.1	36.15	2,443.6	41.24
	(22.9)	(1.08)	(31.6)	(1.26)	(40.8)	(1.43)	(50.2)	(1.61)	(59.8)	(1.78)
14	1,420.1	24.16	1,773.2	30.05	2,126.4	35.94	2,479.6	41.84	2,832.8	47.73
	(28.4)	(1.19)	(39.0)	(1.40)	(49.9)	(1.60)	(60.9)	(1.80)	(72.0)	(2.01)
15	1,629.1	27.64	2,034.5	34.41	2,440.0	41.18	2,845.4	47.94	3,250.9	54.71
	(34.6)	(1.31)	(47.0)	(1.55)	(59.7)	(1.78)	(72.4)	(2.01)	(85.3)	(2.25)
16	1,852.5	31.37	2,313.8	39.07	2,775.2	46.77	3,236.5	54.47	3,697.8	62.17
	(41.4)	(1.44)	(55.7)	(1.71)	(70.2)	(1.97)	(84.8)	(2.24)	(99.5)	(2.51)
17	2,090.4	35.34	2,611.2	44.03	3,132.0	52.72	3,652.7	61.41	4,173.5	70.10
	(48.7)	(1.58)	(65.0)	(1.88)	(81.5)	(2.18)	(98.1)	(2.48)	(114.6)	(2.78)
18	2,342.7	39.55	2,926.5	49.30	3,510.4	59.04	4,094.2	68.78	4,678.1	78.52
	(56.6)	(1.72)	(75.0)	(2.06)	(93.5)	(2.40)	(112.1)	(2.74)	(130.7)	(3.07)

numbers in parentheses give a confidence interval on the mean.

Table 4.—*Balsam fir tree weight and tree volume (95 percent confidence limit on the mean)*

	Tree length (feet)									
	30		**40**		**50**		**60**		**70**	
D.b.h.	**Weight**	**Volume**	**Weight**	**Volume**	**Weight**	**Volume**	**Weight**	**Volume**	**Weight**	**Volun**
Inches	*Pounds*	*Feet³*	*Pounds*	*Feet³*	*Pounds*	*Feet³*	*Pounds*	*Feet³*	*Pounds*	*Fe*
5	202.7	3.79	245.7	4.64	288.7	5.48	331.7	6.32	374.7	7.
	(47.4)[1]	(.40)	(44.2)	(.39)	(41.2)	(.38)	(38.4)	(.37)	(35.9)	(.
6	259.5	4.91	321.4	6.12	383.3	7.34	445.2	8.55	507.1	9.
	(43.2)	(.39)	(39.0)	(.37)	(35.4)	(.36)	(32.5)	(.36)	(30.6)	(.
7	326.5	6.22	410.8	7.88	495.1	9.53	579.4	11.18	663.7	12.
	(38.7)	(.37)	(34.0)	(.36)	(30.9)	(.35)	(29.7)	(.35)	(30.8)	(.
8	403.9	7.74	514.0	9.90	624.1	12.06	734.2	14.22	844.3	16.
	(34.4)	(.36)	(30.4)	(.35)	(30.0)	(.35)	(33.3)	(.36)	(39.3)	(.
9	491.7	9.46	631.0	12.20	770.3	14.93	909.6	17.66	1,048.9	20.
	(31.0)	(.35)	(30.1)	(.35)	(35.0)	(.37)	(43.7)	(.39)	(54.5)	(.
10	589.7	11.39	761.7	14.76	933.7	18.14	1,105.7	21.51	1,277.7	24.
	(29.7)	(.35)	(34.6)	(.36)	(45.5)	(.40)	(59.2)	(.45)	(74.3)	(.
11	698.1	13.51	906.2	17.60	1,114.3	21.68	1,322.4	25.76	1,530.5	29.
	(31.8)	(.36)	(43.5)	(.39)	(60.0)	(.45)	(78.3)	(.52)	(97.4)	(.
12	816.7	15.84	1,064.4	20.70	1,312.1	25.56	1,559.8	30.42	1,807.5	35.
	(37.6)	(.37)	(55.8)	(.43)	(77.3)	(.52)	(100.1)	(.62)	(123.4)	(.
13	945.7	18.37	1,236.4	24.08	1,527.1	29.78	1,817.8	35.48	2,108.5	41.
	(46.4)	(.40)	(70.6)	(.49)	(97.1)	(.61)	(124.4)	(.74)	(152.1)	(.
14	1,085.1	21.11	1,422.2	27.72	1,759.3	34.33	2,096.4	40.95	2,433.5	47.
	(57.5)	(.44)	(87.4)	(.56)	(118.9)	(.71)	(151.0)	(.87)	(183.4)	(1.
15	1,234.7	24.04	1,621.7	31.63	2,008.7	39.23	2,395.7	46.82	2,782.7	54.
	(70.4)	(.49)	(105.9)	(.65)	(142.6)	(.82)	(179.7)	(1.01)	(217.1)	(1.
16	1,394.7	27.18	1,835.0	35.82	2,275.3	44.46	2,715.6	53.10	3,155.9	61.
	(84.8)	(.55)	(126.0)	(.74)	(168.1)	(.95)	(210.6)	(1.17)	(253.2)	(1.
17	1,564.9	30.53	2,062.0	40.27	2,559.1	50.03	3,056.2	59.78	3,553.3	69
	(100.6)	(.62)	(147.7)	(.85)	(195.5)	(1.09)	(243.6)	(1.34)	(291.8)	(1
18	1,745.5	34.06	2,302.8	45.00	2,860.1	55.93	3,417.4	66.87	3,974.7	77.
	(117.6)	(.70)	(170.8)	(.97)	(224.6)	(1.24)	(278.6)	(1.52)	(332.8)	(1

[1] The numbers in parentheses give a confidence interval on the mean.

ble 5.—*Sugar maple tree weight and tree volume (95 percent confidence intervals on the mean)*

	Tree height (feet)											
	40		50		60		70		80		90	
b.h.	**Weight**	**Volume**	**Weight**	**Volume**	**Weight**	**Volume**	**Weight**	**Volume**	**Weight**	**Volume**	**Weight**	**Volume**
ches	*Pounds*	*Feet^3*	*Pounds*	*Feet^3*	*Pounds*	*Feet^3*	*Pounds*	*Feet^3*	*Pounds*	*Feet^3*	*Pounds*	*Feet^3*
5	194.0	2.82	236.0	3.59	277.9	4.37	320.0	5.20	362.0	5.97	403.9	6.75
	(21.3)[1]	(.39)	(20.8)	(.37)	(20.3)	(.37)	(20.1)	(.37)	(19.8)	(.36)	(19.5)	(.36)
6	267.8	4.18	328.2	5.30	388.7	6.42	449.3	7.58	509.7	8.70	570.2	9.82
	(20.4)	(.37)	(19.8)	(.36)	(19.5)	(.36)	(19.4)	(.35)	(19.3)	(.35)	(19.3)	(.35)
7	355.1	5.80	437.3	7.31	519.5	8.83	601.8	10.35	684.3	11.92	766.6	13.44
	(19.7)	(.40)	(19.2)	(.34)	(19.0)	(.34)	(19.3)	(.35)	(19.9)	(.36)	(20.6)	(.38)
8	455.8	7.66	563.2	9.64	670.6	11.63	778.0	13.61	885.3	15.59	993.3	17.62
	(19.2)	(.35)	(19.1)	(.35)	(19.6)	(.36)	(20.6)	(.37)	(21.8)	(.39)	(23.85)	(.43)
9	569.9	9.76	705.8	12.28	841.7	14.79	977.6	17.30	1,113.6	19.81	1,250.2	22.37
	(19.1)	(.34)	(19.8)	(.36)	(21.3)	(.39)	(23.3)	(.42)	(25.8)	(.47)	(28.9)	(.53)
10	697.8	12.17	865.3	15.22	1,033.0	18.32	1,200.8	21.42	1,368.6	24.53	1,537.3	27.67
	(20.0)	(.36)	(21.6)	(.39)	(24.3)	(.44)	(27.5)	(.50)	(31.2)	(.57)	(35.7)	(.65)
11	838.8	14.78	1,041.4	18.48	1,244.4	22.23	1,447.5	25.98	1,650.5	29.73	1,854.6	33.53
	(21.5)	(.39)	(24.4)	(.44)	(28.4)	(.52)	(33.1)	(.60)	(38.1)	(.69)	(43.8)	(.80)
12	993.8	17.63	1,234.4	22.04	1,496.0	26.51	1,717.6	30.98	1,959.3	35.44	2,202.1	39.94
	(23.8)	(.43)	(28.3)	(.51)	(33.8)	(.61)	(39.8)	(.73)	(46.1)	(.83)	(53.1)	(.97)
13	1,161.2	20.73	1,444.1	25.92	1,727.7	31.16	2,011.3	36.40	2,294.9	41.64	2,578.4	46.88
	(27.0)	(.49)	(33.0)	(.60)	(40.0)	(.73)	(47.5)	(.86)	(55.1)	(1.00)	(62.9)	(1.14)
14	1,342.5	24.07	1,670.6	30.11	1,999.5	36.18	2,328.4	42.26	2,657.3	48.34	2,986.2	54.42
	(31.0)	(.56)	(38.5)	(.70)	(47.1)	(.85)	(56.0)	(1.02)	(65.1)	(1.18)	(74.3)	(1.35)
15	1,537.3	27.67	1,914.0	34.60	2,291.5	41.58	2,669.1	48.56	3,046.6	55.53	3,424.2	62.51
	(35.7)	(.65)	(44.9)	(.81)	(55.0)	(1.00)	(65.5)	(1.19)	(76.0)	(1.37)	(86.7)	(1.57)
16	1,745.5	31.51	2,175.3	39.45	2,603.6	47.35	3,033.2	55.29	3,462.8	63.22	3,892.3	71.16
	(40.9)	(.74)	(52.4)	(.95)	(63.6)	(1.16)	(75.7)	(1.38)	(87.8)	(1.59)	(100.0)	(1.81)
17	1,967.1	35.60	2,452.3	44.56	2,935.9	53.49	3,420.8	62.45	3,905.7	71.41	4,390.7	80.37
	(46.8)	(.85)	(60.0)	(1.09)	(72.9)	(1.32)	(86.6)	(1.57)	(100.4)	(1.82)	(114.3)	(2.07)
18	2,202.1	39.94	2,746.1	49.99	3,288.2	60.00	3,831.9	70.05	4,375.6	80.09	4,919.3	90.14
	(53.1)	(.97)	(68.2)	(1.24)	(82.8)	(1.51)	(98.3)	(1.79)	(113.9)	(2.06)	(129.5)	(2.35)
19	2,450.6	44.53	3,056.8	55.72	3,660.8	66.88	4,266.5	78.08	4,872.3	89.27	5,478.0	100.47
	(60.0)	(1.09)	(77.0)	(1.40)	(93.5)	(1.69)	(110.7)	(2.01)	(128.2)	(2.32)	(145.6)	(2.65)
20	2,712.6	49.37	3,384.2	61.77	4,053.4	74.14	4,724.6	86.54	5,395.8	98.95	6,067.0	111.35
	(67.3)	(1.22)	(86.3)	(1.57)	(104.6)	(1.90)	(123.9)	(2.24)	(143.2)	(2.60)	(162.6)	(2.95)
21	2,987.9	54.45	3,728.4	68.12	4,466.2	81.77	5,206.2	95.44	5,946.2	109.12	6,686.2	122.80
	(75.0)	(1.36)	(96.2)	(1.75)	(116.5)	(2.11)	(137.8)	(2.50)	(159.1)	(2.89)	(180.5)	(3.28)
22	3,276.7	59.78	4,089.3	74.78	4,899.1	89.77	5,711.3	104.78	6,523.4	119.79	7,335.6	134.80
	(83.2)	(1.51)	(106.6)	(1.94)	(128.9)	(2.34)	(152.5)	(2.77)	(175.8)	(3.19)	(199.3)	(3.62)
23	3,578.9	65.36	4,467.1	81.76	5,355.3	98.15	6,239.8	114.55	7,127.5	130.95	8,015.2	147.35
	(91.9)	(1.67)	(117.5)	(2.13)	(143.2)	(2.60)	(167.5)	(3.05)	(193.3)	(3.51)	(219.0)	(3.97)
24	3,894.6	71.19	4,861.7	89.04	5,828.8	106.90	6,791.9	124.75	7,758.4	142.61	8,725.0	160.47
	(101.0)	(1.83)	(128.9)	(2.34)	(157.0)	(2.85)	(183.5)	(3.33)	(211.5)	(3.84)	(239.6)	(4.35)

e numbers in parentheses give a confidence interval on the mean.

Table 6.—*Aspen bole weight and bole volume (95 percent confidence limit on the mean)*

	Bole length (feet)									
	20		30		40		50		60	
D.b.h.	**Weight**	**Volume**	**Weight**	**Volume**	**Weight**	**Volume**	**Weight**	**Volume**	**Weight**	**Volum**
Inches	*Pounds*	*Feet³*	*Pounds*	*Feet³*	*Pounds*	*Feet³*	*Pounds*	*Feet³*	*Pounds*	*Fee*
5	104.3	2.51	145.6	3.31	187.0	4.11	228.3	4.91	269.6	5.7
	(16.7)[1]	(.47)	(15.7)	(.47)	(14.9)	(.46)	(14.1)	(.45)	(13.5)	(.4
6	140.7	3.21	200.2	4.37	259.7	5.52	319.2	6.67	378.7	7.8
	(15.8)	(.47)	(14.6)	(.46)	(13.6)	(.45)	(13.0)	(.45)	(12.7)	(.4
7	183.7	4.05	264.7	5.61	345.7	7.18	426.7	8.74	507.7	10.3
	(14.9)	(.46)	(13.6)	(.45)	(12.8)	(.45)	(12.8)	(.45)	(13.6)	(.4
8	233.3	5.00	339.0	7.05	444.8	9.09	550.6	11.14	656.4	13.1
	(14.0)	(.46)	(12.9)	(.45)	(12.9)	(.45)	(14.2)	(.46)	(16.4)	(.4
9	289.5	6.09	423.3	8.68	557.2	11.27	691.1	13.86	825.0	16.4
	(13.3)	(.45)	(12.8)	(.45)	(14.3)	(.46)	(17.3)	(.48)	(21.1)	(.5
10	352.3	7.31	517.6	10.50	682.9	13.70	848.2	16.89	1,013.5	20.0
	(12.8)	(.45)	(13.7)	(.46)	(17.1)	(.48)	(21.9)	(.51)	(27.3)	(.5
11	421.7	8.65	621.7	12.51	821.7	16.38	1,021.7	20.25	1,221.7	24.1
	(12.8)	(.45)	(15.6)	(.47)	(21.0)	(.50)	(27.6)	(.56)	(34.6)	(.6
12	497.7	10.12	735.8	14.72	973.8	19.32	1,211.8	23.92	1,449.9	28.5
	(13.4)	(.45)	(18.5)	(.48)	(25.9)	(.54)	(34.20)	(.62)	(42.8)	(.7
13	580.4	11.72	859.7	17.12	1,139.1	22.52	1,418.5	27.92	1,697.8	33.3
	(14.8)	(.46)	(22.2)	(.51)	(31.6)	(.59)	(41.7)	(.70)	(52.0)	(.8
14	669.6	13.44	993.6	19.70	1,317.6	25.97	1,641.6	32.23	1,965.6	38.5
	(16.8)	(.47)	(26.6)	(.55)	(38.0)	(.66)	(49.9)	(.79)	(62.0)	(.9
15	765.5	15.29	1,137.4	22.48	1,509.4	29.68	1,881.3	36.87	2,253.2	44.
	(19.4)	(.49)	(31.6)	(.59)	(45.0)	(.73)	(58.9)	(.89)	(72.9)	(1.
16	868.0	17.28	1,291.2	25.46	1,714.3	33.64	2,137.5	41.82	2,650.7	50.
	(22.5)	(.51)	(37.1)	(.65)	(52.6)	(.82)	(68.5)	(1.01)	(84.6)	(1.
17	977.1	19.38	1,454.8	28.62	1,932.5	37.86	2,410.3	47.09	2,888.0	56.
	(26.0)	(.54)	(43.0)	(.71)	(60.8)	(.92)	(78.9)	(1.14)	(97.0)	(1.
18	1,092.8	21.62	1,628.4	31.98	2,164.0	42.33	2,699.5	52.68	3,235.1	63.
	(30.0)	(.58)	(49.4)	(.78)	(69.5)	(1.02)	(89.8)	(1.28)	(110.3)	(1.

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[1] The numbers in parentheses give a confidence interval on the mean.

able 7.—*White spruce bole weight and bole volume (95 percent confidence limit on the mean)*

	Bole length (feet)									
	20		30		40		50		60	
.b.h.	**Weight**	**Volume**	**Weight**	**Volume**	**Weight**	**Volume**	**Weight**	**Volume**	**Weight**	**Volume**
nches	*Pounds*	*Feet^3*	*Pounds*	*Feet^3*	*Pounds*	*Feet^3*	*Pounds*	*Feet^3*	*Pounds*	*Feet^3*
5	196.3	2.85	228.8	3.55	261.3	4.24	293.8	4.94	326.4	5.64
	(45.4)[1]	(.29)	(43.0)	(.28)	(40.7)	(.26)	(38.5)	(.25)	(36.7)	(.24)
6	224.9	3.47	271.7	4.47	318.5	5.47	365.4	6.47	412.2	7.47
	(43.2)	(.28)	(40.0)	(.26)	(37.1)	(.24)	(34.7)	(.22)	(33.0)	(.21)
7	258.7	4.19	322.4	5.55	386.2	6.92	449.9	8.28	513.7	9.64
	(40.8)	(.26)	(36.9)	(.24)	(33.9)	(.22)	(32.1)	(.21)	(31.9)	(.21)
8	297.7	5.02	381.0	6.81	464.3	8.59	547.5	10.37	630.8	12.15
	(38.3)	(.25)	(34.1)	(.22)	(32.0)	(.21)	(32.3)	(.21)	(35.1)	(.23)
9	342.0	5.97	447.3	8.23	552.7	10.48	658.1	12.73	763.5	14.99
	(35.8)	(.23)	(32.2)	(.21)	(32.4)	(.21)	(36.5)	(.24)	(43.4)	(.28)
10	391.4	7.03	521.5	9.81	651.6	12.60	781.7	15.38	911.8	18.16
	(33.7)	(.22)	(31.9)	(.21)	(36.2)	(.23)	(44.7)	(.29)	(55.6)	(.36)
11	446.0	8.20	603.5	11.57	760.9	14.93	918.3	18.30	1,075.7	21.67
	(32.2)	(.21)	(34.0)	(.22)	(43.2)	(.28)	(56.2)	(.36)	(71.1)	(.46)
12	505.9	9.48	693.2	13.49	880.6	17.49	1,067.9	21.50	1,255.3	25.51
	(31.8)	(.21)	(38.6)	(.25)	(52.9)	(.34)	(70.3)	(.45)	(89.0)	(.57)
13	570.9	10.87	790.8	15.57	1,010.7	20.28	1,230.5	24.98	1,450.4	29.69
	(32.9)	(.21)	(45.4)	(.29)	(64.8)	(.42)	(86.5)	(.56)	(109.2)	(.70)
14	641.2	12.37	896.2	17.83	1,151.2	23.28	1,406.2	28.74	1,661.2	34.20
	(35.6)	(.23)	(54.2)	(.35)	(78.5)	(.51)	(104.6)	(.67)	(131.4)	(.85)
15	716.7	13.99	1,009.4	20.25	1,302.1	26.51	1,594.8	32.78	1,887.6	39.04
	(40.1)	(.26)	(64.7)	(.42)	(93.8)	(.60)	(124.3)	(.80)	(155.4)	(1.00)
16	797.3	15.71	1,130.4	22.84	1,463.4	29.97	1,796.5	38.09	2,129.5	44.22
	(45.9)	(.30)	(76.4)	(.49)	(110.5)	(.71)	(145.7)	(.94)	(181.4)	(1.17)
17	883.2	17.55	1,259.2	25.59	1,635.2	33.64	2,011.1	41.68	2,387.1	49.73
	(53.1)	(.34)	(89.4)	(.58)	(128.6)	(.83)	(168.7)	(1.09)	(209.1)	(1.35)
18	974.2	19.50	1,395.8	28.52	1,817.3	37.54	2,238.8	46.56	2,660.3	55.57
	(61.4)	(.40)	(103.5)	(.67)	(147.9)	(.95)	(193.1)	(1.24)	(238.6)	(1.54)

numbers in parentheses give a confidence interval on the mean.

Table 8.—*Red pine bole weight and bole volumes (95 percent confidence limits on the mean)*

D.b.h.	30 Weight	30 Volume	40 Weight	40 Volume	50 Weight	50 Volume	60 Weight	60 Volume	70 Weight	70 Volum
Inches	*Pounds*	*Feet*^{3}	*Pounds*	*Feet*^{3}	*Pounds*	*Feet*^{3}	*Pounds*	*Feet*^{3}	*Pounds*	*Fee*
5	177.4	3.35	220.5	4.07	263.6	4.79	306.7	5.51	349.8	6.2
	(12.4)[1]	(.20)	(11.6)	(.19)	(10.8)	(.18)	(10.1)	(.17)	(9.5)	(.1
6	234.3	4.30	296.3	5.34	358.4	6.37	420.4	7.41	482.4	8.4
	(11.3)	(.19)	(10.3)	(.17)	(9.4)	(.16)	(8.8)	(.15)	(8.4)	(.1
7	301.5	5.42	385.9	6.83	470.4	8.24	554.8	9.65	639.2	11.0
	(10.2)	(.17)	(9.1)	(.15)	(8.4)	(.14)	(8.3)	(.14)	(8.8)	(.1
8	379.0	6.72	489.3	8.55	599.6	10.40	709.9	12.24	820.1	14.0
	(9.2)	(.15)	(8.4)	(.13)	(8.5)	(.14)	(9.5)	(.16)	(11.3)	(.1
9	466.9	8.18	606.5	10.51	746.0	12.84	885.6	15.17	1,025.2	17.5
	(8.4)	(.14)	(8.5)	(.14)	(10.1)	(.17)	(12.5)	(.21)	(15.4)	(.2
10	565.1	9.82	737.4	12.70	909.7	15.58	1,082.0	18.45	1,254.3	21.3
	(8.3)	(.14)	(9.9)	(.17)	(13.0)	(.22)	(16.7)	(.28)	(20.7)	(.3
11	673.7	11.64	882.2	15.12	1,090.6	18.60	1,299.1	22.08	1,507.6	25.5
	(9.1)	(.15)	(12.4)	(.21)	(16.9)	(.28)	(21.8)	(.36)	(27.0)	(.4
12	792.6	13.62	1,040.7	17.76	1,288.8	21.90	1,536.9	26.05	1,785.0	30.1
	(10.8)	(.18)	(15.8)	(.26)	(21.6)	(.36)	(27.7)	(.46)	(33.9)	(.5
13	921.8	15.78	1,213.0	20.64	1,504.2	25.50	1,795.4	30.36	2,086.5	35.2
	(13.2)	(.22)	(19.8)	(.33)	(26.9)	(.45)	(34.2)	(.57)	(41.7)	(.6
14	1,061.4	18.11	1,399.1	23.74	1,736.8	29.38	2,074.5	35.02	2,412.2	40.6
	(16.2)	(.27)	(24.3)	(.40)	(32.7)	(.55)	(41.3)	(.69)	(50.0)	(.8
15	1,211.3	20.61	1,598.9	27.08	1,986.6	33.55	2,374.3	40.02	2,762.0	46.5
	(19.7)	(.33)	(29.2)	(.49)	(39.1)	(.65)	(49.1)	(.82)	(59.1)	(.9
16	1,371.5	23.28	1,812.6	30.65	2,253.7	38.01	2,694.8	45.37	3,135.8	52.
	(23.6)	(.39)	(34.6)	(.58)	(46.0)	(.77)	(57.4)	(.96)	(68.8)	(1.
17	1,542.1	26.13	2,040.0	34.44	2,538.0	42.76	3,035.9	51.07	3,533.9	59.
	(27.8)	(.46)	(40.5)	(.67)	(53.3)	(.89)	(66.2)	(1.10)	(79.2)	(1.
18	1,723.0	29.15	2,281.2	38.47	2,839.5	47.79	3,397.7	57.11	3,956.0	66.
	(32.4)	(.54)	(46.7)	(.78)	(61.1)	(1.02)	(75.6)	(1.26)	(90.2)	(1.

Bole length (feet): 30, 40, 50, 60, 70

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[1] The numbers in parentheses give a confidence interval on the mean.

Table 9.—*Balsam fir bole weight and bole volume (95 percent confidence limits on the mean)*

	Bole length (feet)									
	20		30		40		50		60	
D.b.h.	Weight	Volume	Weight	Volume	Weight	Volume	Weight	Volume	Weight	Volume
Inches	*Pounds*	*Feet³*	*Pounds*	*Feet³*	*Pounds*	*Feet³*	*Pounds*	*Feet³*	*Pounds*	*Feet³*
5	144.6 (29.3)[1]	2.65 (.24)	180.5 ([illegible])	3.35 ([illegible])	216.5 ([illegible])	[illegible] (.20)	[illegible] ([illegible])	4.76 (.19)	[illegible] (21.7)	[illegible] ([illegible])
6	176.2 (27.3)	3.27 (.22)	[illegible] ([illegible])	[illegible] (.20)	[illegible] ([illegible])	[illegible] ([illegible])	[illegible] ([illegible])	6.30 ([illegible])	[illegible] ([illegible])	[illegible] ([illegible])
7	213.6 (25.2)	4.00 (.20)	294.1 ([illegible])	[illegible] (.18)	[illegible] ([illegible])	[illegible] (.16)	425.0 ([illegible])	[illegible] ([illegible])	[illegible] (22.0)	[illegible] (.18)
8	256.8 (23.0)	4.84 (.19)	348.8 (20.2)	6.64 (.16)	[illegible] ([illegible])	[illegible] (.16)	532.9 (23.6)	10.23 (.19)	[illegible] (28.8)	12.02 (.23)
9	305.6 (21.2)	5.79 (.17)	422.1 (20.1)	8.07 (.16)	[illegible] (22.3)	[illegible] (.19)	655.1 (30.8)	12.61 (.25)	[illegible] (39.2)	[illegible] (.32)
10	360.3 (20.0)	6.86 (.16)	504.1 (22.3)	9.67 (.18)	647.9 (30.3)	12.47 (.25)	791.7 (40.8)	15.28 (.33)	935.5 (52.3)	18.08 (.42)
11	420.7 (20.1)	8.04 (.16)	594.7 (27.0)	11.43 (.22)	768.7 (39.0)	14.83 (.32)	942.7 (52.9)	18.22 (.43)	1,116.7 (67.4)	21.61 (.54)
12	486.8 (21.7)	9.33 (.18)	693.9 (33.5)	13.37 (.27)	901.0 (49.5)	17.41 (.40)	1,108.1 (66.6)	21.45 ([illegible])	1,315.1 (84.3)	25.49 (.68)
13	558.7 (24.9)	10.73 (.20)	801.8 (41.6)	15.47 (.34)	[illegible] ([illegible])	20.21 (.50)	1,287.8 (81.9)	[illegible] ([illegible])	1,530.8 (102.9)	29.69 (.83)
14	636.4 (29.6)	12.25 (.24)	918.2 (50.9)	17.74 (.41)	1,200.1 (74.4)	23.24 (.60)	1,481.9 (98.7)	28.74 (.80)	1,763.8 (123.2)	34.24 (.99)
15	719.8 (35.4)	13.87 (.29)	1,043.3 (61.2)	20.18 (.49)	1,366.9 (88.7)	26.50 (.72)	1,690.4 (116.8)	32.81 (.94)	2,014.0 (145.0)	39.12 (1.17)
16	808.9 (42.1)	15.61 (.34)	1,177.1 (72.5)	22.79 (.59)	1,545.2 (104.1)	29.97 (.84)	1,913.3 (136.2)	37.15 (1.10)	2,281.5 (168.5)	44.33 (1.36)
17	903.9 (49.7)	17.46 (.40)	1,319.4 (84.6)	25.57 (.68)	1,735.0 (120.7)	33.68 (.97)	2,150.6 (157.0)	41.78 (1.27)	2,566.2 (193.5)	49.89 (1.56)
18	1,004.5 (58.0)	19.43 (.47)	1,470.4 (97.7)	28.51 (.79)	1,936.3 (138.2)	37.60 (1.12)	2,402.3 (179.1)	46.69 (1.45)	2,868.2 (220.1)	55.78 (1.78)

[1] The numbers in parentheses give a confidence interval on the mean.

Table 10.—Sugar maple bole weight and bole volume (95 percent confidence intervals on the mean)

	Bole length (feet)											
	10		**20**		**30**		**40**		**50**		**60**	
D.b.h.	**Weight**	**Volume**	**Weight**	**Volume**	**Weight**	**Volume**	**Weight**	**Volume**	**Weight**	**Volume**	**Weight**	**Volum**
Inches	*Pounds*	*Feet^3*	*Pounds*	*Feet^3*	*Pounds*	*Feet^3*	*Pounds*	*Feet^3*	*Pounds*	*Feet^3*	*Pounds*	*Feet*
5	90.7	1.36	136.7	2.18	182.6	2.99	228.6	3.81	274.5	4.62	320.5	5.44
	(7.8)[1]	(.13)	(7.2)	(.12)	(6.7)	(.11)	(6.4)	(.11)	(6.5)	(.11)	(6.8)	(.12
6	111.0	1.72	177.1	2.89	243.3	4.07	309.5	5.24	375.6	6.41	441.8	7.59
	(7.5)	(.13)	(6.7)	(.11)	(6.4)	(.11)	(6.7)	(.11)	(7.5)	(.13)	(8.6)	(.15
7	134.9	2.14	224.9	3.74	315.0	5.34	405.0	6.94	495.1	8.53	585.2	10.13
	(7.2)	(.12)	(6.5)	(.11)	(6.8)	(.11)	(7.9)	(.14)	(9.7)	(.16)	(11.8)	(.20
8	162.4	2.63	280.1	4.72	397.7	6.81	515.3	8.90	633.0	10.98	750.6	13.06
	(6.9)	(.11)	(6.5)	(.11)	(7.8)	(.13)	(10.1)	(.18)	(13.0)	(.22)	(16.0)	(.27
9	193.7	3.19	342.6	5.83	491.4	8.47	640.3	11.11	789.2	13.76	938.1	16.39
	(6.6)	(.11)	(7.0)	(.12)	(9.6)	(.16)	(13.1)	(.22)	(17.0)	(.29)	(21.0)	(.36
10	228.6	3.81	412.4	7.07	596.2	10.33	780.0	13.59	963.8	16.86	1,147.6	20.12
	(6.5)	(.11)	(8.1)	(.14)	(12.0)	(.20)	(16.8)	(.28)	(21.8)	(.37)	(26.9)	(.46
11	267.2	4.49	489.6	8.44	712.0	12.39	934.4	16.33	1,156.8	20.28	1,379.2	24.23
	(6.5)	(.11)	(9.6)	(.16)	(15.0)	(.26)	(21.0)	(.35)	(27.2)	(.46)	(33.4)	(.57
12	309.5	5.24	574.1	9.94	838.8	14.63	1,103.5	19.32	1,368.2	24.02	1,632.8	28.71
	(6.7)	(.11)	(11.5)	(.20)	(18.3)	(.31)	(25.6)	(.43)	(33.1)	(.56)	(40.6)	(.69
13	355.4	6.06	666.0	11.57	976.7	17.07	1,287.3	22.58	1,597.9	28.09	1,908.5	33.6
	(7.2)	(.12)	(13.8)	(.23)	(22.1)	(.38)	(30.8)	(.52)	(39.6)	(.67)	(48.5)	(.8
14	405.0	6.94	765.3	13.33	1,125.5	19.72	1,485.8	26.10	1,846.0	32.49	2,206.3	38.8
	(7.9)	(.13)	(16.4)	(.28)	(26.3)	(.45)	(36.4)	(.62)	(46.7)	(.79)	(57.0)	(.9
15	458.3	7.88	871.9	15.22	1,285.4	22.56	1,699.0	29.89	2,112.5	37.22	2,526.1	44.5
	(8.9)	(.15)	(19.2)	(.33)	(30.8)	(.52)	(42.5)	(.72)	(54.3)	(.92)	(66.2)	(1.1
16	515.3	8.89	985.8	17.24	1,456.4	25.58	1,926.9	33.93	2,397.4	42.27	2,868.0	50.6
	(10.1)	(.17)	(22.4)	(.38)	(35.6)	(.60)	(49.0)	(.83)	(62.5)	(1.06)	(76.1)	(1.2
17	576.0	9.97	1,107.2	19.39	1,638.3	28.81	2,169.5	38.23	2,700.7	47.65	3,231.9	57.0
	(11.5)	(.20)	(25.7)	(.44)	(40.8)	(.69)	(56.0)	(.95)	(71.3)	(1.21)	(86.5)	(1.4
18	640.3	11.11	1,235.8	21.67	1,831.3	32.23	2,426.8	42.80	3,022.4	53.36	3,617.9	63.9
	(13.1)	(.22)	(29.4)	(.50)	(46.3)	(.78)	(63.4)	(1.07)	(80.5)	(1.36)	(97.7)	(1.6

[1] The numbers in parentheses give a confidence interval on the mean.

Table 11.—*Residue weight and volume (95 percent confidence limit on the mean)*

	Aspen		White spruce		Red pine		Balsam fir		Sugar maple pulpwood	
D.b.h.	**Weight**	**Volume**	**Weight**	**Volume**	**Weight**	**Volume**	**Weight**	**Volume**	**Weight**	**Volume**
Inches	*Pounds*	*Feet^3*	*Pounds*	*Feet^3*	*Pounds*	*Feet^3*	*Pounds*	*Feet^3*	*Pounds*	*Feet^3*
5	38.2	0.99	65.0	0.93	26.5	0.51	89.8	1.77	103.2	1.77
	(17.3)[1]	(.37)	(49.0)	(1.01)	(9.0)	(.16)	(32.9)	(.72)	(12.9)	(.27)
6	63.2	1.47	101.0	1.68	48.5	0.87	119.9	2.37	130.8	2.27
	(14.9)	(.32)	(42.5)	(.87)	(7.4)	(.13)	(27.6)	(.60)	(9.9)	(.22)
7	92.9	2.04	143.5	2.58	74.4	1.31	155.3	3.07	163.5	2.85
	(12.9)	(.28)	(36.2)	(.74)	(6.2)	(.11)	(22.8)	(.50)	(9.8)	(.23)
8	127.1	2.69	192.5	3.61	104.3	1.81	196.3	3.88	201.2	3.53
	(12.4)	(.27)	(31.6)	(.65)	(6.4)	(.11)	(20.8)	(.45)	(13.3)	(.31)
9	165.8	3.43	248.1	4.79	138.1	2.37	242.7	4.79	243.9	4.30
	(14.3)	(.31)	(31.4)	(.65)	(8.4)	(.15)	(24.3)	(.53)	(19.5)	(.45)
10	209.1	4.25	310.3	6.10	176.0	3.01	294.6	5.82	291.6	5.26
	(18.4)	(.39)	(37.4)	(.77)	(11.8)	(.21)	(32.8)	(.72)	(27.3)	(.62)
11	257.0	5.17	378.9	7.54	217.9	3.71	351.9	6.95	344.4	6.10
	(24.3)	(.52)	(48.8)	(1.00)	(16.0)	(.28)	(44.8)	(.98)	(36.2)	(.82)
12	309.4	6.17	454.1	9.13	263.7	4.48	414.7	8.19	402.2	7.14
	(31.3)	(.67)	(64.0)	(1.32)	(20.8)	(.37)	(59.0)	(1.29)	(46.3)	(1.05)
13	366.4	7.26	535.9	10.85	313.5	5.31	482.9	9.54	465.0	8.27
	(39.4)	(.84)	(81.9)	(1.68)	(26.2)	(.46)	(75.1)	(1.64)	(57.3)	(1.29)
14	427.9	8.43	624.2	12.71	367.3	6.21	556.7	10.99	532.9	9.49
	(48.3)	(1.03)	(102.0)	(2.10)	(32.1)	(.57)	(92.9)	(2.02)	(69.2)	(1.56)
15	494.0	9.69	719.0	14.71	425.1	7.18	635.8	12.55	605.8	10.80
	(58.0)	(1.24)	(124.1)	(2.55)	(38.4)	(.68)	(112.1)	(2.44)	(82.1)	(1.84)
16	564.6	11.04	820.4	16.85	486.9	8.21	720.5	14.23	683.7	12.20
	(68.4)	(1.46)	(148.0)	(3.04)	(45.3)	(.80)	(132.8)	(2.90)	(95.9)	(2.15)
17	639.9	12.48	928.3	19.12	552.7	9.31	810.5	16.00	766.6	13.69
	(79.6)	(1.70)	(173.6)	(3.57)	(52.6)	(.93)	(155.0)	(3.38)	(110.7)	(2.47)
18	719.6	14.00	1,042.7	21.53	622.4	10.48	906.1	17.89	854.6	15.27
	(91.5)	(1.96)	(200.9)	(4.13)	(60.4)	(1.07)	(178.5)	(3.89)	(126.3)	(2.82)

[1] The numbers in parentheses give a confidence interval on the mean.

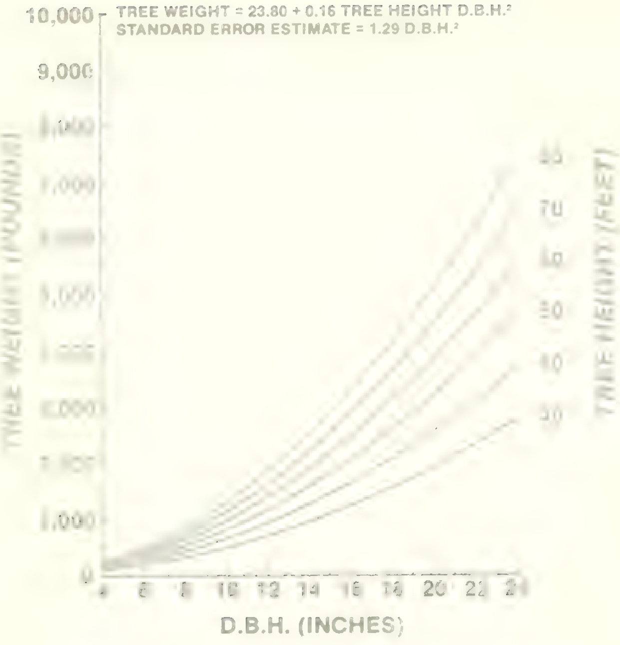

Figure 1.— *Tree weight— aspen.*

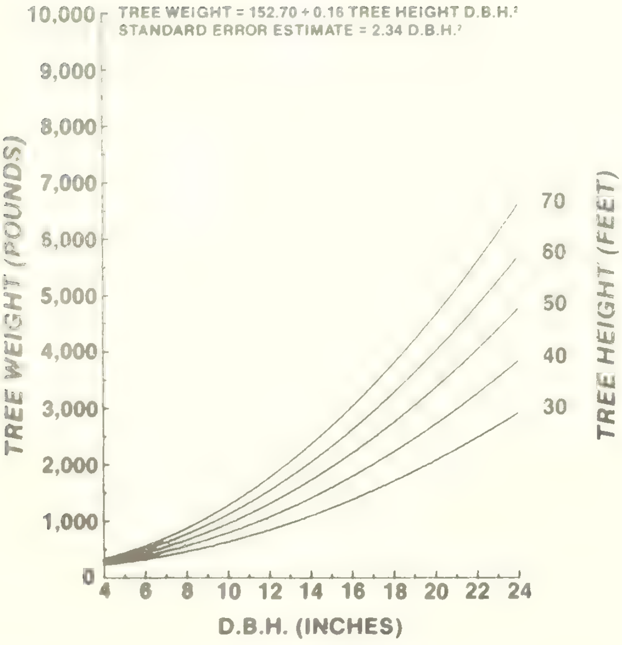

Figure 2.— Tree weight— white spruce.

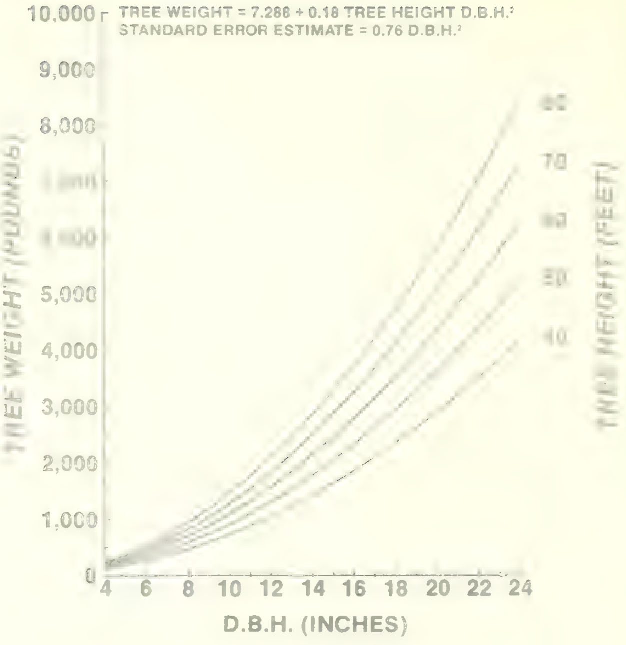

Figure 3.— Tree weight— red pine.

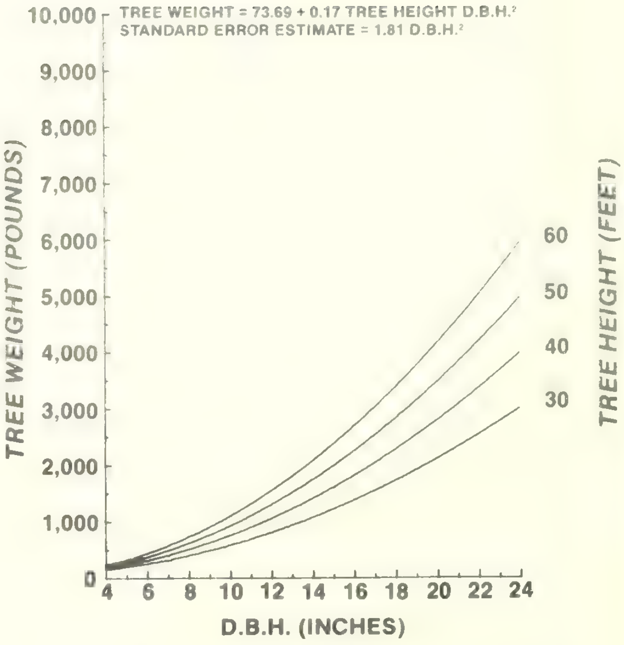

Figure 4.— Tree weight— balsam fir.

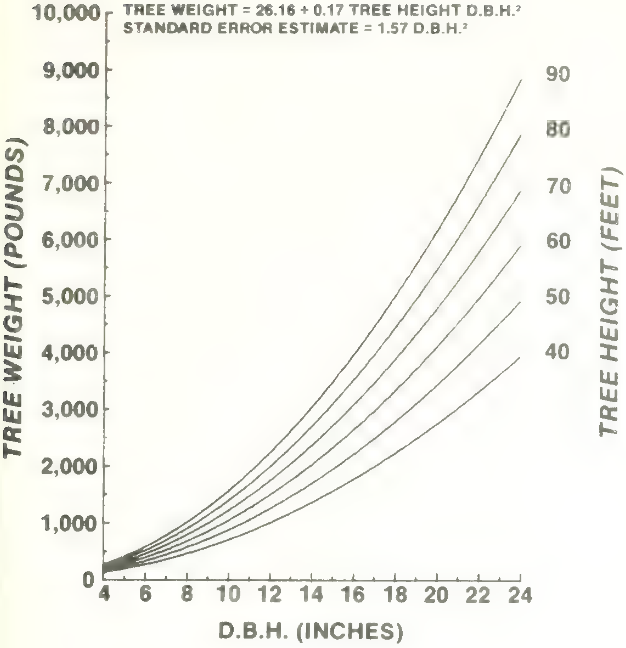

Figure 5.— Tree weight— maple.

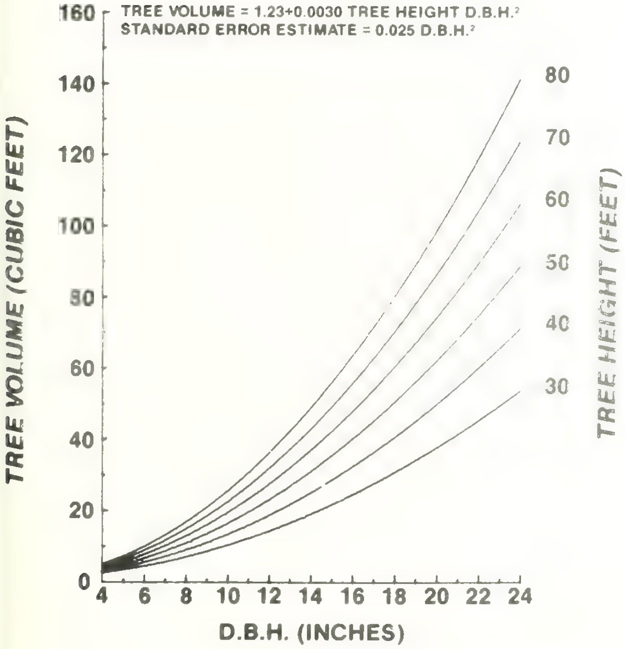

Figure 6.— Tree volume— aspen.

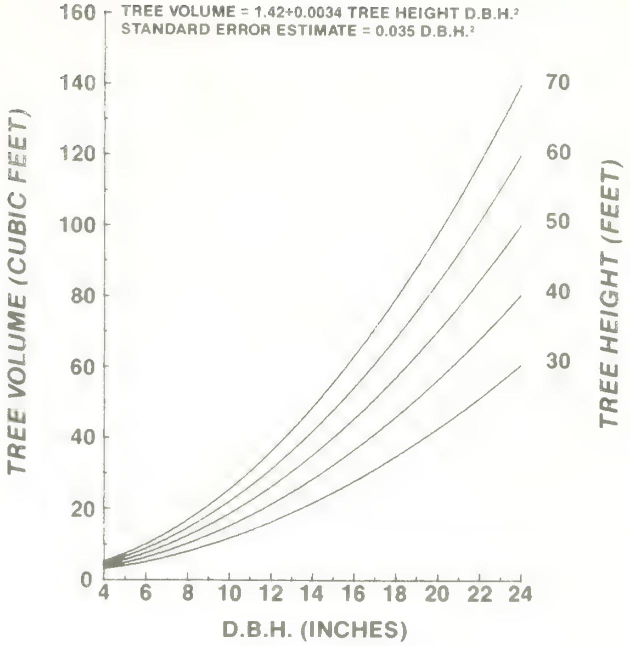

Figure 7.— Tree volume— white spruce.

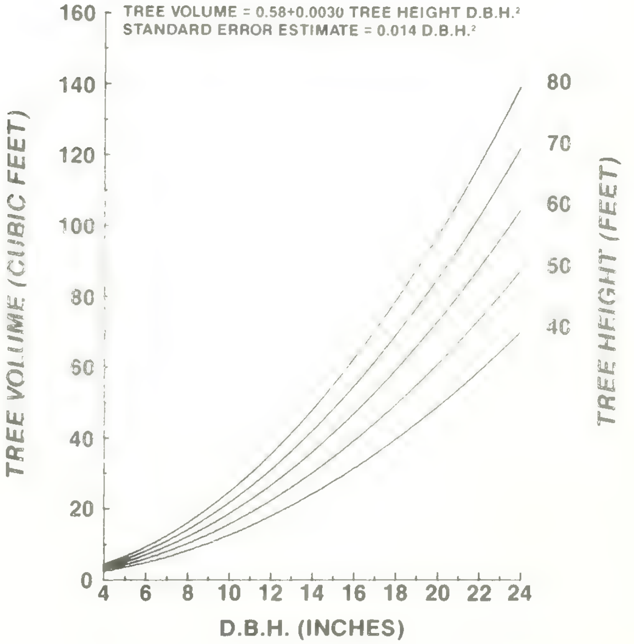

Figure 8.— Tree volume— red pine.

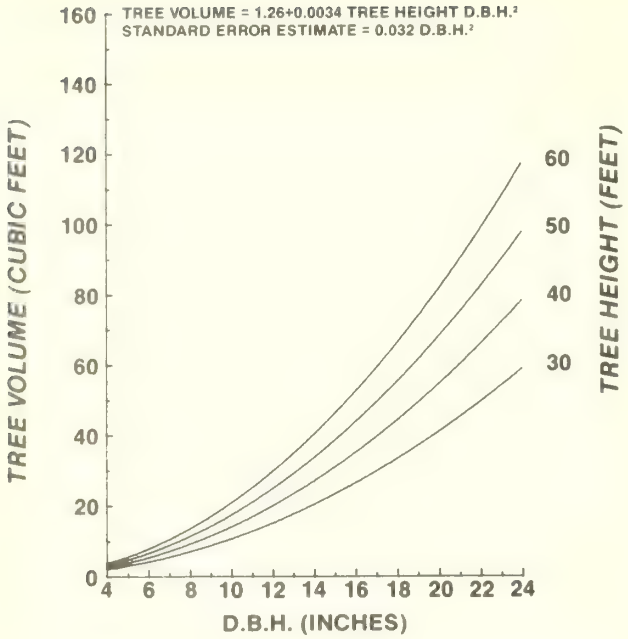

Figure 9.— Tree volume— balsam fir.

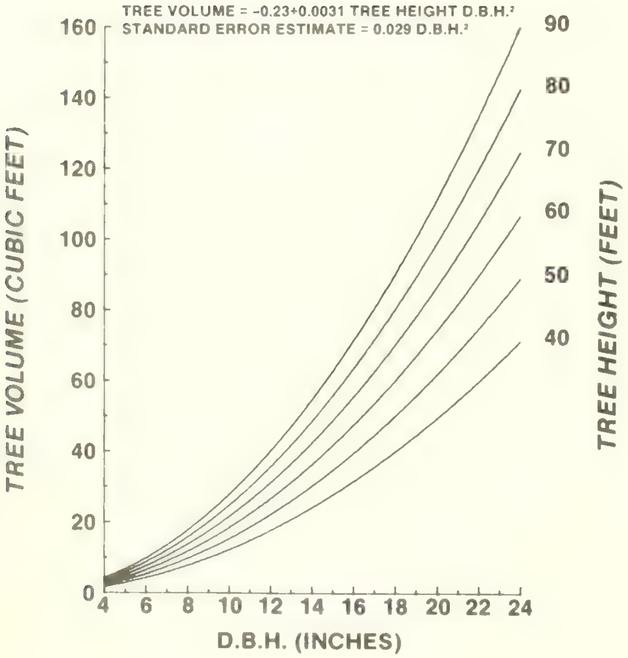

Figure 10.— Tree volume— maple.

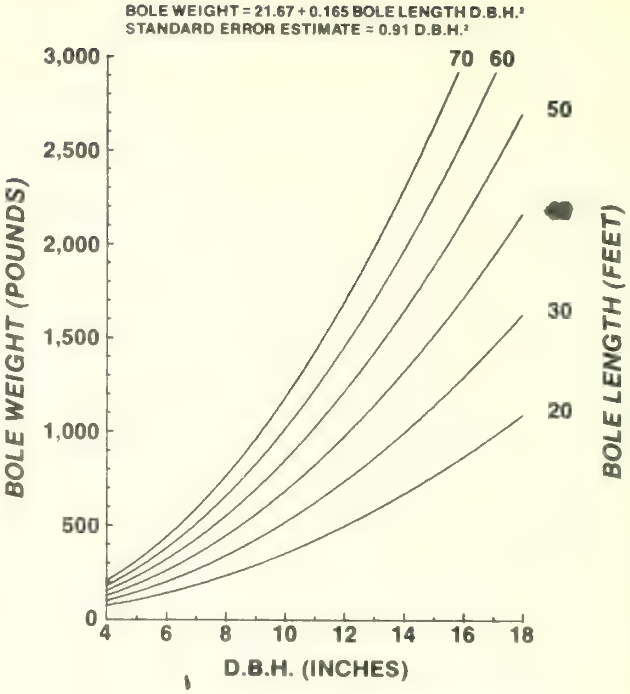

Figure 11.— Bole weight— aspen.

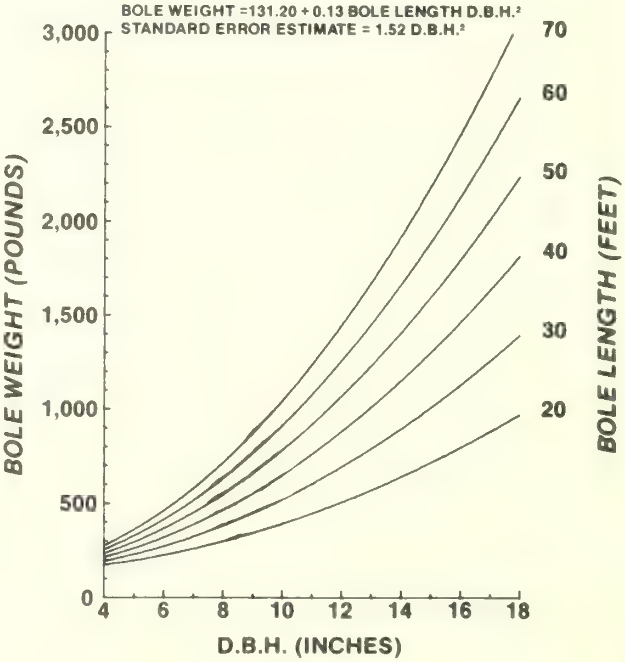

Figure 12.— Bole weight— white spruce.

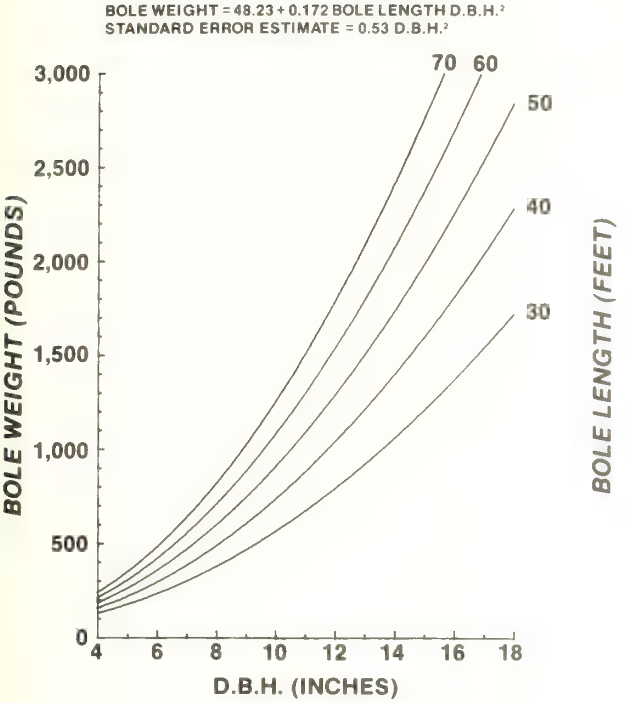

Figure 13.— Bole weight— red pine.

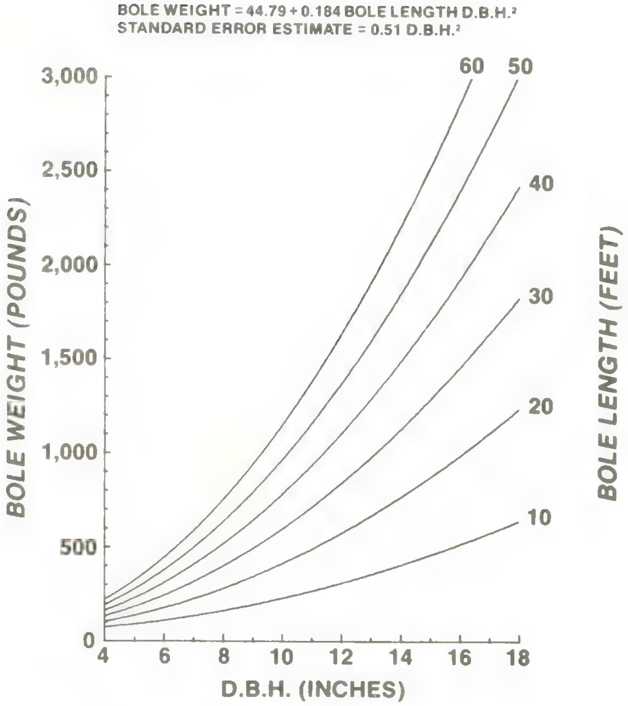

Figure 15.— Bole weight— maple.

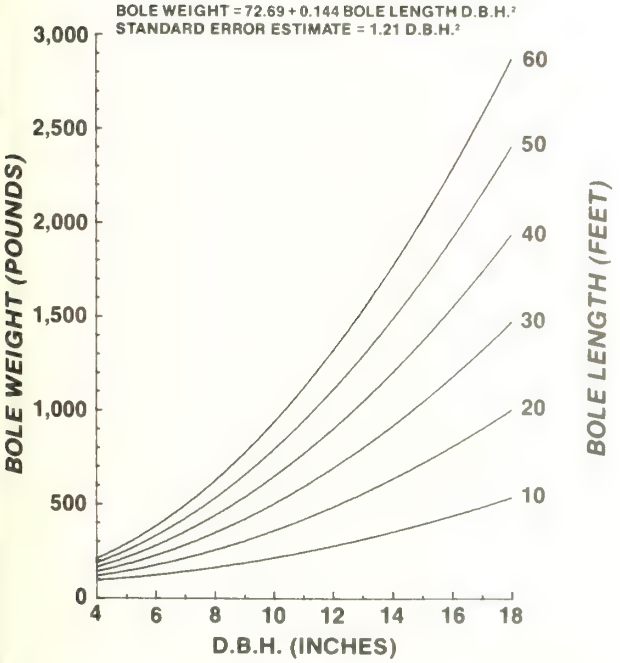

Figure 14.— Bole weight— balsam fir.

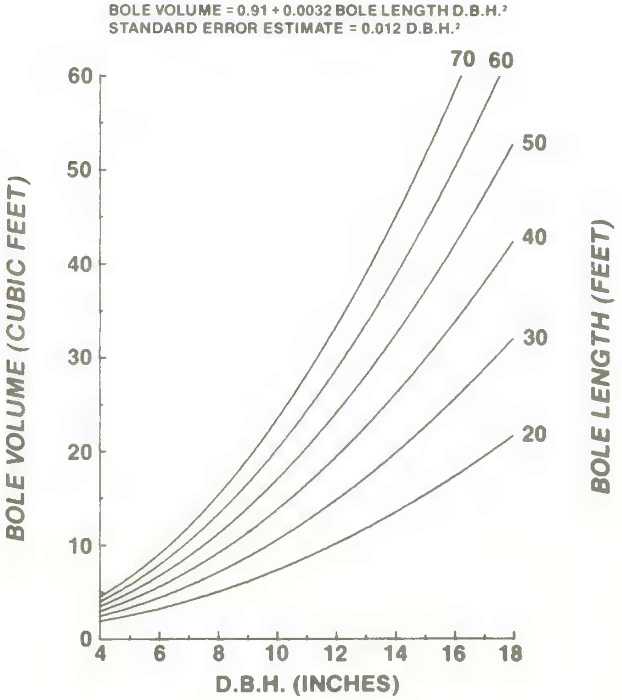

Figure 16.— Bole volume— aspen.

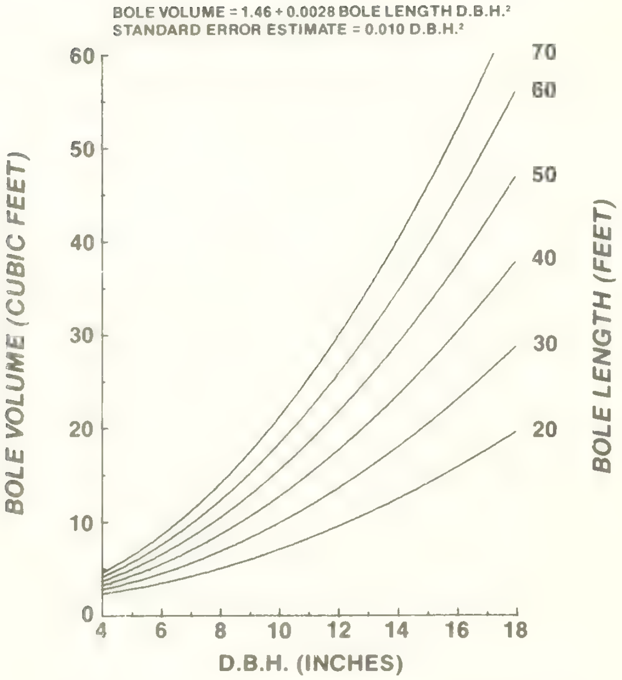

Figure 17.— Bole volume— white spruce.

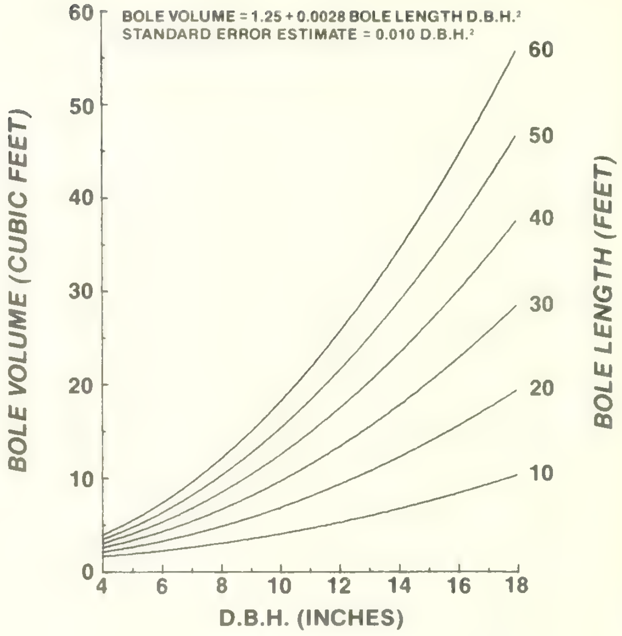

Figure 19.— Bole volume— balsam fir.

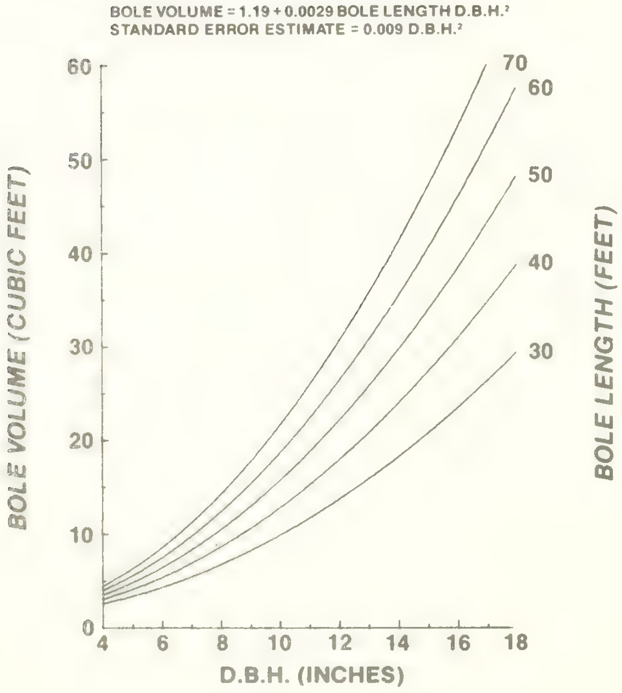

Figure 18.— Bole volume— red pine.

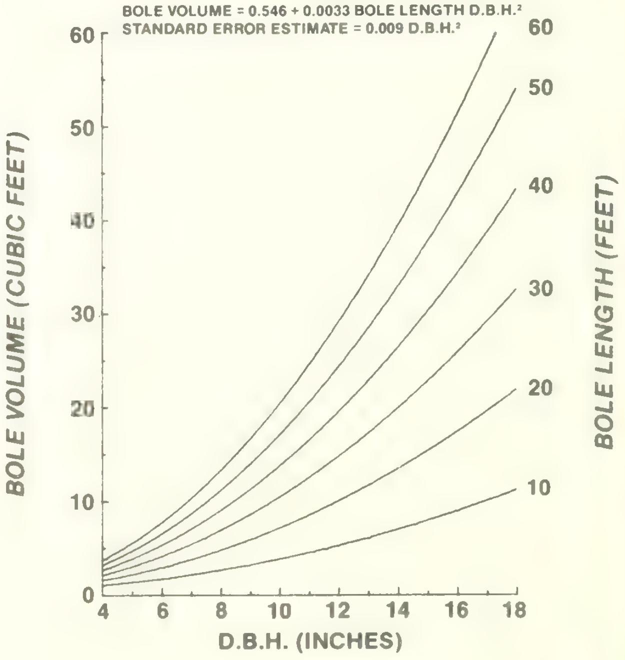

Figure 20.— Bole volume— maple.

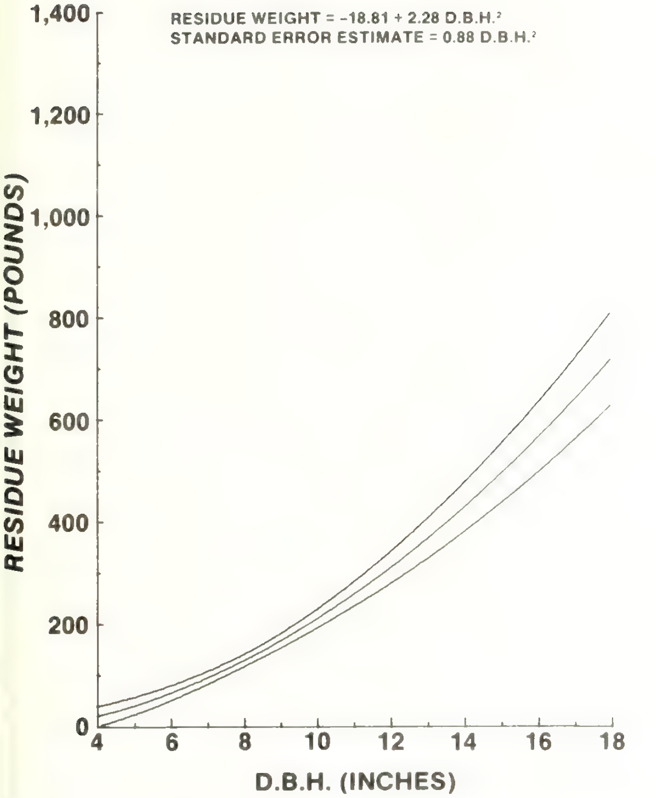

Figure 21.— Aspen residue weight with 95 percent confidence limits on the mean.

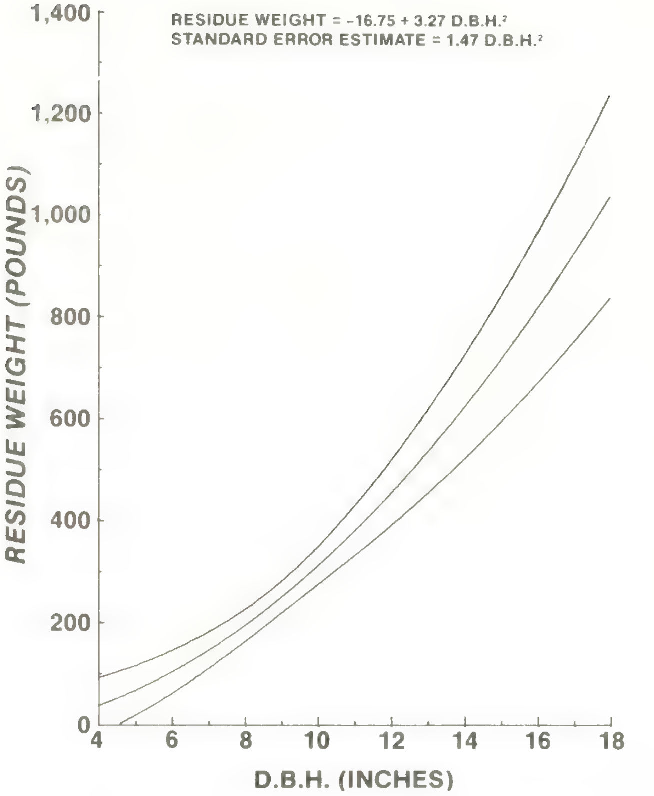

Figure 22.— White spruce residue weight with 95 percent confidence limits on the mean.

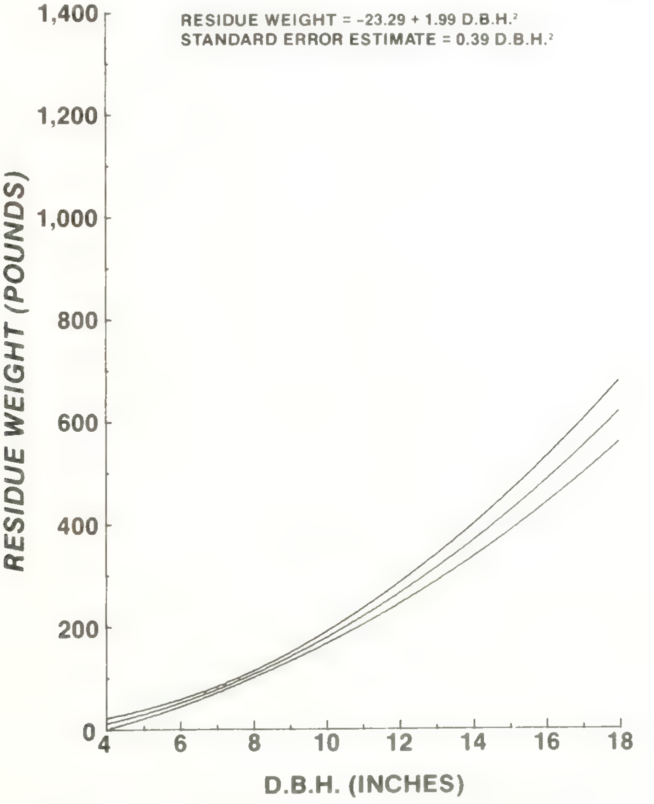

Figure 23.— Red pine residue weight with 95 percent confidence limits on the mean.

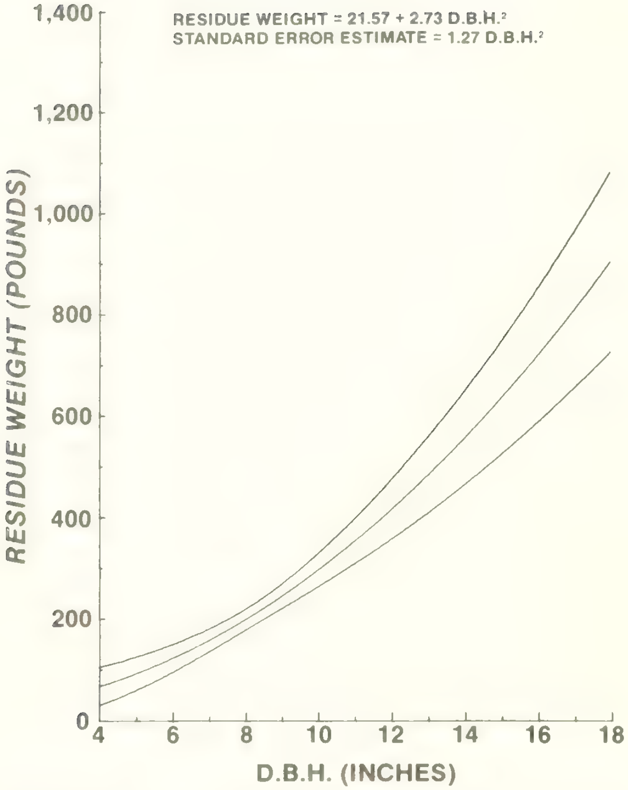

Figure 24.— Balsam fir residue weight with 95 percent confidence limits on the mean.

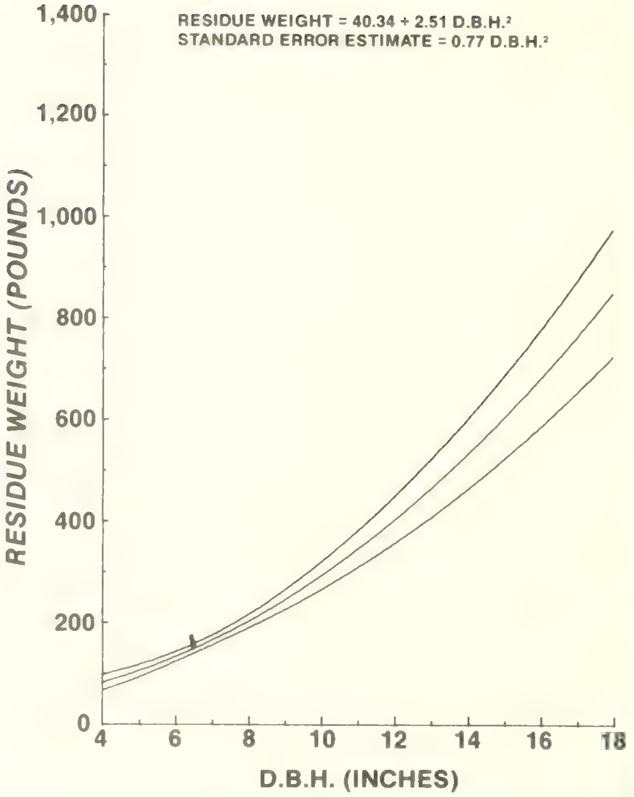

Figure 25.— Maple residue weight with 95 percent confidence limits on the mean.

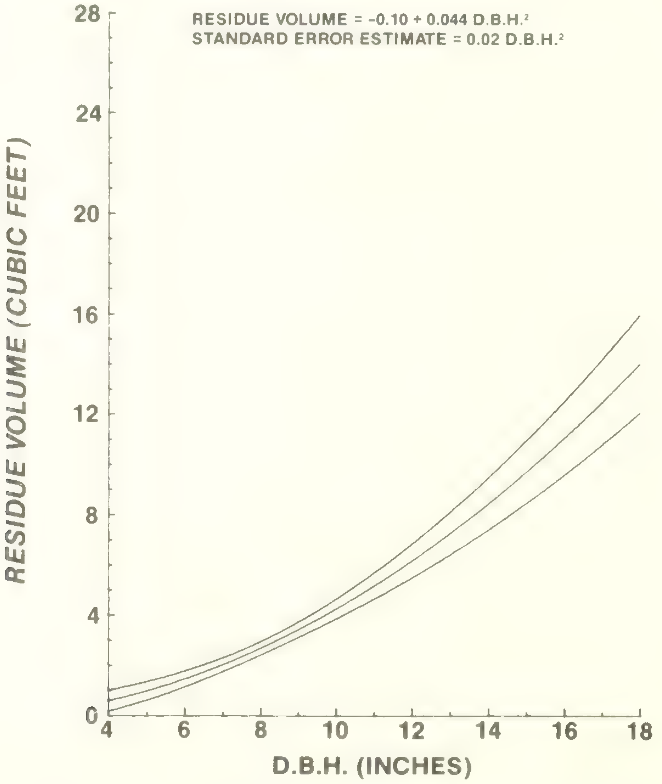

Figure 26.— Aspen residue volume with 95 percent confidence limits on the mean.

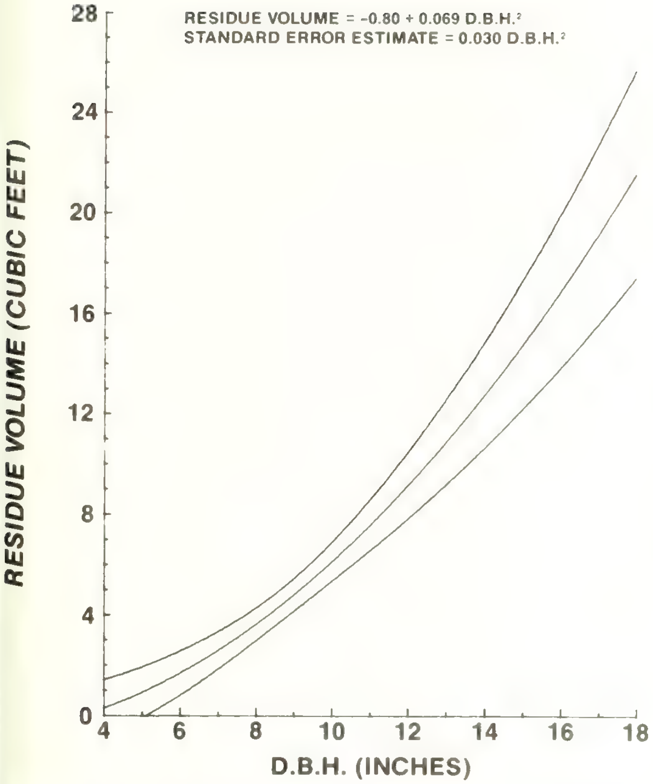

Figure 27.— White spruce residue volume with 95 percent confidence limits on the mean.

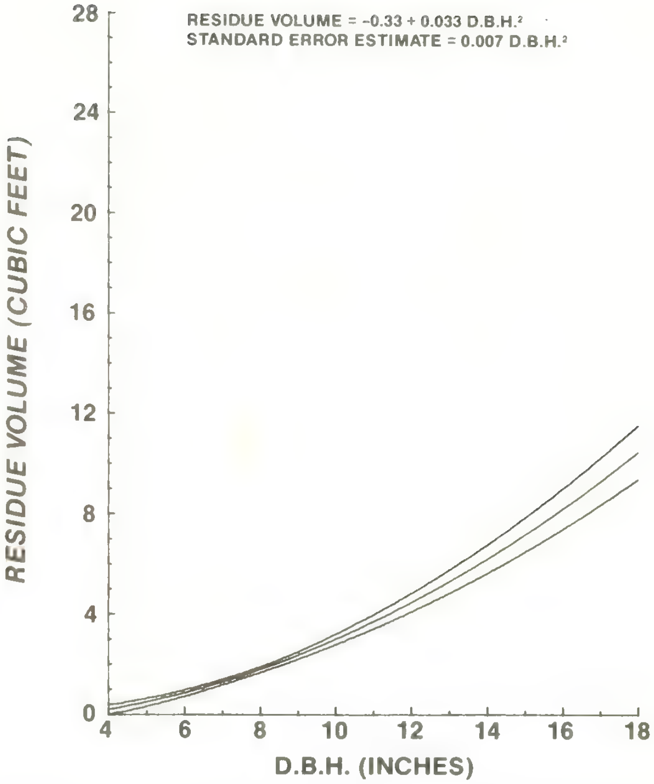

Figure 28.— Red pine residue volume with 95 percent confidence limits on the mean.

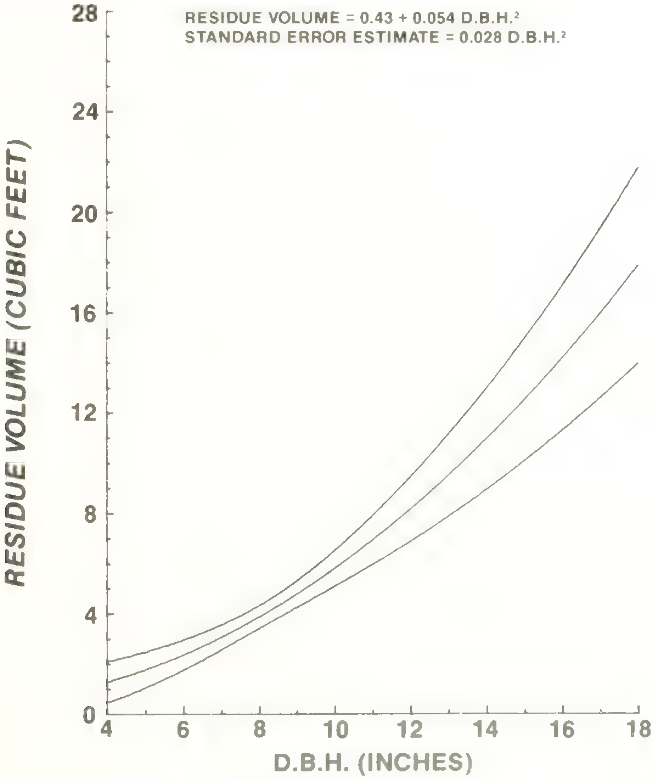

Figure 29.— Balsam fir residue volume with 95 percent confidence limits on the mean.

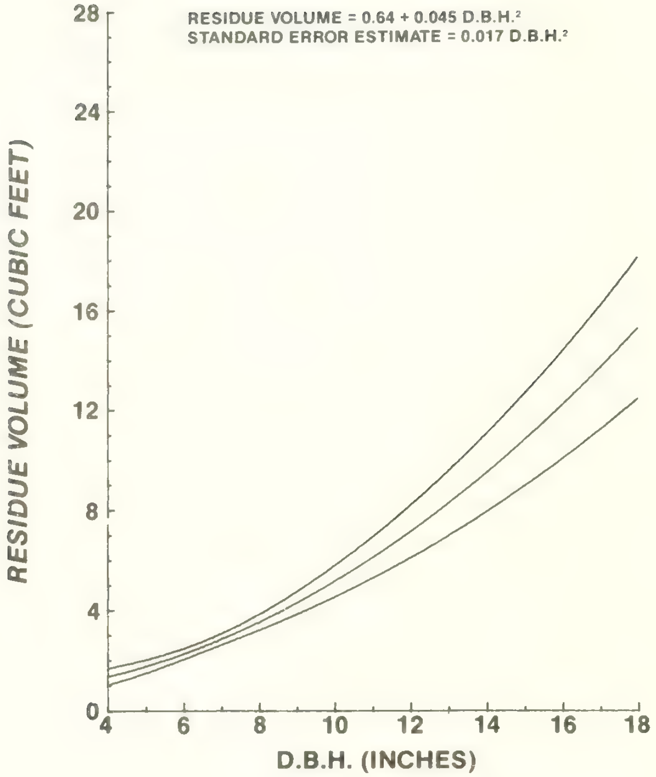

Figure 30.— Maple residue volume with 95 percent confidence limits on the mean.

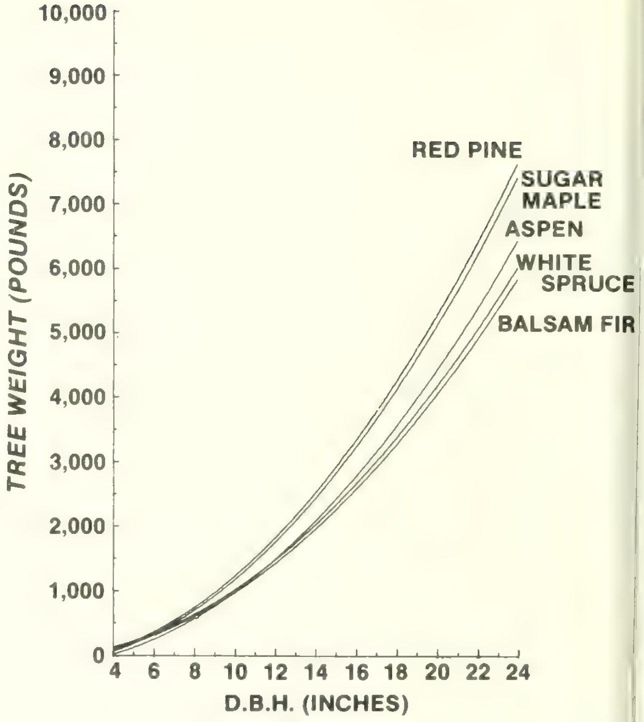

Figure 31.— Tree weight based on d.b.h.— 5 species

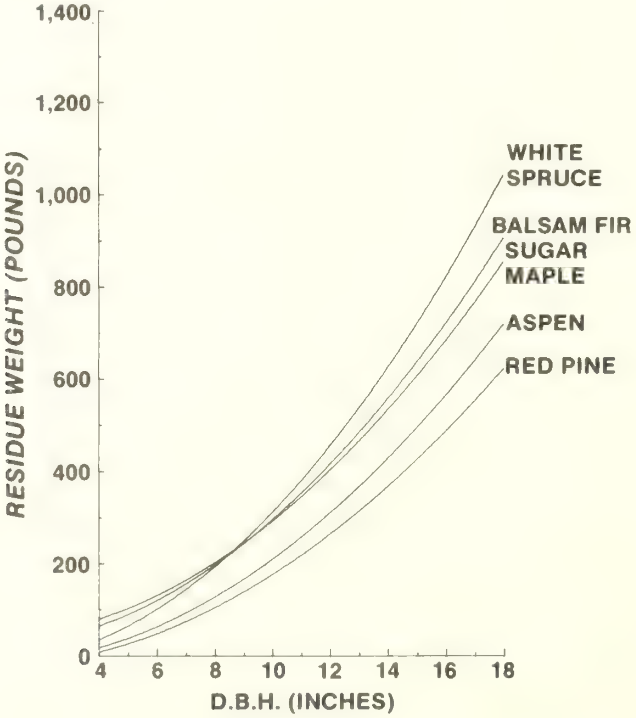

Figure 32.— Residue weight based on d.b.h.— 5 species.

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DA FOREST SERVICE

Winsauer, Sharon A., and Helmuth M. Steinhilb.

1980. Summary of green weights and volumes for five tree species in Michigan. U.S. Department of Agriculture Forest Service, Research Paper NC-191, 22 p., U.S. Department of Agriculture Forest Service, North Central Forest Experiment Station, St. Paul, Minnesota.

Presents and summarizes the green weights and volumes of trees, boles and residue for sugar maple, white spruce, aspen, balsam fir and red pine in Northern Michigan. Equations, tables and graphs are included for each of the five species.

KEY WORDS: Sugar maple, white spruce, aspen, balsam fir, red pine, tree, bole, residue.

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ESEARCH PAPER **NC-192**

A program and documentation for simulation of a **tracked feller/buncher**

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1980

A PROGRAM AND DOCUMENTATION FOR SIMULATION OF A TRACKED FELLER/BUNCHER

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Computer modeling of forest harvesting systems has many applications, each requiring a different approach to simulation. Simulations range from technical descriptions of machine components for improving equipment design to overviews of major systems for estimating large-scale changes in productivity. Forestry Sciences Laboratory personnel at Houghton have been involved for the past several years in developing harvesting simulators for use in forest engineering research (Bradley *et al.* 1976, Bradley and Winsauer 1976, 1978, U.S. Department of Agriculture Forest Service 1978).

The purpose of this paper is to present a computer model and documentation for a tracked feller/buncher (fig. 1). The model was developed to provide a detailed study of this machine's operation in the woods during harvesting operations. It allows the user to identify productive and unproductive conditions, to experiment with ways of increasing machine efficiency, to predict the effects of system changes, and to determine harvest costs for various types of stands and conditions.

THE EQUIPMENT STUDIED

The feller/buncher is a tracked vehicle with a shear mounted on the end of a rotatable hydraulic boom. The shear head can either sever and bunch single stems or accumulate several stems at once. The boom enables the feller/buncher to shear trees up to the boom's maximum reach while maintaining a fairly straight path through the woods; cutting a strip for thinning or in working the face of a clearcut stand.

MODEL OBJECTIVES

The model was designed to study the productivity and operation of the feller/buncher in the woods. Input required includes data on the machine's operating characteristics, the stand itself, and the type of harvest to be carried out.

Model output includes productivity figures such as number of trees, weight and volume harvested per hour or load, number of total cycles (accumulator head loads), number of trees per cycle, total distance traveled, and skid bunches completed.

Additional output includes details of the woods operation, distribution of cycle times, distances, number of trees per bunch, size of skidder bunches, and frequency and length of delays.

Figure 1.—*Tracked feller/buncher.*

SIMULATION LANGUAGE —GPSS

The simulation is written in General Purpose Simulation Language (GPSS), with output subroutines written in FORTRAN. GPSS is a discrete-event simulation language developed by IBM (Schriber 1974). The user constructs a block diagram by arranging the discrete events of a system in their logical structure. The block diagram is made up of a group of specific GPSS block types, which then become the GPSS program. A basic understanding of the GPSS language allows the user to accurately interpret or modify the simulation.

Most versions of GPSS have a standard output format that concisely presents the data. The FORTRAN subroutines are used to present important output values in an organized, labeled form.

MODEL ASSUMPTIONS

The basic time unit used in the model is a "centiminute"— that is, 1/100 of a minute. The feller works one shift a day for the number of days chosen by the user. All volume measures are in 0.01 cu. ft.

The feller/buncher is assumed to operate far enough in advance of the skidder to minimize interactions between machines. To simulate a "hot" logging operation, this model can be combined with a complete skidding-chipping or skidding-loader model. Another alternative would be to add a "black box" skidder segment, a simplified segment used to create the machine interactions without a detailed study of the skidder operation.

Since an efficient skidder load usually contains more trees than the shear can hold, the feller/buncher may shear and drop several loads at one location to create the skidder bunch.

The following assumptions are made about the feller/buncher's behavior:

1. The machine has an accumulating shear. (The model can easily be changed to single-head shear).

2. The feller/buncher travels in a relatively straight row, either along the edge of a clearcut or down a thinning strip, harvesting all trees within reach that are scheduled for cutting. At the end of the strip, it travels through the woods to the next strip, then returns along that strip toward the landing (fig. 2).

3. If there are no more trees within the feller's reach, the bunch it was working on is considered complete and the feller must move forward— it does not back up.

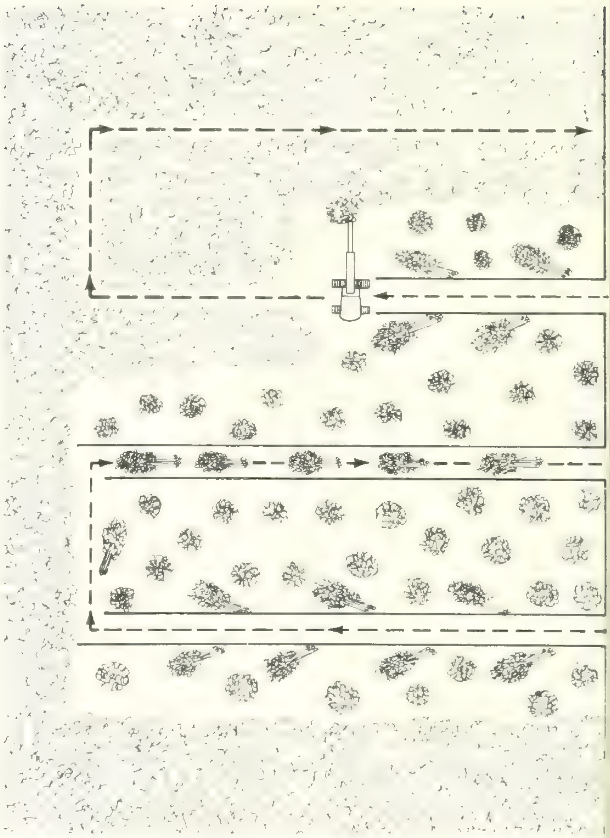


Figure 2.—*Feller/buncher travel pattern.*

4. If a bunch is not started at a given location (only one accumulator head load has been cut), the feller will carry the trees in the shear head to the next location. (Exception: if the end of the row (strip) has been reached, the feller will drop the load there before traveling to the next strip.

5. The feller/buncher can quit for the day or stop for a break only after completing a bunch for the skidder.

6. Mechanical and nonmechanical delays are incorporated into the model. For ease of programming, they are assumed to occur after the feller/buncher drops the current load of trees.

MODEL DESCRIPTION

The model consists of two GPSS segments: (1. **Timer segment**, 2. **Feller/buncher segment**) and two FORTRAN subroutines for easily read output. A complete variable list, program listing, and flow charts are contained in Appendixes A, B, and C

The **Timer segment** (fig. 3) controls the daily schedule, keeps track of the days worked, and sends information to the subroutines. The **Timer** signals the start of the day, the rest breaks and the lunch break (two 15-minute breaks a day and ½ hour lunch break are assumed), and the end of the workday. The **Timer** then completes the 24-hour day and produces a report of the previous day's operation and production. Output is produced at the end of 24 hours— not at the end of the shift— to include the time needed for the feller to complete the bunch being worked on before quitting for the day. If the required number of days has been simulated, the model shuts off. Otherwise the start of another work day is signaled and the process continues.

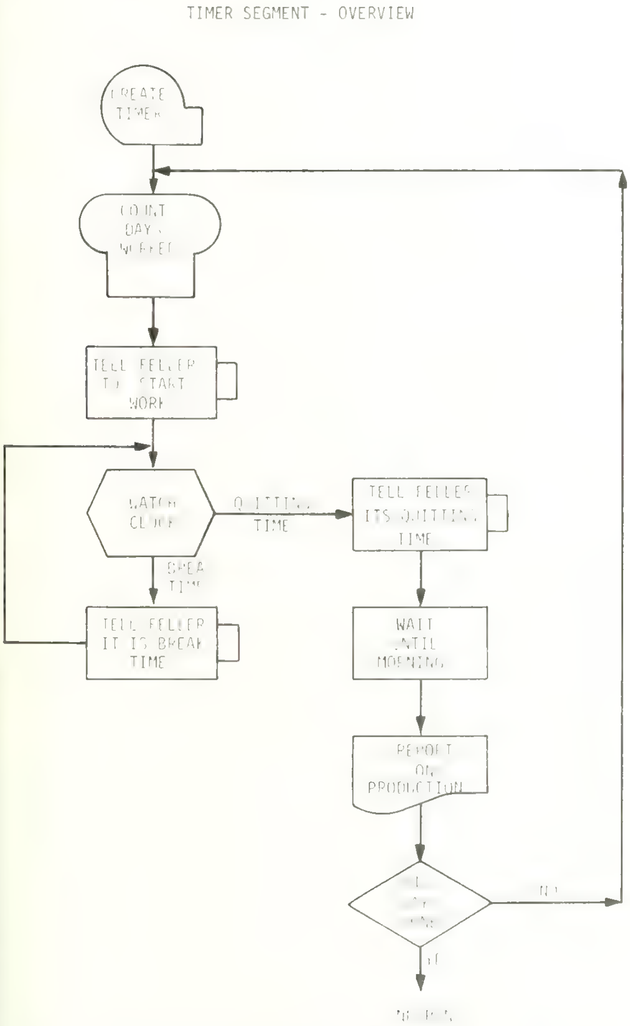


Figure 3.—*Overview of the* **timer segment.**

The **Feller/buncher segment** (fig. 4) simulates a tracked feller/buncher with a boom-mounted shear. This boom enables the machine to remain at a harvesting station while it shears and bunches trees within a radius of 20 feet, (the radius depends on the stand and the harvesting treatment as well as on the physical reach of the boom).

The feller is assumed to move into the woods, cut one or more trees, then drop them to one side to form a bunch. After all the trees to be cut at that location are processed, the feller moves to the next set of trees and repeats the process.

INPUT DATA

GPSS accepts description data in several forms (see table 1). For additional information on data types and card formats, see Appendix D or a GPSS Programming Manual (Schriber 1974).

Most of the data required by this program are needed in the form of VARIABLES. VARIABLES can be defined in terms of the other input types (Appendix D), thus allowing the user flexibility of input data without card shuffling in the main body of the program. For example, a shear-time change from a constant (SAVEVALUE) to a distribution (FUNCTION) can be accomplished by simply redefining the shear-time VARIABLE.

The major exception to this convention is the use of SAVEVALUES (constants) for the summary values (average stand d.b.h., average tree height, etc.) that are used simply for output information.

DATA REQUIRED BY MODEL

Four types of data describing the equipment and harvesting operation must be supplied to run the simulation: (1) stand data (table 2); (2) machine data dependent on stand conditions (table 3); (3) machine data independent of stand conditions (table 4); and (4) simulation run control data (table 5).

The sample output presented in this paper resulted from running the simulation with the input data in tables 2-5. These data were gathered from time studies carried out during actual logging operations. Although the data in the tables may not represent the operating characteristics of the feller/buncher under all conditions, they do present a reasonably accurate picture of its performance in a stand of this type (table 2).

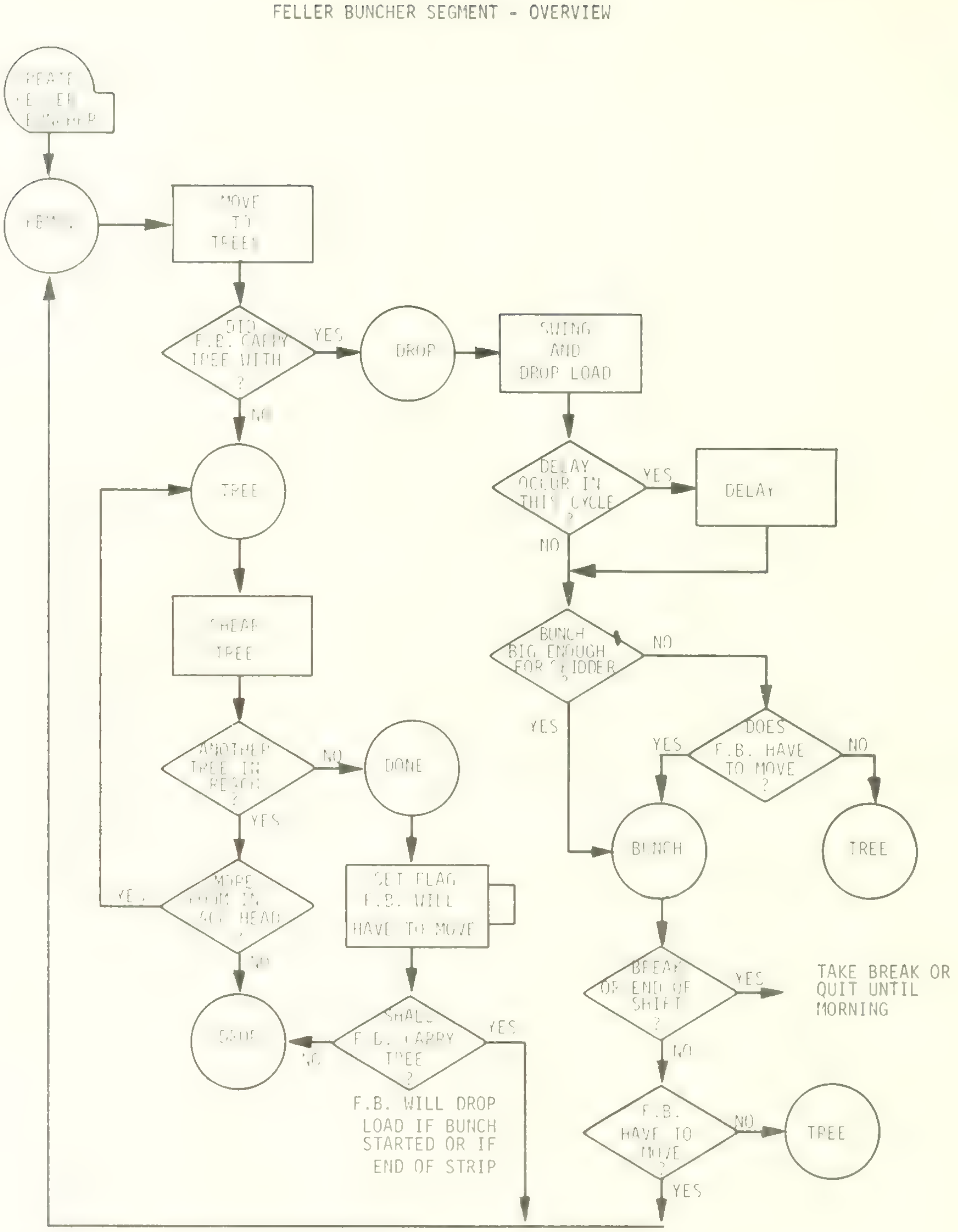


Figure 4.—*Overview of the* **feller/buncher segment.**

SIMULATION OUTPUT

The simulation run produces two pages of labeled output for each day of the run (figs. 5 and 6). These pages contain a summary of the stand data and a cumulative productivity report. Additional output, with complete run details, is produced at the end of the run by the GPSS processor.

The first page of standard output (fig. 7) presents a simulation "map" listing all the blocks in the model and the number of transactions that have moved through each block. This is of primary value while debugging the model. The listing of the QUEUE statistics provides detailed information on how the feller/buncher spends its time in the woods. The SAVEVALUE list contains all the totals necessary to calculate productivity if the FORTRAN subroutines

Table 1.—*GPSS Data input forms*

Input data type	Input form in GPSS	Example
Simple averages or constants	Initialized SAVEVALUES	Ave. d.b.h. = 6 in.
Range of values	Initialized SAVEVALUES for mean and one-half width of interval	Shear time = 10 to 14 centi-min. = 12 ± 2 centi-min.
Equations	VARIABLES	Vol. = .13 d.b.h.^{2} – .28
Frequency distributions	FUNCTIONS	D.b.h.(in.) 4 | 5 | 6 | 7 | 8 percent trees 23 | 25 | 30 | 15 | 5
Mean and variance for a standard distribution such as normal, Poisson Exponential, etc.	SAVEVALUES and FUNCTIONS for the distribution	Wait time is normally distributed with mean = 10 variance = 9

Table 2.—*Stand data*

Data required	Case study	Form required by program	Name
Ave. stand diameter	5.5 in. d.b.h.	SAVEVALUE	X$AVDBH
Ave. stand volume	3,450 cu. ft./acre	SAVEVALUE	X$AVVOL
Ave. tree height	43 ft.	SAVEVALUE	X$AVHGT
Ave. trees/acre	844 trees/acre	SAVEVALUE	X$TRPAC
Strip length	725 ft.	VARIABLE	V$STPLN
Distance between strips	35 ft.	SAVEVALUE	X$MVSTP
Wood density	55 lb./cu. ft.	SAVEVALUE	X$LBCFT
Hours in daily work shift	8 hrs.	SAVEVALUE	X$WKDAY
Actual tree diameters	Diameter distribution: D.b.h.(in.) 3 | 4 | 5 | 6 | 7 | 8 | 9 percent trees 5 | 23 | 30 | 24 | 14 | 3 | 1	VARIABLE	V$TDIA
Tree volume	Volume of trees (cu. ft.): Volume = –0.283 + .0031 (DBH^2) tree ht. = –0.283 + 0.133 (DBH^2) assuming tree ht. = 43 ft.	VARIABLE	V$TVOL

cannot be used. For example:

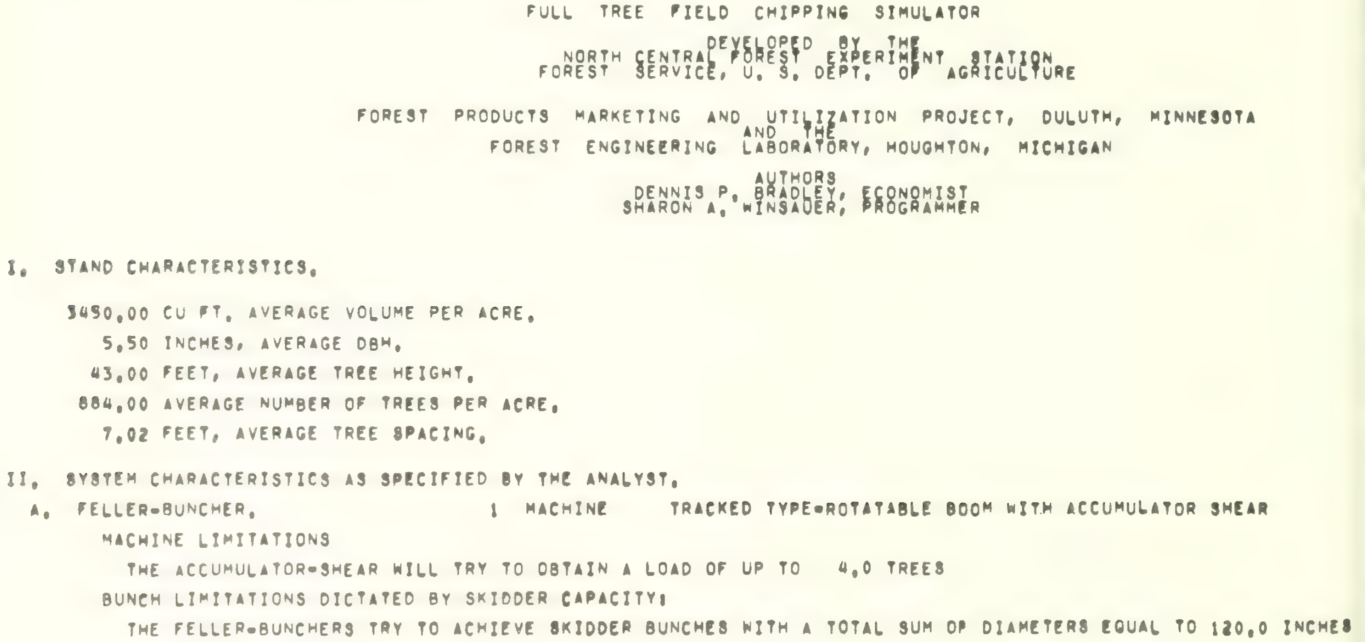
FBHR = 4020 = feller hours × 100
FBTRE = 6663 trees cut
6663/40.2 = 165.75 trees/hr.

Additional details of the woods operations are provided by the output tables (figs. 8-10). The cycle time table (cycle time starts after the feller/buncher drops one load and ends when it drops the next) shows there were 2,667 cycles with an average cycle time of 79 centi-minutes. Of all cycles, 209 cycles or 7.8 percent took between 100 and 125 centi-minutes.

It should be noted that all of the output is based on random processes in the model. Therefore, the output data are themselves random, only a sample of what could happen. If the model is run again with different random numbers, the results will be different. An average over several days or several runs is the best estimate of an actual system.

Table 3.—*Machine data dependent on stand conditions*

Data required	Case study							Form required by program	Name
Number of trees within reach of accumulator head from a given location	Distribution: trees in head							VARIABLE	V$REACH
	Number of trees	2-4	4-6	6-8	10-12	12-16	16-18		
	percent time	3	7	10	20	20	8		
	Number of trees	18-20	20-22	22-24	24-26	26-30	30-38		
	percent time	7	6	5	4	5	5		
Distance feller must move to be well positioned to cut next set of trees	Distribution: feller travel							VARIABLE	V$FBMOV
	ft.	0-5	5-10	10-25	25-35	35-50			
	percent time	10	15	30	20	10			
	ft.	50-60	60-90	90-120					
	percent time	5	5	5					



```
                              FULL  TREE  FIELD  CHIPPING  SIMULATOR

                                         DEVELOPED  BY  THE
                               NORTH CENTRAL FOREST  EXPERIMENT  STATION
                             FOREST  SERVICE, U. S. DEPT.  OF  AGRICULTURE

                   FOREST  PRODUCTS  MARKETING  AND  UTILIZATION  PROJECT,  DULUTH,  MINNESOTA
                                               AND  THE
                        FOREST  ENGINEERING  LABORATORY, HOUGHTON,  MICHIGAN

                                              AUTHORS
                                   DENNIS P. BRADLEY, ECONOMIST
                                  SHARON A. WINSAUER, PROGRAMMER

I.  STAND CHARACTERISTICS.

     3450.00 CU FT. AVERAGE VOLUME PER ACRE.
        5.50 INCHES, AVERAGE DBH.
       43.00 FEET, AVERAGE TREE HEIGHT.
      884.00 AVERAGE NUMBER OF TREES PER ACRE.
        7.02 FEET, AVERAGE TREE SPACING.

II.  SYSTEM CHARACTERISTICS AS SPECIFIED BY THE ANALYST.
  A.  FELLER-BUNCHER.                    1  MACHINE    TRACKED TYPE-ROTATABLE BOOM WITH ACCUMULATOR SHEAR
        MACHINE LIMITATIONS
          THE ACCUMULATOR-SHEAR WILL TRY TO OBTAIN A LOAD OF UP TO   4.0 TREES
        BUNCH LIMITATIONS DICTATED BY SKIDDER CAPACITY:
          THE FELLER-BUNCHERS TRY TO ACHIEVE SKIDDER BUNCHES WITH A TOTAL SUM OF DIAMETERS EQUAL TO 120.0 INCHES
```

Figure 5.—*Simulation output: system and stand characteristics.*

KNOWN GPSS SYSTEMS DIFFERENCES

The program listed in Appendix B is operational on a UNIVAC 1110 under an implementation of GPSS called GPSS-X8, which can be obtained from Use Program Library Interchange (UPLI). It should run under most GPSS Processors with only mino changes. The following should be checked for you system:

INITIAL cards— In GPSS-X8 the INITIAL cards appear last in the deck. They should be moved to th front of the deck for most other GPSS processors

Job control cards— These are unique to each com

Table 4.—*Machine data*

<table>
<tr><th>Data required</th><th>Case study</th><th>Form required by program</th><th>Name</th></tr>
<tr><td>Travel time (based on distance)</td><td>Travel speed:
mean 49 ft./min.
s.d. 19 ft./min.</td><td>VARIABLE</td><td>V$FBTRAV</td></tr>
<tr><td>Shear time per tree</td><td>Distribution: shear time
<table>
<tr><td>time (centi-min.)</td><td>0-10</td><td>10-20</td><td>20-30</td><td>30-40</td></tr>
<tr><td>percent of cuts</td><td>29</td><td>39</td><td>21</td><td>8</td></tr>
<tr><td>time (centi-min.)</td><td>40-50</td><td>50-60</td><td>60-70</td><td>70-90</td></tr>
<tr><td>percent of cuts</td><td>1</td><td>1</td><td>.5</td><td>.5</td></tr>
</table></td><td>VARIABLE</td><td>V$FBSHR</td></tr>
<tr><td>Drop and bunch time per load</td><td>Distribution: drop and bunch time
<table>
<tr><td>time (centi-min.)</td><td>1-10</td><td>10-20</td><td>20-30</td><td>30-40</td></tr>
<tr><td>percent of cuts</td><td>3</td><td>67</td><td>15</td><td>3</td></tr>
<tr><td>time (centi-min.)</td><td>40-50</td><td>50-60</td><td>60-70</td><td></td></tr>
<tr><td>percent of cuts</td><td>1</td><td>.5</td><td>.5</td><td></td></tr>
</table></td><td>VARIABLE</td><td>V$FBDRP</td></tr>
<tr><td>Number of trees per accumulator load</td><td>Distribution: trees/accumulator head load
<table>
<tr><td>number of trees</td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td></tr>
<tr><td>percent loads</td><td>22</td><td>23</td><td>28</td><td>17</td><td>10</td></tr>
</table></td><td>VARIABLE</td><td>V$ACCLM</td></tr>
<tr><td>Maximum size of skidder bunch FB tries to create (total sum of d.b.h.)</td><td>120 in.</td><td>VARIABLE</td><td>V$BUNLM</td></tr>
<tr><td>Gal./hr. fuel used</td><td>5.5 gal./hr.</td><td>SAVEVALUE</td><td>X$FBGPH</td></tr>
<tr><td>Length of nonmechanical delays/cycle (including cycles with zero delay)</td><td>Distribution of nonmechanical delays (min.)
<table>
<tr><td>length of delay</td><td>0</td><td>.15</td><td>.25</td><td>.35</td><td>.40</td><td>.50</td><td>.75</td></tr>
<tr><td>percent of cycles</td><td>98.5</td><td>.2</td><td>.2</td><td>.2</td><td>.1</td><td>.1</td><td>.3</td></tr>
<tr><td>length of delay</td><td>.80</td><td>1.0</td><td>2.0</td><td>3.0</td><td>4.0</td><td>5.0</td><td></td></tr>
<tr><td>percent of cycles</td><td>.3</td><td>.3</td><td>.1</td><td>.1</td><td>.1</td><td>.1</td><td></td></tr>
</table></td><td>VARIABLE</td><td>V$NMDLY</td></tr>
<tr><td>Length of mechanical delays/cycle (including cycles with zero delay)</td><td>Distribution of mechanical delays (min.)
<table>
<tr><td>length of delay</td><td>0</td><td>.5</td><td>1.0</td><td>1.5</td><td>2.0</td><td>2.5</td><td>5.0</td></tr>
<tr><td>percent of cycle</td><td>99</td><td>.1</td><td>.1</td><td>.1</td><td>.1</td><td>.1</td><td>.1</td></tr>
<tr><td>length of delay</td><td>10.0</td><td>20.0</td><td>30.0</td><td>40.0</td><td></td><td></td><td></td></tr>
<tr><td>percent of cycle</td><td>.1</td><td>.1</td><td>.1</td><td>.1</td><td></td><td></td><td></td></tr>
</table></td><td>VARIABLE</td><td>V$MCDLY</td></tr>
</table>

puter lab, and must be obtained locally.

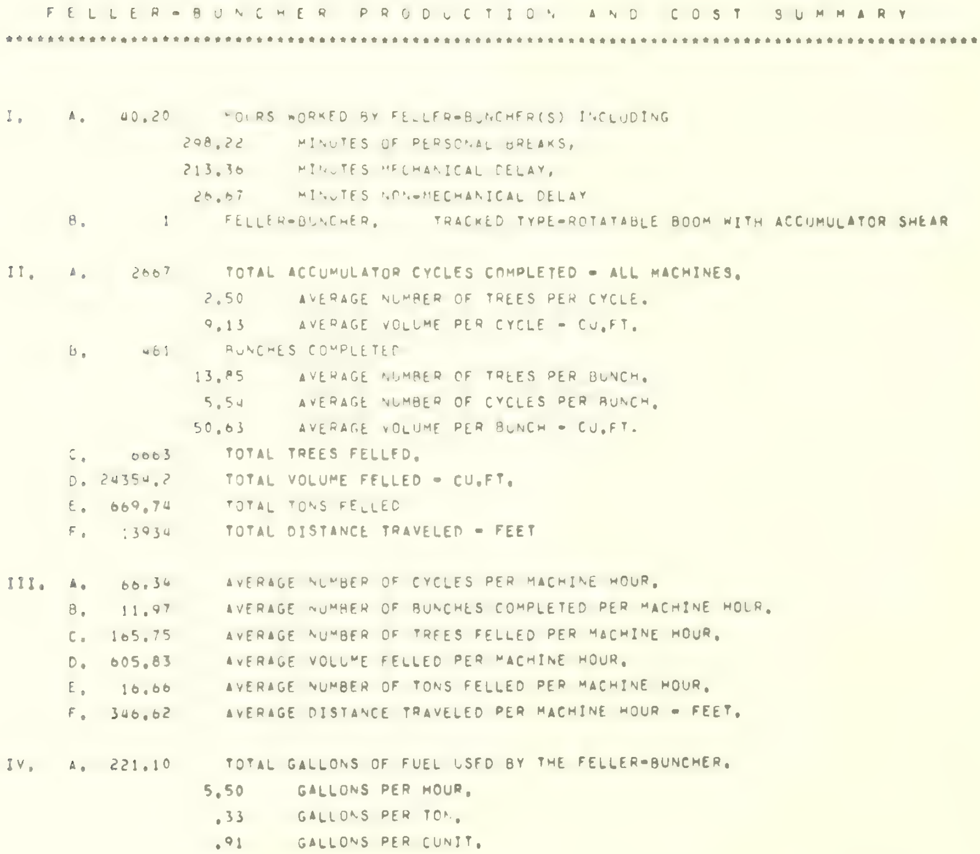
HELP BLOCKS—In GPSS-X8, HELP blocks (lines 65-80 in the program) are used to pass an array of up to five integer values to a FORTRAN subroutine. Only a one-way transfer is permitted; i.e., the subroutine cannot pass arguments back to GPSS. Some versions of GPSS do not allow HELP blocks. In such cases the program can be run without lines 48 to 80; these data can instead be obtained from the standard output. If some form of HELP blocks are allowed, their format and the subroutines may have to be changed. See the GPSS manual for your computer installation.

SENSITIVITY

Table 6 presents the results of a preliminary study of the model's sensitivity. The model was run to fit

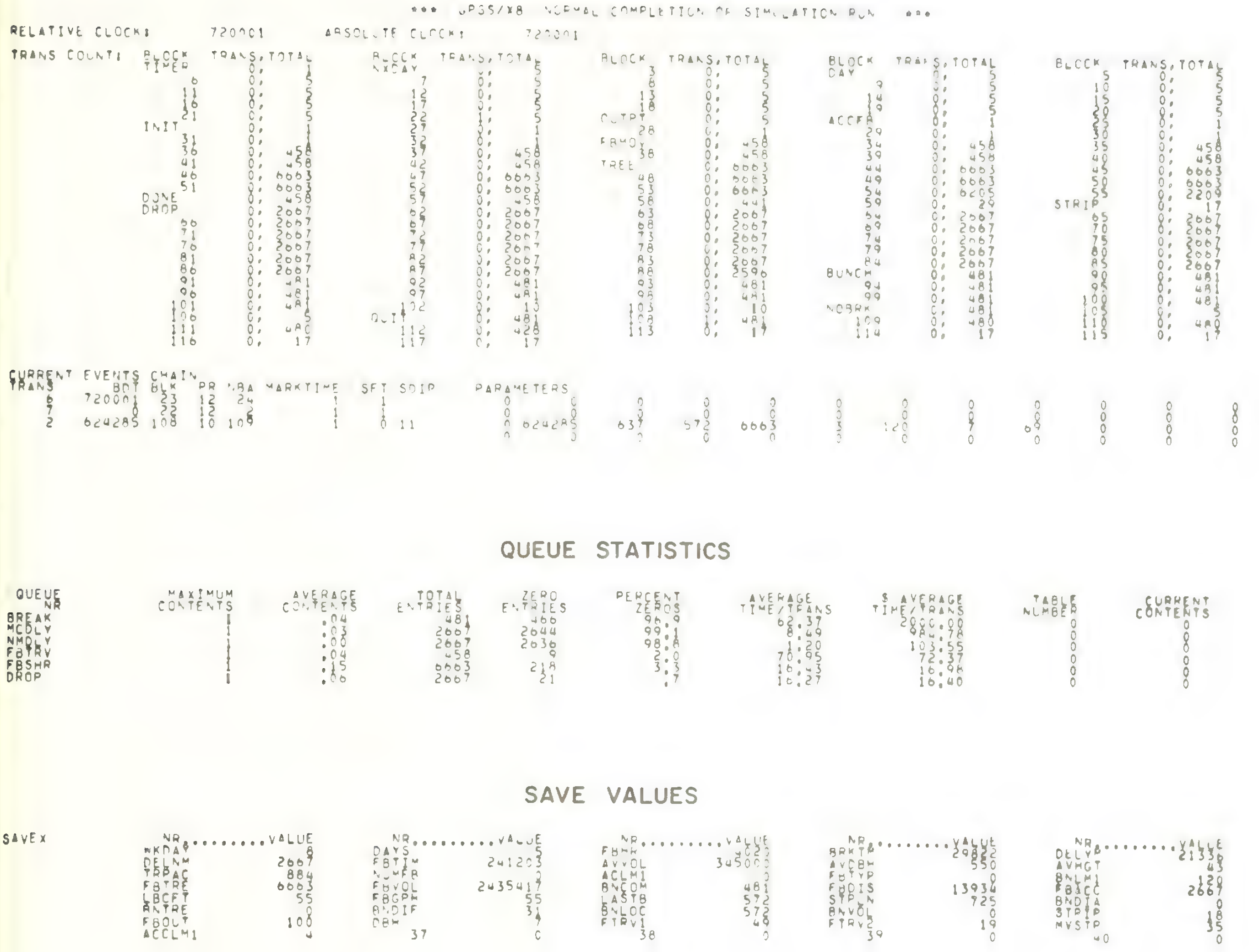
Table 5.—*Simulation run control*

Data required	Case study	Form required by program
Random number generators	Random number use 1—used by GPSS scheduler 2—Shear time and drop time distribution 3—trees in reach and distance to move distributions 4—d.b.h. distribution 5—not used 6—delays distribution	RMULT CARD
Number of days	5 days	START CARD
Standard output	every 5th day	



```
       F E L L E R - B U N C H E R   P R O D U C T I O N   A N D   C O S T   S U M M A R Y
*************************************************************************************************


I.     A.    40.20      HOURS WORKED BY FELLER-BUNCHER(S) INCLUDING
                  298.22      MINUTES OF PERSONAL BREAKS,
                  213.36      MINUTES MECHANICAL DELAY,
                   26.67      MINUTES NON-MECHANICAL DELAY
       B.        1      FELLER-BUNCHER,     TRACKED TYPE-ROTATABLE BOOM WITH ACCUMULATOR SHEAR

II.    A.     2667      TOTAL ACCUMULATOR CYCLES COMPLETED - ALL MACHINES.
                    2.50      AVERAGE NUMBER OF TREES PER CYCLE.
                    9.13      AVERAGE VOLUME PER CYCLE - CU.FT.
       B.      461      BUNCHES COMPLETED
                   13.85      AVERAGE NUMBER OF TREES PER BUNCH.
                    5.54      AVERAGE NUMBER OF CYCLES PER BUNCH.
                   50.63      AVERAGE VOLUME PER BUNCH - CU.FT.
       C.     6663      TOTAL TREES FELLED.
       D.  24354.2      TOTAL VOLUME FELLED - CU.FT.
       E.   669.74      TOTAL TONS FELLED
       F.    13934      TOTAL DISTANCE TRAVELED - FEET

III.   A.    66.34      AVERAGE NUMBER OF CYCLES PER MACHINE HOUR.
       B.    11.97      AVERAGE NUMBER OF BUNCHES COMPLETED PER MACHINE HOUR.
       C.   165.75      AVERAGE NUMBER OF TREES FELLED PER MACHINE HOUR.
       D.   605.83      AVERAGE VOLUME FELLED PER MACHINE HOUR.
       E.    16.66      AVERAGE NUMBER OF TONS FELLED PER MACHINE HOUR.
       F.   346.62      AVERAGE DISTANCE TRAVELED PER MACHINE HOUR - FEET.

IV.    A.   221.10      TOTAL GALLONS OF FUEL USED BY THE FELLER-BUNCHER.
                    5.50      GALLONS PER HOUR.
                     .33      GALLONS PER TON.
                     .91      GALLONS PER CUNIT.
```

Figure 6.—*Simulation output: productivity.*



```
                                   ***  GPSS/X8  NORMAL COMPLETION OF SIMULATION RUN   ***
RELATIVE CLOCK:       720001      ABSOLUTE CLOCK:       720001
TRANS COUNT:  BLOCK   TRANS,TOTAL       BLOCK   TRANS,TOTAL       BLOCK   TRANS,TOTAL       BLOCK   TRANS,TOTAL       BLOCK   TRANS,TOTAL
              TIMER      0,    1        NXDAY      0,    5            3      0,    5        DAY        0,    5            5      0,    5
                  6      0,    5            7      0,    5            8      0,    5            9      0,    5           10      0,    5
                 11      0,    5           12      0,    5           13      0,    5           14      0,    5           15      0,    5
                 16      0,    5           17      0,    5           18      0,    5           19      0,    5           20      0,    5
                 21      0,    5           22      1,    5        OUTPT      0,    5        ACCFR      0,    1           25      0,    1
              INIT       0,    1           27      0,    1           28      0,    1           29      0,    1           30      0,    1
                 31      0,    1           32      0,    1        FRMOV      0,  458           34      0,  458           35      0,  458
                 36      0,  458           37      0,  458           38      0,  458           39      0,  458           40      0,  458
                 41      0,  458           42      0,  458        TREE       0, 6663           44      0, 6663           45      0, 6663
                 46      0, 6663           47      0, 6663           48      0, 6663           49      0, 6663           50      0, 6663
                 51      0, 6663           52      0, 6663           53      0, 6663           54      0, 6205           55      0, 2209
              DONE       0,  458           57      0,  458           58      0,  441           59      0,   29        STRIP      0,   17
              DROP       0, 2667           62      0, 2667           63      0, 2667           64      0, 2667           65      0, 2667
                 66      0, 2667           67      0, 2667           68      0, 2667           69      0, 2667           70      0, 2667
                 71      0, 2667           72      0, 2667           73      0, 2667           74      0, 2667           75      0, 2667
                 76      0, 2667           77      0, 2667           78      0, 2667           79      0, 2667           80      0, 2667
                 81      0, 2667           82      0, 2667           83      0, 2667           84      0, 2667           85      0, 2667
                 86      0, 2667           87      0, 2667           88      0, 2596        BUNCH      0,  481           90      0,  481
                 91      0,  481           92      0,  481           93      0,  481           94      0,  481           95      0,  481
                 96      0,  481           97      0,  481           98      0,  481           99      0,  481          100      0,  481
                101      0,  481          102      0,   13          103      0,   10        NOBRK      0,  481          105      0,    5
                106      0,    5        QUIT       0,  481          108      1,  481          109      0,  480          110      0,  480
                111      0,  480          112      0,  428          113      0,   17          114      0,   17          115      0,   17
                116      0,   17          117      0,   17

CURRENT EVENTS CHAIN
TRANS      BDT BLK  PR NBA MARKTIME   SET SDIP    PARAMETERS
  6     720001  23  12  24        1     1           0       0       0       0       0       0       0       0       0       0       0       0
  7          0  22  12   2        1     1           0       0       0       0       0       0       0       0       0       0       0       0
  2     624285 108  10 109        1     0 11        0  624285     637     572    6663       3     120       7      69       0       0       0
                                                    0       0       0       0       0       0       0       0       0       0       0       0

                                                   QUEUE  STATISTICS

 QUEUE            MAXIMUM      AVERAGE      TOTAL       ZERO       PERCENT        AVERAGE       $ AVERAGE      TABLE       CURRENT
    NR            CONTENTS     CONTENTS    ENTRIES     ENTRIES      ZEROS       TIME/TRANS     TIME/TRANS     NUMBER      CONTENTS
BREAK                   1         .04         481         466        96.9           62.37        2000.00          0            0
MCDLY                   1         .03        2667        2644        99.1            8.49         984.78          0            0
NMDLY                   1         .00        2667        2636        98.8            1.20         103.55          0            0
FBTRV                   1         .04         458           9         2.0           70.95          72.37          0            0
FBSHR                   1         .15        6663         218         3.3           16.43          16.98          0            0
DROP                    1         .06        2667          21          .7           16.27          16.40          0            0

                                                     SAVE  VALUES

SAVEX           NR.........VALUE        NR.........VALUE        NR.........VALUE        NR.........VALUE        NR.........VALUE
                WKDAY          8        DAYS           5        FBHR        4023        BRKTM      29822        DELYB      21336
                DELNM       2667        FBTIM     241203        AVVOL     345000        AVDBH        550        AVHGT         43
                TRPAC        884        NUMFB          0        ACLM1          0        FBTYP          0        BNLM1        120
                FBTRE       6663        FBVOL    2435417        BNCOM        481        FBDIS      13934        FBSCC       2667
                LBCFT         55        FBGPH         55        LASTB        572        STPLN        725        BNDIA          0
                ANTRE          0        BNDIF         31        BNLOC        572        BNVOL          0        STPIP         18
                FBOUT        100        DBH            7        FTRV1         49        FTRV2         19        MVSTP         35
                ACCLM1         4          37           0          38           0          39           0          40           0
```

Figure 7.—*Simulation output: standard GPSS form.*

actual data as closely as possible. Then one parameter at a time was varied and the effect on productivity noted.

These sensitivity figures can be used (1) to give some indication of the accuracy required for the input data (the greater the sensitivity the more accurately that parameter should be specified), and (2) to give an indication of what factors should be further examined for their impact on the machine's productivity.

It should be noted that even parameters which did not show major changes in productivity at the levels of change examined could have larger effects when changed to a greater degree or when combined with other changes. In all cases, the better the input information, the more accurate the output data will be.

CONCLUSION

With the proper choice of input variables, the simulation model can be used to study productivity of feller/bunchers under a variety of stand or harvesting conditions. It is possible to study the effects of a change in just one parameter or the effects of many changes at the same time. This model can also be combined with a model of skidding and chipping operations to provide productivity information for whole-tree systems.

Perhaps the greatest value of a GPSS model is the ease by which it can be modified to suit the exact requirements of a harvesting system. Although this requires some knowledge of GPSS, it makes simulation an extremely valuable tool.

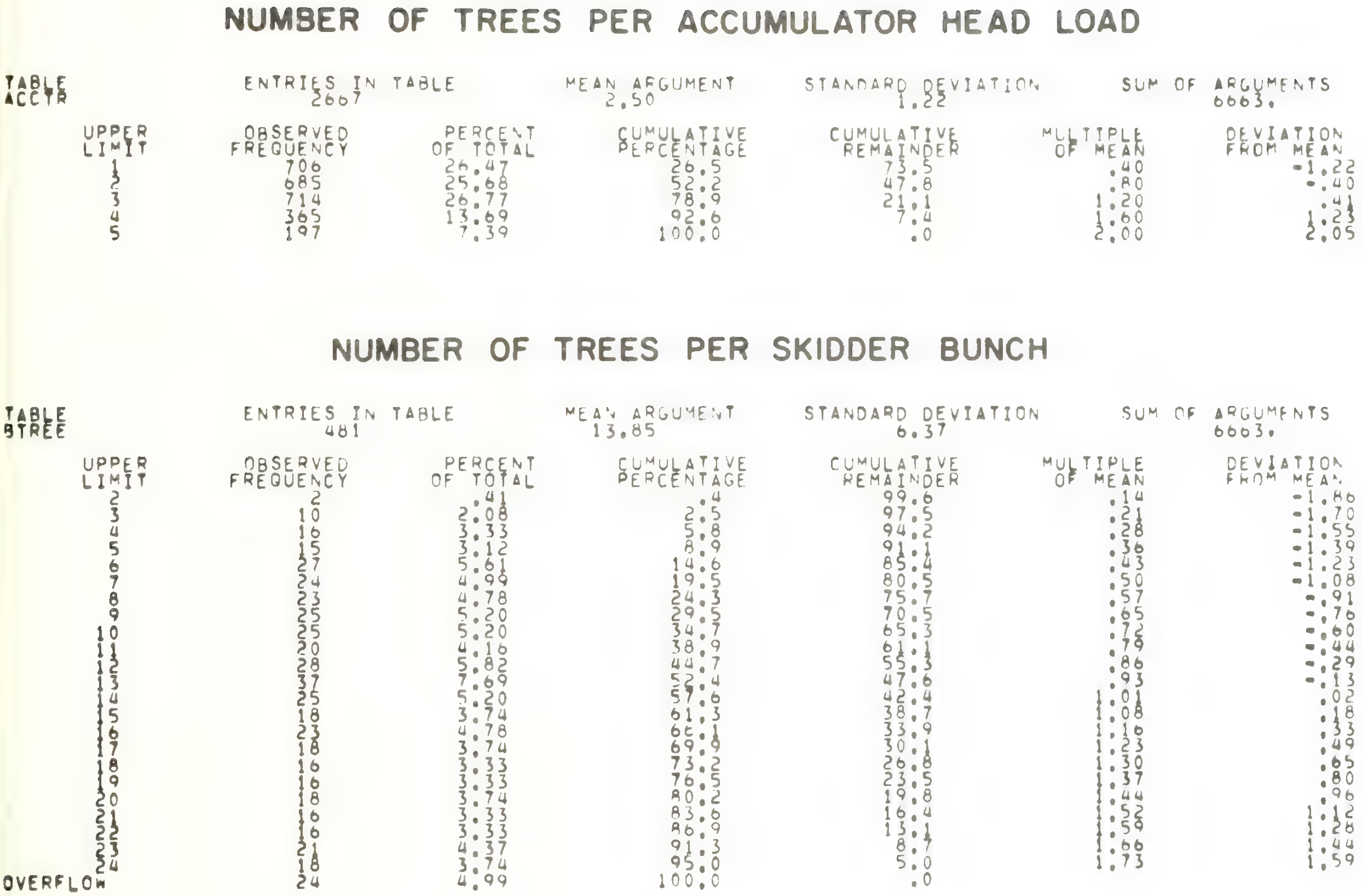
CYCLE TIME (CENTI-MINUTES)

```
TABLE              ENTRIES IN TABLE         MEAN ARGUMENT        STANDARD DEVIATION          SUM OF ARGUMENTS
FBTIM                    2667                   79.19                  167.70                     211203.

       UPPER            OBSERVED           PERCENT           CUMULATIVE          CUMULATIVE           MULTIPLE           DEVIATION
       LIMIT           FREQUENCY           OF TOTAL          PERCENTAGE           REMAINDER            OF MEAN           FROM MEAN
          25                 226              8.47                  8.5                91.5                .31                -.32
          50                 837             31.38                 39.9                60.1                .63                -.17
          75                 716             26.85                 66.7                33.3                .94                -.02
         100                 416             15.60                 82.3                17.7               1.26                 .12
         125                 209              7.84                 90.1                 9.9               1.58                 .27
         150                  99              3.71                 93.9                 6.1               1.89                 .42
         175                  37              1.39                 95.2                 4.8               2.21                 .57
         200                  31              1.16                 96.4                 3.6               2.53                 .72
         225                  25               .93                 97.3                 2.7               2.84                 .86
         250                  20               .75                 98.1                 1.9               3.16                1.02
         275                  13               .48                 98.6                 1.4               3.47                1.17
         300                   9               .33                 98.9                 1.1               3.79                1.32
         325                   5               .18                 99.1                  .9               4.10                1.47
         375                   2               .07                 99.2                  .8               4.74                1.76
         400                   1               .03                 99.2                  .7               5.05                1.91
         425                   2               .07                 99.3                  .7               5.37                2.06
         450                   2               .07                 99.4                  .6               5.68                2.21
         475                   2               .07                 99.4                  .5               6.00                2.36
         550                   4               .15                 99.6                  .4               6.95                2.81
         575                   1               .03                 99.6                  .3               7.26                2.96
         600                   1               .03                 99.7                  .3               7.58                3.11
OVERFLOW                       9               .33                100.0                  .0
```

VOLUME (CU. FT. x 100) PER ACCUMULATOR HEAD LOAD

```
TABLE              ENTRIES IN TABLE         MEAN ARGUMENT        STANDARD DEVIATION          SUM OF ARGUMENTS
ACCVL                    2667                  913.17                  538.03                    2435417.

       UPPER            OBSERVED           PERCENT           CUMULATIVE          CUMULATIVE           MULTIPLE           DEVIATION
       LIMIT           FREQUENCY           OF TOTAL          PERCENTAGE           REMAINDER            OF MEAN           FROM MEAN
         500                 767             28.76                 28.8                71.2                .54                -.76
        1000                 861             32.28                 61.0                39.0               1.10                 .16
        1500                 626             23.47                 84.5                15.5               1.64                1.09
        2000                 311             11.66                 96.2                 3.8               2.19                2.02
        2500                  87              3.26                 99.4                  .5               2.74                2.95
        3000                  15               .56                100.0                  .0               3.29                3.88
```

Figure 8.—*Simulation output: productivity tables (1,*



NUMBER OF TREES PER ACCUMULATOR HEAD LOAD

```
TABLE               ENTRIES IN TABLE          MEAN ARGUMENT      STANDARD DEVIATION      SUM OF ARGUMENTS
ACCTR                     2667                     2.50                  1.22                   6663.

     UPPER          OBSERVED           PERCENT         CUMULATIVE         CUMULATIVE          MULTIPLE         DEVIATION
     LIMIT          FREQUENCY          OF TOTAL        PERCENTAGE          REMAINDER           OF MEAN         FROM MEAN
         1               706             26.47              26.5               73.5                .40             -1.22
         2               685             25.68              52.2               47.8                .80              -.40
         3               714             26.77              78.9               21.1               1.20               .41
         4               365             13.69              92.6                7.4               1.60              1.23
         5               197              7.39             100.0                 .0               2.00              2.05
```

NUMBER OF TREES PER SKIDDER BUNCH

```
TABLE               ENTRIES IN TABLE          MEAN ARGUMENT      STANDARD DEVIATION      SUM OF ARGUMENTS
BTREE                      481                    13.85                  6.37                   6663.

     UPPER          OBSERVED           PERCENT         CUMULATIVE         CUMULATIVE          MULTIPLE         DEVIATION
     LIMIT          FREQUENCY          OF TOTAL        PERCENTAGE          REMAINDER           OF MEAN         FROM MEAN
         2                 2               .41                .4               99.6                .14             -1.86
         3                10              2.08               2.5               97.5                .21             -1.70
         4                16              3.33               5.8               94.2                .28             -1.55
         5                15              3.12               8.9               91.1                .36             -1.39
         6                27              5.61              14.6               85.4                .43             -1.23
         7                24              4.99              19.5               80.5                .50             -1.08
         8                23              4.78              24.3               75.7                .57              -.91
         9                25              5.20              29.5               70.5                .65              -.76
        10                25              5.20              34.7               65.3                .72              -.60
        11                20              4.16              38.9               61.1                .79              -.44
        12                28              5.82              44.7               55.3                .86              -.29
        13                37              7.69              52.4               47.6                .93              -.13
        14                25              5.20              57.6               42.4               1.01               .02
        15                18              3.74              61.3               38.7               1.08               .18
        16                23              4.78              66.1               33.9               1.16               .33
        17                18              3.74              69.9               30.1               1.23               .49
        18                16              3.33              73.2               26.8               1.30               .65
        19                16              3.33              76.5               23.5               1.37               .80
        20                18              3.74              80.2               19.8               1.44               .96
        21                16              3.33              83.6               16.4               1.52              1.12
        22                16              3.33              86.9               13.1               1.59              1.28
        23                21              4.37              91.3                8.7               1.66              1.44
        24                18              3.74              95.0                5.0               1.73              1.59
OVERFLOW                  24              4.99             100.0                 .0
```

Figure 9.—*Simulation output: productivity tables (II).*

DISTANCES (FT) BETWEEN CONSECUTIVE BUNCHES

```
TABLE                 ENTRIES IN TABLE         MEAN ARGUMENT       STANDARD DEVIATION        SUM OF ARGUMENTS
BDIF                         481                   25.93                   27.60                    12474.

      UPPER            OBSERVED        PERCENT          CUMULATIVE          CUMULATIVE          MULTIPLE          DEVIATION
      LIMIT            FREQUENCY      OF TOTAL          PERCENTAGE           REMAINDER           OF MEAN          FROM MEAN
          0                   58         12.06                12.1                87.9              0.00               -.94
          5                   54         11.23                23.3                76.7               .19               -.75
         10                   55         11.43                34.7                65.3               .38               -.57
         15                   37          7.69                42.4                57.6               .57               -.39
         20                   51         10.60                53.0                47.0               .77               -.21
         25                   47          9.77                62.8                37.2               .96               -.03
         30                   44          9.15                71.9                28.1              1.16                .14
         35                   26          5.41                77.3                22.7              1.35                .32
         40                    9          1.87                79.2                20.8              1.54                .51
         45                   14          2.91                82.1                17.9              1.74                .69
         50                   17          3.53                85.7                14.3              1.93                .87
         55                    9          1.87                87.5                12.5              2.12               1.05
         60                   11          2.29                89.8                10.2              2.31               1.23
         65                    6          1.25                91.1                 8.9              2.51               1.42
         70                    2           .41                91.5                 8.5              2.70               1.60
OVERFLOW                      41          8.52               100.0                  .0
```

VOLUME (CU.FT. x 100) PER SKIDDER BUNCH

```
TABLE                 ENTRIES IN TABLE         MEAN ARGUMENT       STANDARD DEVIATION        SUM OF ARGUMENTS
BVOL                         481               5063.24                 2341.80                  2435417.

      UPPER            OBSERVED        PERCENT          CUMULATIVE          CUMULATIVE          MULTIPLE          DEVIATION
      LIMIT            FREQUENCY      OF TOTAL          PERCENTAGE           REMAINDER           OF MEAN          FROM MEAN
       1000                    8          1.66                 1.7                98.3               .19              -1.74
       1500                   19          3.95                 5.6                94.4               .29              -1.52
       2000                   18          3.74                 9.4                90.6               .39              -1.31
       2500                   29          6.03                15.4                84.6               .49              -1.09
       3000                   33          6.86                22.2                77.8               .59               -.88
       3500                   38          7.90                30.1                69.9               .69               -.66
       4000                   30          6.24                36.4                63.6               .79               -.45
       4500                   41          8.52                44.9                55.1               .88               -.24
       5000                   29          6.03                50.9                49.1               .98               -.02
       5500                   37          7.69                58.6                41.4              1.09                .18
       6000                   29          6.03                64.7                35.3              1.19                .40
       6500                   31          6.44                71.1                28.9              1.28                .61
       7000                   24          4.99                76.1                23.9              1.38                .82
       7500                   18          3.74                79.8                20.2              1.48               1.04
       8000                   17          3.53                83.4                16.6              1.58               1.25
       8500                   33          6.86                90.2                 9.8              1.68               1.47
       9000                   29          6.03                96.3                 3.7              1.78               1.68
       9500                   13          2.70                99.0                 1.0              1.88               1.89
      10000                    4           .83                99.8                  .2              1.98               2.11
      10500                    1           .20               100.0                  .0              2.07               2.32
```

Figure 10.—*Simulation output: productivity tables (III).*

Table 6.—*Sensitivity of the simulation*

Change in run parameters	Productivity	
	Tons/hr.	Effect
Standard run	16.66	
Decrease shearing time by 10 percent	17.48	Increase 5 percent
Decrease swing & drop time by 10 percent	16.84	([1])
Increase travel speed by 10 percent	16.70	([1])
Increase average number of trees in accumulator head load from 2.5 to 3.5	17.82	Increase 7 percent
Increase average number of trees within reach from 14 to 16	16.72	([1])
Increase average d.b.h. by 1 inch	23.94	Increase 43 percent
Increase frequency of mechanical delay from 1 percent to 2 percent of the cycles	14.64	Decrease 12 percent

[1] No major change in productivity observed for this level of change in parameter.

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APPENDIX A

VARIABLE LISTS AND DEFINITIONS

Definitions

IMPLICIT TIME UNIT— Centi-minute
MODEL SEGMENTS, TRANSACTIONS, AND PARAMETERS
  Segment 1—**timer**
    Transactions—1 time keeper
    Parameters—NONE
  Segement 2—**feller/buncher**
    Transactions—feller/buncher
    Parameters
      P1—not currently used.
      P2—clock time marking start of cycle.
      P3—next location of feller/buncher (distance in feet from the beginning of this strip or row).
      P4—current location of feller bunches (distance down strip in feet).
      P5—tree number being cut.
      P6—limit for trees in accumulator head (number of trees).
      P7—maximum size of skidder bunch attempted (sum of diameters).
      P8—diameter of current tree.
      P9—distance feller/buncher must travel to next set of trees.
      P10—number of trees currently within reach of boom.
      P11—actual sum of diameter of accumulator load.
      P12—total volume in accumulator head.
      P13—number of trees in load.

Functions

ACCLM	Distribution of the number of trees in accumulator loads.
DBH	Distribution of diameters in the stand.
FBDRP	Distribution of drop times.
FBMOV	Distribution of the distances feller must move to reach more trees.
FBSHR	Distribution of shear times.
MCDLY	Distribution of mechanical delay times in each cycle (including cycles with zero delay).
NMDLY	Distribution of nonmechanical delay times in each cycle (including cycles with zero delay).
REACH	Distribution of trees within reach from a random spot.
SNORM	Distribution used to obtain a normal distribution for sampling with a mean = 0, variance = 1. Lower end truncated.

Savevalues

ACLM1	Mean accumulator head limit (number of trees).
AVDBH	Mean stand diameter (inches × 100).
AVHGT	Mean stand height (feet).
AVVOL	Mean vol./acre (cu.ft. × 100).
BNCOM	Number of skidder bunches complete and ready for skidding.
BNDIA	Sum of diameters of trees in the bunch (inches).
BNDIF	Distance between bunches (feet).
BNLM1	Limit for skid bunch size— maximum sum of diameters.
BNLOC	Location of bunch (distance from end of strip).
BNTRE	Number of trees in a bunch.
BNVOL	Volume of bunch (cu.ft. × 100).
BRKTM	Total time spent on breaks (centi-minutes).
DAYS	Number of days worked.
DBH	Diameter breast high (d.b.h.) of current tree (inches).
DELNM	Total time lost to nonmechanical delays (centi-minutes).
DELYM	Total time lost to mechanical delays (centi-minutes).
FBACC	Total number of feller/buncher accumulator loads.
FBDIS	Total distance feller/buncher has traveled (feet).
FBGPH	Feller/buncher fuel usage (gal./hr.).
FBHR	Total time feller has worked (hours × 100).
FBOUT	Distance feller travels to get to the woods (feet).

FBTIM	Total time feller has been on job (minutes × 100).
FBTRE	Total trees cut.
FBTYP	Feller/buncher type; tracked = 0, rubber-tired = 1.
FBVOL	Total volume cut (cu.ft. × 100).
FTRV1	Mean travel speed (ft./min.).
FTRV2	Standard deviation of travel speed.
LASTB	Location of last bunch.
LBCFT	Density of plot species (lb./cu. ft.).
MVSTP	Distance feller/buncher travels between strips.
NUMFB	Number of feller/bunchers on the job.
STPLN	Length of strip or row (feet).
STRIP	Number of strips harvested.
TRPAC	Mean stand density (trees/acre).
WKDAY	Length of work shift (hours).

Switches

COFFE	Set by timer to indicate coffee break.
DAY	Set by timer to indicate beginning of work day.
FBMOV	Set by feller when he must move (no more trees in reach).
LUNCH	Set by timer to indicate lunch break.
STRIP	Set by feller/buncher when he has cut the last tree of current strip.

Tables

ACCTR	Trees per accumulator load.
ACCVL	Volume per accumulator load (cu.ft. × 100).
BDIA	Sum of diameter of trees in a skid bunch (inches).
BDIF	Distance between bunches (feet).
BLOC	Bunch location— distance down strip (feet).
BTREE	Number of trees in skidder bunch.
BVOL	Volume per skidder bunch (cu.ft. × 100).
FBTIM	Cycle time for feller/buncher, from drop to drop, including delays (centi-minutes).

Queues

BREAK	Coffee and lunch break time.
DROP	Swing and drop time.
FBSHR	Position and shear time.
FBTRV	All travel time.
MCDLY	Mechanical delays.
NMDLY	Nonmechanical delays.

Variables

ACCLM	Accumulator head size limit (number of trees).
BNDIF	Calculate distance between bunches (feet).
BREAK	Time between breaks (centi-minutes).
BRKTM	Time spent on breaks (centi-minutes).
BUNLM	Skidder bunch limit (sum of diameter).
DELNM	Nonmechanical delay time (centi-minutes).
DELYM	Mechanical delay time (centi-minutes).
FBDRP	Swing and drop time (centi-minutes).
FBHR	Total hours worked.
FBMOV	Distance feller/buncher must move to put more trees in reach (feet).
FBSHR	Shear time (centi-minutes).
FBTRV	Travel time (centi-minutes).
MCDLY	Length of mechanical delay (centi-minutes).
NEXTY	Next harvesting location down strip = current position + 95 percent distance traveled (allows for travel not in a straight line).
NIGHT	Remainder of 24 hours after work shift (centi-minutes).
NMDLY	Nonmechanical delay time (centi-minutes).
REACH	Number of trees within reach of boom at current feller/buncher position.
SPEED	Travel speed (ft./min.).
STEND	Distance to the end of strip (feet).
STPLN	Length of strip or plot (feet).
TDIAM	Tree diameter (inches).
TVOL	Tree volume (0.01 cu. ft.).
WKDAY	Length of work shift (centi-minutes).

APPENDIX B
PROGRAM LISTING

```
      / - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
      *
      *          FELLER BUNCHER SIMULATOR
      *             UPDATED  JULY 1979
      *
      *
      *        U.S. FOREST SERVICE, NORTH CENTRAL FOREST EXPERIMENT STATION
      *        MARKETING PROJECT, DULUTH, MINNESOTA
      *        ENGINEERING PROJECT, HOUGHTON, MICHIGAN
      *
      *          AUTHORS:  SHARON A. WINSAUER
      *                    DENNIS P. BRADLEY
      * - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
      *
      *
      * - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
      *
      *                     MASTER TIMER AND REPORT GENERATOR
      *
      * - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - - -
      *
      *          THIS SEGMENT CONTROLS THE STOP AND START OF THE FELLER BUNCHER,
      *            THE HOURS WORKED  PER DAY, XSWKDAY, AND THE NUMBER OF
      *            DAYS WORKED(ARGUMENT A ON START CARD)
      *
      *          IT ALSO CALCULATES OUTPUT VALUES,VALUES TO BE SENT TO HELP BLOCKS,
      *
      *
      *
       WKDAY VARIABLE   X$WKDAY*6000          WORKDAY IN CENTIMINUTES
       BREAK FVARIABLE  V$WKDAY/4             TIME BETWEEN BREAKS
       NIGHT VARIABLE   (24-X$WKDAY)*6000     REST OF 24 HOURS IN CENTIMINUTES
      *
   1   TIMER GENERATE   ,,,1,12
   2   NXDAY SAVEVALUE  DAYS+,1               NUMBER OF CURRENT WORKING DAY
   3         LOGIC S    DAY
   4   DAY   ADVANCE    V$BREAK               TIME FOR COFFEE BREAK
   5         LOGIC S    COFFE
   6         ADVANCE    V$BREAK               WORK UNTIL LUNCH TIME
   7         LOGIC S    LUNCH
   8         ADVANCE    V$BREAK               AFTERNOON COFFEE
   9         LOGIC S    COFFE
  10         ADVANCE    V$BREAK               END OF WORK DAY
  11         LOGIC R    DAY
  12         ADVANCE    V$NIGHT               WAIT UNTIL NEXT MORNING
      *
      * * * *  HELP BLOCKS  GENERATE REPORT AT END OF EACH DAY
      *
      *
      * * * * REPORT VARIABLES
      *
  13         SAVEVALUE  FBHR,V$FBHR           HOURS FB HAVE WORKED
  14         SAVEVALUE  BRKTM,V$BRKTM         TIME FB SPENT ON BREAKS IN MIN*100
  15         SAVEVALUE  DELYM,V$DELYM         MECHANICAL DELAY TIME OF FB
  16         SAVEVALUE  DELNM,V$DELNM         NON-MECHANICAL DELAY TIME OF FB
       FBHR  FVARIABLE  X$FBTIM/60
       BRKTM FVARIABLE  QT$BREAK*QC$BREAK
       DELYM FVARIABLE  QT$MCDLY*QC$MCDLY
       DELNM FVARIABLE  QT$NMDLY*QC$NMDLY
      *
      * * * *  STAND DATA AND MACHINE CHARACTERISTICS REPORT
      *
  17         HELP       SYSTM,X$AVVOL,X$AVDBH,X$AVHGT,X$TRPAC
  18         HELP       SYSTM,X$NUMFB,X$ACLM1,X$FBTYP,X$BNLM1
      *               AVE VOL,AVE DBH,AVE HEIGHT,TREES/ACRE,NUM OF FELLERS
      *           FB ACCUMULATOR HEAD LIMIT,FB TYPE,SKIDDER BUNCH LIMIT
      *
      * * * *  FELLER BUNCHER  PRODUCTION REPORT
      *
  19         HELP       FELBN,X$NUMFB,X$FBTYP,X$BRKTM,X$DELYM,X$DELNM
      *         NUM OF FELLER BUNCHERS, FB TYPE,BREAKTIME,DELAY TIME
      *
  20         HELP       FELBN,X$FBTRE,X$FBVOL,X$BNCOM,X$FBHR,X$FBDIS
      *         TOT TREES,TOT VOL,SKID BUNCHES COMPLETED,FB HOURS,TOT DIST TRAVELED
      *
  21         HELP       FELBN,X$FBACC,X$LBCFT,X$FBVOL,X$FBGPH
      *         NUM OF ACC LOADS, WOOD DENSITY LB/CUFT, TOT VOL, GAL PER HOUR USED
      *
  22         SPLIT      1,NXDAY
  23   OUTPT TERMINATE  1
```

```
/
*  * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*
*      GENERAL FUNCTIONS NEEDED IN MODEL
*
*  * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*
* * * *  FN$SNORM IS USED TO OBTAIN A SAMPLING OF AN APPROXIMATELY
*           NORMAL DISTRIBUTION OF MEAN 0 AND STANDARD DEV 1
*
*        NOTE: TO AVOID DATA LOSS FROM INTERGERAZATION,
*              FUNCTION VALUES HAVE BEEN
*              MULTIPLIED BY 10
*      *  *    USE     MEAN+(FN$SNORM * S.DEV)/10
*
*        NOTE: LOWER END OF FUNCTION HAS BEEN TRUNCATED
*              TO AVOID NEGATIVE ADVANCE BLOCKS
*              WHEN STANDARD DEVIATIONS ARE LARGE
*
*
SNORM FUNCTION   RN2,C20
0,-15/.0668,-15/.1151,-12/.1587,-10/.2119,-8/.2742,-6/.3446,-4
.4207,-2/.5,0/.5793,2/.6544,4/.7258,6/.7881,8/.8413,10/.8849,12
.9332,15/.9772,20/.9938,25/.9986,30/.9999,40/1.,50
*
*  * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*
*      TRACKED TYPE FELLER BUNCHER
*
*  * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*
*
*      THIS SEGMENT IS A FELLER BUNCHER WITH A BOOM MOUNTED SHEAR
*         IT CAN BE USED AS A SINGLE STEM OR ACCUMULATING HEAD FB
*
*      THE FELLER BUNCHER IS ASSUMED TO WORK IN A ZIG-ZAG PATTERN
*         - OUT ONE STRIP BACK THE NEXT.
*
*      THE FB COMBINES MULTIPLE ACCUMULATOR HEAD BUNCHES TO OBTAIN A
*         BUNCH BIG ENOUGH FOR THE SKIDDER.
*
*
*  * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*
*
*  * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
*
*                 FELLER BUNCHER PARAMATER ASSIGNMENTS
*
*          P1   NOT USED
*          P2   CLOCK TIME
*          P3   CURRENT LOCATION OF FB
*          P4   BUNCH TIME
*          P5   TREE NUMBER
*          P6   CURRENT ACCUMULATOR LIMIT
*          P7   CURRENT BUNCH SIZE LIMIT
*          P8   TREE DIA
*          P9   DIST FB WILL TRAVEL
*          P10  # TREES IN REACH
*          P11  SUM OF DIAMETER IN ACC. HEAD
*          P12  TOTAL VOLUME IN ACC. HEAD
*          P13  NUMBER OF TREES IN LOAD
*
*
* * * *  GENERATE FELLER BUNCHERS , INITILIZE ACC HEAD
*
* * * *  DEFINING VARIABLES FOR FELLER BUNCHER
*
*
BNDIF FVARIABLE  P4-XSLASTB               DISTANCE BETWEEN BUNCHES
NEXTY FVARIABLE  P9*957100+P3             ACTUAL DIST DOWN STRIP (FT)
STEND FVARIABLE  P3-XSSTPLN               DISTANCE TO END OF STRIP
*
FBTIM TABLE      MP2,0,25,25              OUTPUT TABLES FOR FB
ACCVL TABLE      P12,0,500,20               CYCLE DATA
ACCTR TABLE      P13,0,1,12
*
BDIA  TABLE      XSBNDIA,0,5,25           TABLES OF SKIDDER
BTREE TABLE      XSBNTRE,0,1,25             BUNCHES CREATED
BDIF  TABLE      XSBNDIF,0,5,15
BLOC  TABLE      XSBNLOC,0,20,50
BVOL  TABLE      XSBNVOL,0,500,40
```

```
      /
      *
      * * * *   GENERATE FELLER BUNCHERS,INITIALIZE FIRST DIST,ACCUMULATOR HEAD
      *
24     ACCFB GENERATE   ,,,1,10,15
      *
25           SAVEVALUE  STRIP,1                 INITIALIZE STRIP COUNT
26     INIT  ASSIGN     11,0                    INITIALIZE ACCUMULATOR HEAD
27           ASSIGN     12,0
28           ASSIGN     13,0
29           ASSIGN     6,V$ACCLM               ACC. LOAD LIMIT
30           ASSIGN     7,V$BUNLM               BUNCH SIZE LIMIT
31           ASSIGN     9,X$FBOUT               DIST FB TRAVELS TO START WORK
32           MARK       2                       MARK START OF CYCLE
      *
      * * * * FB MOVES TO NEXT LOCATION,RESETS SWITCH FBMOV,RECORDS
      *         TRAVEL DISTANCE AND TIME AND DETERMINES # OF TREES
      *          WITHIN REACH AT THIS LOCATION.
      *
33     FBMOV QUEUE      FBTRV
34           ADVANCE    V$FBTRV                 FB MOVES TO NEW LOCATION
35           DEPART     FBTRV                   RECORD TRAVEL TIME
36           SAVEVALUE  FBDIS+,P9                     AND DISTANCE
      *
37           ASSIGN     10,V$REACH              DETERMINE # OF TREES IN REACH
38           ASSIGN     4,P3                    ACTUAL DISTANCE DOWN THE STRIP OF
      *                                           THE FELLER BUNCHER
39           ASSIGN     9,V$FBMOV               DISTANCE FB WILL HAVE TO MOVE
      *                                           WHEN DONE HERE
40           ASSIGN     3,V$NEXTY               NEXT LOCATION OF FB
41           LOGIC R    FBMOV                   RESET TO INDICATE FB NOT
      *                                           READY TO MOVE
      *
      * * * * CHECK IF FB HAS CARRIED A TREE TO THIS LOCATION
      *         IF SO GO TO DROP
      *
42           TEST E     P13,0,DROP              IF # OF TREES IN HEAD > 0 DROP
      *
      * * * * TREE-    FELLER BUNCHER DEFINES AND SHEARS TREES UNTIL ACCUMULATOR
      *                 HEAD IS FULL OR UNTIL HE RUNS OUT OF
      *                 TREES WITHIN REACH
      *
43     TREE  ASSIGN     5+,1                    TREE NUMBER
44           ASSIGN     8,V$TDIAM               DBH
      *
45           QUEUE      FBSHR
46           ADVANCE    V$FBSHR                 SHEAR TREE
47           DEPART     FBSHR                   RECORD SHEAR TIME
      *
48           ASSIGN     11+,P8                  TOTAL SUM OF DBH OF LOAD
49           ASSIGN     13+,1                   # OF TREES IN ACC HEAD
50           SAVEVALUE  DBH,P8
51           ASSIGN     12+,V$TVOL              TOTAL VOL OF ACC. LOAD
52           ASSIGN     10-,1                   ONE LESS TREE IN REACH
      *
53           TEST G     P10,0,DONE              IF NO MORE TREES HERE GO TO DONE
54           TEST GE    P13,P6,TREE             IF ACC NOT FULL & A TREE IN REACH
      *                                           GO TO TREE TO CUT IT
55           TRANSFER   ,DROP                   ACC HEAD FULL GO TO DROP
      *
56     DONE  LOGIC S    FBMOV                   SET SWITCH THAT THE FB MUST MOVE
57           TEST L     P3,V$STPLN,STRIP        IF AT END OF STRIP GO TO STRIP
58           TEST E     X$BNTRE,0,DROP          IF BUNCH IS ALREADY STARTED,DROP LOAD
      *                                           OTHERWISE,CARRY TREES IN ACC. HEAD
      *                                           ALONG WITH (FBMOV)
59           TRANSFER   ,FBMOV
60     STRIP LOGIC S    STRIP                   SET SWITCH INDICATING END OF STRIP
      *
```

```
       / * * * DROP-   SWING AND DROP THE FB LOAD, ACCUMULATE LOAD STATISTICS
       *                 SEE IF THE BUNCH IS LARGE ENOUGH FOR SKIDDERS
       *
 61     DROP  QUEUE       DROP
              ADVANCE     VSFBDRP                 SWING AND DROP BUNCH
 63           DEPART      DROP                    RECORD SWING & DROP TIME
       *
 64           SAVEVALUE   BNLOC,P4                DISTANCE DOWN STRIP
 65           SAVEVALUE   BNVOL+,P12              TOTAL VOLUME
 66           SAVEVALUE   BNDIA+,P11              TOTAL DIA OF LOAD
 67           SAVEVALUE   BNTRE+,P13              TOTAL NO OF TREES
       *
       * * * * DELAY-   IF A DELAY IS DUE TO OCCUR, IT HAPPENS HERE
       *
 68           QUEUE       MCDLY
 69           ADVANCE     VSMCDLY                 MECHANICAL DELAY
 70           DEPART      MCDLY
 71           QUEUE       NMDLY
 72           ADVANCE     VSNMDLY                 NON-MECHANICAL DELAY
 73           DEPART      NMDLY
       *
 74           SAVEVALUE   FBACC+,1                KEEP TRACK OF NUMBER OF ACC. LOADS
 75           SAVEVALUE   FBTRE+,P13              FB RECORDS PRODUCTION OF
 76           SAVEVALUE   FBVOL+,P12                BOQUETS AND OF TIME
 77           SAVEVALUE   FBTIM+,MP2
 78           TABULATE    FBTIM
 79           TABULATE    ACCVL
 80           TABULATE    ACCTR
 81           MARK        2                       REINITIALIZE ACC HEAD
 82           ASSIGN      11,0
 83           ASSIGN      12,0
 84           ASSIGN      13,0
 85           ASSIGN      6,VSACCLM               NEW ACCUMULATOR LIMIT
 86           ASSIGN      7,VSBUNLM               NEW BUNCH LIMIT
       *
 87           TEST L      XSBNDIA,P7,BUNCH
       *                                                    TO BUNCH
 88           GATE LS     FBMOV,TREE                     IF MORE TREES IN REACH -
       *                                                    GO TO TREE FOR
       *                                                    ANOTHER ACC. LOAD
       *
       * * * * BUNCH-  TABULATE BUNCH DATA TO USE FOR SKIDDERS,REINITIALIZE
       *                  PARBN MATRIX ,CHECK IF FB IS AT END OF STRIP
       *
       *
 89     BUNCH TABULATE    BDIA                    RECORD BUNCH DATA FOR SKID SEG
 90           TABULATE    BTREE
 91           TABULATE    BVOL
 92           TABULATE    BLOC
       *
 93           SAVEVALUE   BNDIF,VSBNDIF           DISTANCE BETWEEN BUNCHES
 94           TABULATE    BDIF
 95           SAVEVALUE   LASTB,P4
 96           SAVEVALUE   BNVOL,0                 REINITIALIZE BUNCH DATA
 97           SAVEVALUE   BNDIA,0                   FOR NEXT BUNCH
 98           SAVEVALUE   BNTRE,0
 99           SAVEVALUE   BNCOM+,1                IF TIME FOR COFFEE OR LUNCH,
       *                                            TAKE BREAK
100           QUEUE       BREAK
101           GATE LS     COFFE,NOBRK              CHECK IF BREAK
102           ADVANCE     1500                     15 MINUTE COFFEE BREAK
103           LOGIC R     COFFE
104     NOBRK GATE LS     LUNCH,QUIT
105           ADVANCE     3000                     30 MINUTE LUNCH BREAK
106           LOGIC R     LUNCH
       *
       * * * * QUIT-   TABULATE TIME ON BREAKS AND CHECK IF
       *                  IT'S TIME TO QUIT FOR THE DAY
       *
107     QUIT  SAVEVALUE   FBTIM+,MP2               TABULATE TIME SPENT ON BREAK
108           DEPART      BREAK
109           GATE LS     DAY                     IF SHIFT IS OVER, STOP UNTIL TOMORROW
110           MARK        2                       MARK START OF CYCLE
111           GATE LS     FBMOV,TREE              MORE TREES IN REACH -GO TO TREE
112           GATE LS     STRIP,FBMOV             IF NOT END OF STRIP -GO TO FBMOVE
       *
113           ASSIGN      3,VSSTEND               STRIP DISTANCE
114           SAVEVALUE   LASTB,0
115           SAVEVALUE   STRIP+,1                COUNT STRIPS
116           LOGIC R     STRIP
117           TRANSFER    ,FBMOV
```

```
/ * * * INPUT DATA
*
*
 FBTRV FVARIABLE  P9*100/VSSPEED           TRAVEL TIME (DIST/SPEED) IN CENTIMIN,
*                                                            P9 - DISTANCE
 SPEED FVARIABLE  XSFTRV1+XSFTRV2*FNSSNORM/10    FELLER BUNCHER TRAVEL
 FBSHR FVARIABLE  FNSFBSHR                 POSITION & SHEAR TIME
 FBDRP FVARIABLE  FNSFBDRP                 SWING AND DROP TIMES
*
 ACCLM FVARIABLE  FNSACCLM                 ACCUMULATOR HEAD LIMIT
 BUNLM FVARIABLE  XSBNLMI                  SKIDDER BUNCH SIZE LIMIT
*
*
 REACH FVARIABLE  FNSREACH                 NUMBER OF TREES WITHIN REACH
 FBMOV FVARIABLE  FNSFBMOV                 DIST FB MUST MOVE TO REACH MORE TREES
 TDIAM FVARIABLE  FNSDBH                   SUPPLIED FROM STAND DBH DATA
 MCDLY FVARIABLE  FNSMCDLY                 MECHANICAL DELAY
 NMDLY FVARIABLE  FNSNMDLY                 NON-MECHANICAL DELAY
 STPLN VARIABLE   XSSTPLN
 TVOL  FVARIABLE  (133*P8*P8-283)/10       TREE VOL IN TERMS OF DIA(P8)
*                                          100 TH'S OF CU FT.
*
*         DEFINING FUNCTIONS - MACHINE DATA
*
*      THIS INPUT DATA WAS OBTAINED FROM ACTUAL TIME STUDIES
*         CARRIED OUT IN 1978
 ACCLM FUNCTION   RN2,D5                   # TREES IN ACC HEAD
.22,1/.45,2/.73,3/.9,4/1.,5
*       POSITION AND SHEAR - PER STEM  TIME' IN CENTI-MIN
 FBSHR FUNCTION   RN2,C9
0,0/.29,10/.68,20/.89,30/.97,40/.98,50/.99,60/.995,70/1.0,90
*
*       SWING AND DROP   TIME IN CENTI-MIN
 FBDRP FUNCTION   RN2,C8
0,0/.13,10/.80,20/.95,30/.98,40/.99,50/.995,60/1.0,70
*
*         DEFINING FUNCTIONS - STAND DATA
*
 DBH   FUNCTION   RN4,D7                   TREE DIAMETER  INCHES
.05,3/.28,4/.58,5/.82,6/.96,7/.99,8/1.0,9
*
 REACH FUNCTION   RN3,C12                  TREES IN REACH AT A GIVEN SPOT
0,2/.03,4/.1,6/.2,8/.6,16/.68,18/.75,20/.81,22/.86,24/.9,26/.95,30/1,36
*
 FBMOV FUNCTION   RN3,C9                   DISTANCE FELLER MUST MOVE
0,0/.1,5/.25,10/.55,25/.75,35/.85,50/.9,60/.95,90/1.,120
*
 MCDLY FUNCTION   RN6,D11                  MECHANICAL DELAY
.99,0/.991,50/.992,100/.993,150/.994,200/.995,250/.996,500/.997,1000
.998,2000/.999,3000/1.0,4000
*
 NMDLY FUNCTION   RN6,D13                  NON-MECHANICAL DELAY
.985,0/.987,15/.989,25/.991,35/.992,40/.993,50/.994,75/.995,80/.996,100
.997,200/.998,300/.999,400/1.0,500
*
* * * * INITIAL CONDITIONS FOR STAND
*
*               INITIAL DATA TAKEN FROM MPH TIME STUDY
        INITIAL     XSAVDBH,550            AVE. DBH  (IN)*100
        INITIAL     XSAVHGT,43             AVE TREE HGT, APPROX 42'
        INITIAL     XSAVVOL,345000         CU FT/ACRE*100
        INITIAL     XSTRPAC,884            TREES/ACRE
        INITIAL     XSSTPLN,725            AVE. STRIP LENGTH
        INITIAL     XSMVSTP,35             DISTANCE BETWEEN STRIPS
        INITIAL     XSLBCFT,55             LB PER CU FT - RED MAPLE
        INITIAL     XSWKDAY,8              HRS IN A WORK DAY
*
* * * * INITIAL CONDITIONS FOR EQUIPMENT -DATA TAKEN FROM USFS MPH TIME STUDY
*
        INITIAL     XSACLM1,4              MAX # TREES IN ACC LOAD
        INITIAL     XSBNLM1,120            MAX ATTEMPTED SKID BUNCH SIZE
        INITIAL     XSFTRV1,49             MEAN TRAVEL SPEED  FT/MIN
        INITIAL     XSFTRV2,19             STD. DEV. TRAVEL SPEED  FT/MIN
        INITIAL     XSFBGPH,55             FB  GAL/HR*10
        INITIAL     XSFBTYP,0              DROTT 0   RUBBER TIRED 1
        INITIAL     XSFBOUT,100            DIST FB TRAVELS TO WOODS
*
*
        RMULT       ,,,37
        START       5,,5,1
        END
```

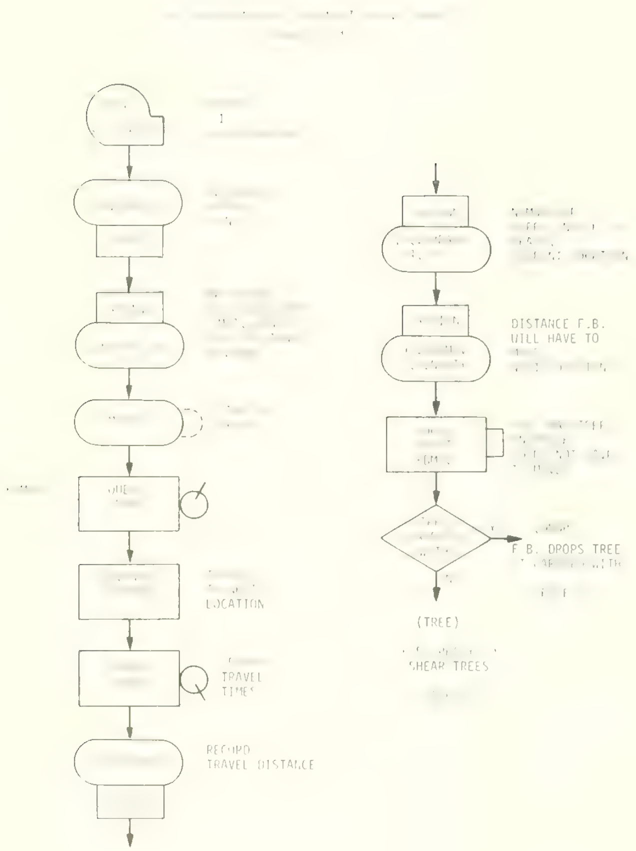
```
      SUBROUTINE SYSTM(IX)
      DIMENSION IX(5)
      DATA I/0/
C
    1 FORMAT(1H1,43X,'FULL  TREE  FIELD  CHIPPING  ',
     A 'SIMULATOR'/1H0,58X,'DEVELOPED  BY  THE'/1H ,46X,'NORTH CENTRAL '
     B,'FOREST  EXPERIMENT  STATION'/1H ,44X,'FOREST  SERVICE, U. S. DEP
     CT.  OF  AGRICULTURE'//1H0,29X, 'FOREST  PRODUCTS  MARKETING  AND
     TUTILIZATION  PROJECT,  DULUTH,  MINNESOTA'/1H ,61X,'AND  THE'/1H ,
     E40X,'FOREST  ENGINEERING  LABORATORY, HOUGHTON,  MICHIGAN'/1H0,62X
     F,'AUTHORS '/1H ,52X,'DENNIS P. BRADLEY, ECONOMIST'/1H ,51X,'SHARON
     G A. WINSAUER, PROGRAMMER'//)
C
    2 FORMAT(1H0,'I.  STAND CHARACTERISTICS.'//1H0, F12.2,' CU FT. ',
     A  'AVERAGE VOLUMF',
     B' PER ACRE.'/1H0,F12.2,' INCHES, AVERAGE DBH.'/1H0,F12.2,' FEET,',
     C' AVERAGE TREE HEIGHT.'/1H0,F12.2,' AVERAGE NUMBER OF TREES ',
     D'PER ACRE.'/1H0,F12.2,' FEET, AVERAGE TREE SPACING.'/)
C
    3 FORMAT(1H0,'II.  SYSTEM CHARACTERISTICS AS SPECIFIED BY THE ',
     A'ANALYST.'//1H ,2X,'A.  FELLER-BUNCHER.',10X ,I10,'  MACHINE',
     B  5X,'TRACKED TYPE-ROTATABLE BOOM WITH ACCUMULATOR SHEAR'
     C  , //9X,'MACHINE LIMITATIONS '/)
C
    4 FORMAT(1H0,'II.  SYSTEM CHARACTERISTICS AS SPECIFIED BY THE ',
     A'ANALYST.'//1H ,2X,'A.  FELLER-BUNCHER.',10X ,I10,'  MACHINE',
     B5X,'RUBBER-TIRED TYPE',//,9X,'MACHINE LIMITATIONS. '/)
C
    5 FORMAT(1H , 14X, 'THE SHEAR CAN HANDLE ONLY ONE TREE.')
C
    6 FORMAT( 1H , 10X, 'THE ACCUMULATOR-SHEAR WILL TRY TO OBTAIN',
     A ' A LOAD OF UP TO',F6.1,' TREES')
C
    7 FORMAT(1H0,8X,'BUNCH LIMITATIONS DICTATED BY SKIDDER CAPACITY:'/
     A1H0, 10X,'THE FELLER-BUNCHERS TRY TO ACHIEVE'   ,
     B ' SKIDDER BUNCHES WITH A TOTAL SUM OF DIAMETERS EQUAL TO',
     C F6.1, ' INCHES')
C
C
      X1 = IX(1)
      X2 = IX(2)
      X3 = IX(3)
      X4 = IX(4)
      X5 = IX(5)
      I = I + 1
      IF ( I .GT. 2 ) I = 1
      GO TO (10,20),I
C
   10 CONTINUE
      AVVOL= X1/100.
C AVVOL = AVERAGE VOLUMN PER ACRE - CUFT.
      AVDBH= X2/100.
C ACDBH = AVERAGE DBH - INCHES
      AVHGT=X3
C AVHGT = AVERAGE TREE HEIGTH - FEET
      TRPAC=X4
C TRPAC = AVERAGE NUMBER TREES PER ACRE
      TRSPC=(43560./TRPAC)**.5
C TRSPC = AVERAGE TREE SPACING - FEET
      WRITE (6,1)
      WRITE(6,2) AVVOL,AVDBH,AVHGT,TRPAC,TRSPC
      RETURN
C
   20 CONTINUE
      NUMFB=1
C NUMFB = NUMBER OF FELLER-BUNCHERS
      ACCLM =  X2
C ACCLM ACCUMULATOR LIMIT SUM OF DBH
      FBTYP=X3
C  FBTYP  FELLER BUNCHER TYPE  0 = DROTT  1 = RUBBER-TIRED TYPE
      BUNLM = X4
C  BUNLM  BUNCH SIZE LIMIT
      IF(FBTYP.EQ.0)WRITE(6,3)NUMFB
      IF(FBTYP.EQ.1)WRITE(6,4)NUMFB
      IF (ACCLM .LT. 1.) WRITE(6,5)
      IF (ACCLM .GE. 1.) WRITE(6,6) ACCLM
      WRITE(6,7) BUNLM
      RETURN
C
      END
```

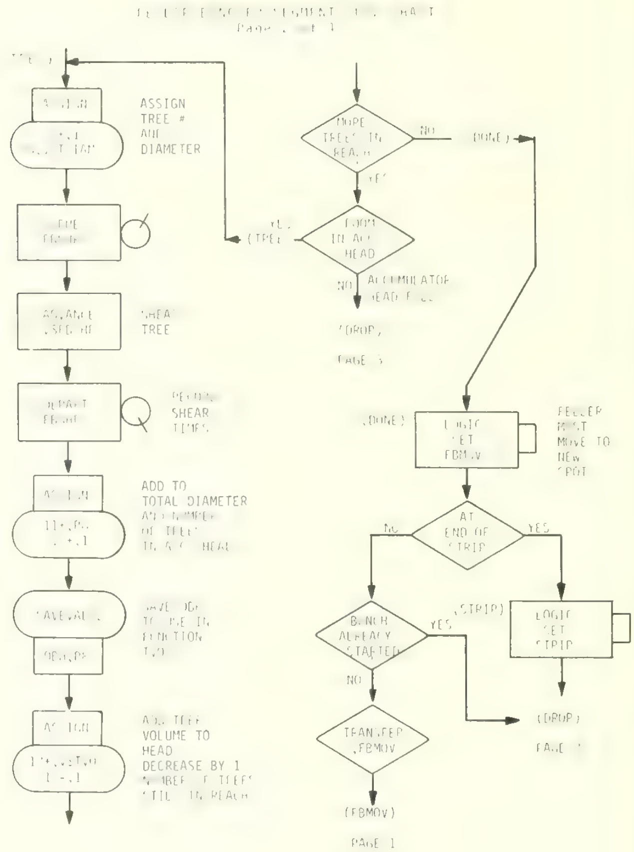
```
      SUBROUTINE FELBN (IX)
      DIMENSION IX(5)
      DATA I/0/
      INTEGER FBACC,FBDIS,BNCOM
C
    1 FORMAT (1H1,4X,'F E L L E R - B U N C H E R   P R O D U C T',
     A' I O N   A N D   C O S T   S U M M A R Y',//,1H ,132('*'),////
     B//,1H,'I.     A.',F8.2,5X,'HOURS WORKED BY FELLER-BUNCHER(S)'
     1 ,' INCLUDING'//16X,F8.2,
     2 5X      'MINUTES OF PERSONAL BREAKS, ',//16X,F8.2,
     3    5X,    'MINUTES MECHANICAL DELAY, ',/  / 16X,F8.2,
     4 5X,     'MINUTES NON-MECHANICAL DELAY',
     C//,7X,'B.',I8,5X,'FELLER-BUNCHER.',5X,
     D 'TRACKED TYPE-ROTATABLE BOOM WITH ACCUMULATOR SHEAR'///)
C
    2 FORMAT (1H1,4X,'F E L L E R - B U N C H E R   P R O D U C T',
     A' I O N   A N D   C O S T   S U M M A R Y',//,1H ,132('*'),////
     B//,1H,'I.     A.',F8.2,5X,'HOURS WORKED BY FELLER-BUNCHER'
     1 ,' INCLUDING'//16X,F8.2,
     2 5X,     'MINUTES OF PERSONAL BREAKS, ',//16X,F8.2,
     3    5X,    'MINUTES MECHANICAL DELAY, ',/  / 16X, F8.2,
     4 5X,     'MINUTES NON-MECHANICAL DELAY',
     C//,7X,'B.',I8,5X,'FELLER-BUNCHER.',5X,
     D'RUBBER-TIRED TYPE.'///)
C
    3 FORMAT(1H,'II.    A.',I8,5X,'TOTAL ACCUMULATOR CYCLES COMPLETED',
     A' - ALL MACHINES.',//,16X,F8.2,5X,'AVERAGE NUMBER OF TREES PER',
     B' CYCLE.',//,16X,F8.2,5X,'AVERAGE VOLUME PER CYCLE - CU.FT.',/)
C
    4 FORMAT(1H,6X,'B.',I8,5X,'BUNCHES COMPLETED',//,
     A16X,F8.2,5X,'AVERAGE NUMBER OF TREES PER BUNCH.',/)
C
    5 FORMAT(1H,15X,F8.2,5X,'AVERAGE NUMBER OF CYCLES PER BUNCH.',/)
C
    6 FORMAT(1H,15X,F8.2,5X,'AVERAGE VOLUME PER BUNCH - CU.FT.',//,
     A7X,'C.',I8,5X,'TOTAL TREES FELLED.',//,7X,'D.',F8.1,5X,
     B'TOTAL VOLUME FELLED - CU.FT.',//,7X,'E.',
     CF8.2,5X,'TOTAL TONS FELLED',//,7X,'F.',I8,5X,
     D    'TOTAL DISTANCE TRAVELED - FEET',///)
C
    7 FORMAT(1H,'III.   A.',F8.2,5X,'AVERAGE NUMBER OF CYCLES PER',
     A' MACHINE HOUR.',/)
C
    8 FORMAT(1H,6X,'B.',F8.2,5X,'AVERAGE NUMBER OF BUNCHES COMPLETED',
     A' PER MACHINE HOUR.',//,7X,'C.',F8.2,5X,'AVERAGE NUMBER OF',
     B' TREES FELLED PER MACHINE HOUR.',//,7X,'D.',F8.2,5X,'AVERAGE',
     C' VOLUME FELLED PER MACHINE HOUR.',//,7X,'E.',F8.2,5X,'AVERAGE',
     D' NUMBER OF TONS FELLED PER MACHINE HOUR.',//,7X,'F.',F8.2,5X,
     E'AVERAGE DISTANCE TRAVELED PER MACHINE HOUR - FEET.',///)
C
C
   11 FORMAT(1H,'IV.    A.',F8.2,5X,'TOTAL GALLONS OF FUEL USED BY',
     A' THE FELLER-BUNCHER.',//,16X,F8.2,5X,'GALLONS PER HOUR.',//,16
     BX,F8.2,5X,'GALLONS PER TON.',//,16X,F8.2,5X,'GALLONS PER CUNIT.')
C
      X1 = IX(1)
      X2 = IX(2)
      X3 = IX(3)
      X4 = IX(4)
      X5 = IX(5)
      I = I+ 1
      IF (I .GT. 3 ) I = 1
      GO TO ( 10,20,30),I
   10 CONTINUE
      NUMFB = 1
C NUMFB =  NUMB. OF FELLER-BUNCHERS
      FBTYP = X2
C  FELLER-BUNCHER TYPE  0 = DROTT  1 = RUBBER-TIRED TYPE
```

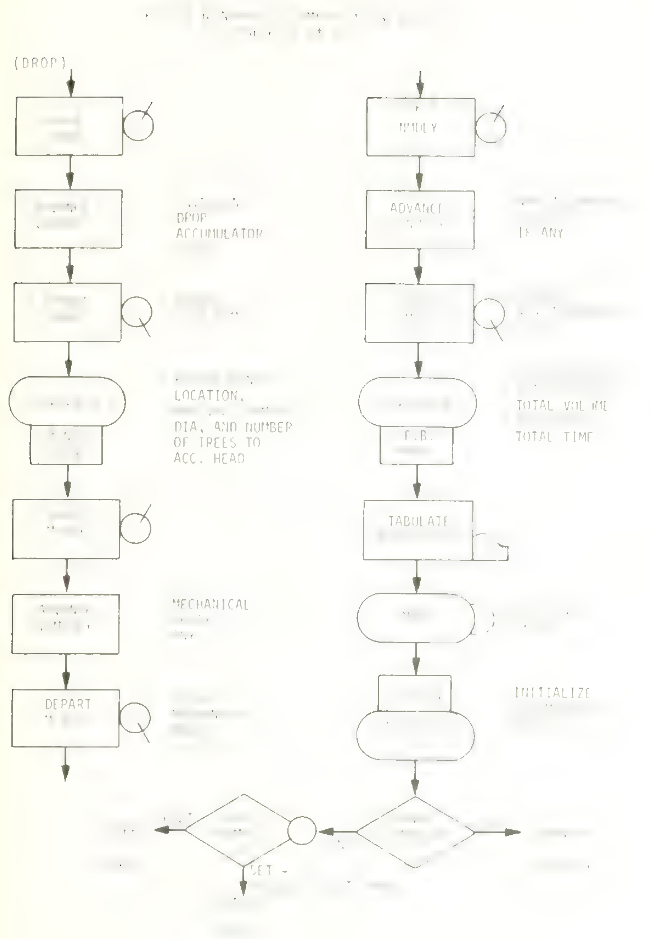
```
C  BREAK AND DELAY TIMES IN MINUTES
      BREAK=X3/100
      DELAY=X4/100
      DELNM=X5/100
      RETURN
   20 CONTINUE
      NTREE =   X1
      FBVOL = X2/100.
C FBVOL =    VOL. FELLED ALL MACHINES
      FBCNT = FBVOL/100.
C  FBCNT  FELLER-BUNCHER VOL. IN CUNITS.
      BNCOM = X3
C BNCOM =  BUNCHES COMPLETED
      FBHR = X4/100.
      FBDIS =   X5
C FBDIS =    DIST. TRAV. ALL MACHINES
      RETURN
   30 CONTINUE
      FBACC = X1
C  FBACC  NUMBER OF ACCUMULATOR COMPLETED CYCLES.
      XDEN = X2
C  POUNDS OF WOOD PER CUBIC FOOT.
      FBTNS = X3*XDEN/200000
      FBGPH = X4/10
C  FELLER-BUNCHER TOTAL GALLONS USED
C  FELLER-BUNCHER VOL. IN TONS
C
      IF( FBTYP.EQ.0 )WRITE(6,1)FBHR,BREAK,DELAY,DELNM,NUMFB
      IF( FBTYP.EQ.1 )WRITE(6,2)FBHR,BREAK,DELAY,DELNM,NUMFB
C
      FBTPC = NTREE*1./FBACC
C  FBTPC  TREES PER CYCLE
      FBVPC = FBVOL/FBACC
C  FBVPC  VOLUME PER CYCLE
      WRITE(6,3)FBACC,FBTPC,FBVPC
C
      FBTPB =  NTREE*1./BNCOM
C FBTPB =  AVE. TREES PER COMPLETED BUNCH.
      WRITE(6,4)BNCOM,FBTPB
C
      FBCPB = FBACC*1./BNCOM
      WRITE(6,5)FBCPB
C
      FBVPB = FBVOL/BNCOM
C FBVPB =  AVE. VOL. PER BUNCH
      WRITE (6 ,6) FBVPB,NTREE,FBVOL,FBTNS,FBDIS
C
      CYCHR = FBACC/FBHR
      WRITE(6,7)CYCHR
C
      FBBMH = BNCOM/FBHR
C FBBMH = AVE. BUNCHES PER MACHINE HOUR
      FBTMH = NTREE/FBHR
C FBTMH = TREES FELLED PER MACHINE HOUR
      FBVMH = FBVOL/ FBHR
C FBVMH = VOL. FELLED PER MACHINE HOUR
      FBATH = FBTNS/FBHR
C  FBATH  AVERAGE TONS PER HOUR
      FBDMH = FBDIS/FBHR
C FBDMH = DIST. TRAV. PER MACHINE HOUR
      WRITE (6 ,8) FBBMH,FBTMH,FBVMH,FBATH,FBDMH
C
C  FELLER-BUNCHER GALLONS/HOUR
      FBGPT = FBGPH/FBATH
C  FELLER-BUNCHER GALLONS PER TON
      FBGPC = FBGPH/(FBVMH/100)
C  FELLER-BUNCHER GALLONS PER CUNIT
      FBTGU = FBGPH*FBHR
      WRITE(6,11)FBTGU,FBGPH,FBGPT,FBGPC
      RETURN
      END
```

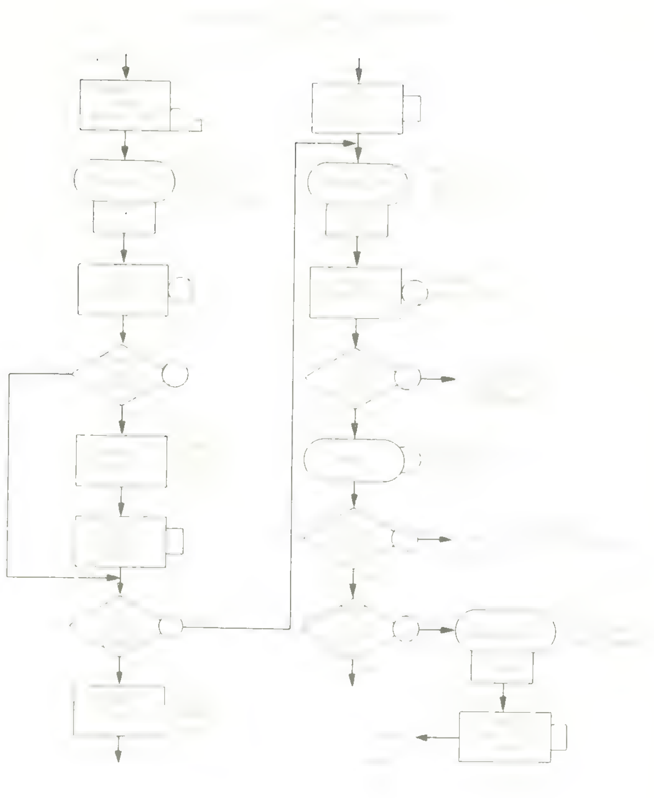
APPENDIX C

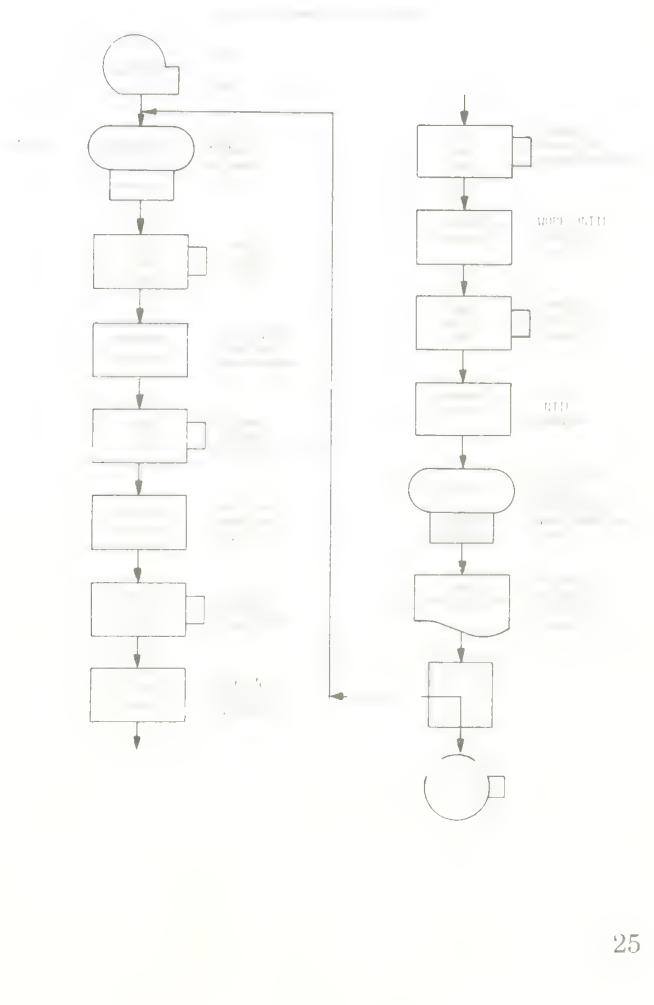
COMPLETE FLOW CHARTS






(DROP)
DROP
ACCUMULATOR
LOCATION,
DIA, AND NUMBER
OF TREES TO
ACC. HEAD
MECHANICAL
DEPART
NMDLY
ADVANCE
IF ANY
TOTAL VOLUME
TOTAL TIME
F.B.
TABULATE
INITIALIZE
SET




WORK UNTIL
NTIL

Winsauer, Sharon A.

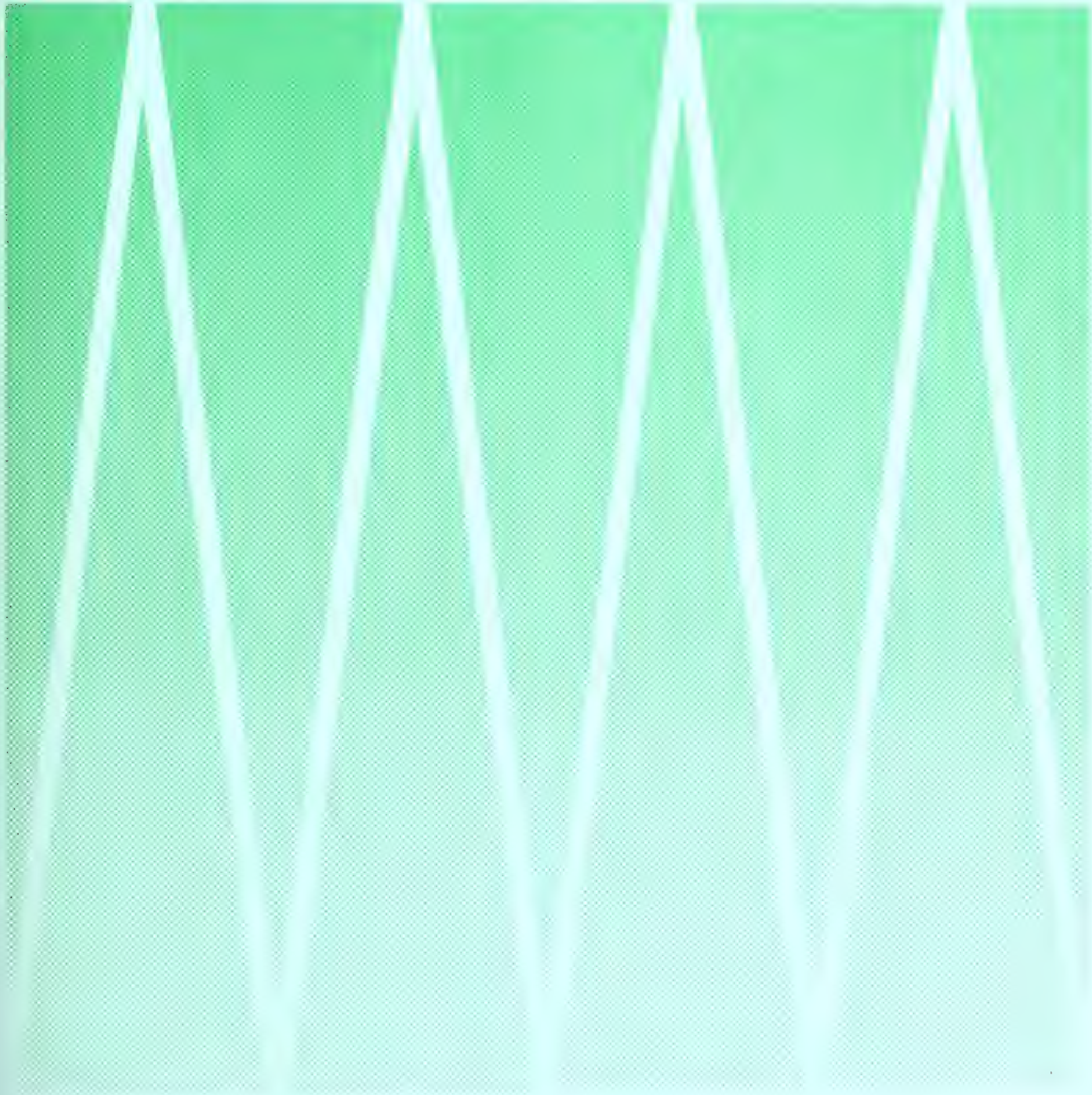
1980. A program and documentation for simulation of a tracked feller/buncher. U.S. Department of Agriculture Forest Service, Research Paper NC-192, 26 p. U.S. Department of Agriculture Forest Service, North Central Forest Experiment Station, St. Paul, Minnesota.

Presents a computer model written in GPSS (General Purpose Simulation System) designed to simulate and study the productivity and operation of a tracked feller/buncher.

KEY WORDS: GPSS (General Purpose Simulation System), computer, harvesting, productivity, modeling.

SDA FOREST SERVICE
ESEARCH PAPER **NC-193**

The effect of initial number of trees per acre and thinning densities on timber yields from RED PINE PLANTATIONS in the Lake States



North Central Forest Experiment Station
Forest Service, U.S. Department of Agriculture

Allen L.

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Forest Service—U.S. Department of Agriculture
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St. Paul, Minnesota 55108
Manuscript approved for publication January 8, 1980

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THE EFFECT OF INITIAL NUMBER OF TREES PER ACRE AND THINNING DENSITIES ON TIMBER YIELDS FROM RED PINE PLANTATIONS IN THE LAKE STATES

Allen L. Lundgren,
Principal Economist

In red pine (*Pinus resinosa* Ait.) stands the initial density (number of established trees per acre), timing of thinnings, and stand density left after thinning (basal area per acre) greatly affect tree diameter growth, and thus the salable timber output. Planting fewer trees reduces establishment costs and accelerates diameter growth of individual trees, resulting in larger, but fewer, trees at any given age. Thinning to low densities also results in fewer but larger trees. But the effects of initial density and subsequent thinning on the quantity and quality of timber product yields are not immediately obvious. A careful evaluation of stand density alternatives is needed to determine the best course of action to meet management goals.

A wide range of initial tree spacings have been recommended for red pine (Evert 1973). Generally, recommendations based primarily on physical yield considerations tend to favor a higher initial density than those based on economic considerations. Wambach (1967), in his analysis of initial spacing in red pine plantations, concluded that a wide spacing, with 400 established trees per acre, is economically preferable to a higher number of trees per unit area, and suggested that under some conditions even fewer trees may be more desirable. Wambach's findings were not published, and his suggestion has not been followed by an evaluation of lower initial densities. It has become apparent that an analysis of such low initial densities is needed.

This paper summarizes the effects of stand density on tree and stand characteristics and timber yields in red pine plantations in the Lake States region of the United States for a wide range of initial numbers of trees and subsequent thinning densities. Simulations of growth and yield in red pine plantations were made using REDPINE, an unpublished growth and yield computer program developed by the author from growth models by Buckman (1962) and Wambach (1967), along with other data.

The initial densities analyzed ranged from 50 to 1,600 established trees per acre; the thinning densities ranged from 60 to 180 square feet of basal area per acre left after thinning. This information should help forest landowners and managers who must decide which initial stocking level and subsequent program of thinnings will best meet their objectives in growing red pine for timber.

SUMMARY

Volume Yields

Several graphs have been prepared to summarize and better illustrate the effects of initial density, thinning density, and site index on volume yields from red pine plantations. These graphs display contour lines of equal annual volume production for a range of initial and residual thinning densities for each site index. They show major differences in production over the range of sites, initial densities, and thinning densities considered.

Total cubic-foot volume production (mean annual increment) drops rapidly on all sites with fewer than 200 established trees per acre (figs. 1-3). As initial density increases above 200 trees per acre, production rises gradually. As initial densities approach 1,200 to 1,600 trees per acre, production levels off, rising very little with additional trees per acre. Production is highest with a thinning density of from 120 square feet on site index 50 to 140 square feet on site index 70. Production falls off for thinning densities lower or higher than these.

Merchantable cubic-foot volume production displays a different pattern (figs. 4-6). Again, a deep trough of low merchantable volume production is noticeable with fewer than 200 trees per acre, but a peak of maximum production is evident at about 800 trees and 120 square feet of basal area on site index

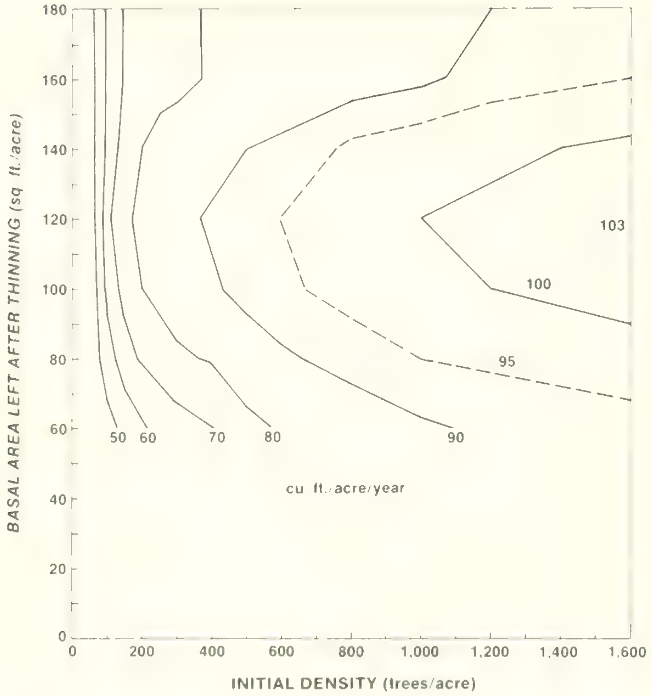

Figure 1.—*The effect of initial and thinning densities on maximum total cubic-foot mean annual increment in red pine plantations on site index 50.*

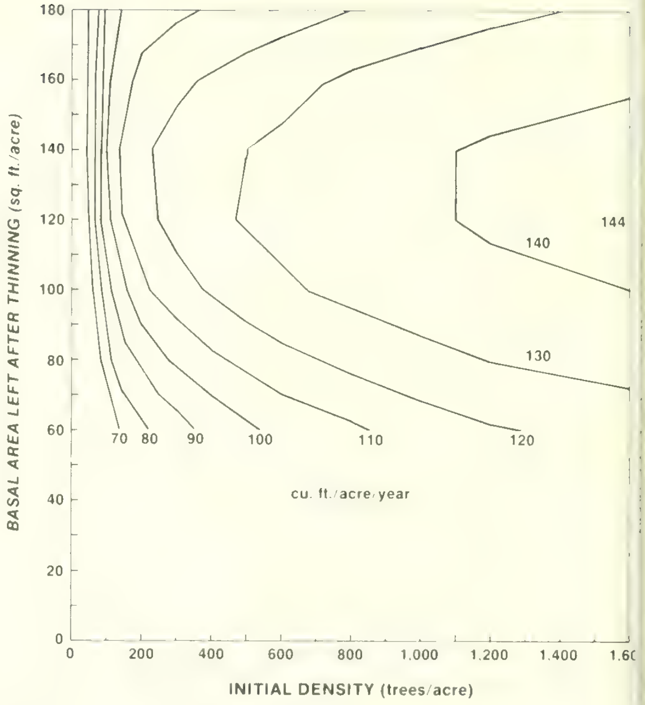

Figure 2.—*The effect of initial and thinning densities on maximum total cubic-foot mean annual increment in red pine plantations on site index 60.*

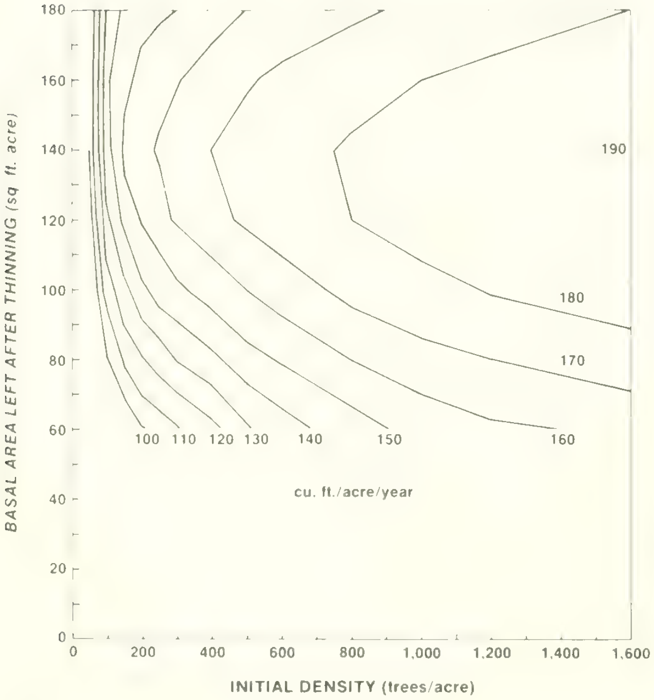

Figure 3.—*The effect of initial and thinning densities on maximum total cubic-foot mean annual increment in red pine plantations on site index 70.*

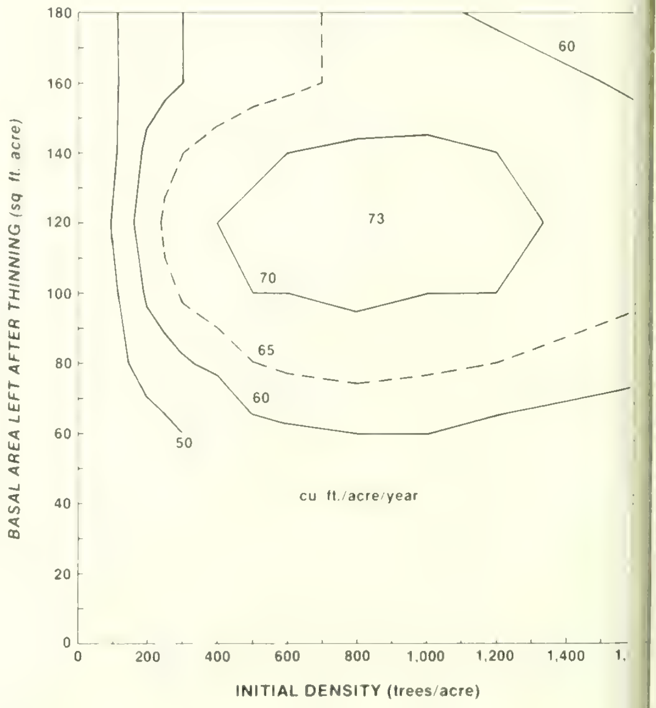

Figure 4.—*The effect of initial and thinning densities on maximum merchantable cubic-foot mean annual increment in red pine plantations on site index 50.*

50, and 1,000 trees and 140 square feet on site index 70. Production drops off at thinning densities above and below these levels.

Board-foot volume production displays an even more noticeable peak in production (figs. 7-9). Once again, there is a distinct depression in production below 200 trees per acre. A sharp peak in production occurs with 200 trees per acre on all sites in stands thinned to 120 square feet of basal area on site index 50, and to 140 square feet on site index 70. Production falls off as numbers of trees per acre increase beyond 200. The choice of thinning density becomes critical at higher numbers of trees per acre, with rapid decreases in production resulting from thinning either too much or too little.

Users of these results should keep in mind that the term "initial density" refers to the number of trees per acre that became established following early mortality the first few years after planting, and assumes reasonably even spacing of the established trees.

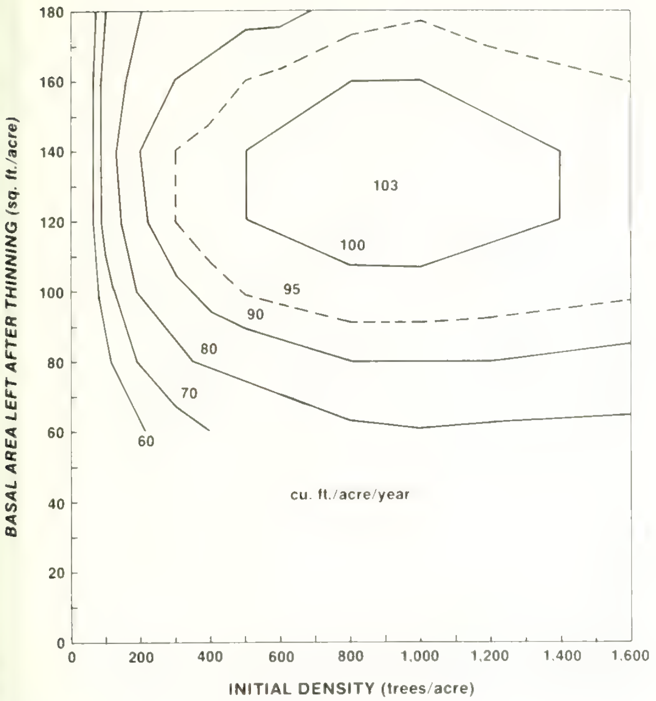

Figure 5.—*The effect of initial and thinning densities on maximum merchantable cubic-foot mean annual increment in red pine plantations on site index 60.*

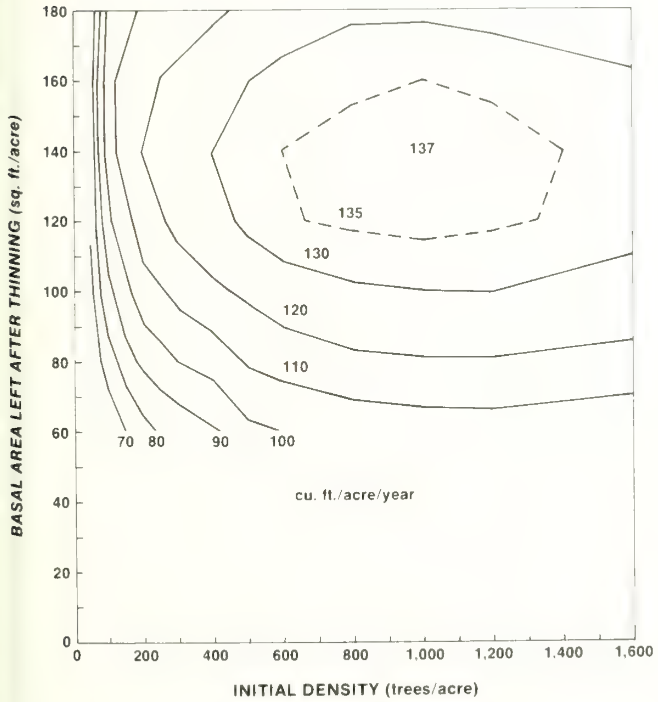

Figure 6.—*The effect of initial and thinning densities on maximum merchantable cubic-foot mean annual increment in red pine plantations on site index 70.*

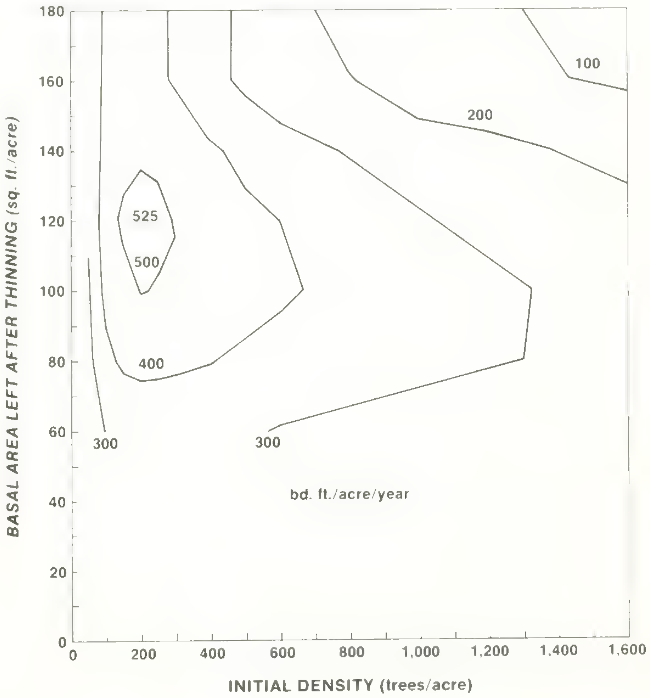

Figure 7.—*The effect of initial and thinning densities on maximum board-foot mean annual increment in red pine plantations on site index 50.*

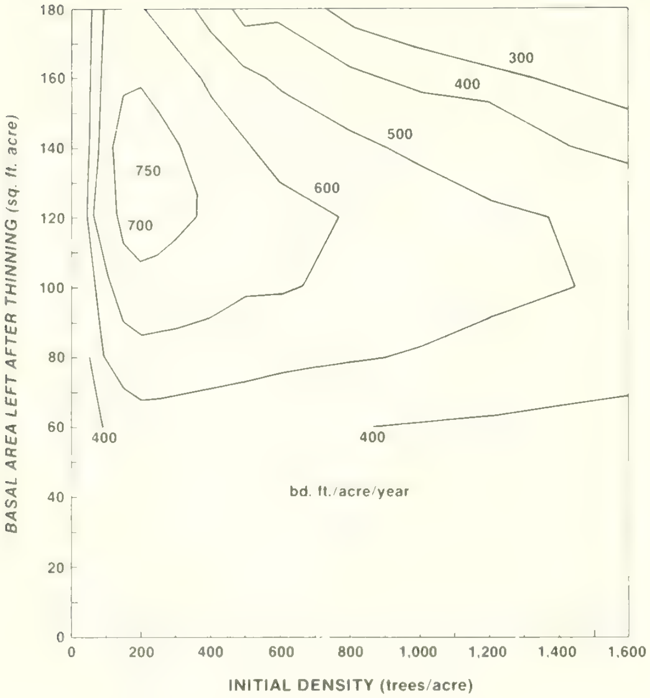

Figure 8.—*The effect of initial and thinning densities on maximum board-foot mean annual increment in red pine plantations on site index 60.*

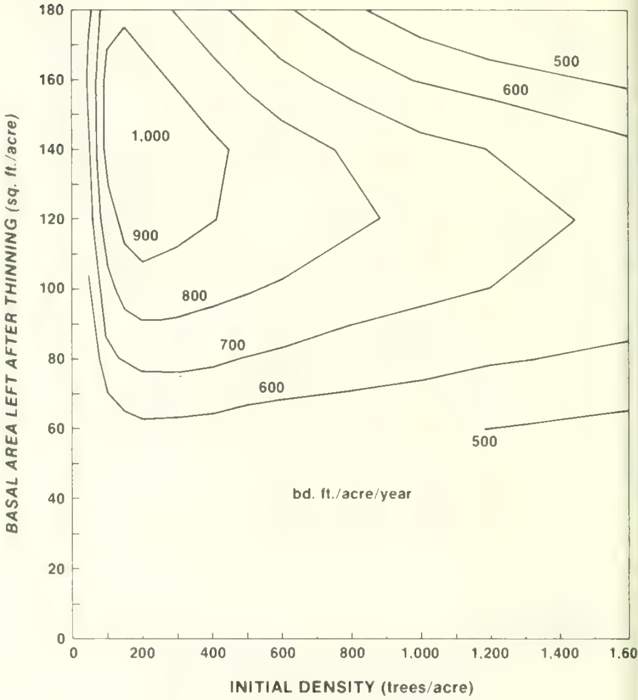

Figure 9.—*The effect of initial and thinning densities on maximum board-foot mean annual increment in red pine plantations on site index 70.*

Tree and Stand Characteristics

Diameter growth is strongly affected by both the initial number of trees per acre and by the stand density left after thinning. Lower initial numbers of trees and lower densities result in fewer but larger trees at a given age, and the effect is great. One of the lowest initial and residual density combinations evaluated here (100 initial trees/acre thinned to 60 square feet of basal area/acre) produced trees 6 inches larger at age 40 and 14 inches larger at age 80 than the highest combination (1,600 initial trees/acre thinned to 180 square feet).

Wood produced with a low initial number of trees/acre has a slightly lower specific gravity than wood produced with a high initial number of trees, varying on site index 60 from 0.34 for 100 trees/acre to 0.35 for 1,600 trees per acre. The average diameter of dead branches at a height of 17 feet was larger for low initial densities, but the difference in branch size between 100 and 1,600 initial trees per acre was less than 3/4 inch.

The initial number of trees per acre has a major impact on the size of trees harvested over a given rotation. With fewer initial trees, fewer trees are harvested over a rotation, but the trees harvested are larger in diameter. On site index 60 stands thinned regularly to 140 square feet, with only 200 established trees per acre, almost all trees harvested for timber over an 80-year rotation were larger than 12 inches d.b.h. and they averaged about 16 3/4 inches. In contrast, almost all trees harvested in the same stands over the same rotation with 1,200 established trees were smaller than 12 inches, and averaged only 7 3/4 inches.

For a given established number of trees per acre, leaving lower basal areas after thinning decreases the average size of trees harvested. Although individual trees grow more rapidly in diameter in stands thinned to low densities, more trees must be cut at an earlier age to reduce the stand to this lower density, and this reduces the average diameter of trees cut. In stands thinned to low basal area densities, more trees have to be harvested to get a thousand cubic feet of total volume than in stands thinned to high basal areas. However, the reverse is true for board-foot volume. Fewer trees have to be cut to get a thousand board feet from stands thinned to low basal areas. These findings, and the analyses from which they are derived, are explained more fully in the sections that follow.

PLANTATION MANAGEMENT REGIMES

Through choices of the initial spacing, the timing, kind, and intensity of thinning, and the final rotation age, a manager can greatly influence the kind, quantity, quality, and timing of salable products harvested from a red pine plantation. An almost endless array of management alternatives exists. Only a limited number are considered here, but these encompass a wide range of choices, making it possible to define regimes that can accomplish a variety of silvicultural and economic objectives.

Initial density is defined as the number of trees successfully established about 5 years after planting; it ranges from 50 to 1,600 trees per acre (T/A) in this analysis, a range in spacing from 29.5 to 5.2 feet between trees.

Trees per acre	**Area per tree** (sq. ft.)	**Square spacing** (ft.)
50	871	29.5
100	436	20.9
150	290	17.0
200	218	14.8
300	145	12.0
400	109	10.4
500	87	9.3
600	73	8.5
800	54	7.4
1,000	44	6.6
1,200	36	6.0
1,600	27	5.2

Trees are considered to be 3-year-old seedlings at the time of planting, and spacing is assumed to be approximately square.The young red pine trees will be released from competing vegetation at 3 and 6 years after planting, and at 15 years if necessary because of low initial density.

Thinnings are to be made at not less than 10-year intervals. The first thinning is to be made 20 years after planting, but only if: (1) height to a 3-inch top d.i.b. is at least 17 feet; (2) the average stand d.b.h. is at least 5 inches; and (3) the potential cut is at least 25 percent of the stand basal area per acre. If the plantation does not meet the above criteria at age 20, the thinning is postponed 5 years, and the stand is checked again. After a thinning, the stand must wait 10 years and have a potential cut of at least 25 percent of the stand basal area per acre to qualify for another thinning. If it does not, thinning is postponed for 5 years, at which time the stand is rechecked to see if it qualifies for a thinning. If it does, it is thinned; if not, it is rechecked each 5 years until it qualifies. This process continues throughout the life of the stand until final harvest.

In this analysis a fixed residual basal area level after thinning is assigned to each stand. This basal area density ranges from 60 to 180 square feet per acre (SF/A), and at each thinning the stand is cut back to the assigned density. The management option of varying residual densities throughout the rotation is not considered. Since basal area growth generally declines with age after the first thinning, the basal area level in each stand follows a declining saw-tooth pattern throughout the rotation (fig. 10). It is assumed that in all thinnings the proportion of trees cut is the same in all diameter classes, so that the diameter of the tree of average basal area does not change. At the end of the assigned rotation the stand is clearcut, and an identical management cycle is repeated. Rotation ages range from 20 to 150 years.

This analysis focuses on only one of many kinds of thinning options: that of choosing a fixed level of residual basal area to which the stand is thinned at a fixed interval of 10 years, and thinning from above and below so that the tree of average basal area is not changed by thinning. Many other thinning options could be selected by the manager, including varying stand densities throughout the rotation, varying intervals between thinnings, and thinning from below or above. Although the findings reported in this study cover only a selected group of management practices, they do cover a broad range of typical recommendations and should help managers in selecting regimes for red pine plantations.

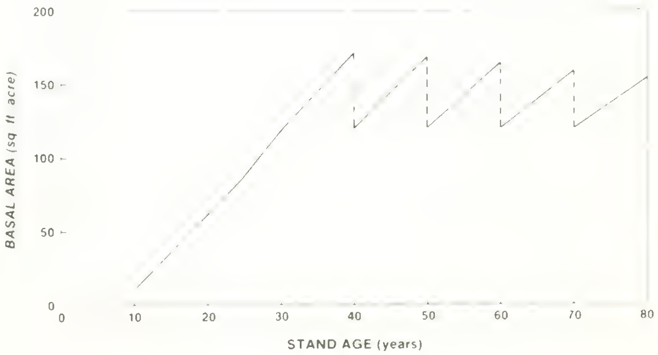

Figure 10.—*Basal area in a red pine plantation with an initial density of 400 established established trees per acre on site index 60, thinned at 10-year intervals to 120 square feet of basal area per acre.*

GROWTH AND YIELD MODEL

A growth and yield model for even-aged red pine plantations and natural stands in the Lake States was developed by modifying, combining, and enlarging the growth and yield models reported by Buckman (1962) and Wambach (1967). Only a brief description of the growth and yield model is given here. Details will be published elsewhere.

Wambach's (1967) reported basal area equation is a relatively simple function that assumes a constant basal area growth regardless of age for a given site and initial number of trees per acre. The original equation (corrected for a misprint of one of the coefficients, and using different symbols for the variables) is:

$$B = 32.278 + 0.001518\,(N)\,(BHA) + 0.6915\,(I)\,(BHA)$$

$R^2 = 0.654 \qquad SE = 29.9\ ft^2$

where B = basal area in square feet per acre,
N = trees per acre,
BHA = breast-height age of the trees, and
I = site index expressed as a 5-year intercept above breast height, in feet.

A more flexible nonlinear function fit to Wambach's original data provided a considerable improvement in fit:

$$B = 6.565\,(S)\,[1 - e^{-.04018A}]^{1.1677}\,[1\ e^{\quad 001885N}]$$

$R^2 = .751 \qquad SE = 25.0\ ft^2$

where S = site index (total height of dominants and codominants at 50 years), and
A = age of the trees in years.

This equation was used to estimate basal area development in stands up to age 25. In practice, basal area growth was determined each year by using the first derivative of the above equation with respect to age. From age 25 on, Buckman's basal area growth equation was used to project stand development:

$$\Delta B = 1.689 + 0.04107B - 0.000163B^2 - 0.07696A + 0.0002274A^2 + 0.06441S,$$

where ΔB = annual basal area growth in square feet per acre.

Wambach's data were from unthinned, fully stocked plantations. When applied to young thinned stands, or to stands with low numbers of trees per acre, the diameter growths implied by the equation derived from his data appeared under some conditions to be too high. To overcome this deficiency, a nonlinear maximum annual diameter growth constraint was imposed on the basal area growth equations:

$$\Delta Dmax = .007\ S\ e^{-.01BHA}.$$

This closely approximates the linear constraint used by Wambach (1967) to overcome this problem. At best this is only an approximation of the complex relation that determines the maximum potential diameter growth of a tree in the absence of competition, but it does impose a needed constraint when applying the model to extremes of spacing. In practice, basal area growth estimated from the equations was reduced when necessary so that this maximum diameter growth was not exceeded.

Starting with an initial number of established trees at a given age below 25 years on a specified site, the revised equation fit to Wambach's data projects stand basal area at future ages. Knowing the site, age, and basal area, Buckman's equation is then used to project basal area growth beyond 25 years. The diameter of the tree of average basal area (D) was computed from stand basal area and number of trees per acre. To determine the proportion of the stand in poletimber and sawtimber size classes, stands were assumed to have a standard deviation (SD) of tree diameters expressed by the following function fit to data reported by Stiell and Berry (1973):

$$SD = .37628\ \bar{D}\ e^{-.093346\bar{D}},$$

where $\bar{D}$ = mean stand diameter.

Heights of dominant and codominant trees (H) were estimated using the nonlinear function reported by Lundgren and Dolid (1970):

$$H = 1.890\ S(1 - e^{-.01979A})^{1.3892}.$$

Total cubic-foot volumes (CF) in poletimber trees (from 5 to 9 inches d.b.h.), in sawtimber trees (9 inches d.b.h. and larger), and in all trees were estimated using the ratio volume equation developed by Buckman (1961):

$$CF = 0.4085\ BH.$$

Merchantable cords were computed as a constant proportion for the total cubic-foot volumes in trees greater than 5 inches d.b.h.:

$$Cords = .0097\ (CF_{5+}).$$

A special function to estimate the board feet (International ¼-inch) per cubic-foot (total) ratio in trees of specified diameter and height was developed from data in Gevorkiantz and Olsen (1955):

$$BdFt/CF = -8.76 + 1.985D - 0.07253D^2 + 0.0008421D^3 + 0.04951H - .00892DH + 0.0003169D^2H - 0.000002786D^3H.$$

This ratio was applied only to the total cubic-foot volume in trees larger than 9 inches d.b.h.

Mortality was approximated by a nonlinear function that limited basal area per acre to a maximum accumulation depending upon site:

$$\text{Basal Area Mortality} = B\,e^{-20S\,B}.$$

The number of trees that died to make up this calculated mortality was estimated by assuming that the dead trees had an average diameter equal to the average stand diameter less one standard deviation.

The final equations were used in a computer simulation program to forecast yields from various sites, initial densities, and thinning schedules. Test runs closely simulated red pine growth and yield reported in stands not used in developing the equations. Subsequent use and comparisons of projected versus observed growth and yield have reaffirmed the results of these earlier tests.

VOLUME YIELD RESPONSE TO STAND DENSITY

The impacts of site, initial density, density after thinning, and rotation age on volume yields in red pine plantations are great. Red pine is a versatile tree and is sold for many products in the Lake States, including posts, pulpwood, poles, piling, and saw logs. Volume outputs can be measured in many ways, but this analysis will consider only three contrasting measures: total cubic feet per acre of the entire stem under bark, including stump and tip for all trees in the stand; merchantable cubic-foot volume per acre in trees 5 inches d.b.h. and larger to a 3-inch top diameter inside bark; and board feet per acre (International ¼-inch rule) in trees 9 inches and larger above a 1-foot stump to a variable top diameter inside bark of not less than 6 inches.

The total-cubic-foot measure reflects total utilization of wood in the central stem. It was determined using Buckman's (1961) stand volume ratio equation, $V = 0.4085BH$,

where V = volume per acre in cubic feet,
B = basal area per acre in square feet, and
H = mean total height in feet of dominant and codominant trees.

Thus, cubic-foot volume is determined solely by the basal area and height of the stand; the diameters of individual trees play no part.

The merchantable cubic-foot volume equation was derived by multiplying Buckman's (1961) cordwood equation, $V = 0.003958BH$, by 79 cubic feet per cord to give:

$$Vm = 0.3127BH,$$

where Vm = merchantable volume per acre in cubic feet.

In effect, this ratio equation assumes a constant 103 cubic feet of total peeled volume of the central stem per merchantable cord, for all merchantable trees. Because only trees 5 inches d.b.h. and larger are considered merchantable, tree diameters do affect this volume estimate.

In contrast, the board-foot volume of a stand is determined by multiplying the total cubic volume by a board-foot recovery factor that is a nonlinear function of average tree diameter and total height. The larger the tree diameter, the higher the board-foot volume per cubic foot of total volume. Thus, the board-foot volume measure is affected by basal area and height, but also is greatly affected by the diameters of trees in a stand.

Comparing volume outputs over time for different sites, initial densities, and thinning schedules can be complex, because the kind, quantity, and quality of outputs vary over time. With the large number of alternatives considered here, some simplification is necessary. This analysis will ignore the timing of outputs and use mean annual increment[1] (MAI) over a rotation as the measure of volume output, expressed as cubic feet per acre per year (CF/A/Y) and board feet per acre per year (BF/A/Y). Most of the examples will be for site index (SI) 60, which is an average site for red pine. Although the details are not included herein, the general conclusions regarding initial density and thinning density appear to hold for a broad range of sites.

[1] *The MAI used here was determined by summing the volume of all prior thinnings (if any), adding the potential volume available for harvest at a given age, and dividing this sum by the total age of the stand since establishment.*

Total Cubic-foot Volume

The pattern of total cubic-foot MAI over a rotation is similar for all stand conditions. A rapid increase for the first 40 to 50 years is followed by a more gradual increase to a maximum MAI at about 60-100 years for most sites, initial numbers of trees per acre, and basal area densities left after thinning. After reaching a maximum, the MAI declines gradually through 150 years. Site index (SI) has a pronounced effect on the level of MAI (fig. 11). For an initial density of 400 established trees per acre (T/A) thinned to 120 square feet per acre (SF/A), for example, maximum MAI ranges from 91 CF/A/Y for SI 50 to 166 CF/A/Y for SI 70, culminating at about 80 to 90 years. Shortening or lengthening the rotation age by 10 years has only a small effect on MAI, usually reducing it by less than 1 percent.

Increasing the initial density also increases cubic-foot MAI, but the effect is less pronounced, varying from 116 CF/A/Y for 200 T/A to 141 CF/A/Y for 1,200 T/A when stands are thinned every 10 years to 120 SF/A of basal area (fig. 12). Quadrupling stocking from 200 to 800 T/A increases total cubic-foot volume production per acre by only 17 percent over the rotation.

Cubic-foot MAI increases with increasing basal area left after thinning, up to a maximum attained with 120-140 SF/A (fig. 13). But with 400 T/A initial density, leaving 120 rather than 80 SF/A (a 50-percent increase in residual stocking) increases cubic-foot volume production by less than 20 percent. With higher initial numbers of trees the percent increase in MAI is less.

In general, the higher the initial and residual stand densities, the higher the total cubic-foot volume production (table 1). It is important to note, however, that although total cubic-foot volume production increases as density increases, it does so at a declining rate. For example, the first 200 red pine trees per acre, thinned to 120 SF/A of basal area, produces 116 CF/A/Y; the second 200 trees (bringing the total to 400 T/A) adds only 12 CF/A/Y to this total MAI production; the third 200 trees increases the total MAI by only 5 CF/A/Y; and the fourth 200 trees adds only 4 CF/A/Y. This decreasing marginal productivity becomes especially important in determining optimum initial densities.

The effect of initial density and density after thinning on MAI is more easily seen when it is graphed (fig. 14). Here it is readily apparent that the

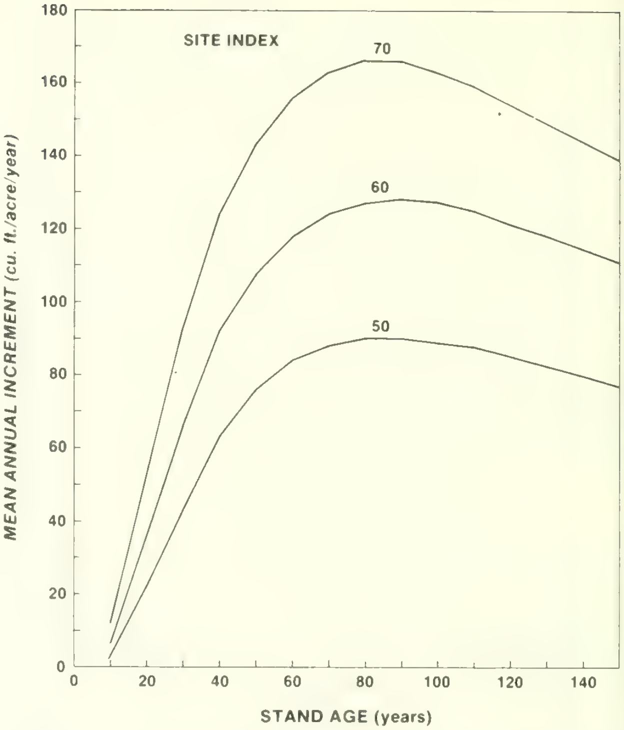

Figure 11.—*The effect of site index on total cubic-foot mean annual increment over a rotation in red pine plantations with an initial density of 400 established trees per acre, thinned to 120 square feet of basal area per acre.*

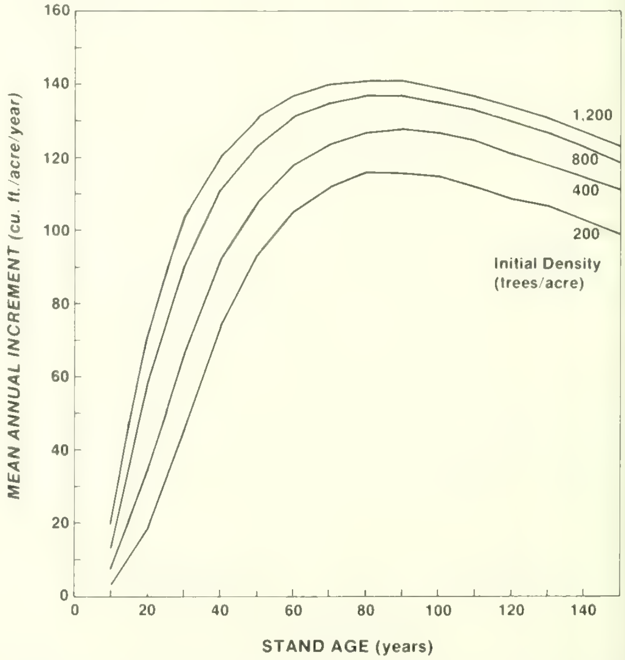

Figure 12.—*The effect of initial number of established trees per acre on total cubic-foot mean annual increment over a rotation in red pine plantations on site index 60, thinned to 120 square feet of basal area per acre.*

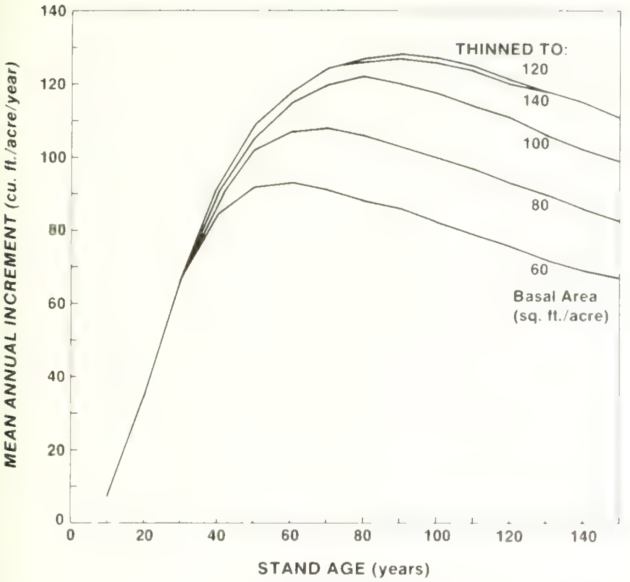

Figure 13.—*The effect of residual basal area left after thinning on total cubic-foot mean annual increment over a rotation in red pine plantations on site index 60, with an initial density of 400 established trees per acre.*

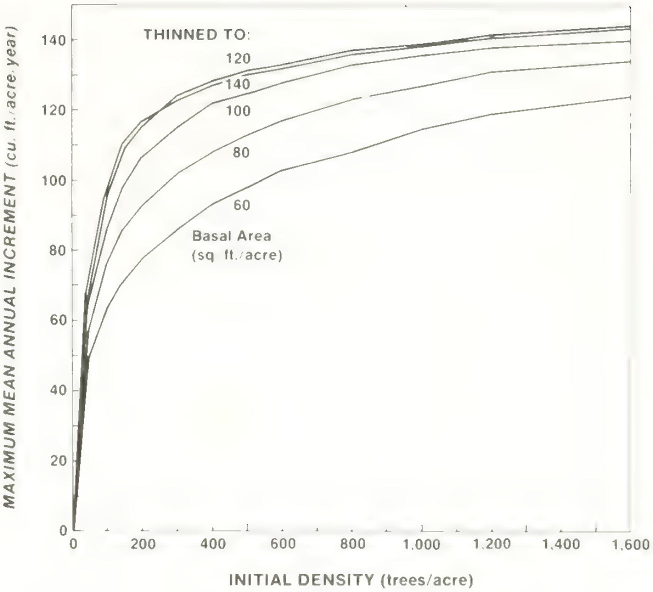

Figure 14.—*The effect of initial and thinning densities on maximum total cubic-foot mean annual increment in red pine plantations on site index 60.*

Table 1.—*Maximum mean annual increment in thinned red pine stands on site index 60, for selected initial numbers of trees and basal areas left after thinning*

Initial stand density (trees/acre)	Basal area left after thinning (sq. ft./acre) 60	80	100	120	140	160
	TOTAL STEM VOLUME UNDER BARK (cu. ft./acre/year)					
100	64	76	87	96	99	97
150	72	87	99	110	112	107
200	78	93	107	116	117	113
300	86	102	115	124	123	118
400	93	108	122	128	127	121
500	98	113	125	131	130	124
600	103	117	128	133	132	126
800	108	123	133	137	136	132
1,000	115	127	136	139	139	134
1,200	119	131	138	141	141	136
1,600	124	134	140	144	143	139
	MERCHANTABLE CUBIC-FOOT VOLUME (cu. ft./acre/year)					
100	49	58	67	73	76	74
150	55	66	76	84	86	82
200	59	71	82	89	90	87
300	66	78	88	95	95	90
400	70	82	93	98	97	92
500	73	85	96	100	100	95
600	75	87	97	101	101	96
800	78	90	99	102	103	100
1,000	79	90	99	102	103	100
1,200	78	90	98	101	102	98
1,600	77	88	96	99	98	95
	BOARD-FOOT VOLUME[1] (bd. ft./acre/year)					
100	417	508	588	656	681	649
150	439	555	647	729	736	687
200	456	569	673	743	741	694
300	446	562	657	718	704	645
400	437	551	643	687	656	583
500	427	535	615	659	608	526
600	421	523	612	634	567	485
800	404	508	573	593	524	424
1,000	393	493	551	557	479	380
1,200	386	467	527	521	436	334
1,600	367	445	485	471	375	228

[1] International ¼-inch rule.

first 200 T/A achieve a relatively high MAI, especially if the stand is thinned to 120-140 SF/A. The increase in MAI from additional trees after the first 200 T/A is relatively minor.

The manager can considerably influence the total cubic-foot output from a red pine plantation by the choice of initial number of trees and the basal area left after thinning. A combination of low initial density, say 200 established T/A, and a schedule of thinnings to low basal areas, say 60 SF/A, will result in an uninspiring 78 CF/A/Y. At the other extreme, a choice of high initial and thinning densities (for example, 1,200 T/A and 140 SF/A) could increase production to 141 CF/A/Y, a sizable gain. However, production from a plantation with low initial density can be increased considerably by choosing a high density after thinning. With 200 T/A, thinning to 140 rather than 60 SF/A will increase production from 78 to 117 CF/A/Y, a substantial increase.

Merchantable Cubic-foot Volume

The relations of merchantable cubic-foot MAI to rotation age, initial density, and thinning density are similar to the total cubic-foot volume relations, with a few significant differences. Merchantable cubic-foot MAI begins at a later stand age, but culminates at about the same age as total cubic-foot MAI, or perhaps only 5 years or so later in some instances. Rotation ages are similar over the range of densities considered here. Merchantable cubic-foot MAI is, of course, less than total cubic-foot MAI at each stand age.

The highest MAI is produced by an initial density of 800-1,000 T/A (fig. 15). Increasing the initial density beyond 1,000 T/A reduces total stand production of merchantable wood over the rotation, in contrast to an increase in total cubic-foot volume production. However, the effect of initial density on merchantable wood production is small over a wide range of initial densities. Production varies by only about 4 percent from 400 to 1,600 T/A in stands thinned to 120-140 SF/A of basal area.

For a given initial number of trees per acre the manager can influence merchantable volume yields by his choice of thinning densities, but over a wide range of basal area densities the effect is not large (fig. 16). With 800 T/A, volume yields vary only 4 percent for thinning densities ranging from 100 to 160 SF/A of basal area. Within this range, the choice of thinning density has only a slight effect on merchantable yields from red pine plantations, but the highest yields are produced from stands thinned to 120-140 SF/A of basal area.

As with total cubic-foot volume, the manager can substantially influence merchantable cubic-foot volume yields from red pine plantations by his choice of initial and thinning densities (table 1). A low initial density and low basal area left after thinning—for example, 200 T/A thinned to 60 SF/A—would produce only 59 CF/A/Y. In contrast, 800 T/A thinned to 140 SF/A would produce 103 CF/A/Y, a 75-percent increase over the low-density choice.

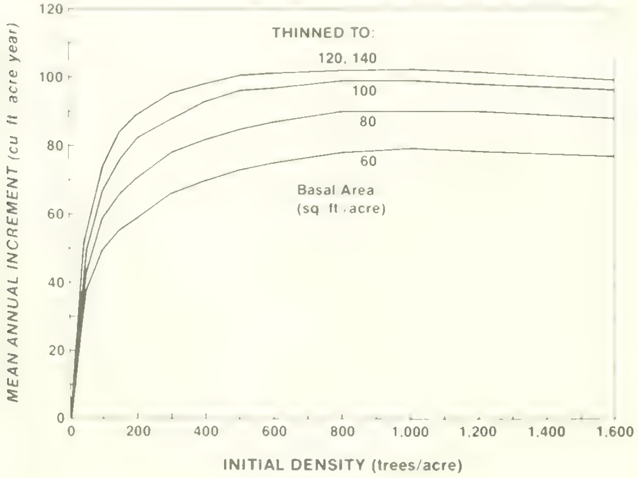

Figure 15.—*The effect of initial density on maximum merchantable cubic-foot mean annual increment for selected basal area densities left after thinning in red pine plantations on site index 60.*

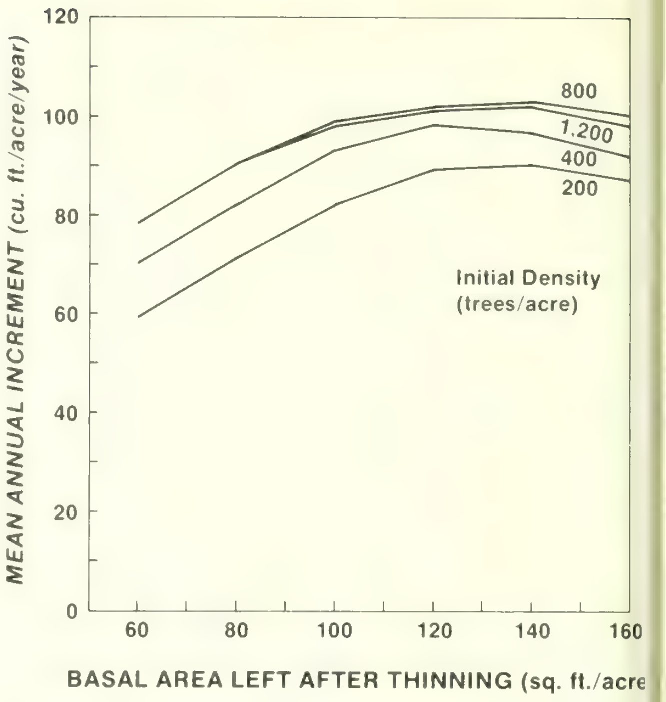

Figure 16.—*The effect of basal area density left after thinning on maximum merchantable cubic-foot mean annual increment for selected initial numbers of established trees per acre.*

Board-Foot Volume

A different picture emerges if we look at board-foot production in relation to stand density. First, although MAI curves for board feet show the same general pattern as those for cubic feet (a rapid initial increase followed by several decades of only slight change), they start at a later date and culminate later than the cubic-foot curves (fig. 17). In general, the better the site, the earlier the initiation of board-foot production.

But the big difference between cubic-foot and board-foot production in relation to stand density shows up when we examine MAI for a range of initial densities (fig. 18): whereas cubic-foot MAI increases as initial density increases from 200 to 1,200 T/A, board-foot MAI shows a reverse pattern, decreasing from the highest MAI with 200 T/A to the lowest with 1,200 T/A. In addition, although the age at which cubic-foot MAI culminates is only slightly affected by initial density (fig. 12), the age at which board-foot MAI culminates is strongly affected by initial density, particularly if the stand is thinned to higher densities (100 SF/A and above). For SI 60 stands thinned to 120 SF/A, board-foot MAI culminates at age 100 with 200 T/A, compared with age 140 with 1,200 T/A (fig. 18).

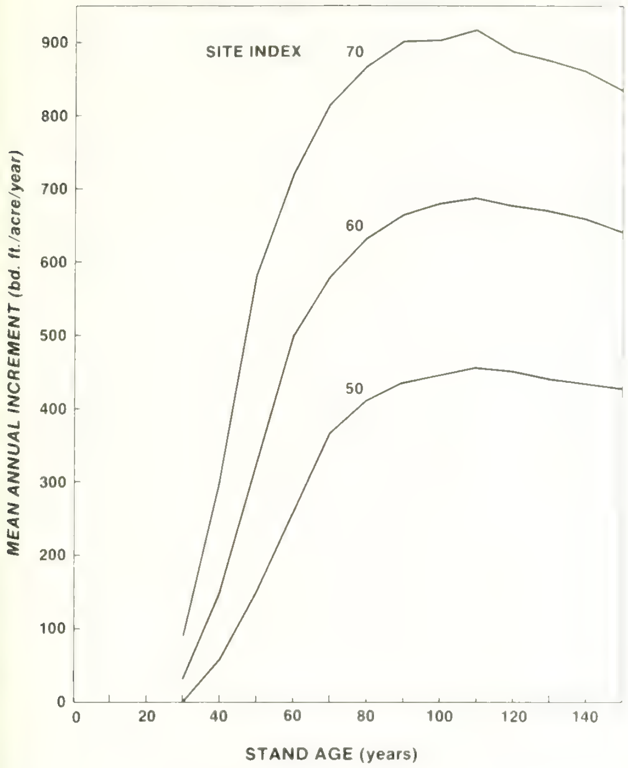

Figure 17.—*The effect of site index on board-foot mean annual increment over a rotation in red pine plantations with an initial density of 400 established trees per acre, thinned to 120 square feet of basal area per acre.*

Stand density after thinning strongly affects the pattern of board-foot MAI over stand age. In general, the higher the basal area left after thinning (up to about 120 SF/A), the higher the production and the later the culmination of MAI. With 400 T/A, thinning a stand to 120 SF/A rather than 60 SF/A increases production from 437 to 687 BF/A/Y, a 57-percent increase (fig. 19). However, at the same time, the age maximizing MAI increases from 85 to 110 years.

The effect of stand density on board-foot volume production (as measured by maximum board-foot MAI) is dramatically evident if MAI is plotted over initial density for a range of basal area densities left after thinning (fig. 20). On SI 60, the highest board-foot MAI's are obtained with 120 SF/A left after thinning for initial densities below 1,200 T/A, and with 100 SF/A for initial densities above 1,200 T/A. The most striking feature about these curves is the rapid increase in MAI from the first 100 T/A, followed by a further increase to a peak MAI with 200 T/A, followed by a decline in board-foot volume production over a rotation as initial stocking is increased beyond

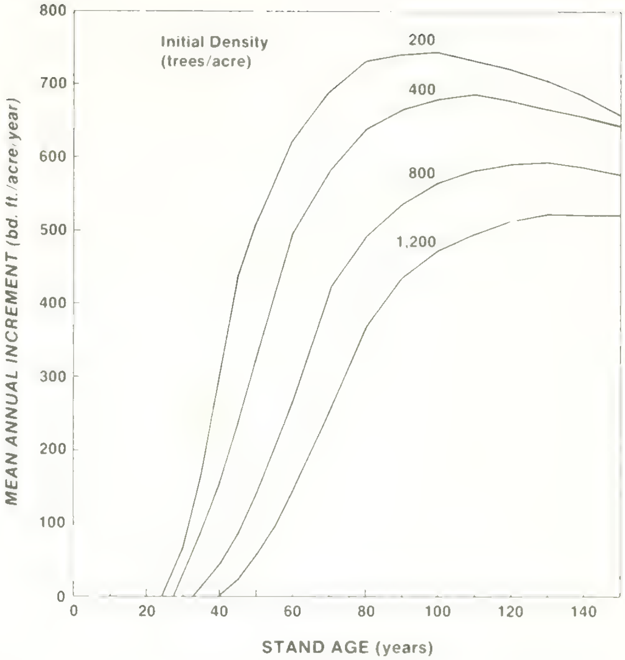

Figure 18.—*The effect of initial number of established trees per acre on board-foot mean annual increment over a rotation in red pine plantations on site index 60, thinned to 120 square feet of basal area per acre.*

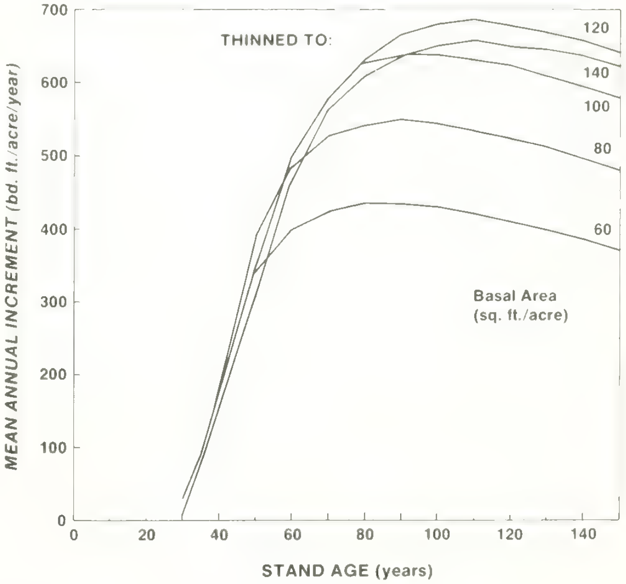

Figure 19.—*The effect of residual basal area density left after thinning on board-foot mean annual increment over a rotation in red pine plantations on site index 60, with an initial density of 400 established trees per acre.*

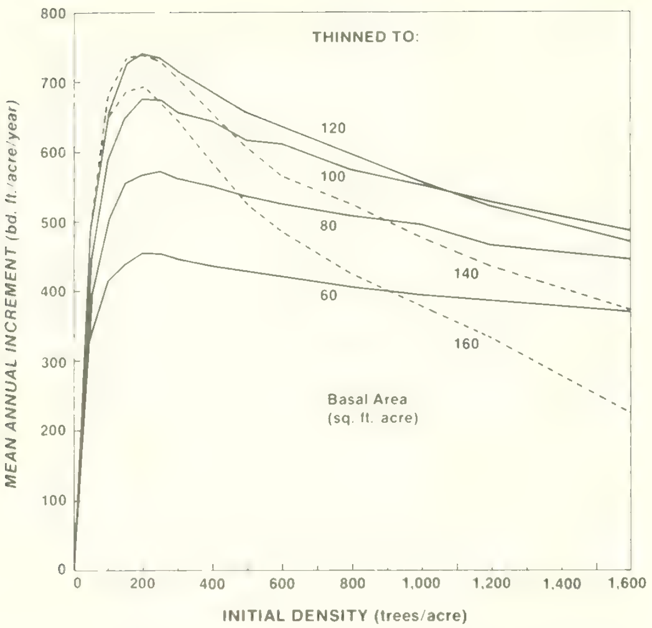

Figure 20.—*The effect of initial number of established trees per acre on maximum board-foot mean annual increment in red pine plantations on site index 60, for selected basal area densities left after thinning.*

200 T/A. It is evident from this figure that the maximum board-foot volume production occurs with an initial density of about 200 T/A thinned to 120 SF/A of basal area every 10 years. In such a stand the first thinning would be made at age 45 and the final harvest would be at age 100.

The combined effect of initial number of trees and density after thinning is large. A choice of 1,600 T/A thinned to 60 SF/A produces less than 370 BF/A/Y. In contrast, choosing 200 T/A thinned to 120 SF/A doubles production, to about 740 BF/A/Y. Thus, through the choice of initial density and densities after thinning, the forest manager can greatly alter the production of board-foot volume from his stand. Once a stand is established with a given number of trees, and has grown for 20-40 years with no thinnings, the manager is somewhat restricted in the effects he can achieve with thinning prescriptions.

For initial densities of 200 to 400 T/A and thinning densities of 80 to 160 SF/A, board-foot volume production is maximized at rotation ages ranging from 80 to 110 years. For initial densities of 500 to 1,000 T/A and the same range of thinning densities, production is usually maximized at rotation ages ranging from 105 to 135 years. Generally, the more established trees per acre, the longer the rotation needed to maximize board-foot MAI.

Timber Production in Relation to Site

To avoid presenting too much detail, most of the previous information was given only for SI 60. However, analyses of timber production for a wide range of SI's (40-80) indicate that the same general conclusions hold for all sites. Total cubic-foot volume production is highest with a high number of trees per acre, but the first 200 T/A accounts for about 80 percent of the MAI obtained with 1,200 T/A. Generally, the highest cubic-foot MAI for any initial number of trees is obtained by thinning to basal areas of about 120 SF/A on poor sites to 140 or more SF/A on good sites. Site quality has a substantial effect on volume production. An initial density of 800 T/A thinned to 120 SF/A on SI 50 produces 98 CF/A/Y over an 80-year rotation. The same number of trees per acre thinned to 140 SF/A on SI 70 will produce 181 CF/A/Y over the same rotation, an increase of 85 percent. In general, maximum MAI in merchantable cubic feet is obtained with slightly higher densities on better sites, ranging from 73 CF/A/Y with 800 trees thinned to 120 SF/A on SI 50, to 137 CF/A/Y with 1,000 trees thinned to 140 SF/A on SI 70.

Board-foot volume production is highest on all sites with an initial density of about 200 T/A. With 200 T/A optimal basal area densities after thinning are lowest (about 120 SF/A) on poor sites. Better sites appear able to support higher basal area densities throughout a rotation.

EFFECT OF STAND DENSITY ON TREE AND STAND CHARACTERISTICS

Volume yields are greatly affected by initial number of trees and thinning density. But stand density also affects other tree and stand characteristics important in choosing a management regime for red pine. In the following discussion, all examples are for SI 60 unless otherwise stated.

Tree Size and Form

In the growth and yield simulation model, height growth of trees in the stand was assumed to follow published site index curves (Gevorkiantz 1957, Lundgren and Dolid 1970) regardless of stand density, and to apply to all trees in the stand on a given site at a given age regardless of diameter (fig. 21).

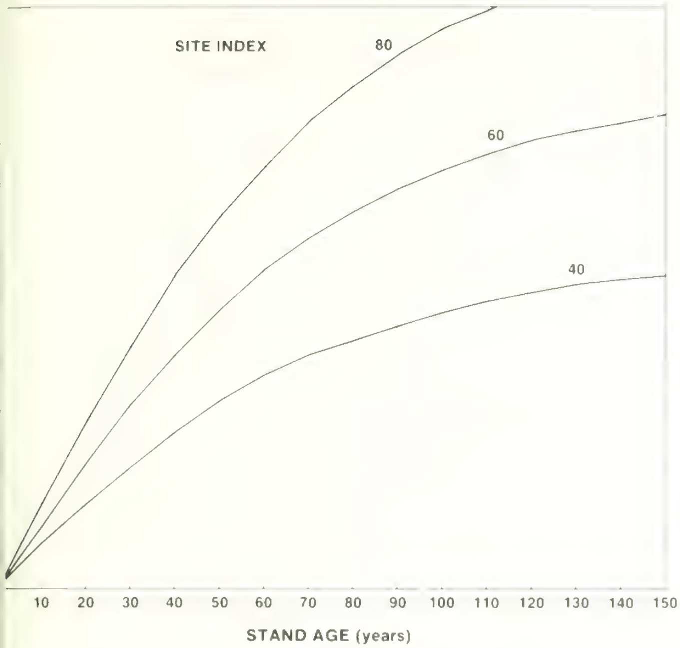

Figure 21.—*Average height of dominant and codominant red pine trees at different ages.*

Although Stiell and Berry (1977) reported a stand density effect on height for a SI 80 red pine plantation, it amounted to only a 2-foot difference at age 20 between extremes of density. Thus, the effect of stand density on height will be ignored in this analysis. Because heights apply to dominant and codominant trees, heights of intermediate and suppressed trees will be overestimated. The exact effect of this is not known, but is expected to be small in all but the densest stands.

In unthinned stands, diameter growth (change in diameter of the tree of average basal area) on a given site is strongly affected by the initial stand density (fig. 22). With 1,200 T/A, for example, diameter growth appears to slow down when the stand is about 11-13 years old, and falls below that in less dense stands. With 800 T/A, diameter growth falls behind at about 12-15 years; with 400 trees, at about 17-20 years; and with 200 trees, at about 25 years. These densities correspond to basal areas of about 40 to 60 SF/A, and mark the onset of competition. This decline in diameter growth occurs earlier on better sites and later on poorer sites.

Average tree diameters in thinned stands are affected by both the initial number of trees and the basal area density left after thinning (Lundgren and Wambach 1963). For example, with 400 T/A, thinning every 10 years to 80 SF/A rather than 120 SF/A results in larger trees throughout the rotation (trees average 3 inches larger in d.b.h. by the end of an 80-year rotation) (fig. 23). Initial density has a similar effect on tree diameters. Establishing 400 T/A rather than 800 results in larger trees throughout the rotation, by about 3 inches towards the end of an 80-year rotation when thinning to 120 SF/A (fig. 24). Establishing only 200 T/A rather than 800 produces trees averaging more than 6 inches larger at the end of an 80 year-rotation. In summary, lower initial numbers of trees and lower basal areas left after thinning both lead to increased tree diameters at a given age, and the effect is substantial.

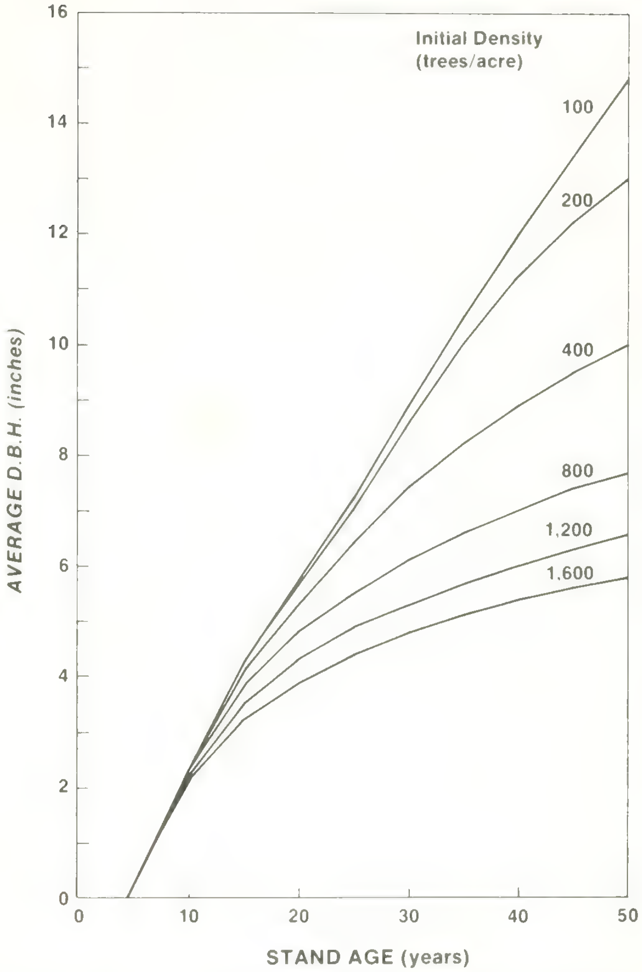

Figure 22.—*Average stand diameters for different numbers of initial trees per acre in unthinned red pine plantations on site index 60.*

The bole form of a tree can influence the product output. For example, less taper in a tree of a given d.b.h. and height indicates not only more total cubic volume, but also more board-foot volume output.

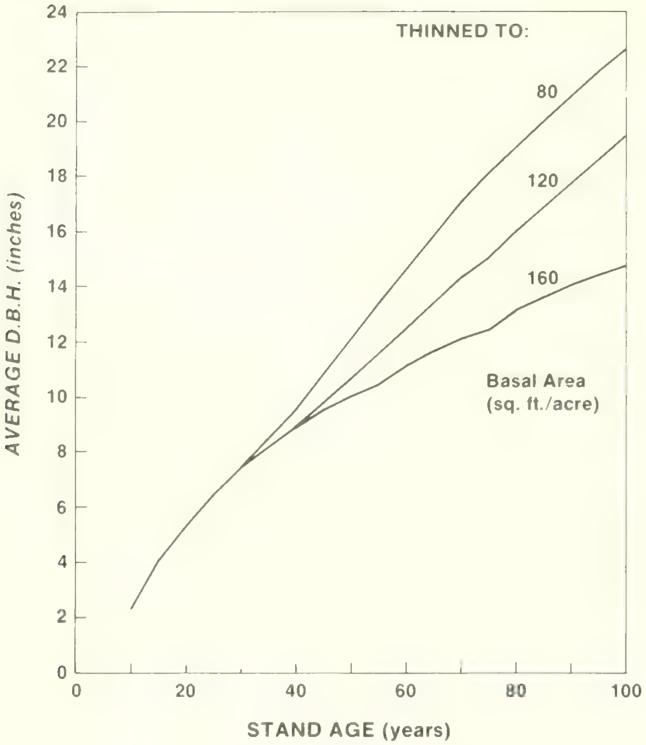

Figure 23.—*Diameter of the tree of average basal area in red pine plantations thinned to different basal area densities on site index 60, with an initial density of 400 established trees per acre.*

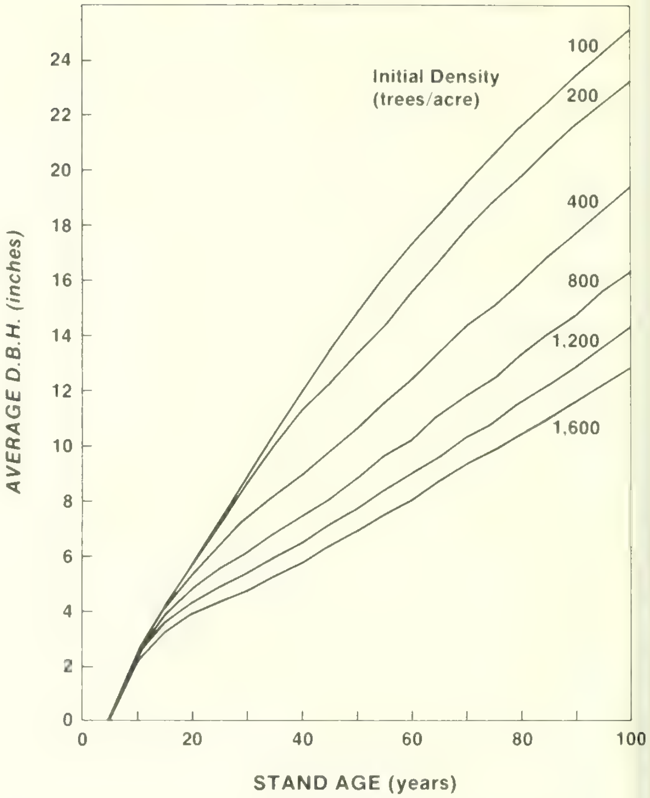

Figure 24.—*Diameter of the tree of average basal area in red pine plantations thinned to 120 square feet of basal area per acre on site index 60, for selected initial numbers of established trees per acre.*

In estimating the product output from red pine stands for this analysis, no allowance was made for possible changes in tree form due to changes in age, site, or stand density. Wambach (1967), after studying form quotients[2] in Lake States' red pine plantations, reported: "No significant relationship was found between form quotient and either stocking, site, or age." He concluded that "...the experience gained in the course of this study lends support to the conclusions drawn by Berry, Eyre and Zehngraff, and others...that spacing does affect tree form, with close spacing leading to slightly better form. But the effect is small and temporary. The influence on yield and quality over the course of a full rotation will not be very important." Apparently, ignoring tree form will have little effect on the outcome of silvicultural and economic analyses.

Timber Quality

Earlier we saw that the highest board-foot volume production per acre is achieved with a low initial density (about 200 T/A thinned to 140 SF/A). But what about the quality of wood produced at such wide initial spacing? Larson (1962) has shown that the size and distribution of the living crown affect the amount and quality of wood produced. Crown development is in turn governed to a large extent by stand structure. Larson has pointed out that stem wood produced within crowns of conifers has a higher proportion of juvenile wood (which is of low quality) than stem wood produced below crowns. Open-grown trees have larger, deeper crowns than more closely spaced trees where crown competition has begun. As a result, the quality of wood from open-grown trees is expected to be lower than that from trees in denser stands. Baker (1969) has documented this for red pine plantations for a range of spacings.

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[2] *Form quotient is defined as the ratio between the diameter of a tree at one-half its total height and at breast height.*

Unfortunately, data were not available to accurately model crown size development in red pine stands in relation to site, age, initial density, and thinning schedules and to relate this in turn to wood quality. Instead, three indirect indicators of the impact of spacing on wood quality were used: diameter growth rate (expressed as rings per inch), number and size of branches, and specific gravity.

Previous studies have reported that conifer trees with more than 6 to 8 rings per inch (a d.b.h. growth rate of from ⅓- to ¼-inch per year) are acceptable for saw logs (Lundgren 1965). In stands thinned to 120 SF/A, only at the earliest ages does tree growth exceed ⅓-inch in diameter per year and produce fewer than six rings per inch. Diameter growth rates of six or more rings per inch are produced after stand age 15 even in stands with only 200 T/A. Even with this low initial density, stands thinned to 120 SF/A produced at least eight rings per inch from age 40 on (table 2).

Diameter growth rates on better sites are higher, prolonging the production period of wood with fewer than six rings per inch. But even on SI 80, with 200 T/A thinned to 120 SF/A, diameter growth has slowed by stand age 30 to produce more than six rings per inch. Thus, it appears that except for a juvenile core of wood, red pine plantations with low initial densities (200 T/A) will produce wood of acceptable quality for saw logs throughout most of a rotation.

Table 2.—*Diameter growth throughout a 100-year rotation of red pine plantations on site index 60, for a range of initial trees per acre thinned to 120 sq. ft. of basal area per acre*

(In inches)

Stand age (years)	Initial density (trees/acre) 200 D[1]	ΔD[2]	RPI[3]	400 D	ΔD	RPI	800 D	ΔD	RPI
10	2.3	—	—	2.3	—	—	2.3	—	—
		0.33	6.1		0.30	6.7		0.25	8.0
20	5.6			5.3			4.8		
		.30	6.7		.21	9.5		.13	15.4
30	8.6			7.4			6.1		
		.26	7.7		.15	13.3		.13	15.4
40	11.2			8.9			7.4		
		.21	9.5		.17	11.8		.14	14.3
50	13.3			10.6			8.8		
		.22	9.1		.18	11.1		.14	14.3
60	15.5			12.4			10.2		
		.23	8.7		.19	10.5		.16	12.5
70	17.8			14.3			11.8		
		.20	10.0		.17	11.8		.15	13.3
80	19.8			16.0			13.3		
		.19	10.5		.17	11.8		.14	14.3
90	21.7			17.7			14.7		
		.16	12.5		.18	11.1		.16	12.5
100	23.3	—	—	19.5	—	—	16.3	—	—

[1] D.b.h. (outside bark).

[2] Average annual growth in d.b.h. over the decade.

[3] Rings per inch growth in d.b.h.

The number and size of branches on a tree affect the number and size of knots in the saw logs from that tree, which in turn affect the grade of lumber output from the tree. Wambach (1967) studied the number of branches per whorl from breast height to 20 feet above the ground. He found that the average number of branches per whorl was related to site, increasing from 4.3 to 5.9 branches per whorl as SI increased from 40 to 70. However, he reported that initial stand densities from 400 to over 2,000 T/A had no significant effect on number of branches per whorl.

If we accept Wambach's conclusion, the manager's choice of initial density on a given site has no effect on the number of branches per whorl. Since height growth is essentially unaffected over the range of stand densities considered here, the number of whorls for a given lineal length of stem (say the butt 16-foot log) will be controlled by the site. A rough estimate indicates the number of whorls in a 16-foot butt log ranges from 16 on SI 40 to 9 on SI 70 (table 3). Thus, even though the average number of branches per whorl increases on better sites, the number of branches per foot of stem decreases because there are fewer whorls due to greater height growth.

Wambach (1967) found that the average diameter of dead branches (measured 1 inch from the stem) was affected by initial stand density. Branch diameter increased as initial density decreased, as site quality increased, and as distance from the ground increased. But the differences in average branch diameter were not large. On SI 40, with 1,200 trees per acre, dead branch diameter at breast height averaged 0.5 inch (table 4). In contrast, on SI 70 with

Table 3.—*Estimated number of branches per butt log in relation to site index in red pine plantations in the Lake States*

Site index	Years to grow to 17 feet[1]	Whorls per butt log[2]	Branches per whorl[3]	Branches per butt log	Branches per foot of butt log
40	21	16	4.3	69	4.3
50	17	13	4.7	61	3.8
60	15	11	5.2	57	3.6
70	13	9	5.9	53	3.3

[1] Computed from Lundgren and Dolid (1970). Based on total years from seed.

[2] Determined by subtracting an estimated 5 years from seed to reach a 1-foot stump height on SI 40 and 4 years for SI 50-70, from total years to reach 17 feet.

[3] Computed from Wambach (1967).

Table 4.—*Average diameter of dead branches in red pine plantations at selected heights in relation to site index and initial stand density*[1]

(In inches)

Initial trees per acre	Average dead branch diameter at 4.5 feet whorl height on site index:				Average dead branch diameter at 17.0 feet whorl height on site index:			
	40	50	60	70	40	50	60	70
200	0.7	0.7	0.8	0.8	1.0	1.0	1.1	1.1
400	.7	.7	.7	.8	.9	1.0	1.0	1.1
600	.6	.7	.7	.8	.9	.9	.9	1.0
800	.6	.6	.7	.7	.8	.9	.9	1.0
1,000	.6	.6	.6	.7	.8	.8	.8	.9
1,200	.5	.6	.6	.7	.7	.8	.8	.9

[1]From Wambach (1967).

200 T/A, at 17 feet (the top of the butt log), dead branch diameter averaged 1.1 inches. Although on a given site at a given distance up the stem initial density did affect dead branch diameter, the effect was not large. An increase in initial density of 1,000 T/A would reduce average branch diameter only by about ¼ inch.

If we accept Wambach's findings we can conclude that the choice of initial stand density has no effect on the number of branches (and thus the number of potential knots) in the butt log, and has only a slight effect on the average size of dead branches over the range of initial densities considered in this study. Laidly and Barse[3] reported that dead branch diameters in the butt log of trees from a SI 70 red pine plantation ranged from 0.7 inches at 5-foot spacing (1,742 T/A) to 1.2 inches at 11-foot spacing (360 T/A). This closely parallels Wambach's findings. Persson (1977) reported that the largest branches in young Scotch pine plantations in Sweden ranged from 0.7 inch at 4,000 T/A to 1.1 inches at 454 T/A, findings similar to the red pine results.

Wambach (1967) estimated specific gravity of trees in the red pine plantations he studied from measurements of large-diameter increment cores. He found that the average specific gravity of cores at breast height decreased with increasing site quality and increased with increasing initial density, although site had considerably more effect than stocking. An increase in SI from 40 to 70 reduced specific gravity from about 0.36 to 0.33, approximately 10 percent, while a change in initial density from 200 to 1,200 T/A increased specific gravity by only about 2 percent (table 5). Wambach found that adding tree age as a variable did not improve the estimates, an unexpected result that he thought might be due to the small range of ages sampled (from 14 to 49 years). Baker and Shottafer (1970) reported similar results in plantation red pine, where an increase in stand density from 440 T/A (10-foot spacing) to 1,210 T/A (6-foot spacing) resulted in an increase in specific gravity of only 2 percent.

Although the specific gravity of an increment core is not necessarily the average specific gravity of the tree, if we accept Wambach's results as indicative of the relative differences in specific gravity due to site and initial density, we must conclude that on a given site the choice of initial density has only a small impact on the specific gravity of the wood produced. It is likely that over an entire rotation the effect of initial spacing on the specific gravity of the trees will be slight. This is in line with Larson's (1972) conclusion that wide spacing has relatively little effect on wood specific gravity in young pines.

Crown Width and Site Occupancy

We saw earlier that the first 200 T/A account for a large amount of the potential stand productivity. This point is so important to this analysis that it bears further explanation. In the following exercise we assume SI 60 with a rotation age of 80 years (the age maximizing MAI of total cubic-foot volume under bark of the entire stem for stands thinned to about 120 SF/A).

Table 5.—*Specific gravity of increment cores at breast height in red pine plantations, in relation to site index and initial stand density*[1]

Initial trees per acre	Site index			
	40	50	60	70
200	0.355	0.347	0.337	0.323
400	.357	.349	.339	.325
600	.358	.350	.340	.326
800	.359	.351	.341	.327
1,000	.361	.353	.343	.329
1,200	.362	.354	.344	.330

[1]From Wambach (1967).

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[3] *Personal communication, 1978.*

Ek (1971) developed a relation between tree diameter and crown width based on 95 red pine trees on 76 different sites in Michigan, Minnesota, and Wisconsin. If we assume that his equation holds for square-spaced red pine plantations, the crown width (CW) in feet just before the crowns touch and competition sets in can be predicted from tree d.b.h. in inches (D) by his equation:

$$CW = 4.2334 + 1.4616D.$$

Using the average stand diameters predicted over time by the red pine growth simulation model for the various initial spacings, and assuming all trees have the diameter of the tree of average basal area, it is possible to predict the age at which the crown width just equals the tree spacing, and the crowns just touch. At this age, assuming a full, circular crown and perfectly square spacing of equal-diameter trees, the crowns in a stand would occupy about 79 percent of the available area. Any growth beyond this point would result in overlapping crowns and increasing crown competition.

Knowing the average stand diameter at each age, one can compute the area per acre occupied by tree crowns and thus determine the percent of the total area covered by crowns at each age until the crowns touch (fig. 25). For example, 400 T/A will average 4.1 inches d.b.h. at stand age 15. A tree this size has an estimated crown width of 10.2 feet, or a crown area of 82 square feet. With 400 trees per acre, crowns would occupy 32,860 SF/A, 75 percent of the total area. In such a stand crowns should begin touching about 1 year later, when the stand is 16 years old and crown width equals tree spacing (10.4 feet). With 200 T/A, crowns would touch about 26 years after planting; with 800 trees, about 10 years after planting; and with 1,200 trees, about 8 years after planting.

As we have seen (fig. 22), projected diameters in simulated stands with 200 T/A begin to slow in potential growth at about 25 years; with 400 T/A, at 17-20 years; with 800 T/A, at 12-15 years; and with 1,200 T/A, at 10-13 years. If we assume that competition among trees begins about the time the crowns touch, the ages at which this occurs agree closely with our estimates of the onset of competition based on reduction in diameter growth. This comparison substantiates the suitability of the simulation model underlying these analyses. Newnham's (1966) earlier model, $CW = 3.417 + 1.609D$, based on a 15-year-old natural stand of red pine in Ontario, predicts almost identical stand ages for crown closure, further substantiating our results.

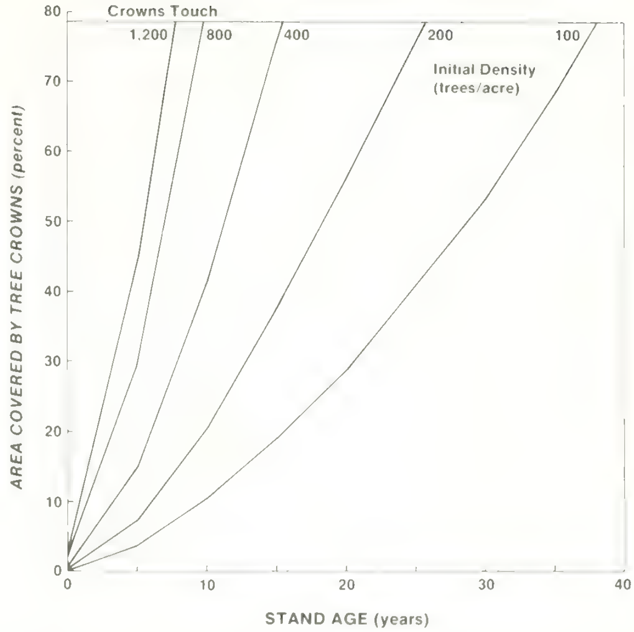

Figure 25.—*Estimated percentages of land area covered by tree crowns in unthinned red pine plantations on site index 60, for a range of initial numbers of established trees per acre.*

The important thing to note is that on SI 60 a decline in potential diameter growth has set in as early as 17-20 years with only 400 T/A, indicating the onset of competition at this age. With only half that many trees, the onset of competition is delayed from 5 to 10 years at most, until about stand age 25. If we use the age at which trees begin to compete with one another as an indicator of full site occupancy (only approximately), we see that even with only 200 T/A, the site would be fully occupied at age 25 for the remaining two-thirds of a 75-year rotation. If we double this initial density to 400 T/A, we get full site occupancy at 17-20 years, but with a 75-year rotation this increases full occupancy only from about 67 percent to perhaps 77 percent of the rotation, at most. The first 200 trees are able to capture a large portion of potential site productivity over the rotation lengths considered here. This leaves only a relatively small amount of unused potential to be captured by increasing the initial density.

Stand Characteristics

Mortality in regularly thinned stands of red pine in the Lake States is relatively small after establishment, except in high-density stands where diameter growth rates are very low (Buchman 1979). In this analysis very few trees died from competition. Essentially all changes in numbers of trees per acre after initial establishment were due to timber harvesting. On a given site, number of trees is controlled by the choice of initial density, thinning schedules, and rotation age (table 6). In general, following a prescribed thinning schedule throughout a rotation on a poor site results in leaving more trees per acre after thinnings than following the same schedule on a good site.

Basal area growth in young plantations is affected by site index, tree age, and initial number of trees per acre, and at later ages by site index, tree age, and basal area density. Establishing more trees per acre allows faster accumulation of basal area per acre; for example, on SI 60, plantations reach 120 SF/A at 38 years with 200 T/A, at 31 years with 400 T/A, at 23 years with 800 T/A, and at 20 years with 1,200 T/A (fig. 26). The effect of increased initial stand density is to shorten the time to full occupancy, when the first thinning can be made.

Buckman's (1962) basal area growth equation[4] specifies that on a given site at a given age, all stands with a specified basal area will have the same basal area growth, regardless of number of trees or past stand history. According to our model, an unthinned plantation with 400 T/A will have about 85 SF/A at age 25; an unthinned plantation with 800 trees will have about 130 SF/A at this age (fig. 26). If, at age 25, the denser stand is thinned from 130 to 85 SF/A (removing about 35 percent of the basal area and thus about 35 percent of the trees), the two stands would be projected to grow the same amounts of basal area during the ensuing years.

Table 6.—*Number of trees per acre in red pine plantations before thinning, for selected initial stand densities and basal areas left after thinning on site index 60*

	Initial density (trees per acre)			
	200		1,200	
Stand age	60 sq. ft./ acre	120 sq. ft./ acre	60 sq. ft./ acre	120 sq. ft./ acre
Years				
0	200	200	1,200	1,200
10	200	200	1,200	1,200
20	200	200	1,200	1,200
30	200	200	1,190	1,190
40	148	200	386	769
50	80	149	206	526
60	52	108	116	373
70	38	79	73	273
80	26	79	52	186
90	26	56	35	185
100	19	56	35	133
110	19	40	25	132
120	19	39	25	93
130	14	39	25	92
140	14	29	18	69
150	14	29	18	69

Harvest Factors

Initial density and the timing and intensity of thinning can greatly affect harvesting operations, and thus indirectly affect the value of volume yields to the timber purchaser. For example, the number of trees per acre affects tree spacing, which can in turn affect future timber harvest options. Access may be difficult in closely spaced plantations, particularly for mechanized harvest operations. Assuming square spacing and full survival, an initial planting of 1,200 T/A results in rows about 6 feet apart, with trees within rows 6 feet apart. By the time of the first thinning the crowns would be touching. Removal of a complete row would leave an access strip at most 6 feet wide between crowns, 12 feet between stems. With only 200 T/A the rows would be spaced about 15 feet apart, leaving a 15-foot access strip with removal of a row. Generally, establishing fewer trees per acre provides more working space for tree harvesting.

Of course, spacing need not be square. For a given number of trees per acre, spacing between rows can be increased by spacing trees within rows closer together. With 1,200 trees per acre, rows could be 8 feet apart with trees spaced 4.5 feet within rows. Although this spacing increases the width of the access strip, it leaves less space for tree felling within rows.

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[4] $\Delta B = 1.6889 + 0.041066B - 0.00016303B^2 - 0.076958A + 0.00022741A^2 + 0.06441S$,

where: ΔB = *periodic net annual basal area increment,*
B = *basal area in square feet per acre,*
A = *tree age in years, and*
S = *site index (50-year base).*

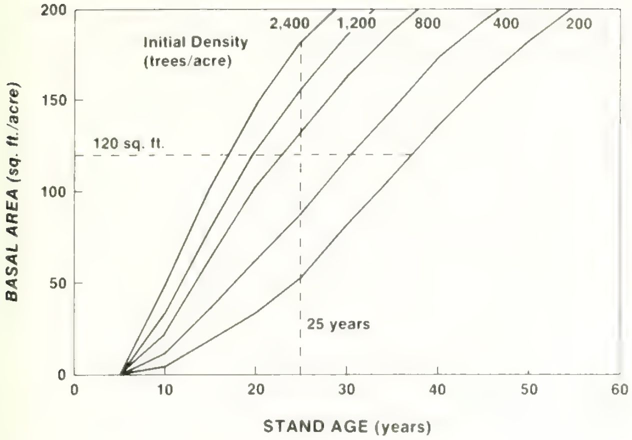

Figure 26.—*Basal area growth in unthinned red pine plantations on site index 60, for a range of initial numbers of established trees per acre.*

In stands with fewer trees per acre and higher residual basal area levels, fewer thinnings would be scheduled than in stands with more trees per acre and lower residual basal area levels. In stands with low initial numbers of trees to be thinned to high basal area levels, first thinnings generally are delayed until age 40 to 50. With higher initial densities and lower basal area levels, first thinnings may be scheduled as early as 20 to 30 years. The timing and thus the number of thinnings can be controlled to some extent by the manager, but generally lower initial densities result in one or two fewer thinnings over a rotation than higher initial densities. Higher numbers of trees per acre may produce more cubic-foot volume over a given rotation, but that also may require more harvest entries, thus increasing timber sale and harvesting costs.

Studies of how tree size affects harvest costs generally have shown a sharp decline in costs as diameters increase immediately above the minimum merchantable limit, followed by a more gradual decline as diameters increase further. For example, Manthy *et al.* (1967) recorded 4.8, 3.5, 2.8, 2.5, and 2.4 man-hours per cord to fell-limb-buck red pine trees in plantations for trees 5, 6, 7, 8, and 9 inches in d.b.h., respectively. Hannula (1971) showed a sharp decline in logging costs in pine and spruce stands in Canada from 5 to 7 inches, with a more gradual decline thereafter.

The initial number of trees per acre has a major impact on the size of trees harvested over a given rotation age. In red pine plantations thinned to 100 SF/A every 10 years over an 80-year rotation, the average diameter of all trees harvested varied from 16 inches for plantations with 200 initial T/A to only 7 inches for plantations with 1,200 T/A (table 7).

The diameter distributions of trees cut over an 80-year rotation in stands thinned to 140 SF/A every 10 years were estimated for extremes of initial stand density (fig. 27).[5] Of the 1,137 trees harvested from the stand with 1,200 trees initial density, 12 percent were less than 5 inches d.b.h. and thus were considered nonmerchantable. More than 40 percent of all the trees cut were less than 7 inches d.b.h. Only 30 percent of those cut were greater than 9 inches d.b.h., the minimum diameter for sawtimber, and only eight trees per acre were larger than 13 inches d.b.h.

Table 7.—*Average diameter of all trees harvested over an 80-year rotation in red pine stands on site index 60, for a range of initial and thinning densities*
(In inches)

Initial stand density	Basal area left after thinning (sq. ft./acre)					
	60	80	100	120	140	160
Trees/acre						
200	13	15	16	16	16	16
400	10	11	12	12	12	12
600	9	10	10	10	10	10
800	8	9	9	9	9	9
1,000	7	8	8	8	8	8
1,200	7	7	7	8	8	8
1,600	6	6	7	7	7	7

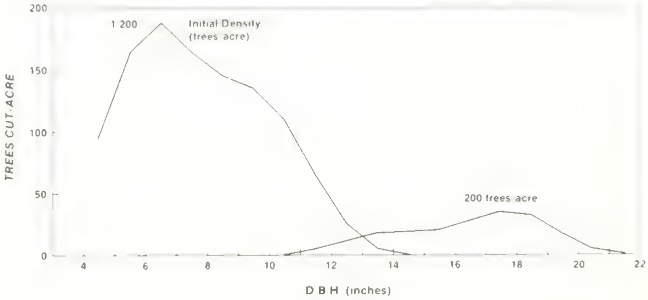

Figure 27.—*Number of cut trees by 1-inch diameter classes in red pine plantations on site index 60 over an 80-year rotation, for initial densities of 200 and 1,200 trees per acre, thinned to 140 square feet of basal area per acre.*

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[5] *Assumes a normal distribution of trees around the average diameter of trees cut, with a standard deviation calculated from the formula given earlier.*

In contrast, all of the 195 trees harvested from the stand with 200 trees initial density were greater than 10 inches d.b.h., and more than half were larger than 16 inches d.b.h.

Densities left after thinning did affect the size of trees harvested, but the effect was not as great as the effect of initial density. Furthermore, the effect was the opposite of what would be expected intuitively. Since trees in stands managed with a low basal area density grow faster, one would expect the average size of trees harvested from these stands to be larger. But the reverse is true.

With a given initial density, leaving lower basal areas after thinning tends to decrease the average size of trees harvested and produce less volume in larger trees. Individual trees grow more rapidly in diameter if a stand is kept at low density by thinning, but more trees are cut in the first thinning to reduce the stand to this level than would be cut if a higher density were maintained (table 8). This heavy first cut, which consists of the smallest trees that will be cut during the rotation, may remove up to half the trees in the stand. The effect of such early heavy thinnings is to reduce the number of trees available for harvest at a later date when they are larger.

The initial number of trees and the thinning density level interact to affect tree size and volume production from the stand. This interaction is reflected in a measure that can affect timber harvest costs—the number of trees that must be cut to produce a unit of volume.

If we establish 200 T/A, and mortality is light, then over the rotation we can expect to harvest almost 200 trees. If we establish 1,200 T/A we can expect to harvest nearly 1,200 trees, or almost six times as many. We have already seen (fig. 14) that 1,200 T/A does not produce six times the cubic-foot volume, but only about 20 percent more than is produced by 200 T/A. So, we should expect that many more trees would have to be harvested to get a unit of volume output from stands with high initial densities, and such is the case. In stands thinned to 120 SF/A every 10 years, we would have to harvest about 20 trees over the rotation for every thousand cubic feet of total tree volume if initial density is only 200 trees (fig. 28). We would have to harvest more than 100 trees for every thousand cubic feet if initial density is 1,200 trees. The effect is even more pronounced for board-foot volumes (fig. 29).

Table 8.—*Diameters and numbers of trees cut per acre over an 80-year rotation in red pine plantations on site index 60, for a range of initial and thinning densities*

Stand age	Basal area left after thinning (sq. ft./acre)					
	60		100		140	
	Ave. d.b.h.	No. of trees cut	Ave. d.b.h.	No. of trees cut	Ave. d.b.h.	No. of trees cut
	200 TREES PER ACRE INITIAL DENSITY					
30	8.6	52	—	—	—	—
35	—	—	—	—	—	—
40	11.7	67	11.2	53	—	—
45	—	—	—	—	—	—
50	14.5	28	13.7	49	—	—
55	—	—	—	—	13.7	60
60	17.1	14	16.2	28	—	—
65	—	—	—	—	—	—
70	—	—	—	—	16.3	38
75	20.5	11	19.6	22	—	—
80	21.5	26	20.6	48	18.1	97
Entire rotation	13.4	198	15.7	200	16.4	195
	1,200 TREES PER ACRE INITIAL DENSITY					
30	5.3	804	5.3	546	—	—
35	—	—	—	—	5.7	380
40	7.3	180	6.7	229	—	—
45	—	—	—	—	6.7	202
50	9.7	90	8.1	137	—	—
55	—	—	—	—	—	—
60	12.3	43	9.8	85	8.1	170
65	—	—	—	—	—	—
70	14.6	21	11.6	54	—	—
75	—	—	—	—	9.5	104
80	16.7	52	13.4	137	10.1	283
Entire rotation	6.2	1,190	7.4	1,188	7.7	1,139

RISKS IN DENSITY CHOICES

In the preceding analyses we have assumed that future yields can be predicted with certainty, that the unexpected will not happen, and that there are no risks to consider in choosing initial number of trees or thinning densities. This section decribes some of the risks that should be kept in mind when planning for red pine plantation establishment and management

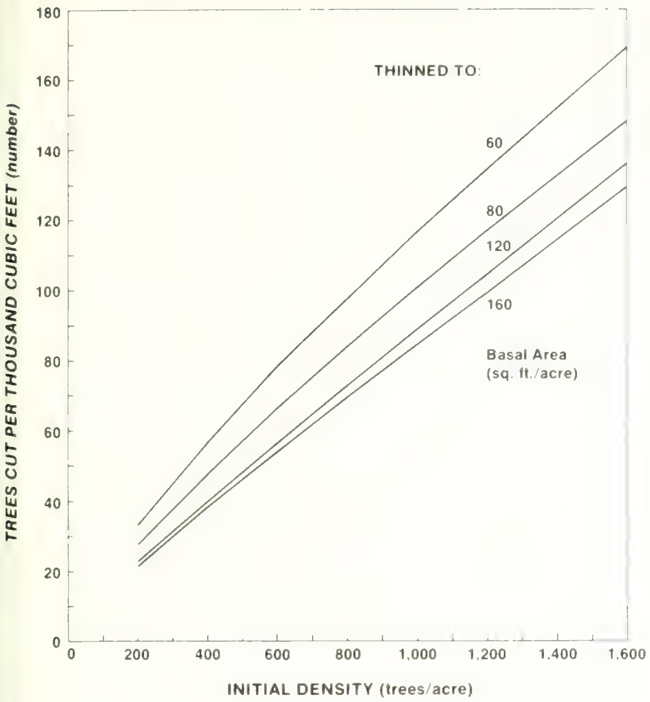

Figure 28.—*Average number of trees cut per thousand cubic feet of total tree volume harvested from red pine plantations over an 80-year rotation on site index 60, for a range of initial and thinning densities.*

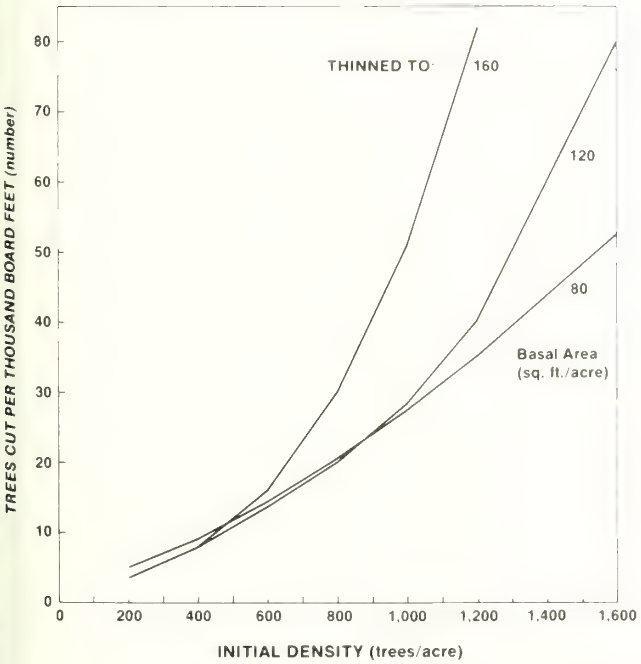

Figure 29.—*Average number of trees cut per thousand board feet of timber harvested from red pine plantations over an 80-year rotation on site index 60, for a range of initial and thinning densites.*

The analyses have assumed that the forest manager or planner can accurately predict the number of established trees per acre. But in truth, the manager may have only limited control over how many trees become established in a plantation. The manager can usually control the selection of areas to be planted, methods and intensity of site preparation, condition of the planting stock, timing of and technique used in planting, spacing and number of trees planted, and subsequent follow-up treatments to improve survival. Yet, at best one can only estimate survival rates, and thus guess at the number and spacing of trees that will result from the planting operation.

Past experience may lead the manager to expect an average tree loss of 25 percent—or a 75-percent survival rate. On this basis, if the objective is to establish 600 T/A, 800 T/A would be planted. However, this 75-percent survival is an average rate, and variations are likely to occur from year to year and from site to site. If conditions are ideal, all planted trees might survive, so the plantation will have 800 established T/A instead of 600. Or, if conditions are bad, half or more of the planted trees might be lost, resulting in a stand with only 400 T/A or fewer. This variation in survival must be considered in choosing the number of trees to plant. How much is the potential loss from a wrong guess?

One approach to answering this question is based on a simple variant of game theory (Luce and Raiffa 1957, Thompson 1968, Halter and Dean 1971). The planting of trees can be viewed as a game against nature. The number of trees to be planted is to be chosen by the forest manager from a range of trees per acre that could be planted. The percentages of planted trees surviving are the states of nature.

We start by asking how many trees per acre would survive and become established for different numbers of trees per acre planted, if we experience different survival rates in a SI 60 red pine stand. We can consider as many planting actions and states of nature as desired, but to keep this example simple we will use only three initial density levels and five survival rates (table 9A). The number of trees surviving (S) for each initial density (N) and survival rate (R) is easily determined by using the formula:

$$S = N \times R.$$

For each number of surviving trees (table 9A) we estimate (in this example, from table 1) the maximum MAI we can expect from a stand with that many surviving trees (assuming that we thin to the basal

Table 9.—*Strategy analysis for deciding how many trees per acre to plant for red pine plantations on site index 60*

Percent of trees surviving	Trees planted per acre 200	300	400
A. NUMBER OF TREES SURVIVING (PER ACRE)			
100	200	300	400
75	150	225	300
50	100	150	200
25	50	75	100
0	0	0	0
B. EXPECTED MAI WITH OPTIMAL THINNING (BD. FT./ACRE/YEAR)			
100	743[1]	718	687
75	736	739	718
50	681	736	743[1]
25	485	580	681
0	0	0	0
C. LOSS IN MAI FROM MAXIMUM (BD. FT./ACRE/YEAR)			
100	0	25	56
75	7	4	25
50	62	7	0
25	258	163	62
0	743	743	743

[1] Maximum possible MAI.

area density that gives the highest MAI for this number of surviving trees). For this example we will use board foot MAI. These board foot MAI's are recorded in table 9B. From table 1 we estimate that the highest board-foot MAI we can get from a red pine stand on SI 60 comes from a plantation with 200 established T/A. We assume that this maximum MAI occurs at one of the initial densities listed in the table, and not a density falling between those listed (for SI 60, this maximum MAI is 743 BF/A/Y). The expected loss (table 9C) is the difference between the maximum MAI, 743 BF/A/Y, and the MAI expected from a given combination of trees planted per acre and percent of trees surviving (from table 9B). For example, if we planted 300 T/A and only 50 percent survived, we would get a MAI of 736 BF/A/Y (table 9B), a loss of 7 BF/A/Y from the site's potential (743 – 736 = 7).

This table of expected losses can be used to explore the consequences of different planting actions if we can assign probabilities of occurrence to each "state of nature", the percentage of trees surviving. For example, suppose past experience indicates that 60 percent of the time we can expect a 75-percent survival rate; 10 percent of the time a 100-percent survival rate; 20 percent of the time a 50-percent survival rate; and 10 percent of the time a 25-percent survival rate; and no complete failures. With these estimates we can calculate the probability of loss in MAI for each number of trees planted.

In each "number of trees planted" column, the loss expected to occur for a given survival rate (table 9C) is multiplied by the corresponding probability that that rate will occur. For 200 trees planted per acre, if 100 percent of the trees survive, we expect a loss of 0 BF/A/Y. Multiplying this by a probability of 0.1 still leaves 0 BF/A/Y as the expected loss.

If 75 percent of the trees survive, the loss is 7 BF/A/Y. Since we expect this to occur 60 percent of the time, the expected loss is 7 BF/A/Y × 0.6 = 4.2 BF/A/Y. If only 50 percent of the trees survive, the expected loss is 62 BF/A/Y × 0.2 = 12.4 BF/A/Y. With 25-percent survival, the expected loss is 258 BF/A/Y × 0.1 = 25.8 BF/A/Y. Finally, if no trees per acre survive, the loss is 743 BF/A/Y, but since there is no chance of this occurring (in our example) the expected loss is 743 BF/A/Y × O = O BF/A/Y. These expected losses for each probability of survival can be summed to get the total expected loss for each planting action (table 10A). For this example, planting 200 T/A results in a total expected loss of 42.4 BF/A/Y. The loss expected from planting 300 T/A is 24.0 BF/A/Y, and from 400 T/A, 26.8 BF/A/Y. To minimize expected losses in board-feet MAI per acre with these probabilities of tree survival, one would choose 300 T/A from among the planting options considered here (200, 300, or 400 T/A).

The effects of other tree survival probabilities on the choice of planting density can be explored (tables 10B and 10C). A slight change in probability of a given survival rate can change the expected loss by a relatively large amount (table 10B), although in this example the density choice is not affected. A fairly large shift in probabilities of survival may have little or no effect on the manager's choice of the number o trees per acre to plant (table 10C).

The exploration of risk examples given here use board-foot MAI, but similar analyses could be done for other product yields. The simple calculations above do not tell the manager what to do, but they help him explore the consequences of an array o actions and so may help him choose a defensible one

Table 10.—*Expected loss in mean annual increment for varying probabilities of tree survival*
(In bd. ft./acre/yr.)

Percent of trees surviving	Probability of occurrence	Trees planted per acre		
		200	300	400
A. FIRST PROBABILITY OF OCCURRENCE EXAMPLE				
100	0.10	0	2.5	5.6
75	.60	4.2	2.4	15.0
50	.20	12.4	2.8	0
25	.10	25.8	16.3	6.2
0	0	0	0	0
Total expected loss		42.4	24.0	26.8
B. SECOND PROBABILITY OF OCCURRENCE EXAMPLE				
100	.10	0	2.5	5.6
75	.60	4.2	2.4	15.0
50	.30	18.6	2.1	0
25	0	0	0	0
0	0	0	0	0
Total expected loss		22.8	7.0	20.6
C. THIRD PROBABILITY OF OCCURRENCE EXAMPLE				
100	.333	0	6.2	18.7
75	.333	2.3	1.3	8.3
50	.333	20.7	2.3	0
25	0	0	0	0
0	0	0	0	0
Total expected loss		23.0	9.8	27.0

CONCLUSION

This analysis of product yields expected from red pine stands with various combinations of initial and thinning densities has led to several interesting conclusions.

The initial number of trees per acre has a major impact on the amount and quality of product yields from red pine stands. The more trees established per acre, the higher the total cubic-foot volume yield. However, this increased volume must be harvested from more and smaller trees. Furthermore, the added production drops off sharply after the first 200 T/A. Merchantable cubic-foot yields (pulpwood) are maximized with about 800 to 1,000 established T/A, but increasing the initial density above 500 established T/A increases production by less than 5 percent. Board-foot yields, which are strongly related to individual tree size, are maximized with relatively low levels of initial density—about 200 established T/A.

With low initial densities it is necessary to maintain stands at higher densities throughout the rotation to obtain highest board-foot yields; this can be accomplished by thinning stands to 120-140 SF/A every 10 years. These are higher than the 90 SF/A residual densities recommended by Benzie (1977) for poletimber stands, but close to his recommended thinning density for sawtimber stands. The higher the site index, the higher the basal area density required to achieve maximum yields.

The red pine growth equations used in this analysis do not explicitly include the effect of shrub and other understory competition on tree growth, other than the undocumented effects of whatever conditions existed on the study plots used in developing the original growth models. Fear has been expressed that the yields reported here for low initial densities may not be achieved in practice because other trees, shrubs, and grasses may invade some sites and compete strongly with the widely spaced red pine trees. The yields reported here were developed from Buckman's and Wambach's growth models, but the 200 T/A that produces maximum board-foot growth is just below the lower end of their data. Wambach's study of red pine plantations did include plots with as few as 270 T/A, and he developed diameter-growth constraints for low initial densities. Diameter growth projections by REDPINE, over a wide range of initial and thinning densities, were compared with those made by an updated version of the FREP Tree Growth Projection System (USDA Forest Service 1979). At low initial densities (400 T/A and fewer) both systems projected almost identical diameters for the tree of average basal area during the first 30-40 years, so the diameter-growth constraint equation in REDPINE that governs maximum diameter growth in early years at low densities appears reasonable. Nevertheless, to be conservative, one should assume that to achieve these growth rates, periodic tree release treatments to remove competing vegetation in low-density red pine stands will be required until the first thinning.

The low initial densities indicated by this analysis for maximum board-foot volume production fall below the densities commonly used in establishing red pine plantations in the Lake States. For this reason these results should be considered tentative until more experience has confirmed their applicability. Still, all the available growth and yield evidence points towards establishing plantations with fewer trees per acre than has been common in the past. This will not only reduce initial costs, but increase future board-foot yields.

Our immediate need is for growth and yield studies to test these lower densities, and to document more accurately the development of low-density plantations throughout the region. But until this information becomes available, this analysis can serve as a guide to those wishing to manage red pine plantations with fewer trees per acre.

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1981. The effect of initial number of trees per acre and thinning densities on timber yields from red pine plantations in the Lake States. U.S. Department of Agriculture Forest Service, Research Paper NC-193, 25 p. U.S. Department of Agriculture Forest Service, North Central Forest Experiment Station, St. Paul, Minnesota.

Describes an analysis of initial density and subsequent thinning options for red pine (*Pinus resinosa* Ait.) plantations in the Lake States. Results showed that the initial number of established trees per acre has a major impact on the amount and quality of timber product yields, with 200 trees per acre (500/ha) thinned to 120 square feet of basal area per acre (27.5 m^2/ha) maximizing board-foot volume yields.

KEY WORDS: Volume yields, timber management, stand density, *Pinus resinosa*, timber quality.

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Estimating northern RED OAK CROWN COMPONENT WEIGHTS *in the northeastern United States*

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ESTIMATING NORTHERN RED OAK CROWN COMPONENT WEIGHTS IN THE NORTHEASTERN UNITED STATES

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Tree crowns, particularly those remaining as debris after logging operations, wind or ice storms, or insect epidemics, may be a significant forest fire fuel. Northern red oak, (*Quercus rubra* L.) widely distributed in the eastern United States, is found in most oak-hickory forests. To appraise potential fire behavior following disturbance in stands containing northern red oak, a method of estimating individual crown fuel weights was developed. These weight estimates are suitable for use in fuel models and also provide estimates of potentially usable fiber. While these estimates are for northeastern northern red oak, they are probably satisfactory for northern red oak and similar black oak species throughout the eastern United States.

A number of methods have been developed for estimating eastern hardwood tree crown (foliage and/or branchwood)[1] weights in addition to, independently of, or together with weights of "merchantable" or specified portions of the upper bole (Storey and Pong 1957, Young *et al.* 1964, Ralston and Prince 1965, Young and Carpenter 1967, Oak Ridge National Laboratory 1971, Zavitkovski 1971, King and Schnell 1972, Sando and Wick 1972, Ribe 1973, Schlaegel 1975, MacLean and Wein 1976, Phillips 1977, Wartluft 1977, Wiant *et al.* 1977, and Wartluft 1978). Two studies established branchwood size classes as needed for fire behavior prediction using the Rothermel (1972) model—(Loomis 1975) for northern red oak, and (Loomis and Roussopoulos 1978) for aspen.

Most investigators developing crown weight prediction methods have used d.b.h. (diameter at breast height) as an independent variable, either alone or combined with tree height, crown length, or crown ratio.[2] While bole diameter at base of crown is an excellent single estimator of crown weights, (Storey and Pong 1957, Loomis *et al.* 1966) it can be difficult to obtain. Using d.b.h. and crown ratio to estimate shortleaf pine crown weights produced more accurate estimates than using d.b.h. alone (Loomis *et al.* 1966). These results were almost as accurate as those obtainable by using the bole diameter at base of crown.

METHODS

Twenty-eight trees from Michigan and 28 from Pennsylvania were destructively sampled in 1973, 1974, and 1978. The trees were from four locations in Wexford, Manistee, and Calhoun Counties in Michigan and from one location in Huntingdon County, Pennsylvania.

The trees, from fully stocked stands on medium or better sites, ranged in size from 1.0 to 20.6 inches d.b.h., and in crown ratio from 27 to 82 percent.[3] A wide range of crown ratios was selected for each d.b.h. class. Vigorous dominant or codominant trees with relatively uniform crowns and branching were chosen. Preference was given to trees with well defined boles extending well into the crown. Sampling was done from mid-summer through early fall while trees were in full foliage, after seasonal growth was completed.

There was noticeable insect defoliation on many sample trees in both States. Selecting trees that were least affected by this minimized influence on foliage weights and resulting estimates but did not completely avoid it.

Tree measurements made included d.b.h., total height, live crown length and width, and basal diameters of all branches at 2 inches from the bole.[4] One hundred fifty-four branches were randomly selected

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[1] *"Branchwood" and also "bolewood" as used in this paper refer to both wood and bark.*

[2] *Crown ratio is the ratio of live crown length to total tree height expressed as a percent.*

[3] *English-metric equivalents: 1 inch = 2.54 cm; 1 pound = 0.4536 kg; 1 acre = 0.40469 hectare.*

[4] *All bole, branch, and branchwood diameters in this paper are outside bark (d.o.b.) measurements.*

and cut from sample trees for a branch sample representing all crown parts and all trees. Bole sections measuring 1 to 3 inches in diameter were weighed.

Field weights of foliage, total live branchwood, and live branchwood in four fuel groups—with diameters of 0 to ¼ inch, ¼ to 1 inch, 1 to 3 inches, and 3 inches or more—were determined for each sample branch. Sample branches ranged from 0.5 to 10.4 inches in basal diameter.

Field weights for dead branchwood in the four size groups were obtained for each tree. The wood was weighed for approximately half the trees. As this was considered a suitable base, ocular weight estimates were included for the other trees, particularly for material falling within the smaller diameter groups.

Factors for converting all field weights to ovendry weights for analysis were obtained by ovendrying foliage, branch, and bole sections at 105° C for 24 hours or more.

Logarithmic transformations were made to adapt to the general equation $\mathrm{Ln}y = a + b\mathrm{Ln}x$ for predicting weights of foliage and total live wood per branch using basal diameter as the independent variable. These and all subsequent equations were adjusted for logarithmic transformation bias (Baskerville 1972).

To aid subsequent mathematical representation, measured dry weights of wood in the three mutually exclusive size classes (0 to ¼ inch, ¼ to 1 inch, 1 to 3 inches) were arithmetically combined by branch into overlapping classes: 0 to ¼ inch, 0 to 1 inch, and 0 to 3 inches. The percent of total branchwood weight per branch in each overlapping size class was then plotted against branch diameter for all sample branches. Curves were drawn defining the relations. Next, the percentage values for size groups—0 to ¼ inch, ¼ to 1 inch, 1 to 3 inches, and 3+ inches were computed using curve values. These basal branch diameter percentages were multiplied by total live branchwood weight for each applicable basal diameter to obtain class weights per branch. Foliage and branchwood weights (total and by size class) for each tree were then computed by summing the predicted weights for the tallied live branch basal diameters. Weight and dimension data for the 56 trees were then used to develop estimating equations.

RESULTS

Regression analysis yielded good relations for predicting foliage weights and total weight of live wood per branch when using basal diameter as the independent variable (table 1). Equations were developed to predict weights of foliage and branchwood per tree using various variables: bole diameter at base of crown, d.b.h., and the combination of d.b.h. and crown ratio (table 2). Resulting estimates for the pair of equations using d.b.h. and crown ratio are presented on table 3 and 4. The prediction improvement from adding crown ratio as a second independent variable was significant at the 0.01 level. Equations to compute ratios of branchwood weights within diameter size class (0 to ¼ inch, 0 to 1 inch, 0 to 3 inches) to total branchwood weight per tree were developed (table 5). These predictions are constrained at a 1.0 value as ratios cannot exceed unity. These ratios, together with available estimates of total live branchwood weight per tree, allowed computation of estimates of live branchwood weights per tree within each of the diameter size groups (table 6). Estimates of bolewood weight in the 1 to 3 inch diameter class were obtained from a curve drawn through data for the bole section weight plotted over tree d.b.h. (table 7).

Table 1.—*Equations for estimating northern red oak foliage and live branchwood[1] dry weights for individual branches*

Dependent variable	Equations	R^2	Sy·x	Percent of mean
Foliage	$Wf = 0.3925(Bd)^{1.5648}$	0.86	0.08	3.9
Total branchwood	$Wb = 1.1852(Bd)^{2.6883}$	.98	.84	2.6

[1] Branchwood includes the topmost section of the bole that is less than 1 inch in diameter. Branchwood refers to both wood and bark.

The abbreviated terms are:
Wf = foliage weight (pounds)
Wb = live branchwood weight (pounds)
Bd = branch basal diameter (inches)
R^2 = coefficient of determination
Sy·x = standard deviation about the regression
Percent of mean = percent error of the mean

Table 2.—*Equations for estimating total dry weight of northern red oak foliage and live branchwood*[1] *using various crown and stem measurements*

Foliage	**R^2**	**Sy·x**	**Percent of mean**	**Live branchwood**	**R^2**	**Sy·x**	**Percent of mean**
$Wf = 0.5953Dc^{1.6428}$	0.98	0.65	3.6	$Wb = 0.4928Dc^{2.8932}$	0.99	11.42	3.7
$Wf = .4590Dbh^{1.5018}$	.96	1.18	6.5	$Wb = .3328Dbh^{2.6360}$	.97	34.07	10.9
$Wf = .0136Dbh^{1.5791} Cr^{.8612}$	.98	.69	3.8	$Wb = .0005Dbh^{2.7768} Cr^{1.5685}$	.99	16.13	5.2

[1] Branchwood includes the topmost section of the bole that is less than one inch in diameter. Branchwood refers to both wood and bark.

The abbreviated terms are:
Wf = foliage weight (pounds)
Wb = live branchwood weight (pounds)
Dc = bole diameter at base of crown, outside bark (inches)
Dbh = diameter at breast height, outside bark (inches) Cr = crown ratio: crown length in feet ÷ tree height in feet, expressed as percent
R^2 = coefficient of determination
Sy·x = standard deviation about regression
Percent of mean = percent error of the mean

Table 3.—*Dry weight of northern red oak foliage*
(In pounds)

	Crown ratio[1] (percent)						
D.b.h. (inches)	**20**	**30**	**40**	**50**	**60**	**70**	**80**
1	0.2	0.3	0.3*	0.4	0.5*	0.5*	0.6
2	0.5	0.8	1.0	1.2*	1.4*	1.6*	1.8
3	1.0	1.4	1.8	2.2*	2.6	3.0*	3.4
4	1.6	2.3	2.9*	3.5	4.1	4.7	5.3
5	2.3	3.2	4.1	5.0	5.9	6.7*	7.5
6	3.0	4.3	5.5	6.7	7.8	9.0	10.0
7	3.9	5.5	7.0*	8.5*	10.0	11.0	13.0
8	4.8	6.8*	8.7*	11.0	12.0	14.0	16.0
9	5.8	8.2	10.0*	13.0	15.0	17.0	19.0
10	6.8	9.7	12.0	15.0*	17.0	20.0	22.0
11	7.9	11.0*	14.0*	17.0*	20.0*	23.0	26.0
12	9.1	13.0	16.0*	20.0*	23.0	27.0	30.0
13	10.0	15.0	19.0*	23.0	26.0	30.0*	34.0
14	12.0	16.0*	21.0*	26.0	30.0*	34.0	38.0
15	13.0	18.0	23.0*	28.0*	33.0	38.0	43.0
16	14.0	20.0	26.0*	31.0	37.0	42.0	47.0
17	16.0	22.0	29.0*	35.0	40.*	46.0	52.0*
18	17.0	24.0	31.0	38.0	44.0	51.0	57.0
19	19.0	27.0	34.0	41.0	48.0*	55.0*	62.0
20	20.0	29.0	37.0*	45.0	52.0*	60.0	67.0
21	22.0	31.0	40.0	48.0	57.0*	65.0	73.0
22	24.0	34.0	43.0	52.0	61.0	70.0	78.0
23	25.0	36.0	46.0	56.0	65.0	75.0	84.0
24	27.0	38.0	49.0	60.0	70.0	80.0	90.0
25	29.0	41.0	53.0	64.0	75.0	85.0	95.0

Note: Asterisks identify observed data.

[1] Crown ratio is the ratio of live crown length to total tree height expressed as a percent.

An equation to estimate total dead branchwood weight per tree was developed:

$$Wb = 0.356\ Dbh^{1.713}$$

where:
Wb = dead branchwood weight per tree (pounds) and
Dbh = diameter at breast height (inches).

The coefficient of determination (r^2) was 0.71 and the standard deviation from the regression (Sy•x) was 3.46 for this equation.

Total dead branchwood weight was subdivided into three size groups by plotting each tree's percentage of the total within size groups (0 to ¼ inch, 0 to 1 inch, and 0 to 3 inches in diameter) over d.b.h. Curves were then drawn through the data. Dead branchwood weights within size groups—0 to ¼ inch, ¼ to 1 inch, 1 to 3 inches, and 3+ inches in diameter—were computed using appropriate calculations on curve values and the equation for estimating total dead branchwood weight per tree (table 8).

Table 4.—*Dry total weight of northern red oak live branchwood*[1]
(In pounds)

D.b.h. (inches)D.b.h.	Crown ratio[2] (percent)						
	20	**30**	**40**	**50**	**60**	**70**	**80**
1	0.1	0.1	0.2	0.2	0.3	0.4	0.5
2	0.4	0.7	1.1	1.6	2.1	2.7	3.3
3	1.2	2.2	3.4	4.9	6.5	8.3	10.0
4	2.6	4.9	7.7	11.0	14.0	18.0	23.0
5	4.8	9.1	14.0	20.0	27.0	34.0	42.0
6	8.0	15.0	24.0	33.0	45.0	57.0	70.0
7	12.0	23.0	36.0	51.0	68.0	87.0	107.0
8	18.0	33.0	52.0	74.0	99.0	126.0	155.0
9	25.0	46.0	73.0	103.0	137.0	175.0	216.0
10	33.0	62.0	97.0	138.0	184.0	234.0	289.0
11	43.0	81.0	127.0	180.0	240.0	305.0	376.0
12	54.0	103.0	162.0	229.0	305.0	389.0	479.0
13	68.0	129.0	202.0	286.0	381.0	485.0	599.0
14	84.0	158.0	248.0	352.0	468.0	596.0	735.0
15	101.0	191.0	300.0	426.0	567.0	722.0	891.0
16	121.0	229.0	359.0	510.0	679.0	864.0	1,065.0
17	143.0	271.0	425.0	603.0	803.0	1,023.0	1,261.0
18	168.0	317.0	498.0	707.0	941.0	1,198.0	1,478.0
19	195.0	369.0	579.0	822.0	1,094.0	1,393.0	1,717.0
20	225.0	425.0	668.0	947.0	1,261.0	1,606.0	1,980.0
21	258.0	487.0	765.0	1,085.0	1,444.0	1,839.0	2,267.0
22	293.0	554.0	870.0	1,234.0	1,643.0	2,092.0	2,580.0
23	332.0	627.0	984.0	1,397.0	1,859.0	2,367.0	2,919.0
24	373.0	705.0	1,108.0	1,572.0	2,092.0	2,664.0	3,285.0
25	418.0	790.0	1,241.0	1,760.0	2,343.0	2,984.0	3,679.0

[1] Branchwood includes bolewood less than 1 inch in diameter. Branchwood and bolewood include all woody parts (wood and bark).

[2] Crown ratio is the ratio of live crown length to total tree height expressed as a percent.

Table 5.—*Equations for estimating ratios of northern red oak live branchwood*[1] *within a size group, to total branchwood per tree*

Live branchwood diameter class	Equation	R^2	Sy·x	Percent of mean	n
0-¼ inch	$R_1 = 0.6262Dbh^{-1.0795}$	0.94	0.007	5.4	
	$R_1 = 0.5094Dc^{-1.1863}$	.97	.005	3.8	56
	$R_1 = 6.4735Dbh^{-1.1313} Cr^{-.5777}$	.96	.007	5.4	
0-1 inch	$R_2 = 3.1018Dbh^{-1.0114}$	.70	.016	6.4	
	$R_2 = 1.7710Dc^{-.9479}$	.82	.012	4.8	42
	$R_2 = 36.8351Dbh^{-.9345} Cr^{-.7014}$	.79	.014	5.6	
0-3 inches	$R_3 = 8.7376Dbh^{-1.0113}$	.64	.018	3.0	
	$R_3 = 4.0290Dc^{-.8443}$	.78	.015	2.5	34
	$R_3 = 28.2916Dbh^{-.8658} Cr^{-.4084}$	.72	.017	2.8	

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[1] Branchwood includes the topmost section of the bole that is less than 1 inch in diameter. Branchwood refers to both wood and bark.

The abbreviated terms are: R_1, R_2, R_3 = Ratios of branchwood within a group to total branchwood weight.
Dbh = Diameter at breast height, outside bark (inches).
Dc = Bole diameter at base of crown, outside bark (inches).
Cr = Crown ratio: Crown length in feet tree height in feet, expressed as a percent.
R^2 = Coefficient of determination.
Sy·x = Standard deviation about regression.
Percent of mean = Percent error of the mean.

Table 6.—*Dry weight of northern red oak live branchwood*[1] *by diameter class*
(In pounds)

	Crown ratio[2]																											
D.b.h.	20 percent diameter class (inches)				30 percent diameter class (inches)				40 percent diameter class (inches)				50 percent diameter class (inches)				60 percent diameter class (inches)				70 percent diameter class (inches)				80 percent diameter class (inches)			
(inches)	0-.25	.25-1	1-3	3+	0-.25	.25-1	1-3	3+	0-.25	.25-1	1-3	3+	0-.25	.25-1	1-3	3+	0-.25	.25-1	1-3	3+	0-.25	.25-1	1-3	3+	0-.25	.25-1	1-3	3+
1	0.1				0.1				0.1	0.1			0.1	0.1			0.2	0.1			0.2	0.2			0.2	0.2		
2	0.2	0.2			0.3	0.4			0.4	0.7			0.5	1.1			0.6	1.5			0.7	2.0	0.1		0.8	2.2	0.4	
3	0.4	0.8			0.6	1.6			0.8	2.6			1.0	3.2	0.7		1.1	3.7	1.6		1.3	4.2	2.7		1.5	4.6	3.9	
4	0.6	2.0			0.9	3.6	0.3		1.2	4.6	1.8		1.6	5.6	3.9		1.8	6.2	6.0		2.1	7.1	8.8		2.5	8.4	12.0	
5	0.9	3.9			1.3	5.5	2.3		1.7	6.9	5.3		2.2	8.4	9.4		2.7	9.8	15.0		3.1	11.0	20.0		3.5	12.0	26.0	
6	1.2	5.5	1.3		1.8	7.8	5.4		2.4	10.0	12.0		2.9	12.0	18.0		3.6	14.0	27.0		4.2	16.0	37.0		4.8	18.0	48.0	
7	1.5	7.2	3.2		2.3	10.0	10.0		3.1	13.0	20.0		3.8	16.0	32.0		4.6	19.0	44.0	0.7	5.4	21.0	55.0	6.1	6.1	24.0	64.0	13.0
8	2.0	9.7	6.3		2.8	13.0	17.0		3.8	17.0	31.0		4.7	20.0	45.0	3.7	5.7	24.0	57.0	12.0	6.7	27.0	69.0	23.0	7.6	30.0	84.0	34.0
9	2.4	12.0	11.0		3.5	16.0	26.0		4.7	22.0	42.0	4.4	5.8	25.0	57.0	15.0	7.0	30.0	71.0	29.0	8.1	34.0	88.0	46.0	9.3	38.0	106.0	63.0
10	2.8	14.0	16.0		4.2	20.0	35.0	2.5	5.5	26.0	51.0	15.0	6.9	32.0	69.0	30.0	8.3	36.0	88.0	52.0	9.6	42.0	108.0	75.0	11.0	47.0	127.0	104.0
11	3.3	17.0	22.0		4.9	24.0	42.0	9.7	6.5	30.0	64.0	27.0	8.1	37.0	85.0	50.0	9.6	43.0	108.0	79.0	11.0	50.0	131.0	113.0	13.0	55.0	154.0	154.0
12	3.7	20.0	29.0	1.6	5.7	28.0	50.0	19.0	7.5	36.0	75.0	44.0	9.4	43.0	101.0	76.0	11.0	50.0	128.0	116.0	13.0	57.0	156.0	163.0	15.0	67.0	182.0	216.0
13	4.3	24.0	33.0	6.8	6.5	34.0	59.0	30.0	8.5	42.0	87.0	65.0	11.0	52.0	114.0	109.0	13.0	60.0	149.0	160.0	15.0	67.0	179.0	223.0	17.0	79.0	210.0	294.0
14	4.9	27.0	39.0	13.0	7.3	39.0	68.0	44.0	9.7	50.0	99.0	89.0	12.0	58.0	134.0	148.0	15.0	70.0	168.0	215.0	17.0	79.0	209.0	292.0	19.0	84.0	250.0	382.0
15	5.5	31.0	44.0	20.0	8.0	44.0	78.0	61.0	11.0	55.0	114.0	120.0	14.0	67.0	153.0	192.0	16.0	81.0	193.0	278.0	19.0	90.0	238.0	375.0	21.0	103.0	276.0	490.0
16	6.1	35.0	50.0	30.0	8.9	48.0	89.0	82.0	12.0	64.0	129.0	154.0	15.0	77.0	173.0	245.0	18.0	91.0	217.0	353.0	21.0	100.0	268.0	475.0	23.0	115.0	320.0	607.0
17	6.7	39.0	57.0	40.0	10.0	55.0	100.0	106.0	13.0	72.0	145.0	196.0	16.0	86.0	193.0	308.0	20.0	100.0	249.0	434.0	24.0	109.0	307.0	583.0	26.0	125.0	366.0	744.0
18	7.4	43.0	64.0	54.0	11.0	62.0	111.0	133.0	14.0	80.0	159.0	244.0	18.0	95.0	219.0	375.0	22.0	110.0	282.0	527.0	25.0	131.0	335.0	707.0	30.0	133.0	414.0	902.0
19	8.0	49.0	70.0	68.0	12.0	69.0	122.0	166.0	16.0	89.0	179.0	295.0	20.0	104.0	247.0	452.0	24.0	118.0	317.0	635.0	28.0	139.0	376.0	850.0	31.0	158.0	446.0	1,082.0
20	8.8	52.0	79.0	86.0	13.0	76.0	136.0	200.0	17.0	96.0	200.0	354.0	22.0	111.0	275.0	540.0	26.0	137.0	340.0	757.0	31.0	146.0	418.0	1,012.0	34.0	164.0	495.0	1,287.0
21	9.6	58.0	88.0	103.0	14.0	83.0	151.0	239.0	19.0	103.0	222.0	421.0	24.0	128.0	293.0	640.0	27.0	146.0	375.0	895.0	33.0	169.0	460.0	1,177.0	36.0	190.0	544.0	1,496.0
22	10.0	63.0	94.0	126.0	15.0	90.0	166.0	283.0	20.0	110.0	244.0	496.0	25.0	136.0	321.0	753.0	30.0	168.0	411.0	1,035.0	36.0	174.0	502.0	1,381.0	41.0	191.0	619.0	1,729.0
23	11.0	69.0	103.0	149.0	16.0	97.0	182.0	332.0	22.0	126.0	266.0	571.0	27.0	155.0	349.0	866.0	33.0	171.0	446.0	1,208.0	38.0	199.0	544.0	1,586.0	44.0	219.0	642.0	2,014.0
24	12.0	74.0	112.0	175.0	18.0	102.0	197.0	388.0	23.0	132.0	288.0	665.0	30.0	159.0	393.0	990.0	36.0	195.0	481.0	1,381.0	40.0	226.0	586.0	1,812.0	46.0	246.0	690.0	2,300.0
25	13.0	79.0	121.0	205.0	19.0	115.0	205.0	450.0	25.0	149.0	310.0	757.0	32.0	180.0	405.0	1,144.0	37.0	197.0	539.0	1,570.0	45.0	224.0	656.0	2,059.0	48.0	250.0	773.0	2,612.0

[1] Branchwood includes bolewood less than 1 inch in diameter. Branchwood and bolewood include all woody parts (wood and bark).

[2] Crown ratio is the ratio of live crown length to total tree height expressed as a percent.

Table 7.—*Dry weight of bole section from 1 to 3 inches in diameter for northern red oak per tree by d.b.h.*

D.b.h. (inches)	Bole section (lbs.)
1	2
2	11
3	12
4	13
5	13
6	13
7	13
8	13
9	13
10	12
11	12
12	12
13	11
14	11
15	10
16	10
17	10
18	9
19	9
20	8
21	8
22	8
23	7
24	7
25	7

Table 8.—*Dry weight of northern red oak dea branchwood*[1] *by four diameter classes and total pe tree by d.b.h.*

D.b.h.	Diameter				Total dea
(inches)	0-.25	.25-1	1-3	3+	branchwoo
1	0.1	0.3			0.4
2	0.2	1.0			1.2
3	0.3	2.0			2.3
4	0.5	3.3			3.8
5	0.6	5.0			5.6
6	0.7	6.9	0.1		7.7
7	0.8	6.1	3.1		10.0
8	0.9	5.6	6.0		13.0
9	0.9	5.2	9.1	0.2	15.0
10	0.9	4.8	12.0	0.9	18.0
11	1.0	4.4	15.0	1.7	22.0
12	1.0	4.0	17.0	2.8	25.0
13	1.0	3.6	21.0	3.7	29.0
14	1.0	3.4	23.0	4.9	33.0
15	1.0	3.4	27.0	5.9	37.0
16	1.0	3.1	30.0	7.4	41.0
17	1.0	2.7	33.0	8.6	46.0
18	1.0	2.7	37.0	10.0	50.0
19	1.1	2.5	40.0	12.0	55.0
20	1.2	2.4	43.0	13.0	60.0
21	1.3	2.3	48.0	14.0	66.0
22	1.4	2.3	51.0	16.0	71.0
23	1.5	2.3	55.0	18.0	77.0
24	1.7	2.5	59.0	20.0	82.0
25	1.8	2.6	63.0	21.0	88.0

[1] Branchwood refers to both wood and bark.

DISCUSSION

The northern red oak equations with two independent variables (d.b.h. and crown ratio) were used to estimate foliage and branchwood weight for two independent sets of data. The first set used six species of hardwood trees (silver maple, *Acer saccharinum* L.; sweet birch, Betula *lenta* L.; pignut hickory, *Carya glabra* Sweet; American beech, *Fagus grandifolia* Ehrh.; yellow-poplar, *Liriodendron tulipifera* L.; and scarlet oak, *Quercus coccinea* Muenchh.) from the Pisgah National Forest in North Carolina (Storey and Pong 1957). A second data set was for quaking aspen, (*Populus tremuloides* Michx.) from northeastern Minnesota (Loomis and Roussopoulos 1978). Results of analysis with this independent data were inconclusive.

The actual and estimated weights were compared by a paired t-test (table 9). No significant difference between actual and estimated foliage weights was indicated for sweet birch, pignut hickory, and aspen. Foliage weight differences for all other species tested were significant. No significant difference between actual and estimated branchwood weights was indicated for pignut hickory, American beech, scarlet oak, and aspen while differences for sweet birch, silver maple, and yellow-poplar were significant.

Specific gravity for wood varies by species, and, to a lesser extent, by location (Phillips 1977). Thus, the effect of specific gravity adjustment on branchwood estimates was examined. Specific gravity values, based on volumes at 12 percent moisture content, were taken from Wood Handbook (USDA 1974). The ratio of specific gravity of each species to specific gravity of northern red oak was computed. This ratio was used as a multiplier to obtain adjusted branchwood weight estimates. The specific gravity adjustment yielded a significant improvement in the gap

Table 9.—*Comparison of actual dry weights of foliage and branchwood[1] per tree with estimated weights using the equations developed for northern red oak[2]*

Species[3]	Crown component	Number of trees	Specific[4] gravity adjustment	D.b.h. range (inches)	Crown ratio range (percent)	Means		Standard error of the difference	Paired[5] t
						Actual (pounds)	Estimated (pounds)		
Aspen, quaking	Foliage		—			12	11	0.8	1.00 NS
(*Populus tremuloides* Michx.)	Branchwood	15	—	1.2-15.0	31-79	88	115	14.9	1.80 NS
			0.60			88	53	10.0	3.53**
Beech, American	Foliage		—			24	15	3.4	2.61*
(*Fagus grandifolia* Ehrh.)	Branchwood	14	—	4.1-15.8	42-79	262	199	34.5	1.82 NS
			1.02			262	203	33.3	1.77 NS
Birch, sweet	Foliage		—			17	14	1.5	2.14*
(*Betula lenta* L.)	Branchwood	17	—	1.9-13.8	31-68	107	140	12.5	2.61*
			1.03			107	144	13.2	2.78*
Hickory, pignut	Foliage		—			31	18	6.7	2.02 NS
(*Carya glabra* Sweet)	Branchwood	16	—	1.9-23.4	25-65	260	327	55.7	1.21 NS
			1.19			260	390	69.8	1.86 NS
Maple, silver	Foliage		—			21	15	2.2	2.64*
(*Acer saccharinum* L.)	Branchwood	16	—	2.2-14.0	27-77	108	163	14.6	3.77**
			.75			108	122	8.8	1.60 NS
Oak, scarlet	Foliage		—			28	16	4.7	2.60*
(*Quercus coccinea* Muenchh.)	Branchwood	14	—	4.1-20.2	30-58	197	199	15.2	0.13 NS
			1.06			197	211	14.1	0.99 NS
Yellow-poplar	Foliage		—			11	14	.9	4.09**
(*Liriodendron tulipifera* L.)	Branchwood	18	—	2.1-21.6	21-63	48	180	51.2	2.58*
			.67			48	121	30.0	2.42*

[1] Branchwood refers to both wood and bark.

[2] Dry weight estimates for foliage and live branchwood per tree obtained using (northern red oak) equations: $Wf = 0.0136\ Dbh^{1\ 5791}$ and $Wb = 0.005\ Dbh^{2\ 7768}\ Cr^{1\ 5685}$ where Wf and Wb = weight of foliage and branchwood respectively in pounds; Dbh = diameter breast height, outside bark in inches; Cr = crown ratio (live crown length ÷ total tree height expressed as a percent).

[3] All species groups except aspen are from Storey and Pong (1957); aspen is the sample tree group used for Loomis and Roussopoulos (1978) publication—data on file at North Central Forest Experiment Station, East Lansing field office.

[4] Specific gravity adjustment is a multiplier for the computed branchwood weight estimates; it is the ratio of the specific gravity of the concerned species to the specific gravity of northern red oak. Specific gravity values obtained from Wood Handbook (USDA 1974).

[5] Levels of significance: 0.01 (**), 0.05 (*), and not significant (NS).

between estimated and actual weights for silver maple, and an insignificant improvement for American beech and yellow-poplar. In contrast, sweet birch, pignut hickory, and scarlet oak had greater differences between estimated and actual values. Quaking aspen results were significantly poorer. In general, using specific gravity adjustment to increase the accuracy of applying the red oak equations to other species has variable results.

The results support use of the northern red oak equations for foliage and for total live branchwood weight for those species where tests indicated no significant difference between actual and estimated values. Under most circumstances, however, better results would probably be obtained by using estimating equations based on data for each species.

Scarlet oak estimated foliage weights averaged only 73 percent of actual weights. Although species and/or site related differences are possible, estimates for northern red oak may be lower due to insect defoliation on sample trees. Foliage, not as constant as branchwood, represents an annual crop, and its quantity may be altered by many things—not only insects, but also unusually strong wind and drought.

The equation, using two independent variables, was also tested on an additional data base for estimating branchwood weight. These data concerned 71 northern red oak trees ranging from 6 to 24 inches d.b.h. from uneven-aged stands on better than average sites on the Pisgah National Forest in North Carolina. The estimates from the equations developed here compared favorably with those using equations that had been developed from the independent data base.[5] This further supports the application of this method throughout the Eastern deciduous forest.

The use of the combination of d.b.h. and crown ratio as independent variables is believed to minimize effects of differences in stand density and site.

The equations presented here for estimating northern red oak crown component weights are applicable to the range of northern red oak in the eastern United States. The branchwood estimates for northern red oak are considered usable for other black oak species, and for approximations for other hard hardwoods with similar crown form such as hickory. (For practical application, see Loomis and Blank 1981.) However, it is suggested foliage estimates be used for other black oak species and other hard hardwoods only when no other estimating procedure is available.

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Equations are described for estimating crown weights for northern red oak trees. These estimates are for foliage and branchwood weights. Branchwood (wood plus bark) amounts are subdivided by living and dead material into four size groups. Applicability of the equations to other species is examined.

KEY WORDS: forest fuels, fuel modeling, biomass.

SDA FOREST SERVICE
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Evaluation of a vest-pocket park

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North Central Forest Experiment Station
Forest Service, U.S. Department of Agriculture

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EVALUATION OF AN URBAN VEST-POCKET PARK

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Liberty Plaza Park

Liberty Plaza is a vest-pocket park in downtown Ann Arbor, Michigan. The park's design was based, in part, on local people's reactions to photographs of simulated park scenes (Kaplan 1978a). These reactions indicated that people desired a "green" place, complete with flowers, grass, and large trees. People living in the vicinity of the proposed park were concerned about safety and security as well. The park designers proceeded with these objectives in mind, and Liberty Plaza was opened to the public in the fall of 1977.

A year later, at the request of the Parks and Recreation Department, I conducted a follow-up survey to find out if people were satisfied with the park. Based on the park's popularity as a place to eat lunch, I expected the frequent users to express a high level of satisfaction. But to determine the public's overall reaction to the park, I felt it was important to reach beyond the group that clearly enjoys it as a place to sit and rest. Therefore, I also sampled the opinions of people who live or work near the park, but who do not necessarily spend time there. The results are detailed here.

PRE-DESIGN SURVEY

Two landscape architects, Terry Brown and Charles Cares, were hired in 1975 to design the park.

The Parks and Recreation Department, as well as the designers, wanted to obtain citizen input during this process. People were asked to respond to photographs of simulated park settings depicting various arrangements of green space, trees, benches, etc. Although the 24 scenes lacked detail, the 180 participants had no difficulty indicating their preferences.

Among the most obvious results was that people wanted a "green" place—a park with color, flowers, grass, and big trees. In addition, the survey showed strong differences in preferences between those who live in the central business district and those who work there. Clearly, the workers saw such a park as an amenity, while for the nearby residents it posed some threats. Because these concerns played a major role in the design of the park, we examined them again in the post-design survey.

POST-DESIGN SURVEY

The post-design evaluation took place in the fall of 1978, about a year after the park dedication. The evaluation was not triggered by problems such as vandalism or citizen discontent, but by the commendable desire of the Parks and Recreation Department to find out if the park was achieving its objectives.

Ann Arbor, with a population of about 106,000, has extensive parks and open space. In addition to the 2,500 acres managed by the Parks and Recreation Department, the school system owns playfields and natural areas, and the University of Michigan has over 600 acres that are available for public use. In the central business district, however, Liberty Plaza—a mere one-fourth of an acre in size—is the only park.

Bordering Liberty Plaza on the south is the Kempf House, a classic example of Greek Revival Architecture, built around 1850. The City's Historical Commission purchased the home in 1969, and it is now open to the public on weekends. Immediately to the west of the park is a large office building that was constructed at about the same time as the park. The building has a restaurant overlooking the park as well as several shops a half-story below street level that open to the park side of the building.

To keep the park compatible with this building, the park was built on several levels, the lowest of which connects to the shops. Seating, in the form of wooden benches with backs, is available at an intermediate level as well as at street level. The benches can accommodate about 100 people, and low ledges around numerous planters also provide seating, especially during planned events. At peak times, during concerts or other performances, there may be as many as 500-600 people in the park.

The Sample

Liberty Plaza is at the intersection of two major thoroughfares. One of these, Division Street, is a one-way arterial carrying heavy traffic volumes much of the time. The other, Liberty Street, is a commercial corridor linking the downtown area with the State Street-campus area. Within a radius of about two blocks, there are apartment units and multi-family houses, shops, offices, relatively large commercial establishments, and some public facilities.

With this diversity of uses in the vicinity, one would expect to find people at Liberty Plaza who live in the area, work nearby, or come to the park while they are in the area shopping, running errands, or whatever. But in addition to asking park users how they feel about the park, we felt it important to sample the opinions of people who have the park in easy reach and may or may not use it. Is the park serving them in any sense? The evaluation thus included two separate groups: park users (on-site sample), and people who live or work within a specified radius of the park (off-site sample).

To obtain the on-site sample, interviewers approached 163 people who were in the park at different times of day and on different days of the week over several weeks. (Only one interviewer was present at a time.) A particularly cold October made the park a less popular place than it had been only a short time earlier. Thus, the interviewing period was extended in the hope that milder days would return.

To obtain the off-site sample, questionnaires were delivered to residences and business establishments within a prescribed radius (fig. 1). For the residences, 339 questionnaires were dropped off and 82 were returned (24 percent). For the businesses, approximately 380 questionnaires were left at 90 places, and about 40 percent were returned. At each business, a responsible person was asked to see that employees had an opportunity to respond.

The business establishments included several doctors' offices and small law firms, many small shops, and a few large employers such as the telephone company, the newspaper, the public library, and some banks. We do not know how the questionnaires were distributed to employees, nor which establishments returned the most questionnaires.

While 61 percent of the off-site sample (n = 233) was comprised of people who work in the area, the on-site sample consisted mostly of people who neither live nor work in the central business district (63 percent). Of these, almost half (45 percent) indicated

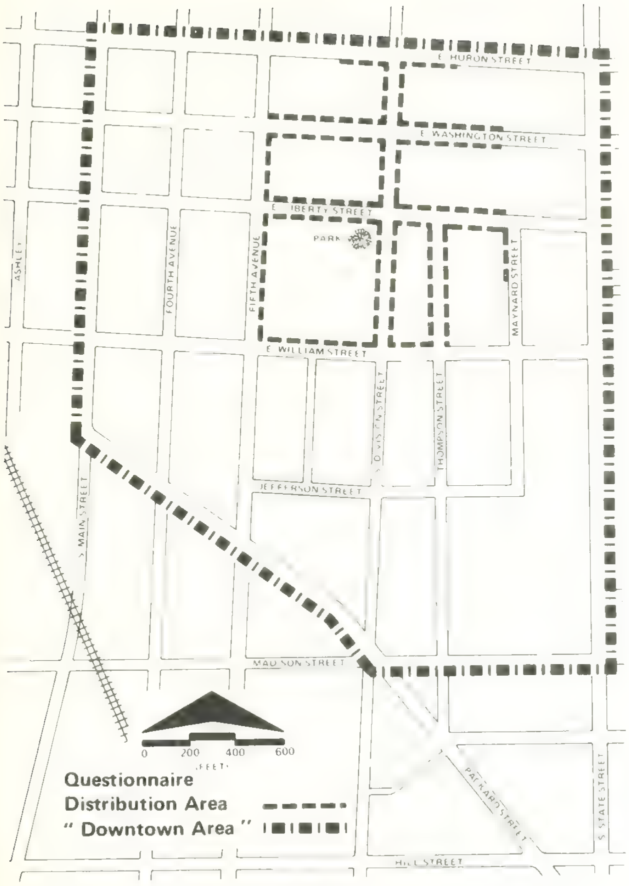

Figure 1.—*Distribution of questionnaires*

The Questionnaire

All participants were administered the same questionnaire (Appendix). It included a cover letter, signed by the Superintendent of the Parks and Recreation Department, urging people to reply. It also mentioned the fact that citizens had participated in designing the park, and pointed out the importance of continued input. The bottom of the page included a small sketch showing the location of the park.

The three-page questionnaire included both open-ended items and scaled items. The major sections of the survey covered the kinds and frequencies of use, satisfactions, problems, and particular places within the park that were favored. The last of these was based on a map of the park (fig. 2) which identified six regions, designated by the letters "A" to "F." The map took most of the middle page of the questionnaire; at the top of the page the question inquired how much the participant liked to be in each area "to sit in this area, or walk through it" using a 5-point scale. Participants were also asked to indicate on the map their favorite places within the park.

The major independent variables included: age, sex, student or not, full-time employment or not, frequency of park use, length of work or residence in the downtown area, whether the park is passed on foot, by bike, or by car, and—of greatest interest—whether the participant lives or works in the area.

they are in the area "quite often," while 33 percent indicated "very often" and 22 percent responded "not very often."

The two samples were remarkably similar with respect to other variables, however. About half of each sample was female, about 40 percent was male, and the rest did not indicate sex on the questionnaire. About 55 percent of the people in each sample were in their twenties; the on-site sample included a few more people in their teens (12 percent as opposed to 3 percent for the off-site group), and a few less people in their forties or fifties (9 percent as opposed to 20 percent). The off-site sample included 29 percent who indicated they were students; for the on-site group 37 percent were students.

The on-site sample was about evenly divided between people who frequent the park at least weekly as opposed to those who are there less often. About one-fifth of the off-site participants indicated they do not spend time in the park, while 42 percent said they visit it at least once a week and 36 percent said they frequent it less often than that.

Background Characteristics

As mentioned earlier, one of the most important differences revealed by the pre-design survey was in the attitudes of people who live downtown versus those who work there. The park was designed with their separate concerns in mind, and the post-design evaluation was structured to obtain responses from both groups.

A little less than half the overall sample (47 percent) consisted of people who work downtown (table 1). Of these, 82 percent had full-time jobs, and only 10 percent were students. Women outnumbered men almost two to one, and about half of the working group was 30 or older.

About a quarter of the sample were residents of the downtown area. Of these, only 37 percent held full-time jobs, and 60 percent were students. Of the latter, 83 percent attended the University of Michigan; the others attended a variety of schools and colleges. The "student" and "full-time job" categories are not mutually exclusive (about 12 percent of the students also

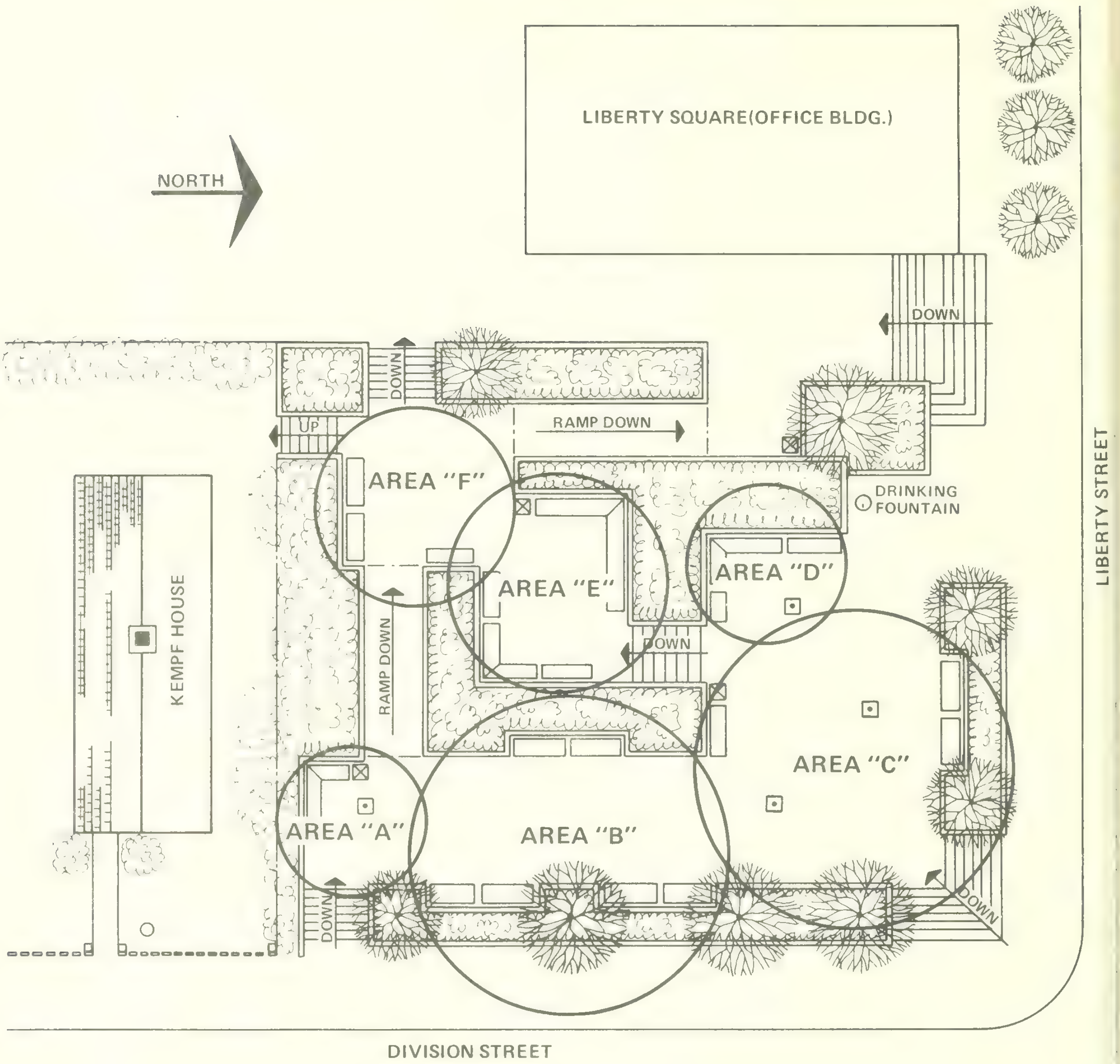

Figure 2.—*Sketch map of the park.*

held full-time jobs). Not surprisingly, the "live downtown" participants were younger, with 80 percent under 30. Men and women were equally represented.

The remaining quarter of the sample (28 percent actually) neither lived nor worked downtown. About 43 percent were students and 42 percent were employed full-time. Women accounted for 52 percent of this group, and about one-third were over 30. This group also included more people in their teens than did either of the other two.

It should be mentioned that 21 participants who lived and worked in the downtown area were included only in the "live downtown" group. The definition of "downtown" was somewhat more inclusive than the area included in the survey itself. People living or working within the area bounded by Main Street, Huron, State, Madison, and Packard were included (fig. 1).

Of those who lived downtown, 46 percent had been there less than a year, and 40 percent for a year or

Table 1.—*Background characteristics of respondents*
(In percent)

Background characteristic	Group: Live downtown (n = 98)	Work downtown (n = 186)	Other (n = 112)	All groups (n = 396)
Sex:				
Male	44	32	38	37
Female	46	61	52	55
No data	10	7	10	8
Age:				
Under 20	6	4	12	7
20-29	74	45	56	56
30-49	12	38	23	27
50 +	3	11	4	6
No data	5	2	5	4
Full-time job	37	82	42	59
Student	60	10	43	32

longer. Among the downtown workers, a majority (59 percent) had worked there for a year or longer and 25 percent for less than a year. Information was not available for the others.

Participants were asked how often they pass the park on foot, by car, and on bike. For those who lived downtown, passing on foot was a very frequent occurrence (70 percent), while passing by car was "not often" for the majority (53 percent). About half of the "work downtown" participants indicated that they pass the park "very often" on foot, and a similar number pass it that frequently by car.

Participants varied considerably in frequency of park use. Just under half of the "live downtown" and "work downtown" samples (45 and 48 percent, respectively) indicated at least weekly use of the park (keep in mind the survey was conducted in the fall). For the rest of the sample, 38 percent indicated at least weekly use.

Participants who worked downtown used the park most heavily during lunchtime, and not much at other times. Those who lived downtown used the park less during lunchtime (only 22 percent), but much more extensively in the evenings, during events, and on weekends.

Uses and Importance

What do people do in the park and in what ways is it important to them? Not surprisingly, the answers to these questions are strongly interrelated. So, for example, the park is important as "a place to rest," "to sit down where there are trees," "to get away from things for a little while" and to "rest, sun, and think." These four items, describing the "sit and rest" functions of the park, define one of its salient features. For the sample as a whole this cluster rated an average of 3.8 on a 5-point scale (table 2). The "sit and rest" cluster is least important to people who live in the downtown area, and particularly important to those who neither live nor work there (mean 4.0). Younger participants (under 30) rated these items significantly higher, especially those who work downtown.[1]

The park is also "a place to have lunch," to "eat and drink." As noted earlier, the downtown residents are not as likely to be lunchtime users and these items rate 2.6 for them. The other two groups, however, average 3.6 on this item. The "eating" function is far more important for women than for men, and higher for the on-site sample than for the off-site.

Some people arrange to meet a friend in the park, or go there to be with other people they know. This is particularly true for the women in the sample (mean 3.3) and for the younger members of the "work downtown" group (mean 3.4). By contrast, "people-watching" seems to be everybody's sport, indulged in by people of all backgrounds and represented by a mean of 3.6 for the sample as a whole.

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[1] *The results discussed in the report are based on t tests and analyses of variance. Only results significant at the 95 percent level are included in this discussion. (Appendix shows sample sizes for the various analyses.)*

Table 2.—*Analysis of uses and importance*[1]

Park use	Rating (1-5)		Respondents'			Access			Relation to park
	Mean	SD	Location on-site/off-site	Age <30/30+	Sex F/M	Bike Yes/no	Foot Yes/no	Car Yes/no	Live/work/other
Link, shops	2.8	1.2						+ + +	
Know it's there	3.4	1.4	–			+		+ + +	+
See it	4.2	1.1					+	+ + +	
Sports	1.3	.8				+ +			
Read, sketch	3.1	1.5		+ + +	+ +	+ + +			
Meet friends	3.2	1.2	+	+	+ + +		+		
Eat, have lunch	3.3	1.4	+ + +		+ + +			– – –	
People-watch	3.6	1.2				+			
Sit and rest	3.8	1.0	+ + +	+ +		+		–	

[1] + indicates first sub-group in comparison rated higher
– indicates second sub-group in comparison rated higher
× indicates the middle group is different from the other two
+ or – = $p<0.05$
+ + = $p<0.01$
+ + + = $p<0.005$.

The "read, sketch, write" function was more important to younger (under 30) than older participants (means 3.3 and 2.7), and more important to women than men among the downtown workers (means 3.3 and 2.5). This function was especially important to frequent park users who neither live nor work downtown (mean 3.9).

The participants were asked how likely they are to engage in sports (jog, skateboard, etc.) while in the park. The results show they are extremely unlikely to do such things (mean 1.3). Those who bike rated the item higher than did the others, but not much higher. While there are occasional skateboarders in the park, they are not represented in the sample. Generally, the park is not conducive to such activites.

The park serves some other functions as well, which are not related to specific activities. The park has shops near it and serves as a midway point between two shopping areas. But in general, the "shopping" item did not receive very high ratings. The most important function of the park is that it is "a nice place to see as you go by." This item received a mean rating of 4.2 for the sample as a whole and seemed equally important to men and women, residents, shoppers, and employees, young and old. The very existence of the park also plays an important role. To "know it is there" is important to people, quite independently of their pattern of use.

Satisfaction

Do people find Liberty Plaza a pleasing place, does it meet their needs? Eight of the items dealing with satisfaction were strongly interrelated and were combined to form an "overall satisfaction" scale. These included such things as the placement of plantings, the "variety of kinds of places," the seating facilities, and the overall appearance of the park. The park fared extremely well in terms of these considerations. The mean rating for the entire sample was 4.1 on a 5-point scale (table 3). Women rated overall satisfaction somewhat higher than men (4.2 and 3.9), as did people who more often pass the park on foot (compared with those who are less likely to walk by it). Among the people who live in the downtown area, those who frequent the park more often (at least weekly) show a great overall satisfaction (means 4.3 and 3.7). While these differences are interesting, the most striking result is that by and large the overall satisfaction level was high for everyone.

Because seating was a source of concern in the predesign study, the two items included in the overall satisfaction scale that dealt with "kinds of benches" and "seating arrangement" were examined separately as well. The mean rating for these was 4.1, and all the differences mentioned above were true for the

Table 3.—*Summary of satisfaction analyses (see table 2 for instructions on interpreting table)*

Satisfaction item	Rating (1-5)		Respondents'			Access Relation to park		Time in park	
	Mean	SD	Location On-site/off-site	Age <30/30 +	Sex F/M	Foot Yes/no	Live/work/ other	Live wkl/<	Work wkl/<
Overall satisfaction	4.1	0.8			+ +	+ + +		+ + +	
Seating	4.1	.9	+ + +		+ +	+ + +		+ + +	+ +
City's care of park	4.1	1.0	+	+	+ + +	+ +	× ×		
People in the park	3.8	1.0	+ + +	−			− − −		+
Activities	3.2	1.1							
Having the park	4.6	.8	+						+

seating questions also. In addition, people in the on-site sample expressed greater satisfaction with seating than did those in the off-site sample (4.6 and 4.3).

The satisfaction items included the "the city's care of the park." This also received a mean of 4.1, expressing overall approval of park care as the first year of park activity neared its end. It is interesting that the "work downtown" group showed the lowest rating on care (3.9), while the downtown residents and "others" were more pleased (4.1 and 4.3). Here again, women were more favorably inclined.

Even a beautifully designed park might not be well received if it attracts "the wrong kind" of people. The item dealing with "people who are in the park" received a mean rating of 3.8; people who neither live nor work downtown rated it highest, and local residents rated it lowest (4.1 and 3.5, respectively, with 3.9 for the "work downtown" group). People in the on-site sample expressed greater satisfaction with the people in the park than those in the off-site group. Interestingly, the older participants rated this item higher than did those under 30.

The lowest ratings among the satisfaction items were given to those dealing with special events in the park: "planned activites, special programs," and "other activities that go on." The mean rating was 3.3 and none of the analyses based on background variables yielded any significant differences. (One exception: the bikers rated these more favorably.) The "activities" issue received considerable mention in the open-ended responses, and appears to be the major sore point with respect to the park. Some local citizens complained of excessive noise and excessive duration of concerts. On the other hand, many residents, as well as people who work in the area and others, expressed a desire for more activities. Well over a third of the participants indicated they would like to have musical events in the park. About 12 percent said they wanted no sponsored activities of any kind. (Interestingly, two-thirds of these are people who work in the downtown area.) While the disgruntled are seriously affected, their numbers seem to be few indeed. Still, this is clearly an issue that needs to be discussed and handled carefully.

While people seem pleased with the physical aspects of the park, with its care, and with the people who frequent it, the biggest source of pleasure is the fact that the park is there. Having 355 people yield an average rating of 4.6 on "having the park there" must be considered an overwhelming vote of appreciation.

The answers to the open-ended question "What kinds of things do you like most about the park?" further reflect these satisfactions. The most frequent comments (and the number of people who made them) were: a place to sit, benches (50); knowledge of it being there (46); natural atmosphere, trees, plants (43); attractive design (34); quiet and peaceful (28); accessible, good location (27); an oasis in the city (24); a sunny atmosphere (16); safe, clean, well-lit (13); watch people (13); place for people (12); private, different levels (10).

Problems

The items dealing with potential problems of the park revealed two noteworthy findings: first, the responses are not highly interrelated. This means that participants' concerns for any one issue do not have a bearing on their concern for other issues. Second, the problems were not generally considered serious.

Of the problems listed in the questionnaire, the biggest by far is traffic, referring to the heavy use of both streets adjoining the park. The mean rating for the item was 2.5, half-way between "a little" and "somewhat" of a problem (table 4). The people responding to the questionnaire while at the park rated traffic significantly more problematic—a mean of 2.7 compared with 2.3 for the off-site group.

Table 4.—*Analyses pertaining to problems (see table 2 for instructions on interpreting table)*

Problem	Rating (1-5)		Respondents'			Relation to park
	Mean	SD	Location On-site/off-site	Age <30/30+	Sex F/M	Live/work/ other
Traffic	2.5	1.3	+ +	+		
Maintenance	2.3	1.0	−			×
Crowds	2.0	1.1	− − −			× × ×
Noise	1.8	1.1	− − −			+
Feeling unsafe:						
Daytime	1.3	.8				
Evening	2.2	1.3	−		+ + +	

The park maintenance and amount of litter were the next greatest problem, with a mean of 2.3 for the sample as a whole. The off-site people considered it a worse problem than did the on-site participants (2.4 and 2.1), and the people who work downtown feel it is a worse problem than do the other two groups. These differences reflect the previously discussed satisfaction with the "city's care of the park" and taken together indicate a relatively high level of satisfaction.

Not surprisingly, crowding during lunchtime was seen as a bigger problem by those who work in the downtown area than by the residents or others (means 2.1, 1.9, and 1.7, respectively). It was also judged a greater problem by the off-site group (which was more heavily represented by people who work downtown) than by the on-site participants. Here again, the ratings suggest that as problems go, this is not a big one.

Some citizens had previously complained about noise at special events, and it was not clear how pervasive a problem it might be. The overall mean rating of 1.8 suggests that it is at most a minor nuisance. Interestingly, it is rated approximately the same by those who live downtown and those who work there, and least by others (1.8, 1.9, and 1.5, respectively).

Finally, there is the issue of safety—both in the daytime and in the evening. In the pre-design survey, people living in the park's vicinity were concerned about the possibility of "muggers" lurking behind retaining walls and trees. For the participants in the current study at least, daytime safety is not an issue. With a mean rating of 1.3 it is clear that few respondents consider it to be a problem at all. "Feeling unsafe in the evening" is seen as a slightly more realistic problem, with a mean of 2.2. (Presumably the fact that only about three-fourths of the participants answered this item indicates that many are not in the vicinity of the park in the evenings.) For the off-site sample, this problem rated somewhat higher than for the on-site participants. In addition, as would be expected, women rated safety as being a bigger problem (2.5) than did men (1.7).

Written comments about problems were widely scattered. The "bees and wasps" in great evidence that summer received 19 mentions, and overflowing trash cans received 13 comments. "Drunks, street people" were listed as a problem by 16 participants, mostly downtown residents. Eleven people expressed the desire for more trees. This was also by far the most frequently mentioned item under "What kinds of things do you wish could be changed about the park?". The desire for more trees, more plants and flowers, more grass, and less concrete was mentioned between 12 and 20 times, reminiscent of some of the comments in the pre-design survey.

Participation

Citizens can express their interest and concern for the well-being of the park in different ways. They were asked about a few of these. For example, the questionnaire inquired whether participants were likely to weed the plantings. The results confirm what one would expect. By and large, this is something people are unlikely to do: mean 1.5 for the sample as a whole (table 5). Picking up litter, however, is a different matter. Here the overall mean was 2.6, and those who frequent the park more often are much more likely to do it.

Another expression of interest involves a more vicarious concern for the plantings and curiosity about "what the city workers are doing in the park". Here the group mean is 2.3, with the people who see the park from their place of work and the participants who have lived downtown longer than a year expressing far greater interest than others. Interestingly,

Table 5.—*Summary of participation questions (see table 2 for instructions on interpreting table)*

								Relation to park				
			Respondents'		Access			Live/	Time in park			See park
Participation	Rating (1-5)		Location	Age	Bike	Foot	Car	work/	Live	Other	Live downtown	from work
item	Mean	SD	On-site/off-site	<30/30+	Yes/no	Yes/no	Yes/no	other	wkl/<	wkl/<	yr/yr+	Yes/no
Weeding	1.5	1.0										
Litter	2.6	1.4							+	+		
Plantings	2.3	1.2	−−−	−		+	+	·			−−−	+++
Own/share	2.4	1.2	−		+++	++		+	+	+++		+

Table 6.—*Preferred places analyses (see table 2 for instructions on interpreting table; the last column indicates the number of votes for each area)*

						Relation to park		
			Respondents'	Access			See park	"Favorite
Preferred	Rating (1-5)		Sex	Bike	Foot	Live/work/	from work	place"
area	Mean	SD	F/M	Yes/no	Yes/no	other	Yes/no	
A	2.7	1.4	+	+++		·	−	16
B	3.1	1.3						35
C	3.4	1.3		+	+			32
D	3.3	1.3				·	+	43
E	3.3	1.4	+	+++				69
F	3.0	1.4		+++				10

people in the off-site sample rated this item higher than those in the on-site, and those who pass the park either on foot or by car say they are more likely to check to see how the plants are doing.

Perhaps the strongest sense of participation is expressed by the items reflecting a "sense of ownership toward the park" and a desire to "share it when people come to visit". Clearly, those who spend more time in the park reflect a greater sense of this, and the downtown residents also express more of this "own/share" characteristic.

Preferred Places

The park has several levels with stairs and ramps connecting them. Partly as a result of the levels, and partly because of its access from both streets as well as a nearby parking lot, there are several distinguishable settings within the park. There are numerous ways for pedestrians to enter the park.

In terms of places to sit, six areas were marked on the questionnaire (fig. 2). The responses reflect different preferences for these settings with mean ratings between 2.7 and 3.4 (table 6). None of the six places showed any noteworthy differences between the on-site and off-site groups, nor for the younger as opposed to the older participants. The diversity and distinctiveness of the different areas within the park met a wide range of desires.

Students seem to prefer Area A, a little "nook" that affords privacy in terms of seating, though not in terms of passers-by. This area is also preferred by women in the sample, but not people who work downtown and can see the park from their working place.

Women also seem to prefer Area E, a fairly large area on the lower level. This area gives a relatively enclosed feeling, providing room for quite a few gatherers.

The area nearest the street corner (C), easily accessible from the corner or from the shopping street, won the favor of those who are most likely to come "on foot."

Area D, by contrast, a corner seating arrangement nearest the entry from the shopping corridor, was highly favored by those who can see the park from their place of work (mean 3.8), and was rated higher by those who work downtown than by local residents (means 3.5 and 3.0). Of people who live nearby, those who frequent the park more often greatly preferred Area D.

CONCLUSIONS AND IMPLICATIONS

The park serves different groups of users, and each group derives different satisfactions. Its primary users are people who work downtown, but many are also people who are downtown to do their shopping and run errands. The nearby residents are less likely to use the park as a place to sit and rest, to have lunch, or meet friends.

Nearby residents were less satisfied with the type of people in the park than the downtown workers and others. One would expect nearby residents to see more problems with the park than people who use it during the working day, but this was not generally the case. The three groups surveyed did not differ in their feelings toward safety, but nearby residents and downtown workers found noise more of a problem than did nonlocals. Downtown workers regarded maintenance and lunchtime crowding as greater problems than the other two groups. This suggests that those who work downtown use the park more than nearby residents, which, in fact, is the case.

Little background information on participants was obtained in the pre-design study, so it is difficult to judge whether the current sample and the earlier one are comparable. Several concerns expressed in the earlier study were not voiced in the post-design survey. For example safety was seen as a problem before the park was built, but not after. The park seems to have satisfied workers who stressed the need for a pleasant place to sit and have lunch. The general satisfaction with "having the park" seems to be common with all user groups, regardless of residence and employment.

This post-design evaluation serves two purposes. The first is its applicability to other small downtown parks. A park that serves a residential clientele and one that serves a daytime working group must meet a variety of demands and must avoid a variety of problems. Where the residents are likely to use the park less extensively than people who work in the area, it is appropriate for the park to be designed with the needs of the working group in the forefront—as long as the concerns of the other group are also met.

The study also has conceptual importance (Kaplan 1978b), in that it is just as important for many people to have the park there as a resource as it is to physically partake of it. This type of enjoyment and satisfaction cannot be assessed by a user count. While the satisfaction of "having it there" was greater for the workers who use it more often, this was the source of greatest satisfaction for users and nonusers alike. The park is passed by hundreds of people each day as they drive along the major thoroughfare at its perimeter; hundreds more pass it on foot as they go to the bank, the library, the shops, or the federal building a block away. No doubt many of these passersby notice the changes in season as they are reflected in the park—benches high with snow, trees showing signs of life. Even people who rarely see or use the park may derive some satisfaction from knowing the city has provided such a place and that it is there should one want to visit it.

Another conceptual facet of the study revolves around people's reaction to the fact that the public had been involved in the planning of the park. The response to an open-ended questionnaire item on this topic was overwhelmingly enthusiastic, with "good idea," "great," and "excellent" the most common responses. The knowledge that the public had been involved was warmly received, which should be a cue to park planners in many situations.

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APPENDIX

SAMPLE SIZE FOR ANALYSES

Each of the analyses presented in tables 2-6 was based on a somewhat different number of participants, depending on how many people answered a particular question. The maximum and minimum number of people involved in each specific analysis is presented here. (Some of these analyses did not appear in the tables but were mentioned in the discussion.)

	Categories	Maximum	Minimum
Sample	On-site/Off-site	160-222	124-177
Age	Under 30/30 & Over	240-126	209-92
Sex	Women/Men	208-141	165-116
Time in park:			
Live downtown	Weekly/Less	43-39	38-33
Work downtown	Weekly/Less	90-57	77-43
"Other"	Weekly/Less	42-60	31-47
Bike	Occasionally/Less	68-248	61-202
Foot	Often/Less	206-167	170-130
Car	Often/Less	173-177	145-140
Live/Work	Live/Work/Other	90-177-108	76-141-87
Student (age in 20's)	Yes/No	95-119	82-96
See Park (Work downtown)	Yes/No	61-119	50-90

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Evaluates the effectiveness of a downtown vest-pocket park in Ann Arbor, Michigan.

KEY WORDS: Urban forestry, urban parks, recreation, public involvement.

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An economic and energy analysis of poplar intensive cultures in the Lake States

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AN ECONOMIC AND ENERGY ANALYSIS OF POPLAR INTENSIVE CULTURES IN THE LAKE STATES[1]

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Interest in the use of intensive silviculture to produce high yields of wood fiber in short rotations has been increasing. This trend is not really a result of foreseen shortages in hardwoods—nationally, hardwood removals are still well below growth (USDA Forest Service 1973)— but instead reflects an increased awareness of the potential economic advantages of growing wood fiber intensively. Through concentration of high yields in small areas close to the mill or plant, intensive short-rotation culture might remove many of the uncertainties connected with fiber supply from small private woodland and public land. It would also reduce hauling costs, an increasingly important consideration due to the energy situation. The actual application of short rotation intensive wood production systems to supply biomass for energy, fiber for pulp mills, or both, will depend on the economic and energy efficiencies of alternative production systems available for producing wood biomass.

The purpose of this paper is to present a close look at the economic and energy efficiencies of intensively growing hybrid poplar in the Lake States in a manner likely to be used by industrial users of wood fiber. Realistic information with respect to all the relevant production costs and biological growth response information are becoming increasingly available. Thus our intent is to make as specific an analysis as possible without having a particular firm or location in mind, in an attempt to help bridge the gap between theory and practice in intensive silviculture. Cash costs and returns of specific production systems are estimated in both dollar amount and relative uncertainty and are evaluated using cash flow techniques. The sensitivity of the investment performance measures (e.g., internal rate of return, net present worth) to various factors of production and yields is carefully evaluated. Detailed sensitivity tables are provided that will permit the manager or analyst to change values for any of the production factors and determine their impact on the financial performance. Thus we believe that this study may be of great utility in forest management planning and in further research. Energy requirements and outputs are estimated and contrasted with cash flows to identify critical cost/energy trade-offs.

RECENT ECONOMIC INVESTIGATIONS OF INTENSIVE CULTURE SYSTEMS

An industry-wide survey was conducted in 1975 to evaluate trends of and needs for intensive culture on forest industry land and to determine potential impacts on future wood supplies (DeBell 1976, DeBell *et al.* 1977, Gansner *et al.* 1977). The survey showed that intensively cultured wood from industrial land is not expected to increase total annual wood harvest in the North by more than 2 percent in the next decade. Lack of knowledge on intensive culture and

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the great uncertainties related to intensive management systems were major reasons that industries had not adopted intensive culture. Furthermore, many industries were not experiencing shortages of poplar supplies.

Several conferences on intensive silviculture during the last few years have brought together existing knowledge on the many different facets of intensive silviculture. But many uncertainties remain and only actual operational testing of specific alternatives can provide the final answer to many questions (Iowa State University 1975, 1976).

Several studies have dealt with economic questions of intensive cultures. DeBell and Harms (1976) identified cost factors associated with intensive culture of short-rotation forest crops. Their study showed that intensive silviculture will be expensive and therefore, must be evaluated carefully. Dutrow and Saucier (1976) reassessed the economic implications of short-rotation systems of coppicing sycamore for silage. They concluded that only industrial landowners would find production profitable.

Rose and DeBell (1978) in their analysis of intensive cultures emphasized the sensitivity of major investment performance measures to wide changes in costs and yields to obtain insight into the economic feasibility of intensive culture. Although the study revealed critical areas such as land cost, site preparation, planting, harvesting, and fertilization, that should be addressed before implementing an intensive culture system, it was not designed to provide conclusive answers. In other studies, Rose found that long-rotation alternatives offer better investment opportunities than short ones but that irrigation does not appear economical (Rose and Kallstrom 1976, Rose 1977).

Intensive silviculture has received attention recently as a possible way to produce large quantities of biomass for energy (Inman *et al.* 1977, Fege *et al.* 1979, Rose 1977, Zavitkovski 1979). However, much of the economic work in this area must be viewed with caution because the analyses deal with untested systems. Typically, assumptions concerning yield appear far too optimistic and various costs, especially harvesting, are probably much too low. One other major criticism is the lack of adequate sensitivity analyses to identify factors critical for economic production and to deal with questions of uncertainty that surround these untried production systems (Rose 1977).

STUDY DESCRIPTION

Scope

Many alternative methods for the intensive production of hybrid poplar are possible. The major variables of alternative systems are spacing, rotation length, and cultural practices (including site preparation, weed control, irrigation, and fertilization). Spacings have been proposed that range from 1 foot by 1 foot (0.3 m by 0.3 m) to 12 feet by 12 feet (3.6 m by 3.6 m). Proposed rotations range from 4 to 15 years.

In this study we evaluated four specific production systems that represent a range of spacings, rotations, and cultural practices. Two spacings, 4 feet by 4 feet (1.2 m by 1.2 m) and 8 feet by 8 feet (2.4 m by 2.4 m), and three rotations, 5, 10, and 15 years, were chosen; irrigation and fertilization were treated as options, whereas site preparation and weed control were assumed the same for all four alternatives (table 1).

Table 1.—*Specifications for four intensive-culture alternatives*

Alternative	Spacing	Rotations	Origin of stands	Irrigation & fertilization	Yield[1]	
					(Dry tons/acre/year)	mt/ha/year
1	4 by 4 ft	(1) 10 yrs	cutting	yes	6.3	14.1
	(1.2 by 1.2 m)	(4) 5 yrs	coppice		7.2	16.2
2	4 by 4 ft	(1) 10 yrs	cutting	no	3.2	7.2
	(1.2 by 1.2 m)	(4) 5 yrs	coppice		3.6	8.1
3	8 by 8 ft	(1) 15 yrs	cutting	yes	6.3	14.1
	(2.4 by 2.4 m)	(1) 15 yrs	coppice			
4	8 by 8 ft	(1) 15 yrs	cutting	no	3.2	7.2
	(2.4 by 2.4 m)	(1) 15 yrs	coppice			

[1] Stem and branchwood, including bark. (See table 1, Appendix 1).

The size of operation for each alternative is 1,000 acres of cleared, marginal agricultural land arranged in 10 tracts of from 80 to 120 acres each. All 1,000 acres are put into production at the same time, i.e., the analysis does not deal with a sustained yield operation. The methods of site preparation, plantation establishment, and weed control are a combination of chemical and mechanical means and are the same for each alternative. The method of irrigation is a traveling gun system (one system per tract) that applies 10 inches per acre annually. Fertilization includes only nitrogen additions applied in liquid form through the irrigation water at an annual rate of 110 kg per hectare (100 lbs per acre). Harvesting methods are whole-tree chipping for the 10- and 15-year rotations, and forage-type mechanized harvesting for the 5-year coppice rotations. Financial considerations common to all alternatives are administrative costs, insurance, land purchase and sale, equipment costs, and taxes (property and income). An annual inflation rate of 5 percent and a discount rate of 10 percent are applied to all costs and returns (Appendices 1 and 2 give a complete explanation of the inputs and outputs of the alternative production systems).

Methods

Specific inputs and outputs (both physical and monetary) of each productive system were identified through consultation with the USDA Forest Service researchers at the North Central Forest Experiment Station, Forestry Sciences Laboratory, in Rhinelander, Wisconsin, and with the forester in charge of what is currently the only industrial large-scale application of hybrid poplar intensive culture in the Lake States, in Filer City, Michigan. Along with dollar estimates of each cost and return (Appendices 1 and 2), an estimate was made of the relative uncertainty of each cost and return item (Appendix 1).

Costs and returns for each alternative system were evaluated for a 30-year period using simple cash flow techniques (Appendix 2).

Direct energy inputs and outputs were evaluated in two ways: (1) using cash flow methods, substituting energy units for dollars and discounting future energy flows at 10 percent annually, and (2) directly comparing inputs and outputs without discounting the future. Our rationale for discounting energy flows is that it represents a means for comparing the timing and risk involved in using energy inputs of known practical value (petroleum, electricity) for different energy production schemes. For example, a barrel of oil can be invested today into producing more energy in the form of equipment for mining or for growing trees. Certainly the timing and risks of energy outputs for the same energy inputs are different and need a common basis for comparison. For the benefit of those who do not agree with this rationale, energy inputs and outputs are also compared without discounting (Appendices 3 and 4).

RESULTS

Investment Performance Measures

At the assumed 10 percent discount rate, none of the alternatives have a positive net present worth (table 2). The two systems using irrigation and fertilization have negative internal rates of return, and the two systems that do not use irrigation or fertilization have after-tax rates of return of 8.1 percent (Appendix 2). Economically, the difference between short (5 to 10 years) and long (15 years) rotation alternatives is small but the difference between irrigated and nonirrigated alternatives is large.

Sensitivity Analysis

Sensitivity analysis is a valuable tool for predicting the potential effect of changes in uncertain estimates of costs and returns (Appendix 1 gives a complete explanation of how to interpret sensitivity analyses).

The sensitivity analyses in the cash flows (Appendix 2) can be used to identify the uncertain factors that will critically affect net present worths (NPW) and internal rates of return (IRR). It can also be used to identify conditions under which intensive cultures might be economically attractive.

In each of the alternative systems, the most important estimate affecting investment performance measures is product sale value. For the irrigated systems, a 10 to 12 percent change in product sale value could change the IRR by 2 percent; for the nonirrigated systems, an 18 to 22 percent change would do the same. Product sale value has two components— yield and market price. A change in either one or both from what is estimated could substantially change the economic attractiveness of an investment in hybrid poplar, and such changes are

Table 2.—*Investment performance of four intensive-culture alternatives*

Alternative	Description	Internal rate of return	Net presen worth
		(percent)	($/acre)
1	4- by 4-foot (1.2-m by 1.2-m) spacing, irrigated and fertilized, short rotations (5 to 10 years)	–0.4	–2003.82
2	4- by 4-foot (1.2-m by 1.2-m) spacing, not irrigated or fertilized, short rotations (5 to 10 years)	8.1	–236.78
3	8- by 8-foot (2.4-m by 2.4-m) spacing, irrigated and fertilized, long rotations (15 years)	–1.6	–2149.51
4	8- by 8-foot (2.4-m by 2.4-m) spacing, not irrigated or fertilized, long rotations (15 years)	8.1	–200.30

likely. The most likely direction of change in yield is downward (see the discussion on risks, below). The direction of change in the market prices for whole-tree chips 10 to 30 years from now is a matter of speculation.

Irrigation operating costs are next in importance for the irrigated systems. They would have to be substantially reduced, however, to make these projects look even remotely attractive. Because a large part of the cost of operating a traveling gun irrigation system is due to fuel, a substantial cost reduction in this irrigation system in the future is unlikely. The only way reduction in irrigation costs appears likely is to use different irrigation technology (trickle irrigation), only irrigate during the first few years of each rotation, or irrigate a lesser amount each year which would likely reduce yields and perhaps cancel out the effect of cost reductions through reductions in product sale value. Irrigation equipment costs are of some importance but to a lesser degree than operating costs.

Our cost estimates for irrigation were derived in coordination with the University of Minnesota Agicultural Extension specialist for irrigation and are believed to be valid for Minnesota operations. It is known, however, that large differences can occur from one region to another and between different irrigation systems and power units. Sheffield (1979) compared both the fixed and variable costs for the four major types of power units used for irrigation pumping plants and found that natural gas is the most economical source of irrigation pumping. Electricity is the second most economical source. Sheffield (1979) points to a recent shift to propane or LPG (Liquid Propane Gas), a by-product of the oil refining process, that has shown relatively stable prices in recent months. Diesel fuel is the most expensive way to irrigate, but nonetheless is the most widely used in the Lake States.

Reductions in the variable cost of up to 20 percent appear possible by switching to electric and propane fuel sources and reductions of possibly 50 percent by switching to natural gas. Fixed costs also might be reduced as much as 50 percent by switching to electric power, if power lines are available at the irrigation site.

If costs could be reduced 50 percent both in the variable as well as fixed cost components of irrigation, it would not make NPW positive although it would increase NPW for both irrigation alternatives by $1,135.50. A thorough analysis of the circumstances for irrigation is essential in each specific production situation.

Harvesting, especially whole tree harvesting, is a significant cost for all systems. Roughly a 20 to 40 percent change in harvesting costs would change the rate of return by 2 percent for the long rotation systems because they would use only the whole-tree method. Forage-type mechanized harvesting costs, though much more uncertain, are not nearly as important to the financial appearance of the short rotation alternatives. Both types of harvesting employ new technology and their costs depend on many variable stand and terrain factors, which makes future cost predictions difficult. However, even though these costs are uncertain, they are important to the economic performance of any hybrid poplar investment.

The other uncertain estimates—fertilization, land sale value, and income tax—do not significantly affect investment performance.

Energy Flows

Energy output was measured in terms of **gross heat value**, which does not account for losses during conversion of the biomass into other forms of energy. Discounted and nondiscounted energy flows were used to calculate energy output/input ratios (table 3). The two irrigated systems have lower output/input ratios than the two nonirrigated systems. (Details on the energy analysis in terms of energy inputs and outputs are found in Appendix 3.)

These comparisons are valid for the specific assumptions of this analysis. If, for example, fertilization and associated energy inputs are considered necessary for nonirrigated systems, the nondiscounted energy output/input ratios would drop. Naturally, yields or energy outputs might also increase and counteract a decline in the ratios. For irrigated systems energy inputs for irrigation might be lower because of an alternative system used or a less intensive irrigation schedule. For example, a 50 percent reduction in irrigation energy inputs would increase the energy output/input ratios by about 0.45. Under both conditions, i.e., need for fertilization in nonirrigated crops and lower irrigation energy inputs, irrigated and nonirrigated systems would be about equally energy efficient.

DISCUSSION

A Proper Perspective in the Economic Evaluation of Intensive Culture Investments

From the viewpoint of an industrial user of wood, the economic performance of an investment in hybrid poplar does not mean much in isolation, but must instead be compared with alternative investments in other sources of supply. The real value of intensive culture is not its return on investment (though for nonirrigated systems, an 8 percent after-tax return is not bad compared to other forestry investments), but its ability to provide a secure source of supply to a mill or plant that would be very costly to shut down. For a particular firm, its location, access to wood supplies (including present or potential environmental regulations and restrictions), and the amount of competition it must face for the wood supply are more important factors to consider than the economic performance measures of intensive culture investments, although these can be used as guides in choosing between particular investment opportunities.

Table 3.—*Net present worths (NPW) and output/input (O/I) ratios of energy flows under two discount rates (10 percent and 0 percent), when energy output is the gross energy value of wood*

Alternative	Description	Net present worth (MMBTU's/acre)[1]		Output/input ratio[2]	
		10 percent	0 percent	10 percent	0 percent
1	4- by 4-foot spacing, irrigated and fertilized, short rotations (5 to 10 years)	453.42	2,346.82	2.62	3.08
2	4- by 4-foot spacing, not irrigated or fertilized, short rotations (5 to 10 years)	285.08	1,362.00	4.50	4.61
3	8- by 8-foot spacing, irrigated and fertilized, long rotations (15 years)	251.60	2,129.80	2.15	3.04
4	8- by 8-foot spacing, not irrigated or fertilized, long rotations (15 years)	184.74	1,254.10	4.64	4.76

[1] Net present worth at 0 percent discount rate equals the sum of the returns minus the sum of the costs. Net present worth at 10 percent discount rate obtained from energy flow analysis in Appendix 4.

[2] Output/input ratio at 0 percent discount rate equals the sum of the returns divided by the sum of the costs. Output/input ratio at 10 percent discount rate obtained from investment performance measures in Appendix 4.

Risks and Uncertainties of Intensive Fiber Production

High yields are the most attractive feature of intensive culture systems. Any reduction in yield is therefore significant and deserves careful consideration in any decision regarding investment in intensive culture systems. Yields may be lower than we have predicted for three major reasons: (1) yield data have been reported only for carefully tended research plots grown for short periods, not for long-term operations; (2) risks from insects and disease damage are significant— they may reduce annual growth or even destroy entire portions of a crop; (3) yields for nonirrigated, nonfertilized crops are speculative because little data are available. The lack of irrigation and fertilization may reduce annual growth, as we have assumed, or may make the difference between success or failure of the crop during the establishment period. Yields from nonirrigated crops are no more or less certain than those from irrigated crops; insects and disease are probably the greatest sources of risk, whether the crop is irrigated and fertilized or not.

According to some experts in the field, fertilization is a must for short-rotation intensive culture. If we applied the fertilizer regime described for the irrigated alternatives to the nonirrigated production alternatives, NPW would be reduced by about $200/acre. An offsetting increase in yield may occur, however. With all other assumptions unchanged, this would not change the ranking of the alternatives. In combination with other changes such as the discussed lower cost irrigation alternatives, the ranking of the alternatives could conceivably change in favor of the irrigation alternatives. This, however, does not make them financially attractive.

Even small yield reductions can have substantial impacts on returns and the overall economic performance of an intensive culture project. Uncertainty about yields combined with other financial uncertainties (irrigation and harvesting costs and market value of the product) that can affect economic performance, means that an investment in the intensive culture of hybrid poplar must be regarded as having substantial risk and evaluated accordingly.

Irrigation and Fertilization

Even with optimistic yield estimates, irrigation and fertilization are economically unattractive due largely to the high cost of operating irrigation equipment. Fertilization may be an economical way to increase yields, though from our analyses this is difficult to evaluate because the method of application is not included in its cost. Irrigation, however, seems to be clearly uneconomical.

Nor is irrigation energy efficient. The net energy value when energy output is measured as gross or usable energy is higher for irrigated systems, but the output/input ratio, a measure of efficiency, is lower. In terms of using wood fuel to produce electrical energy, irrigated systems produce only a little more energy than they use in the production process.

Not irrigating means lower yields. However, other things being equal, nonirrigated yields would have to be reduced to less than 10 percent of irrigated yields (roughly ½ dry ton/acre/year) before the NPW of nonirrigated systems would decline to that of irrigated systems. This is not likely. On the other hand, not irrigating would make site selection more important to avoid losing an entire crop due to drought during the establishment period. And such sites might be more expensive.

If irrigation costs can be reduced 50 percent or more by switching to other types of power or by irrigating less frequently, the irrigated systems would more closely compete economically with nonirrigated systems.

Situations might exist in which larger blocks of land can be obtained. Each traveling irrigation gun system can handle up to about 300 acres so the fixed cost could possibly be reduced by 67 percent. However, this reduction, even in combination with a substantial reduction in the variable cost of irrigation, would still not make the irrigated alternatives more attractive than the nonirrigated ones.

Short vs. Long Rotations

The short- (5 to 10 years) and long- (15 years) rotation alternatives we have looked at differ little in terms of economic return and energy efficiency. Each has advantages and disadvantages. Short-rotation production systems return revenues sooner and more frequently. The wood can be harvested with forage harvesting methods that are as yet undeveloped but may be less expensive than traditional methods. The crop is carried for shorter periods of time so the risk of losing a crop is not as great nor would the loss be as severe. Short rotations also allow managers to more quickly incorporate yield improvements, resulting from new genetically improved hybrids, into the plantation operation. However, the type of wood produced may not be usable for all purposes because it contains more juvenile wood and bark than conventional chips. Long-rotation crops produce wood of a more conventional form that can be harvested with proven methods. Planting costs are much lower, but the crops must be carried for long periods so revenues are returned later and less often than with short-rotation crops.

Any initial decision about short or long rotations can be changed as questions are answered about insect and disease risks, uses for wood fiber from young trees, and harvesting technology. Flexibility in rotation length is one advantage of growing wood because it is a crop that can be stored on the stump.

Economies of Scale

The cost estimates used in our analyses were for the most part variable, which does not allow us to make a quantitative estimate of how the overall investment might look on a different scale of operation. We examined investment alternatives as solitary projects, not as sustained yield operations, as would be the most likely practice. For a sustained yield operation of this size (planting 1,000 acres per year), overhead costs such as administrators, full-time employees, a nursery, equipment storage and repair, etc., would certainly increase. However, the most important costs and returns in terms of overall economic performance (product value and harvesting) would not change.

Another important consideration, whether the operation is viewed as sustained yield or not, is the size and distribution of tracts. One large block of 1,000 acres would be less costly to prepare, plant, harvest, and irrigate, though such a block of land near a mill and for sale would be difficult to find in the Lake States. The location of tracts, in relation to each other and to the mill, is probably more important than their individual sizes, because this would affect costs of moving equipment (site preparation, planting, and harvesting) and administration. Economical tract sizes would depend primarily on harvest costs because (1) these are significant in the overall economic outlook of a project, and (2) certain fixed costs of putting in landings and skid roads are necessary for every tract regardless of size.

Cost/Energy Trade-offs

Nonirrigated systems are more energy efficient and also more economical under the assumptions made than irrigated systems so no trade-off is involved. If gross energy is of concern, cost/energy trade-offs could be made (table 3).

Our view is that energy efficiency is the more important criterion. Producing wood biomass without irrigation (and fertilization) is more energy-efficient *and* economical. The short- (5 to 10 years) and long- (15 years) rotation alternatives (both nonirrigated) differ little either in economic performance or energy efficiency.

CONCLUSIONS

Intensive culture of hybrid poplars in the Lake States with our estimates carries substantial risks and does not yield high monetary returns. Intensive culture projects are primarily of interest to industrial users of wood fiber, who can compare them with other sources of supply before making investment decisions.

Nonirrigated production strategies are recommended as long as users find our assumptions about irrigation regimes, costs, and obtainable land tract sizes acceptable. Under the conditions specified, irrigating hybrid poplar does not appear economical nor energy efficient.

Short- (5 to 10 years) and long- (15 years) rotations differ little in terms of economics and energy efficiency. In view of the uncertainties of some costs and returns that may dramatically affect the economic outlook of a project (specifically, product value, irrigation, need for fertilization, and harvest costs), any initial decision about rotation length for a particular project should be regarded as tentative. If a careful site-specific investigation into irrigation technology and costs and available tract sizes can reveal a more favorable cost picture than we assumed, irrigation alternatives could be more attractive.

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APPENDIX 1.— DETAILS OF CASH FLOW ANALYSIS

The following discussion details and documents the assumptions and numbers used in our analysis of alternative investments in hybrid poplar plantations. After the discussion of cash flow methodology and basic assumptions about the projects, an explanation of each item in the cash flow printouts is given (Appendix 2). Those interested in these details may not agree with every estimate, but should find it easy to understand our reasoning, to make changes, and to assess the effect of these changes through the sensitivity analysis tables.

Cash Flow Methodology

The various intensive culture alternatives were analyzed using cash flow analysis and charted in cash flow tables (Appendix 2). The cash flow table is primarily a listing of the amounts of costs and benefits for each year in the production period. In addition, the cash flow presents the total costs, total benefits, and net benefits for each year. The table, therefore, contains the data necessary to calculate several measures of project performance. Given a specified discount rate, four useful intermediate measures can be calculated and included in the cash flow table: discounted net benefits, cumulative discounted net benefits, discounted costs, and cumulative discounted costs. The above measures are listed in the bottom four rows of the cash flow tables generated by the program.

These four intermediate measures are used to calculate several of the investment performance measures described below. Each discounted net benefit equals the net benefit figure for that year (year y) divided by
$(1 + i)^{y-b}$, where:

i = the rate of discount,
y = the year in which the net benefit occurs, and
b = the beginning year of the project (initial year of investment).

Each **cumulative** discounted net benefit equals the sum of the discounted net benefits for all years up to and including that year (year y). Each discounted cost and cumulative discounted cost is determined in exactly the same way as discounted net returns and cumulative discounted net benefits, respectively, except that the total cost row is used instead of the net benefit row. Cumulative discounted net benefits show the incremental yearly totals of discounted net benefits. The final yearly total equals the net present worth. Cumulative discounted costs show the present value of all costs up through the column year. When using the cost-price analytical approach described below, the value of the cumulative discounted costs is important.

Investment performance measures

The four investment performance measures calculated by the program are defined as follows:

(1) **Internal rate of return (IRR)** is the rate of discount that makes the present value of benefits equal the present value of costs, i.e., the rate that makes NPW equal zero.

$$\sum_{y=b}^{e} \frac{B_y}{(1+IRR)^{y-b}} - \sum_{y=b}^{e} \frac{C_y}{(1+IRR)^{y-b}}$$

(2) **Net present worth** (NPW) is the sum of the discounted net benefits for one production period.

$$NFW = \sum_{y=b}^{e} \frac{(NB)_y}{(1+i)^{y-b}}$$

(3) **Net future worth (NFW)** is the sum of the compounded net benefits for one production period.

$$NFW = \sum_{y=b}^{e} (NB)_y\ (1+i)^{e-y} = NPW\ (1+i)^{e-b}$$

(4) **Benefit-cost (B/C)** is the ratio of the total discounted (gross) benefits and total discounted costs.

$$B/C = \frac{\sum_{y=b}^{e} \frac{B_y}{(1+i)^{y-b}}}{\sum_{y=b}^{e} \frac{C_y}{(1+i)^{y-b}}}$$

Where:
b = the beginning year of the project (initial year of investment),
e = the ending year of the project (last year of benefits or costs),
i = the rate of discount,

y = the year designation representing the individual years between year b and year e, inclusive,
B_y = total benefits in year y,
C_y = total costs in year y, and
$(NB)_y$ = net benefit in year y, equals $B_y - C_y$.

Future cost (FC) equals the future value of all project costs and is also calculated by the program although it is not directly an investment performance measure. Future cost is calculated by multiplying the cumulative discounted costs for the last year (year e) by $(1+i)^{e-b}$. Another method of calculating FC is as follows:

$$FC = \sum_{y=b}^{e} C_y \, (1+i)^{e-y}$$

Sensitivity analyses tables

A desirable procedure in any investment analysis is to examine how sensitive various measures of project performance are to changes in costs, prices, interest rates, and other inputs, e.g., machine production rates, time constraints on a silvicultural activity, etc. The reason for such sensitivity analyses is that most estimtes of inputs and outputs are interval rather than point estimates. In other words, individual estimates have errors associated with them that might be expressed by putting limits of confidence around them. Knowledge of the sensitivity of an investment to the various factors is an essential part of the assessment of the risk associated with the investment. It gives valuable insights into what might happen if yields, prices, and/or costs turned out differently than expected. Two types of sensitivity analyses are carried out within the program automatically. Various points will be illustrated on the nonirrigated 4- by 4-foot plantation.

First sensitivity analysis table (Appendix 2)

The first sensitivity analysis table shows changes in NPW due to a percentage change (increase or decrease) in each benefit and cost. The magnitudes of the changes in NPW indicate the impacts of changes in the costs and benefits. The larger the number in a given column, the greater the impact resulting from a given percentage change. In our example the greatest impact would result from changes in product sales and the least impact from changes in administration and site preparation costs. In addition to impacts on the investment performance measures, specific impacts can also be calculated. For example, NPW for the nonirrigated 4- by 4-foot plantation was –\$236.78. If forage harvesting cost decreased by 10 percent, NPW would be –\$215.97 (–\$236.78 + \$20.81). On the other hand, if forage harvesting cost **increased** by 10 percent, NPW would be –\$257.59 (–\$236.78 – \$20.81). Cost increases and benefit decreases of 10 percent **decrease** the four investment performance measures by the amounts indicated in the table, and cost decreases and benefit increases of 10 percent **increase** the measures by the same amounts. Furthermore, changes in NPW resulting from changes in costs and benefits other than 10 percent can be calculated directly from the table. For example, a 50 percent increase in land cost would lower NPW by five times the amount of a 10 percent land cost increase (five times \$40 or \$200).

Combinations of any number of changes in the costs and benefits can be calculated. For example, if all costs were assumed to be 10 percent higher and all benefits 20 percent higher, NPW would be –\$128.20 (–\$236.78 – \$155.94 + \$264.52). In other words, even if the above cost and benefit changes occurred, the investment decision would remain the same because the decision switching value occurs when NPW equals zero.

Sometimes it is useful to know how much change is necessary in one or more costs and benefits to change the investment decision. In the example, one might wish to know by how much product sales values must increase to cause the project to be accepted. This is determined by dividing NPW by the corresponding change in that measure (from the first sensitivity table), and then multiplying the result by the percent change specified in the table (10 percent in the example). Using NPW the result is the following:

$\frac{-\$236.78}{\$114.81} = 2.06$ or a 20.6 percent increase of product sales value would make NPW = 0 and IRR = 10 percent.

Second sensitivity analysis table (Appendix 2)

The second sensitivity analysis table shows the percent changes in activities (costs and benefits) necessary to raise and lower IRR and NPW by specified amounts. This sensitivity table is of most interest when the IRR is close to the specified discount rate. In this case, it is valuable to know how likely it would be that the investment return could be above or below a desired rate of return. For the nonirrigated 4- by 4-foot plantation case presented in Appendix 2, the specified changes were 2 percent in IRR and \$236.78 in NPW. As in the case of the first sensitivity table, the activities are listed in the first column. Columns

2 and 3 show the percent changes in each activity necessary to raise and lower IRR by 2 percent. Columns 4 and 5 similarly show the percent changes in each activity necessary to raise and lower NPW by $236.78. It is apparent in this case that changes in product sales and land cost have the greatest influence on IRR and NPW. For NPW the same percent change is always required to raise and lower the measure by an equal amount—only the sign changes. However, the percent changes necessary to raise and lower IRR by the same percentage amount are seldom equal. Similarly, the additive and multiplicative advantages associated with sensitivity testing of NPW are not applicable to sensitivity testing of IRR. Just because a 22 percent increase in product sales increases the IRR by 2 percent in the example, a 44 percent increase will not necessarily increase IRR by 4 percent. Yet, because a 21 percent increase in product sales will increase NPW by $236.78, a 42 percent increase **will** increase NPW by $473.56. Therefore, it is clear that such sensitivity testing for simultaneous changes in several activities is better performed using NPW than IRR.

Basic Assumptions

Inflation

We chose a 5 percent annual inflation rate, because economic forecasters have predicted this as an average long-term rate. You will note three exceptions to this rate in the cash flow printouts: (1) land resale value, which we estimate will increase more rapidly than other prices (we have said 7 percent annually), (2) income tax, which already takes inflation into account because it is calculated from income and costs in the years they occur, and (3) irrigation equipment insurance, which we assumed to remain constant for a given group of equipment thus declining in real terms to reflect the declining value of aging equipment.

Discount rate

A 10 percent discount rate was used in each cash flow analysis based on an estimated cost of capital. We think a discount rate based on opportunity cost or risk should be accounted for at other stages of the decision making process.

Rotations

For the 4- by 4-foot spacing, the first rotation is 10 years and the four subsequent coppice rotations are 5 years. For the 8- by 8-foot spacing, both the initial and coppice rotations are 15 years. Total project length is 30 years.

Yields

Stem and branch wood dry biomass measured in tons is the unit of product yield. Biomass rather than roundwood is considered because the expected end uses of intensively grown wood are pulp and fuel. Yields for irrigated, fertilized, first-rotation crops were adapted from Ek and Dawson (1976) and are optimistic. Yields for nonirrigated, nonfertilized crops will likely be at least 50 percent less. Yields for the 5-year coppice rotations will be roughly 1¾ times the yields for 5-year first-rotation crops. We expect that this growth increase will be notable only in the first few years. Thus, the yield for the 15-year coppice rotation will be similar to the first rotation (table 4). Total project acreage is larger than the total acreage planted in most cases because some will always be lost to roads, powerlines, swamps, etc. For the analysis, the yields per planted acre had to be spread over total project acreage and are, therefore, smaller for the latter.

We did not include insect and disease control in the costs and returns. Although control measures would almost certainly be needed at some point in an operation of this size and length, we did not include their costs because they are difficult to estimate, both in amount and timing, and because we feel they are best evaluated as risks in the same way as fire and other uncertainties by making adjustments in the harvestable yields.

Explanation of Cash Flow Cost and Return Items

Site preparation and establishment activities considered

Site preparation of already cleared land for this hypothetical plantation includes plowing, disking, and applying a preplanting herbicide (Round-up and Simazine). All these activities take place the late summer or fall prior to spring planting. For the 4- by 4-foot spacing, 3 lbs. of Round-up and 2 lbs. of Simazine/acre are applied in a broadcast application using a tractor-pulled sprayer. For the 8- by 8-foot spacing, the chemical is applied in 3-foot strips using the same equipment. Trees are later planted in these strips.

Table 4.—*Yields of stem and branch wood for four production alternatives*

Spacing	Irrigated	Rotation	Yield of stem and branchwood at end of rotation			
			Dry tons/ planted acre	*mt/ planted ha*	*Dry tons/ project acre*	*mt/ project ha*
4- by 4-ft (1.2 by 1.2 m)	Yes	1st (10 yrs)	70	157	63	141
		2nd (5 yrs)	40	90	36	81
		3rd (5 yrs)	40	90	36	81
		4th (5 yrs)	40	90	36	81
		5th (5 yrs)	40	90	36	81
4- by 4-ft (1.2 by 1.2 m)	No	1st (10 yrs)	35	78	31.5	71
		2nd (5 yrs)	20	45	18	40
		3rd (5 yrs)	20	45	18	40
		4th (5 yrs)	20	45	18	40
		5th (5 yrs)	20	45	18	40
8- by 8-ft (2.4 by 2.4 m)	Yes	1st (15 yrs)	105	235	94.5	212
		2nd (15 yrs)	105	235	94.5	212
8- by 8-ft (2.4 by 2.4 m)	No	1st (15 yrs)	52.5	118	47.25	106
		2nd (15 yrs)	52.5	118	47.25	106

Postplanting establishment activities are cultivation (3 times) using a 20-foot Lilliston[2] cultivator, and a fall and spring treatment of Simazine, applied in the same way as the preplanting Round-up and Simazine treatment.

These methods are not put forth as the one best prescription to follow in raising hybrid poplar but only to explain the derivation of site preparation costs. This sequence was recommended by researchers at the North Central Forest Experiment Station, Forestry Sciences Laboratory in Rhinelander, Wisconsin, and by the Intensive Forestry manager at Packaging Corporation of America as being one method of growing poplar.[3] In practice, a variety of treatments would be used, depending on site conditions. Some additional or substitute treatments we did not consider are liming, spring disking, additional cultivations, cover crop seeding for controlling vegetation, and different types of chemicals. Also, we assume that no additional treatments will be necessary after the first rotation because the rapid initial growth of a coppice crop should be sufficient to stay ahead of the weeds.

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[2] *Mention of trade names does not constitute endorsement of the products by the USDA Forest Service.*

[3] *Personal communication with M. Morin, Packaging Corporation of America, Filer City, Michigan.*

As shown in the following tabulation we have rated each cost and return item as to how accurate we feel our estimates are.

Cost/return item	Uncertainty of estimate	Comment
Site prep., establishment (operating costs)	Fairly certain	—
Planting (operating costs)	Fairly certain	—
Irrigation (operating costs)	Fairly uncertain	Estimates are reliable for the near future only.
Fertilization	Fairly certain to uncertain	Depends on the type of fertilizer and method of application. Estimates are reliable for near future.
Whole-tree harvest	Uncertain	Uncertainty primarily due to distance in the future and yield. No harvest experience with intensive culture stands.
Forage harvest	Extremely uncertain	Uncertainty due to both lack of information and distance in future.
Land cost	Fairly certain	Depends on location.
Administrative	Fairly certain	Depends on scale of operation.
Irrigation equipment	Fairly certain to uncertain	Good estimates available for initial investment only, not future replacement.
Site prep., planting, estab. equipment	Fairly certain	Depends on how cost is accounted for.
Insurance	Fairly certain	—
Income tax	Uncertain	Depends on interaction of all cost and return items.
Property tax	Fairly certain	Estimates reliable for near future only.
Investment tax credit	Fairly certain	Depends on price of irrigation equipment (see above).
Product sale	Very uncertain	Uncertainty due to yields and future prices.
Land sale	Uncertain	Rate of inflation, future markets unknown.

Operating costs

Only variable costs—labor, fuel, repair, and materials—are included. Fixed equipment costs are treated separately. Because only 90 percent of the available acreage in this hypothetical plantation is workable, 900 acres are used as a basis for calculating costs. Total site preparation costs are calculated as follows: for each operation, labor, fuel, and repair costs per hour are multiplied by the time needed to work 900 acres. (Time = 900 acres divided by the production rate in acres/hour.) Time spent moving between tracts and for employee breaks is included in the production rate. Material costs/acre are multiplied by 900 acres and added to the total labor, fuel, and repair costs to give the total cost for the operation. This is divided by 1,000 project acres to give a cost/acre (table 5).

Labor costs are $6/hour for equipment operators and $4/hour for planting crews. Repair costs are based on the American Society of Agricultural Engineers' estimates of total lifetime repair costs for farm equipment (table 6). We estimated diesel fuel consumption for tractors at 0.044 gal/hp and cost at $1/gal. Current prices for Round-up and Simazine are $60/gal (4 lbs/gal) and $2.40/lb, respectively.

Planting

Ten inch unrooted cuttings purchased at $80/thousand are planted in the spring using Holland planters and large tractors. For the 4- by 4-foot spacing, 2,600 trees/plantable acre are planted at a rate of ¾ acre/hour; for the 8- by 8-foot spacing, 650 trees/plantable acre are planted at a rate of 2 acres/hour. We have estimated that about 95 percent of the plantable acreage would be planted, the 5 percent loss being due to row ends, rocks, low spots, etc. To finish planting in a reasonable length of time (maximum 10 weeks) would require 3 tractors and 6 planters for the close spacing and 2 tractors and 4 planters for the wide spacing. Overtime would probably be necessary for the close spacing, though we have not accounted for it.

Table 5.—*Operating costs for site preparation*

		Equipment costs			Production	Total	Material cost/ planted acre[5]		Total cost for operation		Cost/acre	
Year	**Operation**	**Labor**	**Fuel[1]**	**Repair[2]**	**rate**	**hours[4]**	**4- by 4-ft**	**8- by 8-ft**	**4- by 4-ft**	**8- by 8-ft**	**4- by 4-ft**	**8- by 8-ft**
		-----Dollars/hour-----			*Acres/hour[3]*	*No.*						
0	Plow	$6.00	$9.90	$10.75	6.55	137.4	0	0	$3,662	$3,662	$3.66	$3.66
0	Disk	6.00	9.90	9.50	10.04	89.6	0	0	2,276	2,276	2.28	2.28
0	Apply Roundup and Simazine	6.00	9.90	5.71	14.18	63.5	51.00	15.30	47,272	15,142	47.27	15.14
	Total year 0										53.21	21.08
1	Cultivate (3 times)	6.00	9.90	5.53	9.09	297.0 (3 times)	0	0	6,365	6,365	6.36	6.36
1	Apply Simazine	6.00	9.90	5.71	14.18	63.5	6.00	1.80	6,772	2,992	6.77	2.99
	Total year 1										13.13	9.35
2	Apply Simazine	6.00	9.90	5.71	14.18	63.5	6.00	1.80	6,772	2,992	6.77	2.99
	Total year 2										6.77	2.99

[1] Gal/hour = 0.044 gal/hp × 225hp = 9.9 gal/hour.
At $1/gal for diesel fuel, cost/hour = $9.90.

[2] See table 6.

[3] Source: Benson, F. J. 1979. Machinery cost estimates. Unpublished data on file at Agricultural Extension Service, University of Minnesota, St. Paul, Minnesota.

[4] Production rate computed on 900 workable acres.

[5] Current price for Roundup is $60/gal and for Simazine is $2.40/lb.

Table 6.—*Repair costs for site preparation and establishment equipment*

Equipment	Amount of repairs over lifetime in relation to new cost[1]	New cost	Available hours/year	Repair cost/year	Repair cost/hour
	Percent				
225 hp tractor	100	\$49,040[2]	1,200	\$4,904	\$4.09
10 bottom plow	120	13,870[2]	250	1,664	6.66
23-foot offset disk	120	11,290[2]	250	1,355	5.41
30-foot sprayer	100	1,940[2]	120	1,940	1.62
20-foot Lilliston cultivator	120	3,000[3]	250	360	1.44
Planter	120	2,000[3]	250	240	.96

[1] Source: American Society of Agricultural Engineers, 1976 Agricultural Engineering Yearbook, p. 329.

[2] Source: Benson, F. J. 1979. Machinery cost estimates. Unpublished data on file at Agricultural Extension Service, University of Minnesota, St. Paul, Minnesota.

[3] Authors' estimate.

Materials cost per planted acre comes to \$208 for the close spacing and \$52 for the wide spacing. Due to the slower rate of production, fuel, labor, and repair costs are also higher for the close spacing. As shown in the following tabulation, total operating costs for planting are \$221.94/project acre for the 4- by 4-foot spacing and \$59.83/project acre for the 8- by 8-foot spacing.

Item	4- by 4-foot spacing	8- by 8-foot spacing
Equipment	3 225 hp tractors 6 planters	2 tractors 4 planters
Equipment cost/hour (for each equipment group)		
Labor[4]	\$14.00	\$14.00
Fuel	9.90	9.90
Repairs[5]	5.05	5.05
Total equipment cost/hour	28.95	28.95
Production rate (ac/hr)	.75	2.00
Total hours (for all equipment groups)[6]	1,200	450
Total equipment cost	\$34,740	\$13,028
Plant stock cost/acre[7]	\$208	\$52
Total stock cost	\$187,200	\$46,800
Total cost	\$221,940	\$59,828
Cost/acre	\$221.94	\$59.83

Many other types of stock could be used: longer cuttings, soaked cuttings, rooted cuttings, or even 4-foot to 5-foot rooted stock. The planting method and costs would, of course, depend on the type chosen. Most likely a large operation would produce its own stock, though we have assumed that it was purchased elsewhere.

Irrigation

Irrigation is probably the most important, and the most costly, cultural activity involved in intensively growing hybrid poplar. Research predicts high yields using it, but the large capital investment and high operating cost make it uneconomical. On the same site in the Lake States, yields without irrigation may be 50 percent less than those with irrigation. Irrigation may also make the difference between survival and failure in a dry year. In droughty years growth of established plantations may be reduced by 80 to 90 percent without irrigation.

One of the methods recommended for poplar is a traveling gun system. This involves a well and pump that sends water through an aluminum pipe to a rubber hose attached to a traveling sprinkler. The sprinkler propels itself down a lane, dragging the rubber hose as it travels. The sprinkler must be repositioned when it reaches the end of a lane. It can be towed easily with a small tractor. The height of the gun can be adjusted up to 20 feet.

We seriously question whether this system is practical when trees reach 30 feet. For one thing, the gun may not be capable of spraying above the trees. For another, leaves may intercept much of the water and prevent it from reaching the ground. The high humidity may also increase susceptibility to leaf diseases.

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[4] *One equipment operator and two planters.*

[5] *See table 6.*

[6] *Each equipment group (tractor and two planters) works simultaneously; total hours is the additive number of hours for each group.*

[7] *Stock cost estimated to be \$80/M—2,600 trees/acre for close spacing and 650 trees/acre for wide spacing.*

For our analysis we will be optimistic and assume that these difficulties will be resolved and that annual irrigation is possible even for the 15 year rotations. Operating costs were based on a system with a 100-foot well, 600 gal/min sprinkler, turbine pump, right-angle drive, diesel power unit, 3,000 feet of 6-inch aluminum pipe, and 660 feet of 4-inch hose (University of Minnesota 1978). Each system would be sufficient to irrigate from 80 to 120 acres/year 10 times for a total of 10 inches/planted acre/year. Ten such systems would be needed. One 40-horse tractor is considered sufficient to move the sprinklers when needed, though, of course, in practice this would depend on the closeness and accessibility of the tracts. Larger systems would be possible for larger tracts, but the operating costs would be similar for the same amount of water applied.

As shown below the largest portion of the annual operating cost of irrigation is due to fuel—$67.65/acre/year or 68 percent of the total annual cost of $99.74, assuming diesel fuel is used at a cost of $1/gal (University of Minnesota 1978).

Item	**Dollars/acre**[8]
Fuel	$67.65
Pump and motor (lube and repairs)[9]	12.07
Distribution system[10]	11.20
Labor	8.82
Total	$99.74

Fertilization

One hundred pounds of nitrogen/acre/year are applied in liquid form (28 percent solution) in the irrigation water. We have considered only the annual cost of the material ($80/ton = $14.29/irrigated acre = $12.86/project acre) because the labor cost involved is probably small. Of course, other nutrients may be desirable in practice and other methods of application are possible.

Whole-tree harvesting

Harvesting intensively cultured wood is a new and untried concept. Whole-tree chipping, a highly productive, highly mechanized system, appears the most promising for wood larger than 6 inches d.b.h. We assume this method will be used for the 10- and 15-year rotations. In this system trees are severed and accumulated with feller-bunchers then grapple-skidded to a portable chipper that reduces them to chips. The chips are blown into vans for transport to the mill.

Because field trials of whole-tree harvesting of intensively cultured wood are not yet possible, a computer simulation has furnished a rough estimate of harvesting costs (Mattson 1976). The simulation model uses nearly the same yield and spacing assumptions we have. For the 4- by 4-foot spacing, two 70 hp skidders were used, and for the 8- by 8-foot spacing, a single 110 hp skidder was used. For both systems, a tracked feller-buncher and a small chipper were used.

It has been concluded that harvesting costs are dependent on tree size. The 4- by 4-foot spacing produces trees with an average diameter of 6 inches and harvest costs are estimated to be about $18/dry ton (including hauling). Twelve and one-half inch trees are expected from an 8- by 8-foot spacing in 15 years at an estimated cost of $14/dry ton (table 7).

Predicting accurate harvesting costs for intensively grown poplar today would be difficult; predicting them 10 to 30 years from now is nearly impossible. Although they are one of the most significant costs of production, we consider them uncertain.

Table 7.—*Harvest costs*

(In dollars/acre)

Year of harvest	Dry tons/acre[2] Irrigated	Dry tons/acre[2] Nonirrigated	Harvest cost/acre Irrigated	Harvest cost/acre Nonirrigated
4- BY 4-FOOT SPACING (1.2- by 1.2-m)[1]				
10	63	31.5	1,134.00	567.00
15	36	18	288.00	144.00
20	36	18	288.00	144.00
25	36	18	288.00	144.00
30	36	18	280.00	144.00
8- BY 8-FOOT SPACING (2.4- by 2.4-m)[3]				
15	94.5	47.25	1,323.00	661.50
30	94.5	47.25	1,323.00	661.50

[1] Harvest costs: whole tree = $18/dry ton (Source: Mattson, J. A. 1976. Harvesting research for maximum yield systems. Unpublished manuscript on file at the North Central Forest Experiment Station, Forestry Sciences Laboratory, Houghton, Michigan) and forage = $8/dry ton (authors' estimate).

[2] From table 4.

[3] Harvest costs: whole tree = $14/dry ton (Source: Mattson, J. A. 1976. Harvesting research for maximum yield systems. Unpublished manuscript on file at the North Central Forest Experiment Station, Forestry Sciences Laboratory, Houghton, Michigan).

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[8] *Assuming 1 system per 100 acres.*

[9] *Includes lubrication of pump, drive, power unit estimated as a percentage of fuel costs, and maintenance and repair of these units calculated as a percentage of the initial investment.*

[10] *Includes the cost of the tractor required to move the gun, the cost of operating the power unit on the gun, and cost of the maintenance and repairs of the distibution system estimated as a percentage of initial investment.*

Forage harvesting

Forage-type mechanized harvesting of biomass is still in the development stage. Most proposed systems involve multifunction machines that fell and chip the wood and blow the chips into containers for transport to the landing. We expect that this harvesting method would be appropriate for the 5 year coppice rotations. Our cost estimate of $8/dry ton is not based on any particular equipment but is simply a subjective estimate. This estimate is lower than harvesting costs of conventional systems because of the higher degree of mechanization, but not as low as reported figures that are unjustifiably based on agricultural-type forage harvester operations.

Land cost

Cleared agricultural land in the Lake States close to the mill or plant, purchased at an average cost of $400/acre in 10 tracts of 80 to 120 acres, makes up the land base for this hypothetical plantation. Larger tracts would be more desirable but would be hard to find.

Administrative

A modest estimate of $7,500/year ($7.50/acre) for the first 2 years was based on a $15,000/year manager working during the growing season on the project, supervising employees and directing operations.

Irrigation equipment

The type of irrigation equipment has been described in the section on irrigation operating costs. The purchase price of this equipment is charged to the project when first purchased and when replaced (table 8). Most equipment will need to be replaced within 10 years, though in practice certain items will likely wear out sooner than others (the hoses for instance). Aluminum pipe can be expected to last 20 years and the well 30 years (25 years is recommended).

The entire purchase price is charged in 1 year rather than spread out in annual payments because a series of annual payments of both principal and interest (at 10 percent) would have the same present value as the purchase price for cash flow purposes.

Fixed costs of irrigation equipment could be reduced by a factor of 3 with tracts of 300 acres, the upper limit of acreage that can be served with one irrigation system. However, variable costs might increase if the system is used to capacity.

Equipment for site preparation and planting

Site preparation and planting equipment is leased rather than purchased because it is only used for a couple of years. In an ongoing operation it would be used annually on different plantations, but the entire cost could not be fairly charged to one plantation and accounting for it as a lease is one method of allocating it.

Lease payments were determined by equating the 1979 price of the various pieces of equipment to a series of equal annual payments using a 10 percent interest rate (table 9). The full year's lease payment is charged. For certain operations the equipment is used such a short time that renting would make more sense than leasing but the difference to the project's overall return would be minimal.

Insurance

We assume the lessor would insure site preparation and planting equipment. Therefore, only fire and storm insurance for the above-ground irrigation

Table 8.—*Irrigation equipment purchase schedule*

Equipment	Quantity needed	Year purchased	New price[1]
	No.		
40-hp tractor	1	1	$ 9,590
Wells - 100-foot lift	10	1	119,700
Turbine pumps	10	1	60,280
R-angle drives	10	1	13,490
Diesel power units	10	1	66,400
Aluminum pipes	10	1	54,150
Traveling guns	10	1	65,360
Hoses	10	1	41,800
			$430,770[2]
40-hp tractor	1	10	9,590
Turbine pumps	10	10	60,280
R-angle drives	10	10	13,490
Diesel power units	10	10	66,400
Traveling guns	10	10	65,360
Hoses	10	10	41,800
			$256,920[2]
40-hp tractor	1	20	9,590
Turbine pumps	10	20	60,280
R-angle drives	10	20	13,490
Diesel power units	10	20	66,400
Aluminum pipes	10	20	54,150
Traveling guns	10	20	65,360
Hoses	10	20	41,800
			$311,070[2]

[1] Source: University of Minnesota. 1978. Water sources and irrigation economics. Miscellaneous Report 150-1978, 76 p. Agricultural Experiment Station, St. Paul, Minnesota.

[2] Investment tax credit is 10 percent of the new price.

Table 9.—*Cost of site preparation and planting equipment*

Equipment	Year(s)	Useful life	New price[2]	Lease payment[2]
		Years	*Dollars*	
225 hp tractor	0,1,2	7	$49,040	$10,073.08
10 bottom plow	0	7	13,870	2,848.97
23-foot offset disk	0	7	11,290	2,319.03
30-foot sprayer	0,1,2	5	1,940	511.77
20-foot Lilliston cultivator	1	7	3,000[3]	616.22
Planter	1	5	2,000[3]	527.59

[1] Source Benson, F. J. 1979. Machinery cost estimates. Unpublished data on file at Agricultural Extension Service, University of Minnesota, St. Paul, Minnesota.

[2] New price = present value of a series of equal annual payments at 10 percent interest rate.

[3] Authors' estimate.

equipment is included. Insurance is estimated at 1 percent of the new price (University of Minnesota 1978). It will increase when equipment is replaced at a higher cost but not with inflation.

Property tax

We assumed a property tax of $4/acre/year, which is a rough estimate of tax rates in the Lake States for this type of land (University of Minnesota 1978).

Product sale

Current market prices for whole tree chips vary with locality. We used $12.50/green ton delivered, or $25/dry ton, inflated at 5 percent annually, as a representative Lake States price.

Income tax

The federal capital gains tax on timber income is charged at 30 percent of the taxable income, which is the product value less costs for harvesting, site preparation, establishment, planting, irrigation, fertilization, and administration. For all rotations after the first, only irrigation, fertilization, and harvesting costs since the last harvest were deducted from product sale returns. For the last year, capital gains from the sale of land were also taxed. No losses were carried forward or tax benefits from losses computed.

APPENDIX 2—CASH FLOWS

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                 CASH FLOW -- 4' X 4  SPACING -- IRRIGATED
                 FINANCIAL ANALYSIS FOR A 1000 ACRE OPERATIONAL HYBRID POPLAR PLANTATION
                 TOTAL PROJECT AREA IS DIVIDED INTO 10 TRACTS OF 80-120 ACRES EACH.
                 90 PER CENT OF THE TOTAL PROJECT AREA IS PLANTED.
                 TREES/PLANTED ACRE:  2600 10" UNROOTED CUTTINGS
                 ROTATIONS:  (1) 10 YEAR AND (4) 5 YEAR COPPICE ROTATIONS
                 YIELD:  7 DRY TONS/PLANTED ACRE/YR. FOR THE 10 YR. ROTATION
                         8    "    "       "      "    "     "   "  5  "  ROTATIONS
                 IRRIGATION: 10 EFFECTIVE IN./PLANTED ACRE/YEAR
                 FERTILIZATION:  100 LBS. OF NITROGEN/PLANTED ACRE/YEAR
                 NOTE:  ALL COST FIGURES BELOW ARE IN  DOLLARS/PROJECT ACRE

              ANALYSIS INPUTS

       UNIT OF CURRENCY                DOLLARS
            LAND AREA     1.00 ACRE
          PROD. PERIOD    30
         DISCOUNT RATE    10.00 PERCENT
 ANNUAL CHANGE IN COSTS       0 PERCENT
  ANNUAL CHANGE IN BEN.       0 PERCENT


          AMOUNT AND TIMING OF EXPENDIT AND RECEIPTS
                   DOLLARS/ACRE

INPUT NO.      NAME     AMOUNT   ANN. RATE OF INFL.   YEAR(S)
     1  SITE PREP       53.21          5.00            0
     1  SITE PREP       13.13          5.00            1
     1  SITE PREP        6.77          5.00            2
     2  PLANTING       221.94          5.00            1
     3  IRRIGATION      99.74          5.00            1 TO   30
     4  FERTILIZAT'N    12.86          5.00            1 TO   30
     5  WT HARVEST    1134.00          5.00           10
     6  FORG.HARVEST   288.00          5.00           15  20   25   30
     7  LAND COST      400.00          5.00            0
     8  ADMINISTR'TV     7.50          5.00            0 TO    1
     9  IRR.EQUIPM'T   430.77          5.00            1
     9  IRR.EQUIPM'T   256.92          5.00           10
     9  IRR.EQUIPM'T   311.07          5.00           20
    10  SP EQUIPM'T     15.75          5.00            0
    10  SP EQUIPM'T     33.90          5.00            1
    10  SP EQUIPM'T     10.58          5.00            2
    11  INSURANCE        2.57             0            1 TO    9
    11  INSURANCE        4.18             0           10 TO   19
    11  INSURANCE        6.82             0           20 TO   30
    12  INCOME TAX      58.28             0           15
    12  INCOME TAX      74.39             0           20
    12  INCOME TAX      94.94             0           25
    12  INCOME TAX     861.74             0           30
    13  PROPERTY TAX     4.00          5.00            0 TO   30
    14  PRODUCT SALE  1575.00          5.00           10
    14  PRODUCT SALE   900.00          5.00           15  20   25   30
    15  LAND SALE      400.00          7.00           30
    16  INV TAX CRDT    43.08          5.00            1
    16  INV TAX CRDT    25.69          5.00           10
    16  INV TAX CRDT    31.11          5.00           20
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CASH FLOW -- 4' X 4' SPACING -- IRRIGATED
FINANCIAL ANALYSIS FOR A 1000 ACRE OPERATIONAL HYBRID POPLAR PLANTATION
TOTAL PROJECT AREA IS DIVIDED INTO 10 TRACTS OF 80-120 ACRES EACH.
90 PER CENT OF THE TOTAL PROJECT AREA IS PLANTED.
TREES/PLANTED ACRE:  2600 10" UNROOTED CUTTINGS
ROTATIONS:  (1) 10 YEAR AND (4) 5 YEAR COPPICE ROTATIONS
YIELD:  7 DRY TONS/PLANTED ACRE/YR. FOR THE 10 YR. ROTATION
       8   "   "       "     "    "     "   " 5  "  ROTATIONS
IRRIGATION: 10 EFFECTIVE IN./PLANTED ACRE/YEAR
FERTILIZATION:  100 LBS. OF NITROGEN/PLANTED ACRE/YEAR
NOTE:  ALL COST FIGURES BELOW ARE IN  DOLLARS/PROJECT ACRE




INVESTMENT PERFORMANCE MEASURES


DISCOUNT RATE     DISCOUNTED NET RECEIPTS
   PERCENT
-----------------------------------------
    -.3807                  -.93
    -.3818                  -.00
    -.3812 (INTERNAL RATE OF RETURN)
-----------------------------------------



(10.00 PERCENT DISCOUNT RATE)       DOLLARS)ACRE
----------------------------------------------------
     NET PRESENT WORTH               -2003.82
      NET FUTURE WORTH              -34965.47
          FUTURE COSTS               79290.68
      PRESENT BENEFITS                2540.21
         PRESENT COSTS                4544.03
        BENEFITS/COSTS                    .56
----------------------------------------------------
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CASH FLOW -- 4' X 4' SPACING -- IRRIGATED
FINANCIAL ANALYSIS FOR A 1000 ACRE OPERATIONAL HYBRID POPLAR PLANTATION
TOTAL PROJECT AREA IS DIVIDED INTO 10 TRACTS OF 80-120 ACRES EACH.
90 PER CENT OF THE TOTAL PROJECT AREA IS PLANTED.
TREES/PLANTED ACRE:  2600 10" UNROOTED CUTTINGS
ROTATIONS:  (1) 10 YEAR AND (4) 5 YEAR COPPICE ROTATIONS
YIELD:  7 DRY TONS/PLANTED ACRE/YR. FOR THE 10 YR. ROTATION
        8   "   "     "    "   "    "   "  5  "  ROTATIONS
IRRIGATION: 10 EFFECTIVE IN./PLANTED ACRE/YEAR
FERTILIZATION:  100 LBS. OF NITROGEN/PLANTED ACRE/YEAR
NOTE:  ALL COST FIGURES BELOW ARE IN  DOLLARS/PROJECT ACRE

       SENSITIVITY ANALYSIS

   (10.00 PERCENT DISCOUNT RATE)
            DOLLARS/ACRE

                  CHANGE IN NPW
DUE TO A 10.00
PERCENT CHANGE IN
-------------------------------------
 1  SITE PREP                  7.19
 2  PLANTING                  21.19
 3  IRRIGATION               157.58
 4  FERTILIZAT'N              20.32
 5  WT HARVEST                71.22
 6  FORG.HARVEST              41.83
 7  LAND COST                 40.00
 8  ADMINISTR'TV               1.47
 9  IRR.EQUIPM'T              69.52
10  SP EQUIPM'T                5.77
11  INSURANCE                  3.29
12  INCOME TAX                 8.32
13  PROPERTY TAX               6.72
-------------------------------------
14  PRODUCT SALE             229.62
15  LAND SALE                 17.45
16  INV TAX CRDT               6.95
-------------------------------------
```

```
                    CASH FLOW -- 4' X 4' SPACING -- IRRIGATED
                    FINANCIAL ANALYSIS FOR A 1000 ACRE OPERATIONAL HYBRID POPLAR PLANTATION
                    TOTAL PROJECT AREA IS DIVIDED INTO 10 TRACTS OF 80-120 ACRES EACH.
                    90 PER CENT OF THE TOTAL PROJECT AREA IS PLANTED.
                    TREES/PLANTED ACRE:  2600 10" UNROOTED CUTTINGS
                    ROTATIONS:  (1) 10 YEAR AND (4) 5 YEAR COPPICE ROTATIONS
                    YIELD:  7 DRY TONS/PLANTED ACRE/YR. FOR THE 10 YR. ROTATION
                            8  "   "     "      "   "    "  "  5  "  ROTATIONS
                    IRRIGATION: 10 EFFECTIVE IN./PLANTED ACRE/YEAR
                    FERTILIZATION:  100 LBS. OF NITROGEN/PLANTED ACRE/YEAR
                    NOTE:  ALL COST FIGURES BELOW ARE IN  DOLLARS/PROJECT ACRE


                  SENSITIVITY OF INTERNAL RATE OF RETURN

       PERCENT CHANGE IN INPUT OR OUTPUT TO RAISE/LOWER
       ROR BY  2.000 PERCENT AND NPW BY   2003.82      DOLLARS/ACRE

                              RATE OF RETURN         PRESENT NET WORTH
                            UPPER       LOWER       UPPER       LOWER
                         THRESHOLD   THRESHOLD   THRESHOLD   THRESHOLD
                              1.62       -2.38           0    -4007.64
     INPUT/OUTPUT
------------------------------------------------------------------------
  1  SITE PREP            -1620.88     3317.91    -2786.50     2786.50
  2  PLANTING              -523.07     1044.70     -945.86      945.86
  3  IRRIGATION             -23.19       22.23     -127.17      127.17
  4  FERTILIZAT'N          -179.90      172.44     -986.28      986.28
  5  WT HARVEST             -76.25      106.10     -281.37      281.37
  6  FORG.HARVEST           -49.03       38.71     -479.08      479.08
  7  LAND COST             -299.88      623.48     -500.96      500.96
  8  ADMINISTR'TV         -7866.01    16020.45   -13669.47    13669.47
  9  IRR.EQUIPM'T           -85.67      106.92     -288.23      288.23
 10  SP EQUIPM'T          -1932.43     3869.32    -3469.87     3469.87
 11  INSURANCE            -1144.64     1118.31    -6083.96     6083.96
 12  INCOME TAX            -172.44      115.82    -2409.68     2409.68
 13  PROPERTY TAX          -567.42      549.50    -2982.12     2982.12
 14  PRODUCT SALE            12.20      -10.66       87.27      -87.27
 15  LAND SALE               63.78      -39.75     1148.33    -1148.33
 16  INV TAX CRDT           856.68    -1069.19     2882.16    -2882.16
------------------------------------------------------------------------
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                    CASH FLOW -- 4' X 4' SPACING -- NON-IRRIGATED
                    FINANCIAL ANALYSIS FOR A 1000 ACRE OPERATIONAL HYBRID POPLAR PLANTATION
                    TOTAL PROJECT AREA IS DIVIDED INTO 10 TRACTS OF 80-120 ACRES EACH.
                    90 PER CENT OF TH TOTAL PROJECT ACREAGE IS PLANTED.
                    TREES/PLANTED ACRE:  2600 10" UNROOTED CUTTINGS
                    ROTATIONS:  (1) 10 YEAR AND (4) 5 YEAR COPPICE ROTATIONS
                    YIELD:  3.5 DRY TONS/PLANTED ACRE/YR. FOR THE 10 YR. ROTATION
                            4     "   "      "     "   "    "   "  5  "  ROTATIONS
                    IRRIGATION:  NONE
                    FERTILIZATION:  NONE
                    NOTE:  ALL COST FIGURES BELOW ARE IN DOLLARS/PROJECT ACRE.

                 ANALYSIS INPUTS

         UNIT OF CURRENCY               DOLLARS
                LAND AREA     1.00 ACRE
             PROD. PERIOD    30
            DISCOUNT RATE    10.00 PERCENT
   ANNUAL CHANGE IN COSTS        0 PERCENT
    ANNUAL CHANGE IN BEN.        0 PERCENT


            AMOUNT AND TIMING OF EXPENDIT AND RECEIPTS
                      DOLLARS/ACRE

INPUT NO.       NAME     AMOUNT   ANN. RATE OF INFL.   YEAR(S)
      1  SITE PREP       53.21          5.00            0
      1  SITE PREP       13.13          5.00            1
      1  SITE PREP        6.77          5.00            2
      2  PLANTING       221.94          5.00            1
      3  WT HARVEST     567.00          5.00           10
      4  FORG.HARVEST   144.00          5.00           15   20   25   30
      5  LAND COST      400.00          5.00            0
      6  ADMINISTR'TV     7.50          5.00            0 TO     1
      7  SP EQUIPM'T     15.75          5.00            0
      7  SP EQUIPM'T     33.90          5.00            1
      7  SP EQUIPM'T     10.58          5.00            2
      8  INCOME TAX      10.16             0           10
      8  INCOME TAX     178.12             0           15
      8  INCOME TAX     227.33             0           20
      8  INCOME TAX     290.14             0           25
      8  INCOME TAX    1110.88             0           30
      9  PROPERTY TAX     4.00          5.00            0 TO    30
     10  PRODUCT SALE   787.50          5.00           10
     10  PRODUCT SALE   450.00          5.00           15   20   25   30
     11  LAND SALE      400.00          7.00           30
```

```
CASH FLOW -- 4′ X 4′ SPACING -- NON-IRRIGATED
FINANCIAL ANALYSIS FOR A 1000 ACRE OPERATIONAL HYBRID POPLAR PLANTATION
TOTAL PROJECT AREA IS DIVIDED INTO 10 TRACTS OF 80-120 ACRES EACH.
90 PER CENT OF TH TOTAL PROJECT ACREAGE IS PLANTED.
TREES/PLANTED ACRE:  2600 10" UNROOTED CUTTINGS
ROTATIONS:  (1) 10 YEAR AND (4) 5 YEAR COPPICE ROTATIONS
YIELD:  3.5 DRY TONS/PLANTED ACRE/YR. FOR THE 10 YR. ROTATION
        4    "    "       "     "    "     "    "  5  "  ROTATIONS
IRRIGATION:  NONE
FERTILIZATION:  NONE
NOTE:  ALL COST FIGURES BELOW ARE IN DOLLARS/PROJECT ACRE.



INVESTMENT PERFORMANCE MEASURES



DISCOUNT RATE     DISCOUNTED NET RECEIPTS
   PERCENT
----------------------------------------
    8.1174                     -.07
    8.1169                      .00
    8.1171 (INTERNAL RATE OF RETURN)
----------------------------------------



(10.00 PERCENT DISCOUNT RATE)       DOLLARS)ACRE
---------------------------------------------------
     NET PRESENT WORTH              -236.78
      NET FUTURE WORTH             -4131.60
          FUTURE COSTS             27210.08
      PRESENT BENEFITS              1322.59
         PRESENT COSTS              1559.37
        BENEFITS/COSTS                  .85
---------------------------------------------------
```

```
     CASH FLOW -- 4' X 4' SPACING -- NON-IRRIGATED
     FINANCIAL ANALYSIS FOR A 1000 ACRE OPERATIONAL HYBRID POPLAR PLANTATION
     TOTAL PROJECT AREA IS DIVIDED INTO 10 TRACTS OF 80-120 ACRES EACH.
     90 PER CENT OF TH TOTAL PROJECT ACREAGE IS PLANTED.
     TREES/PLANTED ACRE:  2600 10" UNROOTED CUTTINGS
     ROTATIONS:  (1) 10 YEAR AND (4) 5 YEAR COPPICE ROTATIONS
     YIELD:  3.5 DRY TONS/PLANTED ACRE/YR. FOR THE 10 YR. ROTATION
             4     "   "      "     "   "    "   "   5  " ROTATIONS
     IRRIGATION:  NONE
     FERTILIZATION:  NONE
     NOTE:  ALL COST FIGURES BELOW ARE IN DOLLARS/PROJECT ACRE.

            SENSITIVITY ANALYSIS

        (10.00 PERCENT DISCOUNT RATE)
                  DOLLARS/ACRE

                        CHANGE IN NPW
     DUE TO A 10.00
     PERCENT CHANGE IN
--------------------------------------
  1  SITE PREP                   7.19
  2  PLANTING                   21.19
  3  WT HARVEST                 35.61
  4  FORG.HARVEST               20.91
  5  LAND COST                  40.00
  6  ADMINISTR'TV                1.47
  7  SP EQUIPM'T                 5.77
  8  INCOME TAX                 17.08
  9  PROPERTY TAX                6.72
--------------------------------------
 10  PRODUCT SALE              114.81
 11  LAND SALE                  17.45
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                    CASH FLOW -- 4' X 4' SPACING -- NON-IRRIGATED
                    FINANCIAL ANALYSIS FOR A 1000 ACRE OPERATIONAL HYBRID POPLAR PLANTATI
                    TOTAL PROJECT AREA IS DIVIDED INTO 10 TRACTS OF 80-120 ACRES EACH.
                    90 PER CENT OF TH TOTAL PROJECT ACREAGE IS PLANTED.
                    TREES/PLANTED ACRE:  2600 10" UNROOTED CUTTINGS
                    ROTATIONS:  (1) 10 YEAR AND (4) 5 YEAR COPPICE ROTATIONS
                    YIELD:  3.5 DRY TONS/PLANTED ACRE/YR. FOR THE 10 YR. ROTATION
                            4     "   "      "     "   "     "   "  5  "  ROTATIONS
                    IRRIGATION:  NONE
                    FERTILIZATION:  NONE
                    NOTE:  ALL COST FIGURES BELOW ARE IN DOLLARS/PROJECT ACRE.


                  SENSITIVITY OF INTERNAL RATE OF RETURN

        PERCENT CHANGE IN INPUT OR OUTPUT TO RAISE/LOWER
        ROR BY  2.000 PERCENT AND NPW BY    236.78     DOLLARS/ACRE

                             RATE OF RETURN       PRESENT NET WORTH
                           UPPER        LOWER     UPPER        LOWER
                         THRESHOLD   THRESHOLD  THRESHOLD  THRESHOLD
                           10.12        6.12          0     -473.55
      INPUT/OUTPUT
-------------------------------------------------------------------
  1  SITE PREP           -345.44      553.83    -329.26     329.26
  2  PLANTING            -117.34      183.68    -111.76     111.76
  3  WT HARVEST           -70.48       79.08     -66.49      66.49
  4  FORG.HARVEST        -121.43       88.70    -113.22     113.22
  5  LAND COST            -62.08      100.84     -59.19      59.19
  6  ADMINISTR'TV       -1694.84     2703.28   -1615.22    1615.22
  7  SP EQUIPM'T         -430.41      676.19    -410.01     410.01
  8  INCOME TAX          -149.00      100.61    -138.64     138.64
  9  PROPERTY TAX        -374.05      379.55    -352.37     352.37
 10  PRODUCT SALE          22.01      -18.94      20.62     -20.62
 11  LAND SALE            146.92      -78.65     135.69    -135.69
-------------------------------------------------------------------
```

```
                    CASH FLOW -- 8´ X 8´ SPACING -- IRRIGATED
                    FINANCIAL ANALYSIS FOR A 1000 ACRE OPERATIONAL HYBRID POPLAR PLANTATION
                    TOTAL PROJECT ACREAGE IS DIVIDED INTO 10 TRACTS OF 80-120 ACRES EACH.
                    90 PER CENT OF THE TOTAL PROJECT ACREAGE IS PLANTED.
                    TREES/PLANTED ACRE:  650 10" UNROOTED CUTTINGS
                    ROTATIONS:  (2) 15 YEAR
                    YIELD:  7 DRY TONS/PLANTED ACRE/YR. FOR EACH ROTATION
                    IRRIGATION: 10 EFFECTIVE IN./PLANTED ACRE/YEAR
                    FERTILIZATION:  100 LBS. OF NITROGEN/PLANTED ACRE/YEAR
                    NOTE:  ALL COST FIGURES BELOW ARE IN  DOLLARS/PROJECT ACRE.

                 ANALYSIS INPUTS

        UNIT OF CURRENCY                DOLLARS
               LAND AREA     1.00 ACRE
            PROD. PERIOD    30
           DISCOUNT RATE    10.00 PERCENT
   ANNUAL CHANGE IN COSTS       0 PERCENT
    ANNUAL CHANGE IN BEN.       0 PERCENT


           AMOUNT AND TIMING OF EXPENDIT AND RECEIPTS
                      DOLLARS/ACRE

 INPUT NO.       NAME     AMOUNT   ANN. RATE OF INFL.   YEAR(S)
       1  SITE PREP      21.08           5.00           0
       1  SITE PREP       9.35           5.00           1
       1  SITE PREP       2.99           5.00           2
       2  PLANTING       59.83           5.00           1
       3  IRRIGATION     99.74           5.00           1 TO   30
       4  FERTILIZAT´N   12.86           5.00           1 TO   30
       5  WT HARVEST   1323.00           5.00          15  30
       6  LAND COST     400.00           5.00           0
       7  ADMINISTR´TV    7.50           5.00           0 TO    1
       8  IRR.EQUIPM´T  430.77           5.00           1
       8  IRR.EQUIPM´T  256.92           5.00          10
       8  IRR.EQUIPM´T  311.07           5.00          20
       9  SP EQUIPM´T    15.75           5.00           0
       9  SP EQUIPM´T    22.77           5.00           1
       9  SP EQUIPM´T    10.58           5.00           2
      10  INSURANCE       2.57              0           1 TO    9
      10  INSURANCE       4.18              0          10 TO   19
      10  INSURANCE       6.82              0          20 TO   30
      11  INCOME TAX    740.57              0          30
      12  PROPERTY TAX    4.00           5.00           0 TO   30
      13  PRODUCT SALE 2362.50           5.00          15  30
      14  LAND SALE     400.00           7.00          30
      15  INV TAX CRDT   43.08           5.00           1
      15  INV TAX CRDT   25.69           5.00          10
      15  INV TAX CRDT   31.11           5.00          20
```

```
CASH FLOW -- 8′ X 8′ SPACING -- IRRIGATED
FINANCIAL ANALYSIS FOR A 1000 ACRE OPERATIONAL HYBRID POPLAR PLANTATION
TOTAL PROJECT ACREAGE IS DIVIDED INTO 10 TRACTS OF 80-120 ACRES EACH.
90 PER CENT OF THE TOTAL PROJECT ACREAGE IS PLANTED.
TREES/PLANTED ACRE:  650 10" UNROOTED CUTTINGS
ROTATIONS:  (2) 15 YEAR
YIELD:  7 DRY TONS/PLANTED ACRE/YR. FOR EACH ROTATION
IRRIGATION: 10 EFFECTIVE IN./PLANTED ACRE/YEAR
FERTILIZATION:  100 LBS. OF NITROGEN/PLANTED ACRE/YEAR
NOTE:  ALL COST FIGURES BELOW ARE IN  DOLLARS/PROJECT ACRE.




INVESTMENT PERFORMANCE MEASURES



DISCOUNT RATE     DISCOUNTED NET RECEIPTS
   PERCENT
-----------------------------------------
   -1.6122                     .53
   -1.6117                    -.00
   -1.6120 (INTERNAL RATE OF RETURN)
-----------------------------------------



(10.00 PERCENT DISCOUNT RATE)       DOLLARS)ACRE
----------------------------------------------------
     NET PRESENT WORTH               -2149.51
      NET FUTURE WORTH              -37507.75
          FUTURE COSTS               72492.83
      PRESENT BENEFITS                2004.94
         PRESENT COSTS                4154.46
        BENEFITS/COSTS                    .48
----------------------------------------------------
```

```
CASH FLOW -- 8' X 8' SPACING -- IRRIGATED
FINANCIAL ANALYSIS FOR A 1000 ACRE OPERATIONAL HYBRID POPLAR PLANTATION
TOTAL PROJECT ACREAGE IS DIVIDED INTO 10 TRACTS OF 80-120 ACRES EACH.
90 PER CENT OF THE TOTAL PROJECT ACREAGE IS PLANTED.
TREES/PLANTED ACRE:  650 10" UNROOTED CUTTINGS
ROTATIONS:  (2) 15 YEAR
YIELD:  7 DRY TONS/PLANTED ACRE/YR. FOR EACH ROTATION
IRRIGATION: 10 EFFECTIVE IN./PLANTED ACRE/YEAR
FERTILIZATION:  100 LBS. OF NITROGEN/PLANTED ACRE/YEAR
NOTE:  ALL COST FIGURES BELOW ARE IN  DOLLARS/PROJECT ACRE.

       SENSITIVITY ANALYSIS

   (10.00 PERCENT DISCOUNT RATE)
            DOLLARS/ACRE

                   CHANGE IN NPW
DUE TO A 10.00
PERCENT CHANGE IN
--------------------------------------
  1  SITE PREP                  3.27
  2  PLANTING                   5.71
  3  IRRIGATION               157.58
  4  FERTILIZAT'N              20.32
  5  WT HARVEST                98.61
  6  LAND COST                 40.00
  7  ADMINISTR'TV               1.47
  8  IRR.EQUIPM'T              69.52
  9  SP EQUIPM'T                4.71
 10  INSURANCE                  3.29
 11  INCOME TAX                 4.24
 12  PROPERTY TAX               6.72
--------------------------------------
 13  PRODUCT SALE             176.09
 14  LAND SALE                 17.45
 15  INV TAX CRDT               6.95
--------------------------------------
```

```
                    CASH FLOW -- 8' X 8' SPACING -- IRRIGATED
                    FINANCIAL ANALYSIS FOR A 1000 ACRE OPERATIONAL HYBRID POPLAR PLANTATIO
                    TOTAL PROJECT ACREAGE IS DIVIDED INTO 10 TRACTS OF 80-120 ACRES EACH.
                    90 PER CENT OF THE TOTAL PROJECT ACREAGE IS PLANTED.
                    TREES/PLANTED ACRE:  650 10" UNROOTED CUTTINGS
                    ROTATIONS:  (2) 15 YEAR
                    YIELD:  7 DRY TONS/PLANTED ACRE/YR. FOR EACH ROTATION
                    IRRIGATION: 10 EFFECTIVE IN./PLANTED ACRE/YEAR
                    FERTILIZATION:  100 LBS. OF NITROGEN/PLANTED ACRE/YEAR
                    NOTE:  ALL COST FIGURES BELOW ARE IN  DOLLARS/PROJECT ACRE.


                  SENSITIVITY OF INTERNAL RATE OF RETURN

       PERCENT CHANGE IN INPUT OR OUTPUT TO RAISE/LOWER
       ROR BY  2.000 PERCENT AND NPW BY   2149.51      DOLLARS/ACRE

                            RATE OF RETURN       PRESENT NET WORTH
                          UPPER        LOWER      UPPER        LOWER
                        THRESHOLD    THRESHOLD  THRESHOLD  THRESHOLD
                             .39        -3.61          0     -4299.03
     INPUT/OUTPUT
----------------------------------------------------------------------
  1  SITE PREP          -4753.20     10811.18   -6567.54      6567.54
  2  PLANTING           -2592.41      5774.79   -3763.79      3763.79
  3  IRRIGATION           -25.09        25.73    -136.41       136.41
  4  FERTILIZAT'N        -194.57       199.52   -1057.99      1057.99
  5  WT HARVEST           -21.11        17.10    -217.98       217.98
  6  LAND COST           -405.57       940.94    -537.38       537.38
  7  ADMINISTR'TV      -10572.44     24018.70  -14663.36     14663.36
  8  IRR.EQUIPM'T        -100.33       134.59    -309.18       309.18
  9  SP EQUIPM'T        -3172.23      7086.79   -4561.30      4561.30
 10  INSURANCE          -1244.96      1302.11   -6526.31      6526.31
 11  INCOME TAX          -246.05       168.56   -5064.71      5064.71
 12  PROPERTY TAX        -616.03       637.11   -3198.94      3198.94
 13  PRODUCT SALE          11.82        -9.57     122.07      -122.07
 14  LAND SALE             59.84       -41.00    1231.82     -1231.82
 15  INV TAX CRDT        1003.23     -1345.84    3091.71     -3091.71
----------------------------------------------------------------------
```

```
                      CASH FLOW -- 8´ X 8´ SPACING -- NON-IRRIGATED
                      FINANCIAL ANALYSIS FOR A 1000 ACRE OPERATIONAL HYBRID POPLAR PLANTATION
                      TOTAL PROJECT ACREAGE IS DIVIDED INTO 10 TRACTS OF 80-120 ACRES EACH.
                      90 PER CENT OF THE TOTAL PROJECT ACREAGE IS PLANTED.
                      TREES/PLANTED ACRE:  650 10" UNROOTED CUTTINGS
                      ROTATIONS:  (2) 15 YEAR
                      YIELD:  3.5 DRY TONS/PLANTED ACRE/YR. FOR EACH ROTATION
                      IRRIGATION: 10 EFFECTIVE IN./PLANTED ACRE/YEAR
                      FERTILIZATION:  100 LBS./PLANTED ACRE/YEAR OF NITROGEN
                      NOTE:  ALL COST FIGURES BELOW ARE IN  DOLLARS/PROJECT ACRE.

                   ANALYSIS INPUTS

          UNIT OF CURRENCY               DOLLARS
                 LAND AREA     1.00 ACRE
              PROD. PERIOD    30
             DISCOUNT RATE    10.00 PERCENT
    ANNUAL CHANGE IN COSTS        0 PERCENT
     ANNUAL CHANGE IN BEN.        0 PERCENT


             AMOUNT AND TIMING OF EXPENDIT AND RECEIPTS
                        DOLLARS/ACRE

  INPUT NO.       NAME      AMOUNT   ANN. RATE OF INFL.   YEAR(S)
        1  SITE PREP       21.08          5.00            0
        1  SITE PREP        9.35          5.00            1
        1  SITE PREP        2.99          5.00            2
        2  PLANTING        59.83          5.00            1
        3  WT HARVEST     661.50          5.00           15   30
        4  LAND COST      400.00          5.00            0
        5  ADMINISTR´TV     7.50          5.00            0 TO     1
        6  SP EQUIPM´T     15.75          5.00            0
        6  SP EQUIPM´T     22.77          5.00            1
        6  SP EQUIPM´T     10.58          5.00            2
        7  INCOME TAX     271.08             0           15
        7  INCOME TAX    1369.54             0           30
        8  PROPERTY TAX     4.00          5.00            0 TO    30
        9  PRODUCT SALE  1181.25          5.00           15   30
       10  LAND SALE      400.00          7.00           30
```

```
CASH FLOW -- 8′ X 8′ SPACING -- NON-IRRIGATED
FINANCIAL ANALYSIS FOR A 1000 ACRE OPERATIONAL HYBRID POPLAR PLANTATION
TOTAL PROJECT ACREAGE IS DIVIDED INTO 10 TRACTS OF 80-120 ACRES EACH.
90 PER CENT OF THE TOTAL PROJECT ACREAGE IS PLANTED.
TREES/PLANTED ACRE:  650 10" UNROOTED CUTTINGS
ROTATIONS:  (2) 15 YEAR
YIELD:  3.5 DRY TONS/PLANTED ACRE/YR. FOR EACH ROTATION
IRRIGATION: 10 EFFECTIVE IN./PLANTED ACRE/YEAR
FERTILIZATION:  100 LBS./PLANTED ACRE/YEAR OF NITROGEN
NOTE:  ALL COST FIGURES BELOW ARE IN  DOLLARS/PROJECT ACRE.



INVESTMENT PERFORMANCE MEASURES


DISCOUNT RATE     DISCOUNTED NET RECEIPTS
   PERCENT
------------------------------------------
    8.0555                    -.12
    8.0545                     .00
    8.0550 (INTERNAL RATE OF RETURN)
------------------------------------------


(10.00 PERCENT DISCOUNT RATE)       DOLLARS)ACRE
-----------------------------------------------------
     NET PRESENT WORTH                -200.30
      NET FUTURE WORTH               -3495.08
          FUTURE COSTS               21903.48
      PRESENT BENEFITS                1054.96
         PRESENT COSTS                1255.26
        BENEFITS/COSTS                    .84
-----------------------------------------------------
```

```
CASH FLOW -- 8' X 8' SPACING -- NON-IRRIGATED
FINANCIAL ANALYSIS FOR A 1000 ACRE OPERATIONAL HYBRID POPLAR PLANTATION
TOTAL PROJECT ACREAGE IS DIVIDED INTO 10 TRACTS OF 80-120 ACRES EACH.
90 PER CENT OF THE TOTAL PROJECT ACREAGE IS PLANTED.
TREES/PLANTED ACRE:  650 10" UNROOTED CUTTINGS
ROTATIONS:  (2) 15 YEAR
YIELD:  3.5 DRY TONS/PLANTED ACRE/YR. FOR EACH ROTATION
IRRIGATION: 10 EFFECTIVE IN./PLANTED ACRE/YEAR
FERTILIZATION:  100 LBS./PLANTED ACRE/YEAR OF NITROGEN
NOTE:  ALL COST FIGURES BELOW ARE IN  DOLLARS/PROJECT ACRE.

      SENSITIVITY ANALYSIS

   (10.00 PERCENT DISCOUNT RATE)
            DOLLARS/ACRE

                  CHANGE IN NPW
DUE TO A 10.00
PERCENT CHANGE IN
------------------------------------
  1  SITE PREP                3.27
  2  PLANTING                 5.71
  3  WT HARVEST              49.31
  4  LAND COST               40.00
  5  ADMINISTR'TV             1.47
  6  SP EQUIPM'T              4.71
  7  INCOME TAX              14.34
  8  PROPERTY TAX             6.72
------------------------------------
  9  PRODUCT SALE            88.05
 10  LAND SALE               17.45
------------------------------------
```

CASH FLOW -- 8′ X 8′ SPACING -- NON-IRRIGATED
FINANCIAL ANALYSIS FOR A 1000 ACRE OPERATIONAL HYBRID POPLAR PLANTATION
TOTAL PROJECT ACREAGE IS DIVIDED INTO 10 TRACTS OF 80-120 ACRES EACH.
90 PER CENT OF THE TOTAL PROJECT ACREAGE IS PLANTED.
TREES/PLANTED ACRE: 650 10" UNROOTED CUTTINGS
ROTATIONS: (2) 15 YEAR
YIELD: 3.5 DRY TONS/PLANTED ACRE/YR. FOR EACH ROTATION
IRRIGATION: 10 EFFECTIVE IN./PLANTED ACRE/YEAR
FERTILIZATION: 100 LBS./PLANTED ACRE/YEAR OF NITROGEN
NOTE: ALL COST FIGURES BELOW ARE IN DOLLARS/PROJECT ACRE.

SENSITIVITY OF INTERNAL RATE OF RETURN

PERCENT CHANGE IN INPUT OR OUTPUT TO RAISE/LOWER
ROR BY 2.000 PERCENT AND NPW BY 200.30 DOLLARS/ACRE

		RATE OF RETURN		PRESENT NET WORTH	
		UPPER THRESHOLD 10.06	LOWER THRESHOLD 6.06	UPPER THRESHOLD 0	LOWER THRESHOLD -400.60
	INPUT/OUTPUT				
1	SITE PREP	-625.42	1034.46	-611.98	611.98
2	PLANTING	-358.52	580.98	-350.72	350.72
3	WT HARVEST	-41.92	32.48	-40.62	40.62
4	LAND COST	-51.16	86.04	-50.07	50.07
5	ADMINISTR′TV	-1396.41	2305.76	-1366.37	1366.37
6	SP EQUIPM′T	-434.46	707.18	-425.03	425.03
7	INCOME TAX	-144.40	99.18	-139.70	139.70
8	PROPERTY TAX	-306.30	321.15	-298.09	298.09
9	PRODUCT SALE	23.48	-18.19	22.75	-22.75
10	LAND SALE	119.05	-65.93	114.78	-114.78

APPENDIX 3—DISCUSSION OF ENERGY ANALYSIS

Only direct energy expenditures (fuel and chemicals) were considered in the energy analysis. Energy expended in manufacturing equipment and in labor was not considered because it is an insignificant part of the total energy picture.

Preparing Site and Establishing Trees

Energy inputs for preparing the site and establishing the trees include fuel and herbicides. Fuel energy was calculated from the total hours spent and the fuel consumption rates/hour (table 5), using a conversion factor of 0.138 MMBTU's/gal. of diesel. Herbicides were estimated to contain 11,000 kcal/lb (Eidman *et al.* 1975).

Planting, Irrigating

Fuel was the only energy input accounted for in planting and irrigating and was calculated in the same way as above, using information from Appendix 1.

Fertilizing

Energy content of nitrogen fertilizer was estimated to be 8,400 kcal/lb, or for 100 lbs/acre, 3.33 MMBTU's /acre (Eidman *et al.* 1975).

Whole Tree and Forage Harvesting

Fuel consumption/dry ton was estimated using information from the simulation of a whole tree harvesting system for intensively grown poplar[11]. For lack of a better estimate, we assumed that forage harvesting would take the same amount of energy (table 10).

Table 10.—*Harvesting energy expenditures*[1]

Machine	**Trees harvested**			**Diesel fuel used**	
	4- by 4-foot spacing	**8- by 8-foot spacing**		**4- by 4-foot spacing**	**8- by 8-foot spacing**
	Green tons/hr		*Gal/hr*	*Gal/green ton*	
Medium skidder	—	14.7	3.30	—	0.224
Small skidders(2)	12.4	—	4.20	0.339	—
Feller-buncher	21.2	70.3	4.71	.222	.067
Chipper/baler	12.4	14.7	7.65	.617	.520
			Total	1.178	.811
			Gal/dry ton	2.356	1.622

[1] Source: Mattson, J. A. 1976. Harvesting research for maximum yield systems. Unpublished report on file at North Central Forest Experiment Station, Forestry Sciences Laboratory, Houghton, Michigan.

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[11] *Mattson, J. A. 1976. Harvesting research for maximum yield systems. Unpublished report on file at the North Central Forest Experiment Station, Forestry Sciences Laboratory, Houghton, Michigan.*

Hauling

A 50-mile round trip over 10 miles of good gravel road and 15 miles of average paved road using a 40-foot van holding 12 dry tons of chips was used to estimate fuel consumption/dry ton. Hauling energy expenditures were as follows[12]:

25 mile haul (one way)—
loaded: 10 miles class II county roads × 0.276 gal/mile = 2.76 gal
unloaded: 10 miles class II county roads × 0.110 gal/mile = 1.10 gal
loaded: 15 miles class I paved road × 0.224 gal/mile = 3.36 gal
unloaded: 15 miles class I paved road × 0.120 gal/mile = 1.80 gal
9.02 gal

Given 12 dry tons/van then 9.02 gals ÷ 12 tons = .75 gal of diesel/dry ton

Drying

An estimated 3.184 MMBTU's/dry ton is used to dry wood chips (Blankenhorn *et al.* 1978).

Wood energy

The gross heat content of hybrid poplar is 16.8 MMBTU's/dry ton, a weighted average of the heat content for stem and branch wood (Zavitkovski 1979). Blankenhorn *et al.* (1978) estimate that 86 percent of this gross heat energy is usable, and that only 35 percent of this is converted into electrical energy. We used gross energy in the energy flow analysis.

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[12] *Source: Aube, P. J. 1979. University of Minnesota.*

APPENDIX 4.—DISCOUNTED ENERGY FLOWS

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                  ENERGY BUDGET -- 4' X 4' SPACING -- IRRIGATED
                  ENERGY ANALYSIS FOR A 1000 ACRE OPERATIONAL HYBRID POPLAR PLANTATION
                  TOTAL PROJECT ACREAGE IS DIVIDED INTO 10 TRACTS OF 80-120 ACRES EACH.
                  90 PER CENT OF THE TOTAL PROJECT ACREAGE IS PLANTED.
                  TREES/PLANTED ACRE:  2600 10" UNROOTED CUTTINGS
                  ROTATIONS:  (1) 10 YEAR AND (4) 5 YEAR COPPICE ROTATIONS
                  YIELD:  7 DRY TONS/PLANTED ACRE/YR. FOR THE TEN YEAR ROTATION
                          8  "     "      "      "    "     "    " FIVE YEAR ROTATIONS
                  IRRIGATION:  10 EFFECTIVE INCHES/PLANTED ACRE/YEAR
                  FERTILIZATION:  100 LBS. OF NITROGEN/PLANTED ACRE/YEAR
                  NOTE:  ALL ENERGY INPUTS AND OUTPUTS BELOW ARE EXPRESSED IN MMBTU'S/ACRE

               ANALYSIS INPUTS

        UNIT OF CURRENCY                MMBTU'S
              LAND AREA     1.00 ACRE
           PROD. PERIOD    30
          DISCOUNT RATE    10.00 PERCENT
   ANNUAL CHANGE IN COSTS       0 PERCENT
    ANNUAL CHANGE IN BEN.       0 PERCENT


          AMOUNT AND TIMING OF COSTS    AND BENEFITS
                   MMBTU'S/ACRE

INPUT NO.       NAME    AMOUNT   ANN. RATE OF INFL.   YEAR(S)
      1  SITE PREP         .52             0          0
      1  SITE PREP         .59             0          1
      1  SITE PREP         .19             0          2
      2  PLANTING         1.64             0          1
      3  IRRIGATION       9.34             0          1 TO   30
      4  FERTILIZAT'N     3.33             0          1 TO   30
      5  WT HARVEST      20.47             0         10
      6  FORG.HARVEST    11.70             0         15   20   25   30
      7  HAULING          6.52             0         10
      7  HAULING          3.72             0         15   20   25   30
      8  DRYING         200.59             0         10
      8  DRYING         114.62             0         15   20   25   30
      9  WOOD ENERGY   1058.40             0         10
      9  WOOD ENERGY    604.80             0         15   20   25   30
```

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ENERGY BUDGET -- 4' X 4' SPACING -- IRRIGATED
ENERGY ANALYSIS FOR A 1000 ACRE OPERATIONAL HYBRID POPLAR PLANTATION
TOTAL PROJECT ACREAGE IS DIVIDED INTO 10 TRACTS OF 80-120 ACRES EACH.
90 PER CENT OF THE TOTAL PROJECT ACREAGE IS PLANTED.
TREES/PLANTED ACRE:  2600 10" UNROOTED CUTTINGS
ROTATIONS:  (1) 10 YEAR AND (4) 5 YEAR COPPICE ROTATIONS
YIELD:  7 DRY TONS/PLANTED ACRE/YR. FOR THE TEN YEAR ROTATION
        8  "    "      "       "   "    "   " FIVE YEAR ROTATIONS
IRRIGATION:  10 EFFECTIVE INCHES/PLANTED ACRE/YEAR
FERTILIZATION:  100 LBS. OF NITROGEN/PLANTED ACRE/YEAR
NOTE:  ALL ENERGY INPUTS AND OUTPUTS BELOW ARE EXPRESSED IN MMBTU'S/ACRE

(10.00 PERCENT DISCOUNT RATE)       MMBTU'S)ACRE
----------------------------------------------------
     NET PRESENT WORTH                  453.42
      NET FUTURE WORTH                 7911.98
          FUTURE COSTS                 4882.34
      PRESENT BENEFITS                  733.22
         PRESENT COSTS                  279.80
        BENEFITS/COSTS                    2.62
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ENERGY BUDGET -- 4' X 4' SPACING -- IRRIGATED
ENERGY ANALYSIS FOR A 1000 ACRE OPERATIONAL HYBRID POPLAR PLANTATION
TOTAL PROJECT ACREAGE IS DIVIDED INTO 10 TRACTS OF 80-120 ACRES EACH.
90 PER CENT OF THE TOTAL PROJECT ACREAGE IS PLANTED.
TREES/PLANTED ACRE:  2600 10" UNROOTED CUTTINGS
ROTATIONS:  (1) 10 YEAR AND (4) 5 YEAR COPPICE ROTATIONS
YIELD:  7 DRY TONS/PLANTED ACRE/YR. FOR THE TEN YEAR ROTATION
        8  "    "      "       "   "    "   " FIVE YEAR ROTATIONS
IRRIGATION:  10 EFFECTIVE INCHES/PLANTED ACRE/YEAR
FERTILIZATION:  100 LBS. OF NITROGEN/PLANTED ACRE/YEAR
NOTE:  ALL ENERGY INPUTS AND OUTPUTS BELOW ARE EXPRESSED IN MMBTU'S/ACRE

       SENSITIVITY ANALYSIS

   (10.00 PERCENT DISCOUNT RATE)
            MMBTU'S/ACRE

                   CHANGE IN NPW
DUE TO A 10.00
PERCENT CHANGE IN
--------------------------------------
  1  SITE PREP                 .12
  2  PLANTING                  .15
  3  IRRIGATION               8.80
  4  FERTILIZAT'N             3.14
  5  WT HARVEST                .79
  6  FORG.HARVEST              .63
  7  HAULING                   .45
  8  DRYING                  13.90
--------------------------------------
  9  WOOD ENERGY             73.32
--------------------------------------
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                      ENERGY BUDGET -- 4' X 4' SPACING -- NON-IRRIGATED
                      ENERGY ANALYSIS FOR A 1000 ACRE OPERATIONAL HYBRID POPLAR PLANTATION
                      TOTAL PROJECT ACREAGE IS DIVIDED INTO 10 TRACTS OF 80-120 ACRES EACH.
                      90 PER CENT OF THE TOTAL PROJECT ACREAGE IS PLANTED.
                      TREES/PLANTED ACRE:  2600 10" UNROOTED CUTTINGS
                      ROTATIONS:  (1) 10 YEAR AND (4) 5 YEAR COPPICE ROTATIONS
                      YIELD:  7 DRY TONS/PLANTED ACRE/YR. FOR THE TEN YEAR ROTATION
                              8  "     "      "    "    "    " FIVE YEAR ROTATIONS
                      IRRIGATION:  NONE
                      FERTILIZATION:  NONE
                      NOTE:  ALL ENERGY INPUTS AND OUTPUTS BELOW ARE EXPRESSED IN MMBTU'S/ACRE

                   ANALYSIS INPUTS

          UNIT OF CURRENCY               MMBTU'S
                 LAND AREA     1.00 ACRE
              PROD. PERIOD    30
             DISCOUNT RATE    10.00 PERCENT
    ANNUAL CHANGE IN COSTS        0 PERCENT
     ANNUAL CHANGE IN BEN.        0 PERCENT


             AMOUNT AND TIMING OF COSTS    AND BENEFITS
                       MMBTU'S/ACRE

INPUT NO.       NAME    AMOUNT   ANN. RATE OF INFL.   YEAR(S)
      1  SITE PREP          .52            0           0
      1  SITE PREP          .59            0           1
      1  SITE PREP          .19            0           2
      2  PLANTING          1.64            0           1
      3  WT HARVEST       10.24            0          10
      4  FORG.HARVEST      5.85            0          15  20  25  30
      5  HAULING           3.26            0          10
      5  HAULING           1.86            0          15  20  25  30
      6  DRYING          100.30            0          10
      6  DRYING           57.31            0          15  20  25  30
      7  WOOD ENERGY     529.20            0          10
      7  WOOD ENERGY     302.40            0          15  20  25  30
```

```
ENERGY BUDGET -- 4´ X 4´ SPACING -- NON-IRRIGATED
ENERGY ANALYSIS FOR A 1000 ACRE OPERATIONAL HYBRID POPLAR PLANTATION
TOTAL PROJECT ACREAGE IS DIVIDED INTO 10 TRACTS OF 80-120 ACRES EACH.
90 PER CENT OF THE TOTAL PROJECT ACREAGE IS PLANTED.
TREES/PLANTED ACRE:  2600 10" UNROOTED CUTTINGS
ROTATIONS:  (1) 10 YEAR AND (4) 5 YEAR COPPICE ROTATIONS
YIELD:  7 DRY TONS/PLANTED ACRE/YR. FOR THE TEN YEAR ROTATION
        8  "    "      "       "   "    "   " FIVE YEAR ROTATIONS
IRRIGATION:  NONE
FERTILIZATION:  NONE
NOTE:  ALL ENERGY INPUTS AND OUTPUTS BELOW ARE EXPRESSED IN MMBTU´S/ACRE

(10.00 PERCENT DISCOUNT RATE)       MMBTU´S)ACRE
----------------------------------------------------
     NET PRESENT WORTH                     285.08
      NET FUTURE WORTH                    4974.40
          FUTURE COSTS                    1422.76
      PRESENT BENEFITS                     366.61
         PRESENT COSTS                      81.54
        BENEFITS/COSTS                       4.50
----------------------------------------------------
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```
ENERGY BUDGET -- 4´ X 4´ SPACING -- NON-IRRIGATED
ENERGY ANALYSIS FOR A 1000 ACRE OPERATIONAL HYBRID POPLAR PLANTATION
TOTAL PROJECT ACREAGE IS DIVIDED INTO 10 TRACTS OF 80-120 ACRES EACH.
90 PER CENT OF THE TOTAL PROJECT ACREAGE IS PLANTED.
TREES/PLANTED ACRE:  2600 10" UNROOTED CUTTINGS
ROTATIONS:  (1) 10 YEAR AND (4) 5 YEAR COPPICE ROTATIONS
YIELD:  7 DRY TONS/PLANTED ACRE/YR. FOR THE TEN YEAR ROTATION
        8  "    "      "       "   "    "   " FIVE YEAR ROTATIONS
IRRIGATION:  NONE
FERTILIZATION:  NONE
NOTE:  ALL ENERGY INPUTS AND OUTPUTS BELOW ARE EXPRESSED IN MMBTU´S/ACRE

       SENSITIVITY ANALYSIS

   (10.00 PERCENT DISCOUNT RATE)
            MMBTU´S/ACRE

                  CHANGE IN NPW
DUE TO A 10.00
PERCENT CHANGE IN
--------------------------------------
  1  SITE PREP                   .12
  2  PLANTING                    .15
  3  WT HARVEST                  .39
  4  FORG.HARVEST                .31
  5  HAULING                     .23
  6  DRYING                     6.95
--------------------------------------
  7  WOOD ENERGY               36.66
--------------------------------------
```

```
                    ENERGY BUDGET -- 8' X 8' SPACING -- IRRIGATED
                    ENERGY ANALYSIS FOR A 1000 ACRE OPERATIONAL HYBRID POPLAR PLANTATION
                    TOTAL PROJECT ACREAGE IS DIVIDED INTO 10 TRACTS OF 80-120 ACRES EACH.
                    90 PER CENT OF THE TOTAL PROJECT ACREAGE IS PLANTED.
                    TREES/PLANTED ACRE:  650 10" UNROOTED CUTTINGS
                    ROTATIONS:  (2) 15 YEAR
                    YIELD:  7 DRY TONS/PLANTED ACRE/YR. FOR EACH ROTATION
                    IRRIGATION:  10 EFFECTIVE INCHES/PLANTED ACRE/YEAR
                    FERTILIZATION:  100 LBS. OF NITROGEN/PLANTED ACRE/YEAR
                    NOTE:  ALL ENERGY INPUTS AND OUTPUTS BELOW ARE EXPRESSED IN MMBTU'S/ACRE

                 ANALYSIS INPUTS

        UNIT OF CURRENCY                MMBTU'S
               LAND AREA     1.00 ACRE
            PROD. PERIOD    30
           DISCOUNT RATE    10.00 PERCENT
  ANNUAL CHANGE IN COSTS        0 PERCENT
   ANNUAL CHANGE IN BEN.        0 PERCENT


           AMOUNT AND TIMING OF COSTS    AND BENEFITS
                      MMBTU'S/ACRE

INPUT NO.       NAME    AMOUNT   ANN. RATE OF INFL.    YEAR(S)
      1  SITE PREP         .43             0           0
      1  SITE PREP         .52             0           1
      1  SITE PREP         .12             0           2
      2  PLANTING          .61             0           1
      3  IRRIGATION       9.34             0           1 TO    30
      4  FERTILIZAT'N     3.33             0           1 TO    30
      5  WT HARVEST      21.14             0          15  30
      6  HAULING          9.78             0          15  30
      7  DRYING         300.89             0          15  30
      8  WOOD ENERGY   1587.60             0          15  30
```

```
ENERGY BUDGET -- 8′ X 8′ SPACING -- IRRIGATED
ENERGY ANALYSIS FOR A 1000 ACRE OPERATIONAL HYBRID POPLAR PLANTATION
TOTAL PROJECT ACREAGE IS DIVIDED INTO 10 TRACTS OF 80-120 ACRES EACH.
90 PER CENT OF THE TOTAL PROJECT ACREAGE IS PLANTED.
TREES/PLANTED ACRE:  650 10" UNROOTED CUTTINGS
ROTATIONS:  (2) 15 YEAR
YIELD:  7 DRY TONS/PLANTED ACRE/YR. FOR EACH ROTATION
IRRIGATION:  10 EFFECTIVE INCHES/PLANTED ACRE/YEAR
FERTILIZATION:  100 LBS. OF NITROGEN/PLANTED ACRE/YEAR
NOTE:  ALL ENERGY INPUTS AND OUTPUTS BELOW ARE EXPRESSED IN MMBTU′S/ACRE

(10.00 PERCENT DISCOUNT RATE)       MMBTU′S)ACRE
---------------------------------------------------
     NET PRESENT WORTH                  251.60
      NET FUTURE WORTH                 4390.24
          FUTURE COSTS                 3829.16
      PRESENT BENEFITS                  471.04
         PRESENT COSTS                  219.44
        BENEFITS/COSTS                    2.15
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ENERGY BUDGET -- 8′ X 8′ SPACING -- IRRIGATED
ENERGY ANALYSIS FOR A 1000 ACRE OPERATIONAL HYBRID POPLAR PLANTATION
TOTAL PROJECT ACREAGE IS DIVIDED INTO 10 TRACTS OF 80-120 ACRES EACH.
90 PER CENT OF THE TOTAL PROJECT ACREAGE IS PLANTED.
TREES/PLANTED ACRE:  650 10" UNROOTED CUTTINGS
ROTATIONS:  (2) 15 YEAR
YIELD:  7 DRY TONS/PLANTED ACRE/YR. FOR EACH ROTATION
IRRIGATION:  10 EFFECTIVE INCHES/PLANTED ACRE/YEAR
FERTILIZATION:  100 LBS. OF NITROGEN/PLANTED ACRE/YEAR
NOTE:  ALL ENERGY INPUTS AND OUTPUTS BELOW ARE EXPRESSED IN MMBTU′S/ACRE

       SENSITIVITY ANALYSIS

   (10.00 PERCENT DISCOUNT RATE)
           MMBTU′S/ACRE

                 CHANGE IN NPW
DUE TO A 10.00
PERCENT CHANGE IN
-------------------------------------
 1  SITE PREP                   .10
 2  PLANTING                    .06
 3  IRRIGATION                 8.80
 4  FERTILIZAT′N               3.14
 5  WT HARVEST                  .63
 6  HAULING                     .29
 7  DRYING                     8.93
-------------------------------------
 8  WOOD ENERGY               47.10
-------------------------------------
```

```
                    ENERGY BUDGET -- 8′ X 8′ SPACING -- NON-IRRIGATED
                    ENERGY ANALYSIS FOR A 1000 ACRE OPERATIONAL HYBRID POPLAR PLANTATION
                    TOTAL PROJECT ACREAGE IS DIVIDED INTO 10 TRACTS OF 80-120 ACRES EACH.
                    90 PER CENT OF THE TOTAL PROJECT ACREAGE IS PLANTED.
                    TREES/PLANTED ACRE:  650 10" UNROOTED CUTTINGS
                    ROTATIONS:  (2) 15 YEAR
                    YIELD:  3.5 DRY TONS/PLANTED ACRE/YR. FOR EACH ROTATION
                    IRRIGATION:  NONE
                    FERTILIZATION:  NONE
                    NOTE:  ALL ENERGY INPUTS AND OUTPUTS BELOW ARE EXPRESSED IN MMBTU′S/ACRE

                 ANALYSIS INPUTS

       UNIT OF CURRENCY                MMBTU′S
              LAND AREA     1.00 ACRE
           PROD. PERIOD    30
          DISCOUNT RATE    10.00 PERCENT
  ANNUAL CHANGE IN COSTS        0 PERCENT
   ANNUAL CHANGE IN BEN.        0 PERCENT


           AMOUNT AND TIMING OF COSTS   AND BENEFITS
                      MMBTU′S/ACRE

INPUT NO.       NAME    AMOUNT   ANN. RATE OF INFL.   YEAR(S)
      1  SITE PREP        .43                0          0
      1  SITE PREP        .52                0          1
      1  SITE PREP        .12                0          2
      2  PLANTING         .61                0          1
      3  WT HARVEST     10.57                0         15   30
      4  HAULING         4.89                0         15   30
      5  DRYING        150.45                0         15   30
      6  WOOD ENERGY   793.80                0         15   30
```

```
ENERGY BUDGET -- 8′ X 8′ SPACING -- NON-IRRIGATED
ENERGY ANALYSIS FOR A 1000 ACRE OPERATIONAL HYBRID POPLAR PLANTATION
TOTAL PROJECT ACREAGE IS DIVIDED INTO 10 TRACTS OF 80-120 ACRES EACH.
90 PER CENT OF THE TOTAL PROJECT ACREAGE IS PLANTED.
TREES/PLANTED ACRE:  650 10" UNROOTED CUTTINGS
ROTATIONS:  (2) 15 YEAR
YIELD:  3.5 DRY TONS/PLANTED ACRE/YR. FOR EACH ROTATION
IRRIGATION:  NONE
FERTILIZATION:  NONE
NOTE:  ALL ENERGY INPUTS AND OUTPUTS BELOW ARE EXPRESSED IN MMBTU′S/ACRE

(10.00 PERCENT DISCOUNT RATE)       MMBTU′S)ACRE
----------------------------------------------------
     NET PRESENT WORTH                  184.74
      NET FUTURE WORTH                 3223.58
          FUTURE COSTS                  886.12
      PRESENT BENEFITS                  235.52
         PRESENT COSTS                   50.78
        BENEFITS/COSTS                    4.64
----------------------------------------------------
```

```
ENERGY BUDGET -- 8′ X 8′ SPACING -- NON-IRRIGATED
ENERGY ANALYSIS FOR A 1000 ACRE OPERATIONAL HYBRID POPLAR PLANTATION
TOTAL PROJECT ACREAGE IS DIVIDED INTO 10 TRACTS OF 80-120 ACRES EACH.
90 PER CENT OF THE TOTAL PROJECT ACREAGE IS PLANTED.
TREES/PLANTED ACRE:  650 10" UNROOTED CUTTINGS
ROTATIONS:  (2) 15 YEAR
YIELD:  3.5 DRY TONS/PLANTED ACRE/YR. FOR EACH ROTATION
IRRIGATION:  NONE
FERTILIZATION:  NONE
NOTE:  ALL ENERGY INPUTS AND OUTPUTS BELOW ARE EXPRESSED IN MMBTU′S/ACRE

       SENSITIVITY ANALYSIS

   (10.00 PERCENT DISCOUNT RATE)
            MMBTU′S/ACRE

                   CHANGE IN NPW
DUE TO A 10.00
PERCENT CHANGE IN
--------------------------------------
 1  SITE PREP                 .10
 2  PLANTING                  .06
 3  WT HARVEST                .31
 4  HAULING                   .15
 5  DRYING                   4.46
--------------------------------------
 6  WOOD ENERGY             23.55
--------------------------------------
```

U.S. Government Printing Office: 1981—766-984/201

Rose, Dietmar, Karen Ferguson, David C. Lothner, and J. Zavitkovski.

1981. An economic and energy analysis of poplar intensive cultures in the Lake States. U.S. Department of Agriculture Forest Service, Research Paper NC-196, 44 p. U.S. Department of Agriculture Forest Service, North Central Forest Experiment Station, St. Paul, Minnesota.

Short- (5 to 10 years) and long- (15 years) rotation, irrigated and nonirrigated intensive cultures of hybrid poplar were analyzed economically via cash flow analysis. Energy balances were also calculated for each alternative. Nonirrigated systems offer reasonable economic returns whereas irrigated systems do not. All systems produce more energy than they use as production inputs.

KEY WORDS: Poplar hybrids, cash flow analysis, energy balances, agriforestry, biomass management.

DA FOREST SERVICE
SEARCH PAPER **NC-197**

A two-plane internally irrigated root observation system for forest nursery stock

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1981

A TWO-PLANE INTERNALLY IRRIGATED ROOT OBSERVATION SYSTEM FOR FOREST NURSERY STOCK

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Columbia, Missouri,
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George O. White State Forest Nursery,
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The capacity of forest nursery stock to produce new roots when field planted has long been recognized a factor in subsequent survival and growth. The potential for this new root growth usually has been measured in a controlled environment such as a greenhouse or growth chamber. Traditionally, root growth measurements have been made of seedlings transplanted to pots; new root lengths that have developed over a 4- to 8-week period then are measured (Webb 1977, Stone and Schubert 1959, Farmer 1975). However, this approach does not permit the simultaneous evaluation of root and shoot growth, and thus time-dependent root-shoot interactions. Our research on oak (*Quercus* spp.) nursery stock indicates that timing as well as amount of root growth relative to initial shoot growth after field planting may be a factor governing future growth and survival (Johnson 1979). Time-dependent root-shoot relations may be particularly important in hardwoods exhibiting periodic shoot elongation (Borchert 1975).

Root observation chambers offer a solution to the problem of simultaneously observing root and shoot development. Although many root observation techniques have been developed, most rely on the positive geotropic response of roots which forces them to grow along a sloping transparent surface (Murdoch *et al.* 1974, Lonkerd and Ritchie 1979). For studying forest nursery stock, slopes of root observation chambers have generally been 30° or less from vertical, with the entire seedling tilted to this angle (Larson 1962).

We designed a root observation chamber specifically for forest nursery stock that also uses a sloping transparent surface. However, our system has two other important features. First, the detachable planter (upper) section of our system maintains the transplanted seedling in a normal vertical plane; only the newly regenerated roots grow against the slanted (60° from vertical) plexiglass root observation plane. The 60° angle assures that most new roots will be observable through the plexiglass. Second, the root observation (lower) section is internally irrigated throughout its length to facilitate uniform moisture distribution. Details of the design, construction, and use of this root observation system are described below.

SYSTEM DESCRIPTION

Materials and Construction

The root observation system consists of two components: (1) an upper vertical section (planter) that accommodates a seedling with a root system up to 23 cm long and the potting medium, and (2) a lower root observation section sloped 60° from vertical that contains the rooting medium and irrigation tubing (fig. 1).

Both components can be constructed of 3 mm (0.10 in.) transparent plexiglass mounted on strips of 19 by 19 mm (¾ by ¾ in.) pine. However, thinner and less expensive clear styrene sheeting 2 mm (0.08 in.) thick can be substituted for all or part of the plexiglass components. We used the more expensive plexiglass only for the root observation window, i.e., the bottom of the lower section. However, to simplify

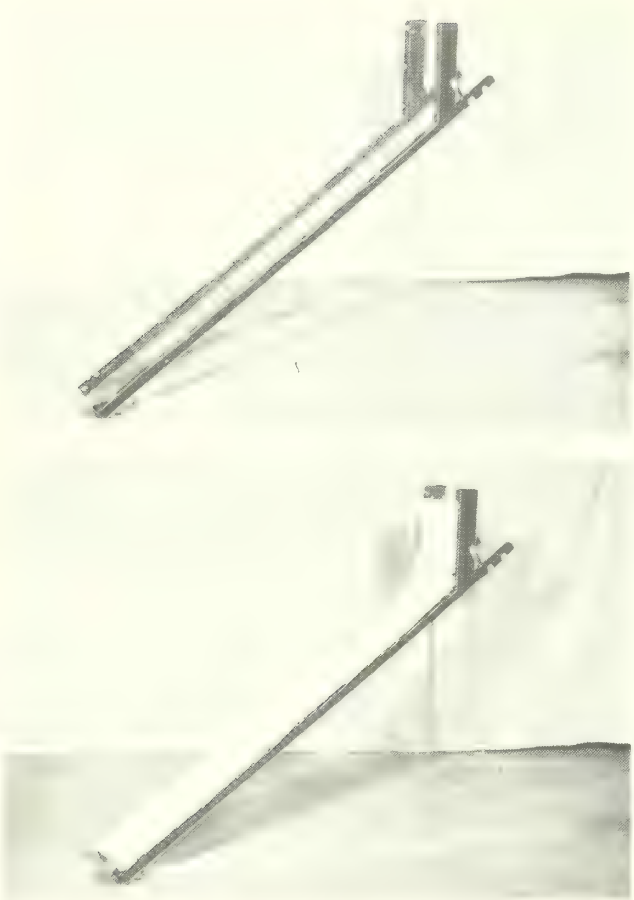

Figure 1.—*Root observation chamber constructed of plexiglass and wood (a); with styrofoam insulation shields in place (b).*

further description, both materials will be referred to as plexiglass. Most of the plexiglass pieces can be cut on a table saw with a fine-toothed blade. Round-head #6 screws 1.9 cm (¾ in.) long fitted with washers 1.2 cm (½ in.) in diameter were used throughout.

The planter section is constructed of four pieces of plexiglass mounted on four strips of pine. The front plate is 13.8 cm (5½ in.) wide by 23.5 cm (9¼ in.) high. The back plate is the same width, but 21.8 cm (8⅝ in.) high. The two side plates are 5.0 cm (2 in.) wide by 23.5 cm (9¼ in.) high at the front and 21.8 cm (8⅝ in.) high at the rear. The bottom edge of each side plate is cut at an angle of 30°.

Each side plate is mounted on the inside of the two pine strips with screws. The front and rear edge of each side plate is framed with the pine strips which are cut at a 30° angle on their bottom ends so they parallel the edges of the side plates. The front and back plates are then attached to form a box with interior measurements of 5.0 cm (2 in.) by 9.7 cm (3⅞ in.) and a maximum depth of 23 cm (9⅛ in.). The interior volume of the planter is approximately 1067 cc (65 in.^{3}) (fig. 2).

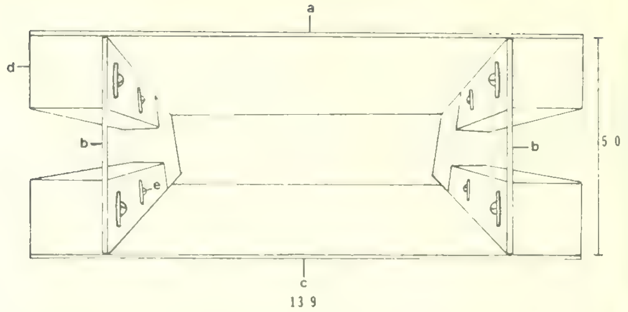

Figure 2.—*Top perspective of planter section—a. plexiglass back plate; b. plexiglass front plate; c. plexiglass side plate (2); d. 19 by 19 mm (¾ by ¾ in.) pine strip; e. 19 mm (¾ in.) #6 screws fitted with 16 mm (½ in.) diameter washers (dimensions are in cm).*

The root observation section is constructed of two plexiglass plates which also are mounted on pine strips. The top plate is 101.6 cm (40 in.) long and 13.8 cm (5½ in.) wide. The bottom plate (root observation window) is 121.9 cm (48 in.) long and 13.8 cm (5½ in.) wide. These two plates are mounted with screws on two parallel side stops 121.9 cm (48 in.) long and a 10 cm (4 in.) long stop across the bottom. Screws are spaced 15 cm (6 in.) apart when using the heavier plexiglass and about half this distance when the styrene is used.

The bottom pine strip has eight 3 mm (⅛ in.) holes drilled through it for water drainage and a 1.6 cm (⅝ in.) hole at the center of its length to accommodate the irrigation tubing (fig. 3). Twelve additional 3 mm (⅛ in.) water drain holes were drilled in the bottom plate within 2 cm of its lower end. The interior volume of the root observation section from the upper edge of the top plate to the bottom of the chamber is approximately 1932 cc (118 in.^{3}). The viewing surface for observing root growth is 10 cm (4 in.) by approximately 1 m (40 in.).

Prior to assembling the root observation chambers, the wood components can be treated with a wood preservative such as copper napthanate; pentachlorophenol should not be used because it is extremely phytotoxic.

The two components are fastened together by a pair of 8.9 cm (3½ in.) flat metal corner braces and six screws (fig. 4). A sheet of styrofoam 1.9 cm (¾ in.) thick was placed over the top plate of the root observation section to provide insulation from direct

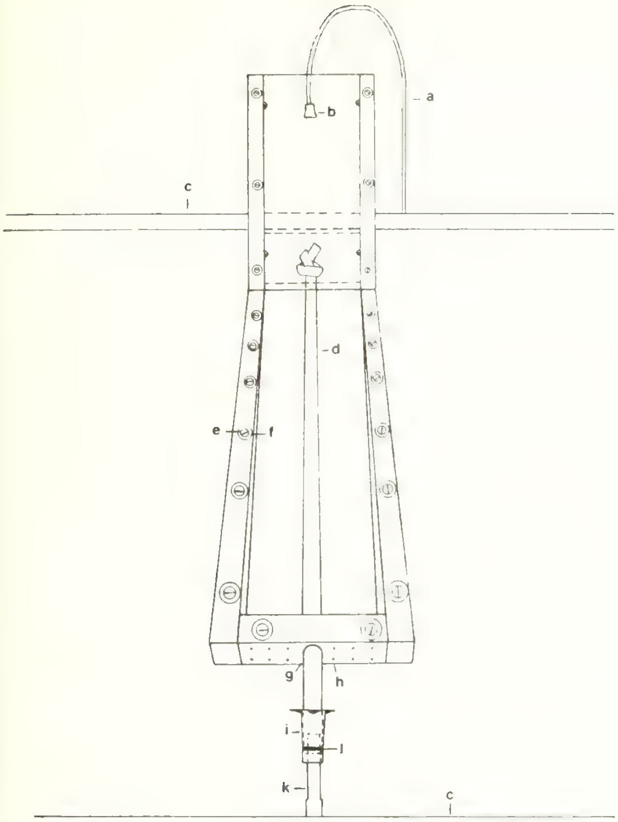

Figure 3.—*End perspective of the complete root observation chamber showing irrigation system—a. 1.5 mm (0.05 in.) inside diameter Chapin Leader Tubing; b. drop-in weight; c. 1.9 cm (3/4 in.) PVC main water line; d. 1.5 cm (0.60 in.) Viaflo tubing; e. 19 mm (3/4 in.) #6 screw; f. 13 mm (1/2 in.) diameter washer; g. 16 mm (5/8 in.) hole in bottom pine stop for Viaflo tubing; h. 3 mm (1/8 in.) drain hole; i. Viaflo cone connector; j. o-ring; and k. feeder tubing.*

sunlight. Styrofoam was held in place by 6.4 cm (2½ in.) long sections of 2.5 cm (1 in.) wide galvanized drywall corner bead. A shorter piece of styrofoam was similarly held in place on the planter wall with south exposure (fig. 1b). Over the insulation, extra heavy duty aluminum foil was wrapped around both upper and lower components to keep the growth chamber dark and to reflect solar radiation. The foil over the root observation window was removed for periodic measurements.

To irrigate the root observation section, we used DuPont Viaflo[1] irrigation tubing.[2] This tubing is made from a ribbon-like porous plastic that inflates under pressure and allows the slow passage of water through micron-size pores in the tubing wall. Flow rate for the 1.5 cm (0.60 in.) diameter tubing is about 2 liters per minute (3 gpm) per 300 m (1,000 ft.) of tubing. The tubing requires line pressures of 21 to 34 kPa (3 to 5 psi). This low pressure requirement ordinarily will necessitate the installation of a pressure regulator and gauge on the main irrigation line.

Connecting the irrigation tubing to a main line can be done with connectors designed for the Viaflo system which include a connector cone, o-ring, and feeder tube (fig. 3i, j, k). If the main water line is constructed of PVC, the feeder tube can be inserted directly into it by cutting a hole 9 mm (3/8 in.) in diameter in the PVC; the insertion hole should be drilled with a tapered bit available for this purpose. To minimize the amount of feeder tubing needed, we installed a 1.9 cm (3/4 in.) PVC main water line about 10 cm (4 in.) from the lower end of the root observation section (fig. 3); this main line could then be used to service a series of chambers.

After connection to the main line, the irrigation tubing is inserted through the tubing hole in the pine strip of the bottom of the root observation section (fig. 3g) and extended up to and under the base of the back plate of the planter section. Because the tubing is ribbon-like when not inflated, it can be slipped between the bottom of the planter's back plate and the inside of the root observation window. About 15 cm (6 in.) of tubing should extend beyond (above) the back plate wall of the planter section; a half-hitch knot was used to stop water flow out this free end of the tubing.

The planter section was irrigated with 1.5 mm (0.06 in.) inside diameter Chapin Leader Tubes[1] with "drop-in" weights. The leader tubes were connected to a 1.9 cm (3/4 in.) PVC main line that rested on the pine strips of the observation section (fig. 3). This irrigation line was used periodically to apply a complete nutrient solution via a nutrient proportioner and an automatic timer system; it was independent of the Viaflo system which was connected to a separate timer system.

Materials cost (1980) per growth chamber, with 2 mm (0.08 in.) styrene substituted for plexiglass for all but the root observation window, was approximately $12; this includes all materials except the irrigation system components. Construction time per growth chamber unit was approximately one man-hour.

---

[1] *Mention of trade names does not constitute endorsement of the product by the U.S. Department of Agriculture, Forest Service.*

[2] *This product is no longer available but similar products are available from other manufacturers.*

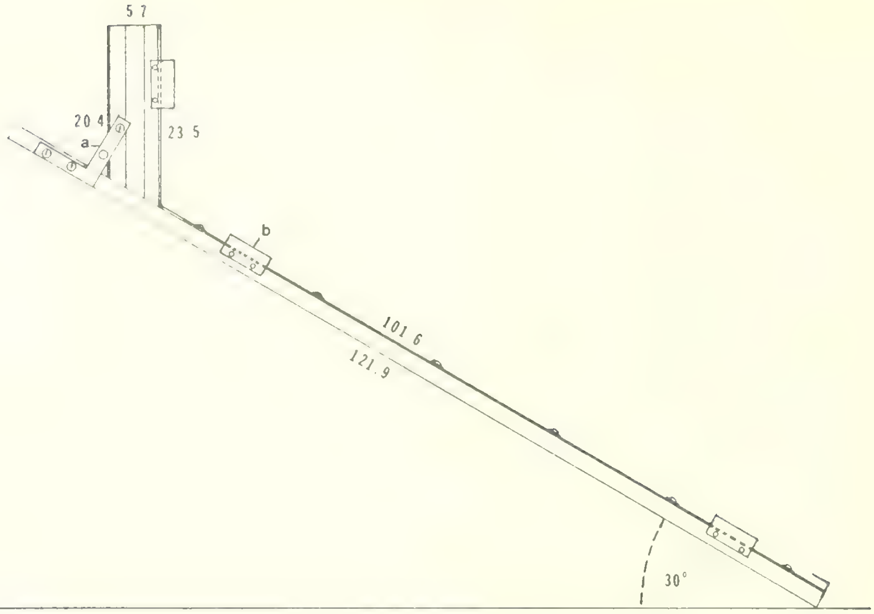

Figure 4.—*Side view of root observation chamber—a. 8.9 cm (3½ in.) flat metal corner brace; b. 2.5 cm (1 in.) wide drywall corner bead to hold styrofoam insulation in place (dimensions are in cm).*

Using the System

Almost any kind of potting medium can be used with the system, including soil. In our root growth studies, we found the commercially available mixtures of fine vermiculite and peat worked well. The root observation chamber can be filled through the planter section if the rooting medium is fine and dry; otherwise it may be better to fill the chamber with the planter section removed. When filling, the chamber can be lightly tapped on the floor to eliminate voids; while doing this, care should be taken to keep the Viaflo tubing centered. With wet potting materials or those that don't flow easily, filling may best be accomplished by laying the root observation section flat, removing the top plate, and evenly spreading the medium by hand.

To monitor temperatures inside the root observation section, we inserted thermistor probes through 6 mm (¼ in.) holes drilled through the sides of the pine stop. Soil moisture similarly could be monitored psychrometrically.

Bare-root seedlings must be root pruned to no more than 23 cm (9 in.) in length before they can be transplanted to the planter section. If longer roots are needed or desired, the planter section easily can be redesigned to accommodate them. In our work with oaks, we press all first-order lateral roots up to and parallel with the tap root with one hand, and then clip both the tap root and laterals at a point 20 cm below the root collar. Thus, the root pruning point for all major roots will be at the same depth when transplanted. In oaks and other tap-rooted species, practically all of the new root regeneration will originate at or near the point of root pruning. With containerized seedlings that have "air-pruned" roots (Tinus and McDonald 1979), no root pruning will be necessary; most new root regeneration after transplanting will occur at the tip of the root plug.[3]

When the seedling is transplanted to the root observation chamber, it should be positioned in the planter section so the lower tips of all pruned roots or the root plug just touch the inside of the root observation window. The point at which these roots meet the root observation window can then be marked on the bottom of the window with a strip of masking tape or a waterproof, fine-point, felt-tip marking pen. New roots then can be measured from this initial reference

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[3] *An exception to this will occur when container stock is grown in containers with walls treated with a growth inhibitor. In tap-rooted species, this will create a tap root bearing very short first-order laterals that produce a "bottle-brush" root morphology (Burdett 1978).*

line. Roots can be measured until they reach the bottom of the root observation section. In our oak studies this has usually permitted an 8- to 10-week study period and allowed us to follow root growth through 2 or 3 flushes.

We devised a line intersection method for estimating total root lengths observable through the root observation window. To facilitate this, we used a strip of clear acetate 10 cm wide by 100 cm long. A series of parallel lines were drawn across the width of the strip at 1 cm intervals. These lines were made with a waterproof, fine-point, felt-tip marker and numbered consecutively from 1 to 100 (for measuring roots up to 1 m below reference line).

When root measurements were being made, the acetate strip was overlaid on the root observation window, and the top edge (zero line) aligned with the masking tape reference line. Starting at line number one on the acetate strip, the number of observable roots intersecting each line was recorded on 80 column computer code sheets. From these data entries, an estimate of total root length was calculated by summing the number of roots at each intersection. One-half cm was added to each root at its last (lowermost) intersection, based on the assumption that, on the average, roots will extend half the distance between the last intersection at which they were observed and the next line. This correction was not actually made during data recording, but was made in the data summary computer program. In this program, a "last" root intersection was identified whenever there was a decrease in the number of root intersections between consecutive lines from the reference line to the 100 cm line. This correction also was applied to the last (lowermost) observed intersection in a series. Computationally, total root length (TRL) was thus estimated as:

$$\begin{aligned} \mathrm{TRL} = \Sigma[& n_1 + 0.5(n_1-n_2) + n_2 + 0.5(n_2-n_3) + n_3 + 0.5(n_3-n_4) + \\ & n_{99} + 0.5(n_{99}-n_{100}) + n_{100} + 0.5(n_{100})]. \end{aligned}$$

where TRL = estimated total root length (cm); n_1, n_2, n_3 .... n_{100} = number or roots (n) intersecting cm lines 1, 2, 3, ... 100; n_1-n_2, n_2-n_3, etc., are set equal to zero when their values are negative.

This method provides a relatively quick and precise way to estimate total root length *in situ*. However, the method assumes that roots are growing in a straight line at right angles to the intersection lines. These assumptions are fairly well met when the rooting medium consists of fine and low density materials like peat and fine vermiculite. When coarse or higher density materials are used, roots may kink and turn as they encounter resistance in the rooting medium. Under these conditions, the line-intercept technique described by Newman (1966) may be more appropriate because it does not assume that individual roots form a straight line or grow in any particular direction.

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1981. A two-plane internally irrigated root observation system for forest nursery stock. U.S. Department of Agriculture Forest Service, Research Paper NC-197, 6 p. U.S. Department of Agriculture Forest Service, North Central Forest Experiment Station, St. Paul, Minnesota.

A root observation chamber designed for forest nursery stock is described. The chamber consists of a lower root observation section and a detachable upper "planter" section, both constructed of plexiglass and wood; the lower section is internally irrigated by a porous irrigation tube and the upper section by a "leader tube."

KEY WORDS: Root chamber, root growth, root regeneration, rhizotron.

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GROWTH RESPONSE of speckled alder and willow to DEPTH OF FLOODING

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1981. Growth response of speckled alder and willow to depth of flooding. U.S. Department of Agriculture Forest Service, Research Paper NC-198, 6 p. U.S. Department of Agriculture Forest Service, North Central Forest Experiment Station, St. Paul, Minnesota.

Growth and survival of speckled alder and willow were determined for two growing seasons with continuous flooding at different depths. Growth was at least four times greater when the water table was below the root crown than when it was 15 cm above. Mortality increased with flooding depth and was greatest for alder.

KEY WORDS: *Alnus rugosa*, *Salix*, inundation, flooding, growth, survival, management, Minnesota, wildlife impoundments.

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GROWTH RESPONSE OF SPECKLED ALDER AND WILLOW TO DEPTH OF FLOODING

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An aggressive wildlife management program on the Chippewa National Forest in north-central Minnesota has led to the establishment of more than 45 wildlife impoundments in recent years; 105 more are planned. Similiar impoundments are part of forest wildlife management programs on several National Forests in the north-central States.

These impoundments are constructed specifically to increase the available area of deep marsh habitat (Mathisen 1970). Water levels are manipulated to favor a host of game and nongame birds, and small mammals. This requires maintenance of shrubs that Harris and Marshall (1963) indicated would die-out within 2 to 4 years after flooding. The depth of flooding that kills the plants is not known, nor do we know what depth of drained soil is needed for good growth. Also, we do not know the extent to which the physical and chemical properties of the soil, and water, alter shrub response to flooding.

Reviews of the information available on the flooding tolerance of woody species were made by Gill (1970, 1977) and Tattar (1972). Most studies have been case histories of flooded plant communities associated with river flood plains or those in the zone of fluctuating water levels of reservoirs. There are few studies where water level was specifically controlled to assess the response of woody species; none have considered the prevalent species of willow and alder present in the north-central States.

The present study examined the response of speckled alder (*Alnus rugosa* (Du Roi) Spreng.) and several willows (*Salix* spp. L.) to depth of flooding. All are known for their tolerance to temporary flooding (Hall and Smith 1955, Broadfoot 1967), and are prominent members of wetland communities in North America (Parker and Schneider 1974, White 1965).

METHODS

Rooted stems of speckled alder and willow were collected from wildlife impoundments in north-central Minnesota and transplanted into tanks where water level could be controlled. The shrubs were grown through two growing seasons under five water regimes. Survival and net woody increment were measured to assess shrub response. Water chemistry and temperature were monitored routinely and were maintained at levels observed concurrently in wildlife impoundments. Volunteer competing vegetation was permitted to grow without interference to simulate field conditions, and at the end of each growing season it was clipped and its dry weight was determined for each insert tank.

Six galvanized stock watering tanks (3.0 m long by 90 cm wide by 60 cm deep) were buried to within 5 cm of their tops within a fenced enclosure near the Forestry Sciences Laboratory, Grand Rapids, Minnesota (approximately 47°32′N, 93°28′W) (fig. 1). Five smaller tanks (61 cm long by 46 cm wide by 38 cm deep) fabricated from 16-gauge galvanized sheet metal were inserted into each stock tank. The insert tanks rested on individual platforms at 7.5 cm height intervals; different heights were randomly located in each tank. Holes 6.4 mm in diameter were drilled into the sides and bottom of each insert tank to permit ready movement of water. The side holes were spaced on 5-cm centers and the bottom holes were spaced on 10-cm centers.

All metal surfaces were coated with Sherwin-Williams Wash Primer Green (Catalog No. P60 G2)[1] mixed with Catalyst Reducer (Catalog No. R7 K 44)

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[1] *Mention of trade names does not constitute endorsement of the products by the USDA Forest Service.*

Figure 1.—*Stock tank and insert tank installation at the Forestry Sciences Laboratory, Grand Rapids, Minnesota.*

and followed by one coat of Sherwin-Williams C + M enamel. This provided a stabilized chlorinated rubber finish recommended by the manufacturer for surfaces exposed to excessive moisture. The coating was intended to prevent zinc toxicity that might develop from the galvanized metal.

In early May 1977, the insert tanks were filled with soil from four wildlife impoundments. The soils were common wetland series, Nebish, Shooks, Swatara, and Beltrami, and ranged in texture from sandy-loam to silt-loam. These soils had an organic surface horizon 1 to several cm thick. In addition, an organic soil from a fifth impoundment and an upland mineral loamy-sand subsoil were used. All five insert tanks in a given stock tank were filled with one soil in a manner that reconstructed the natural horizons.

A 200-liter drum adjacent to each stock tank was used for a reserve supply of water. The drum was connected to the stock tank through a float-valve that maintained a constant water level in the stock tank providing five water levels in relation to the shrub root crown: +15 cm, +7.5 cm, 0 cm, –7.5 cm, and –15 cm.

Alder and willow transplants were collected in early April 1977, from the seasonally flooded edge of the three wildlife impoundments (table 1). The buds showed no signs of swelling at this time. The willow transplants were later identified to species after leafing out, but the alder could be identified readily without leaves. All alder samples were collected at the Bear Brook impoundment. In most cases the roots were less than 15 cm deep and the plants were 1 to 1.5 m tall. The transplants were kept in plastic bags at 2 to 4°C until May 10, 1977, when they were pruned, weighed, tagged, and planted in the insert tanks. After pruning, the transplants were 50-60 cm tall. The pruning was done to give more uniform initial weights, to reduce initial leaf area as an aid in establishment, and to encourage branching.

Table 1.—*Willow transplants collected from wildlife impoundments in north-central Minnesota, by species*
(In number)

Impoundment	*Salix gracilis*	*Salix discolor*	*Salix Bebbiana*	*Salix* spp.
Ketchum	11	14	2	3
Bear Brook	6	12	12	0
Ball Club	30	0	0	0

Four shrubs, one from each of the three willow sites and the alder site, were planted in the corners of each insert tank. To allow the transplants to become established, flooding was delayed until June 10, 1977, when the stock tanks were filled with water. All transplants leafed out and appeared to be established and vigorous before flooding.

The stock tanks were filled with water from Cuba and Ketchum wildlife impoundments (3 tanks each). The chemical composition of the water in these impoundments represents the extremes of surface water chemistry present in north-central Minnesota (table 2). Water conductivity, pH, and total phosphorus concentrations were monitored in the stock tanks at 2- to 3-week intervals through each growing season. When the water chemistry changed significantly from values measured concurrently in the two impoundments, water in the tanks was exchanged for fresh water from the impoundments. Exchanges

Table 2.—*Mean and standard error of several properties of the water used to represent extremes found in north-central Minnesota on 14 sampling dates during 1977*

Water properties	Source: Cuba	Source: Ketchum
Conductivity (mhos at 25°C)	68.4 ± 18.4	326.0 ± 45.7
pH	6.1 ± 0.4	6.8 ± 0.3
Calcium (ppm)	6.9 ± 1.64	48.6 ± 8.55
Total nitrogen (ppm)	3.8 ± 2.0	1.52 ± 1.66
Total phosphorus (ppm)	0.47 ± 0.14	0.15 ± 0.28

were made in July 1977 and May 1978. Apparently the change in water chemistry in the tanks was dilution by precipitation.

Water temperature and dissolved oxygen (DO) concentration were also measured at 2- to 3-week intervals in the stock tanks. DO was controlled at 3 levels (2 tanks per level) during the growing season: (1) stagnant, (2) aerated once each week, and (3) aerated 3 times each week. Tanks were aerated with a water pump, garden hose, and nozzle to circulate water through the nozzle and back into the tank under pressure. This procedure saturated the water with oxygen in less than 3 hours but aeration was continued for 7 to 8 hours each time.

Each of the six stock tanks represented one replication of the five water level treatments in a completely randomized block design. Analysis of variance was used to determine significant differences. An additional but less sensitive test of effect of DO levels was also made in a factorial analysis of variance with two replications. All tests were made with $\alpha = 0.05$ or less.

The 2-year wet-weight increment and the 2-year dry-weight (48 hours at 80°C) increment of woody tissue were used as estimates of growth in separate analyses. Pretreatment ovendry weight of each shrub was estimated using regression equations derived from the relation of final wet-weight to dry-weight (table 3). The regression equation is $Y = A + BX$ where Y = pretreatment ovendry weight and X = pretreatment wet-weight with the appropriate coefficients. Wet-weight and dry-weight increments were determined by subtracting pretreatment weights from post-treatment weights.

Alder, and the willows from the three impoundments were tested separately. When weight increments were less than zero they were set equal to zero to avoid the suggestion of negative growth. A test for correlation between original shrub weight and final shrub weight was made to determine if covariance analysis was needed to adjust for disparities in original shrub weights. Differences between treatment means were tested using the Least Significant Difference method.

Table 3.—*Coefficients and 95 percent confidence intervals for the equations*[1] *used to predict pretreatment dry weight (gm) of shrub woody tissue*

	Coefficients and confidence intervals		
Shrub	**A**	**B**	**r**
Alder	8.18 ± 12.94	0.512 ± 0.060	0.98
Willow (all sites)	5.606 ± 2.339	0.45 ± 0.016	0.99

[1] Equations are derived from the relation of final wet weight to dry weight.

Results

Net growth of all shrubs was severely reduced when the water level was at or above the root crown (fig. 2). These differences were not visible during the first growing season but became readily apparent as the second season progressed. The foliage on the flooded shrubs became chlorotic and sparse, and some new stems were dead by early August. Original shrub size did not alter the response to flooding. This was evident from a lack of correlation between original and final weights of individuals. Apparently treatment effects were so overwhelming that any advantage a shrub might have had due to original size, was eliminated. Original branches that died were collected and their weights were added to the final weight of the individual. Some dead branches sloughed off through natural causes such as weight of the winter snowpack, wind, and insect feeding, and were not found. This resulted in negative net growth for some individuals despite prolific adventitious rooting.

Mortality became apparent during the second year of flooding with alder being most sensitive (table 4). All shrubs survived the first growing season with at least a few leaves. Most of the mortality became

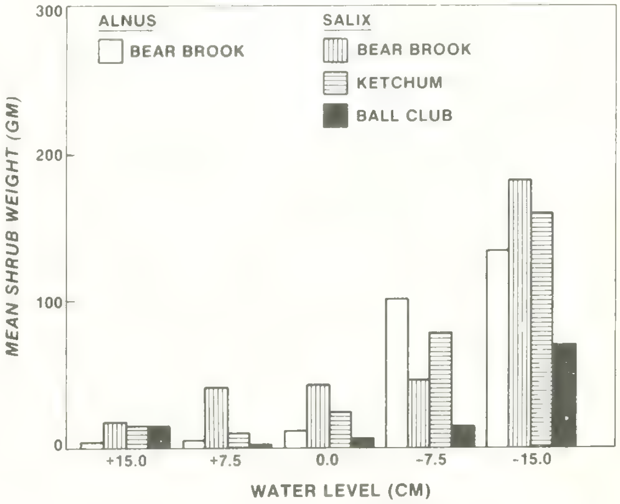

Figure 2.—*Net 2-year wet-weight increment of woody tissue at five levels of flooding. Water level is in relation to root crown.*

Table 4.—*Shrub mortality (i.e., no evidence of above-ground living tissue) after two growing seasons of continuous flooding at different water levels*

(In percent)

	Mortality				
	Water level relative to root crown (cm)				
Shrub	+15.0	+7.5	0.0	–7.5	–15.0
Alder	33	33	16	0	0
Willow					
Ketchum	16	0	0	0	0
Bear Brook	16	0	0	0	0
Ball Club	0	16	0	16	0

apparent when shrubs failed to leaf out at the beginning of the second growing season; moreover, some shrubs that did leaf out died later as the season progressed.

Shrub root development in the soil was restricted severely by flooding, but adventitious rooting above the soil (in the water) was abundant (fig. 3). When the water level was maintained at the soil surface (at the root crown) a new root system developed in the first 0-5 cm of soil. The deeper old root system appeared dead.

The physical and chemical properties of the water in the stock tanks remained fairly close to properties measured concurrently in the impoundments (fig. 4). Dissolved oxygen showed the greatest discrepancy because it is influenced by wind action and it was not possible to synchronize tank aeration with wind action. Nevertheless, the range in DO maintained in the tanks reflected the variation in field conditions. The study was not designed to evaluate the effects of different soil and water properties on shrub survival and growth. They were included simply to cover the range of these properties that are common in impoundments of the region. No analysis of interaction with these properties was possible except for a weak test of the effect of oxygen saturation which proved to be not significant ($\alpha = 0.05$).

The competing vegetation was primarily sedges (*Carex* spp. L.) and beggar's ticks (*Bidens* spp. L.). Its standing crop biomass in the insert tanks ranged from 0 to 1,200 g/m^2 the first year and 0 to 200 g/m^2 the second year but showed no correlation with water depth. Therefore, effects of competition (if any) on shrub growth were not confounded with depth of flooding.

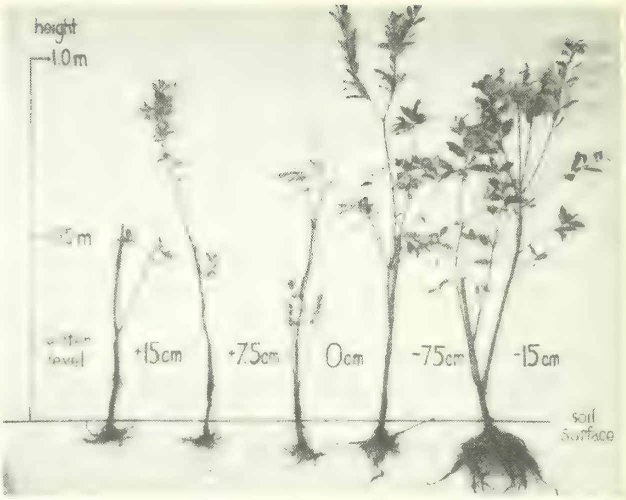

Figure 3.—*Examples of willow after 2 years of inundation at five water levels. Adventitious rooting is apparent on the shrubs to the left.*

Discussion

The species of alder and willow that were studied are tolerant to prolonged flooding of their root crowns; however, shrub growth essentially stops and after two growing seasons significant mortality can be expected. These effects occur regardless of the DO concentration in the surrounding water. This is somewhat surprising because others have found that woody species are not as severely affected by flowing water as they are by stagnant water (Hook *et al.* 1970, Hunt 1951).

The assumption has been that flowing water has a high DO concentration and the plants are able to utilize it. It may be that the DO concentration in the soil rather than the water is of greatest importance, at least with prolonged flooding. This is in spite of adventitious rooting by submerged stems. Apparently, soil DO is limited by the biological oxygen demand and the diffusion rate rather than by the DO concentration of surrounding water (Gill 1977). Zimmerman (1930) suggested the threshold figure of 10 to 11 percent for 0_2 concentration in the soil atmosphere; below which injurious effects were produced. It is possible that the DO concentration in the soil atmosphere of the submerged insert tanks never exceeded this threshold although in some cases the surrounding water was saturated. Similar conditions would be expected in soils associated with impounded waters wherein the DO in the water may be maintained at high concentrations by wind action, but the soil atmosphere DO concentrations may be very low (Bouldin 1968).

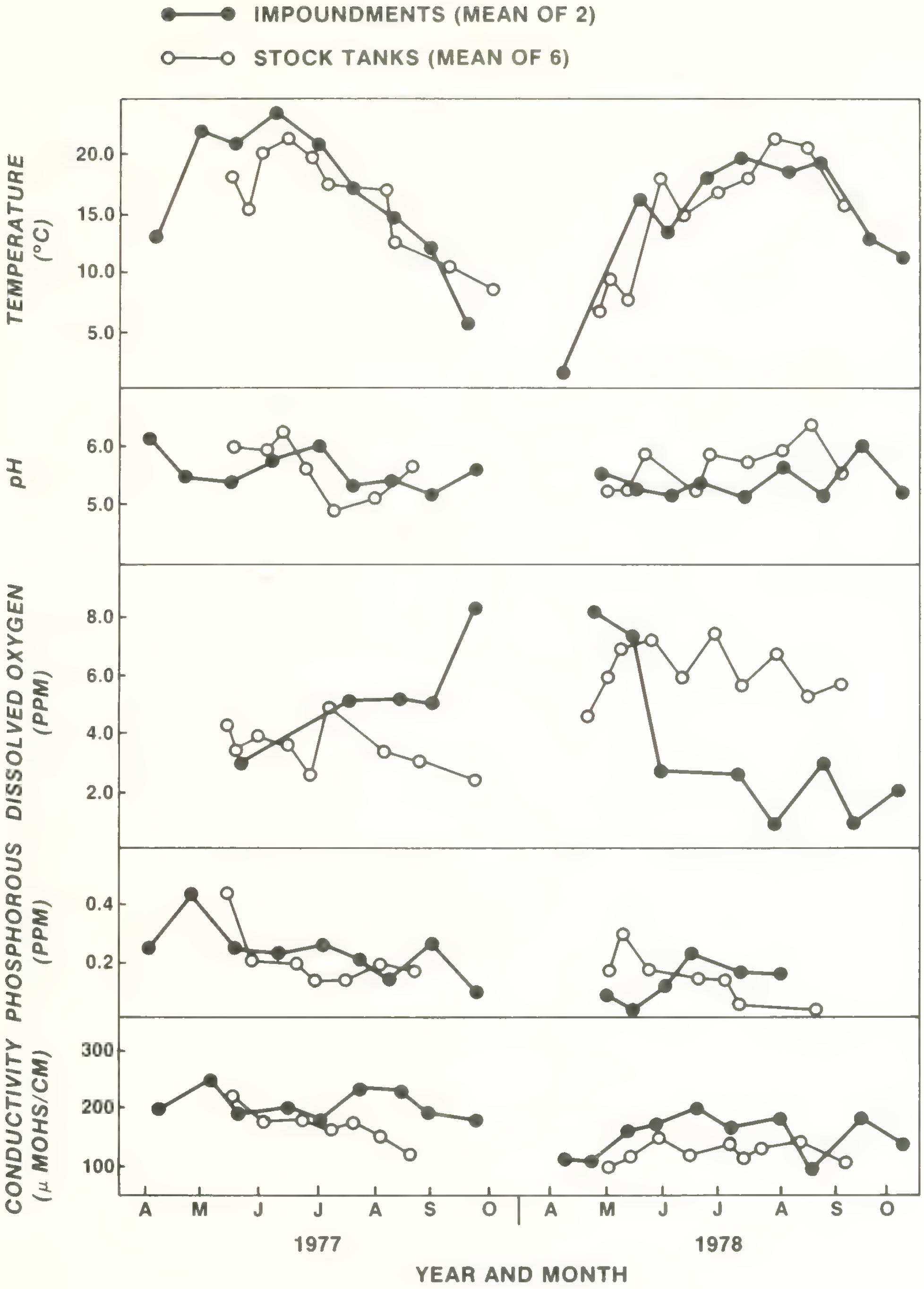

Figure 4.—*Mean water properties in two impoundments and the stock tanks.*

Shrub root development did respond to what may have been available DO in the surface 0-3 cm of soil in the insert tanks when the soil surface, water surface, and root crown were at the same level. A new root mass developed above the old mass and it appeared to be healthy (fig. 5); however, these shrubs had no better growth than more deeply flooded shrubs. The new root mass may have contributed to the higher survival experienced at this level of flooding. Both alder and willow exhibited good growth in as little as 7.5 cm of aerated soil; however, growth is substantially greater in 15 cm of aerated soil.

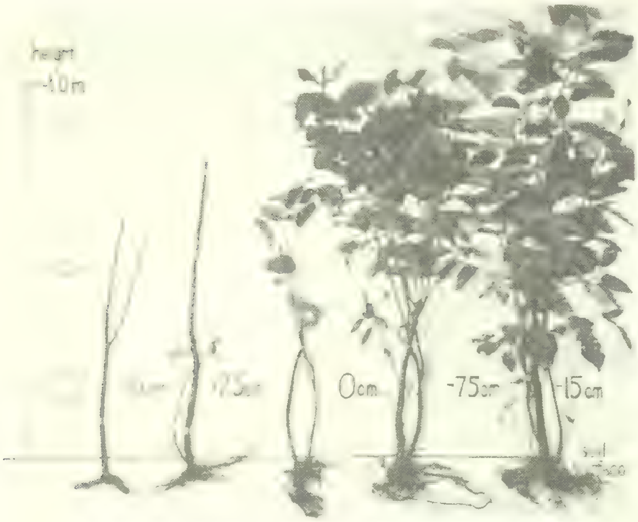

Figure 5.—*Examples of alder after 2 years of inundation at five water levels. A new growth of roots at the soil surface is apparent in the middle shrub and the lower residual root appeared to be dead.*

MANAGEMENT IMPLICATIONS

1. Flooding for 3 or more years may be required to kill enough willow to substantially reduce stem density. The same is true for alder although it apparently is more sensitive.
2. Shrubs growing on <15 cm of drained soil will suffer loss of vigor.
3. Dissolved oxygen content of flood water has no effect on shrub survival and growth.

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SDA FOREST SERVICE
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Stocking and Structure for maximum growth in SUGAR MAPLE selection stands

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STOCKING AND STRUCTURE FOR MAXIMUM GROWTH IN SUGAR MAPLE SELECTION STANDS

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Determining optimal stocking, stand structure, and cutting cycle for various management objectives is basic to developing guides for managing forest stands. The existing stocking guide for uneven-aged hardwoods in the Lake States (Eyre and Zillgitt 1953) was based on a synthesis of cutting method studies. This interim guide was thought reliable, but was to be revised and modified as more data became available (Eyre and Zillgitt 1953).

In 1951 a study began at the Upper Peninsula Experimental Forest in northern Michigan to specifically test the effects of stocking level and cutting cycle on growth rates in uneven-aged northern hardwood stands. The stocking levels in this study were 30, 50, 70, and 90 square feet of basal area per acre in trees 9.6 inches d.b.h. and above. Cutting cycles of 5, 10, and 15 years were applied to stocking levels of 50, 70, and 90 square feet. A 20-year cutting cycle was assigned to the 30-foot level. These treatments were applied to mature saw log stands. The 20-year results in terms of basal area and volume growth are reported here. The thousands of measurements made in the 20 years of the study help provide a comprehensive evaluation of existing recommendations for stocking, structure, and cutting cycle in uneven-aged northern hardwood forests. The study results apply best to sugar maple stands on average to better sites ($SI_{50} = 55$ to 69) in the Lake States.

STUDY AREA

The study was conducted in three hardwood stands dominated by sugar maple (*Acer saccharum* Marsh.). Most stand volume was in saw logs, with relatively little volume in pole-size trees, which is characteristic of mature hardwood stands. Before cutting, the study areas contained from 100 to 152 square feet of basal area per acre (trees 4.6 inches d.b.h. and larger) and averaged 15,000 board feet gross or 11,000 board feet net per acre (Scribner Decimal C). From 1943 to 1946, the entire area was given a light improvement cut. This cut removed an average of 1,300 net board feet per acre. A 1949 salvage cutting removed only dead and windthrown trees, and did not materially change study area stocking.

Sugar maple generally accounted for 70 to 80 percent of the total stand basal area. Other predominant species were yellow birch (Betula *alleghaniensis* Britton), beech (*Fagus grandifolia* Ehrh.), and red maple (*Acer rubrum* L.). Species generally representing less than 1 percent of stand basal area included hemlock (*Tsuga canadensis* (L.) Carr.), basswood (*Tilia americana* L.), elm (*Ulmus americana* L.), red oak (*Quercus rubra* L.), and ironwood (*Ostrya virginiana* (Mill.) K. Koch). Sugar maple reproduction was abundant throughout the study areas.

The study areas were level, and well drained soils predominated. A soil survey lists three common series: Trenary fine sandy loam, Trenary sandy loam, and Munising sandy loam. The Munising series are well to moderately well drained podsols on acidic sandy loam glacial till. The profile is characterized by a friable fine sandy loam in the A horizon, a fragipan at depths of 15 to 30 inches, and a slight to medium acid C horizon (pH 6.0-5.5). It has a better developed fragipan and a more acid C horizon than the similar Trenary series. All three series are considered average or above in site quality. Site index on Munising sandy loam soils on the study sites generally range from 60 to 69[1]. Stand measurements before treatment indicate no significant differences in species composition, stocking, estimated cull, and stand height among the soil series.

STUDY DESIGN AND METHODS

The study consisted of three replications in a completely randomized block design. The first replication was established in the winter of 1951-1952 and the second and third were done during two succeeding winters. Each replication had 10 compartments (10 to 15 acres in size), one for each stocking level-cutting cycle combination. Compartment treatment was randomly assigned. The main effects in the experimental design were cutting cycle (C_i) and residual stocking level (S_j). Assuming no interaction between the replication (R_k) and main effects, the model for any observed value (X) was the sum of an overall mean (μ), treatment effects and their interaction, and a random error:

$$X = \mu + C_i + S_j + R_k + CS_{ij} + E_{e(ijk)}.$$

Cutting cycle was considered a fixed variable. Stocking level, which could not be controlled exactly, was considered a random variable. ANOVA was used to calculate the sum of squares, degrees of freedom, mean square, and F statistic for each factor and the interaction.

Stand measurements were confined to a series of permanent ⅕-acre plots located at fixed intervals along compartment cruise lines. At least 10, and as many as 17 plots were established per compartment. All trees 4.6 inches d.b.h. and larger were mapped, numbered, and listed by species and d.b.h. After each plot's basal area was computed, enough trees were marked for cutting to reduce the plot's residual basal area of trees 9.6 inches d.b.h. and larger to prescribed levels. Most ⅕-acre plots were marked to within ±2 square feet of the desired residual area. The remainder of the stand within a compartment was marked to the desired stocking level by ocular estimates. In marking, poor quality and high risk trees were generally selected for removal, leaving the most promising trees for growing stock. After the first 5-year cycle, each compartment was partitioned into 0.8- to 1.0-acre blocks, 100 percent tallied, and marked to ±3 feet of the prescribed stocking for trees 9.6 inches d.b.h. and over. The methodology change avoided the difficulties of controlling stocking on small plots, but growth data collection continued on the same ⅕-acre plots. Compartments were marked using Arbogast's guide (1957).

Measurements were made at 5-year intervals following the establishment of each replication. The 5-year cycle cuts for the first replication were in 1951, 1956, 1961, and 1966. The 10- and 15-year cycle cuts were done in 1951 and 1962, and 1951 and 1966, respectively. The 20-year cycle cut (30 square-foot level only) was made in 1951. Cuts in replications two and three were 1 and 2 years later, respectively. The cutting history of each replication and treatment is presented in table 1.

Following the initial cutting, all ⅕-acre plots were checked to make corrections for trees lost during logging and to detect any trees marked but not cut. Data on total height, merchantable saw log height, height to the lowest living branch, cull class, tree quality and form were also taken on five or more sample trees per plot as part of the post-logging measurements.

A wind storm occurred on June 30, 1953, after replications one and two were established and cut but before replication three was installed. Severe damage was limited to a narrow strip across the Experimental Forest. Flanking this strip, scattered patches of breakage and windthrow occurred. Parts of replications one and two were within the strip of maximum destruction and three compartments—30/20 rep 2, 50/5 rep 1, and 50/15 rep 2—were replaced at the same time and in the same general area as replication 3.

Both volume and basal area growth were analyzed for the four study measurement periods. Fifth-acre measurements were summed to a per acre basis and growth was computed annually for each period. The recognized units of growth included survivor growth, ingrowth, and gross and net growth. Mortality was also recorded. The study used definitions presented by Erdmann and Oberg (1973):

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[1] *Personal communication with G. Erdmann.*

Table 1.—*Summary of original stocking and cutting history by treatments for trees 4.6 inches d.b.h. and larger and for trees 9.6 inches d.b.h. and larger*

Stocking (percent)	Cutting cycle (years)	Original stand			Initial cut			Second cut			Third cut			Fourth cut		
		Replications														
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
BA (sq ft/acre)—TREES ≥ 4.6 INCHES D.B.H.																
30	20	130.1	125.8	138.2	92.7	87.6	100.7									
50	5	109.3	147.9	100.8	46.1	90.8	41.9	8.3	6.1	5.8	9.8	6.9	8.5	8.5	7.0	13.8
	10	152.5	127.5	124.9	96.7	69.1	68.9				10.4	19.5	18.1			
	15	110.1	110.9	132.4	51.5	46.7	73.1							19.6	20.5	22.4
70	5	146.6	123.5	122.6	70.4	44.5	45.3	8.6	0.0	7.8	6.5	16.9	7.9	12.5	11.1	12.6
	10	124.7	132.8	129.7	48.2	51.9	53.1				6.5	12.2	19.3			
	15	142.2	146.2	121.1	60.5	69.4	43.3							19.2	18.8	20.3
90	5	143.5	141.5	142.4	51.8	44.7	44.9	3.7	5.5	6.3	3.4	11.1	12.8	8.0	7.1	5.6
	10	130.8	127.7	120.6	31.8	32.1	25.1				10.0	16.1	5.9			
	15	139.9	138.4	127.8	46.1	40.3	30.3							12.6	10.3	8.4
BA (sq ft/acre)—TREES ≥ 9.6 INCHES D.B.H.																
30	20	118.9	114.4	125.6	89.1	84.2	96.6									
50	5	93.3	135.6	88.9	43.6	86.0	39.6	7.6	5.9	5.8	9.5	6.9	7.9	8.4	6.9	13.5
	10	143.9	116.0	113.4	93.7	64.6	66.0				6.7	19.1	17.2			
	15	98.5	89.0	118.8	49.1	42.0	68.4							12.9	20.5	22.1
70	5	136.3	111.3	109.4	67.5	42.2	42.5	8.5	0.0	7.4	6.4	16.6	7.4	3.5	10.8	12.6
	10	113.5	117.6	118.5	45.5	35.1	49.4				6.4	11.9	19.0			
	15	131.5	136.2	109.1	59.3	66.7	40.3							18.5	18.8	20.3
90	5	133.9	129.6	129.4	49.4	41.8	40.4	3.6	5.5	5.8	3.4	11.0	12.7	7.4	7.0	5.5
	10	119.8	117.8	108.1	30.4	24.8	22.1				9.8	14.6	6.0			
	15	130.3	126.2	118.2	43.0	37.8	27.6							12.2	19.6	4.7
VOLUME (cu ft/acre)—TREES ≥ 4.6 INCHES D.B.H.																
30	20	4245.0	4038.0	4491.8	3066.2	2833.6	3310.8									
50	5	3516.1	4830.0	3271.4	1513.4	2987.6	1380.9	263.8	203.0	191.1	323.5	230.6	279.5	280.9	226.6	458.2
	10	5005.7	4160.7	4065.9	3197.0	2275.2	2269.8				343.6	538.5	596.2			
	15	3591.4	3545.7	4296.3	1701.5	1523.1	2394.4							646.3	679.4	742.3
70	5	4793.6	4013.5	3982.3	2322.2	1466.8	1482.3	284.0	0.0	256.6	216.6	560.1	259.6	409.9	369.7	420.2
	10	4067.5	4292.1	4229.2	1586.4	1697.4	1736.1				215.1	400.8	635.9			
	15	4639.9	4764.7	3940.3	1996.3	2264.4	1417.7							636.7	624.6	677.8
90	5	4691.0	4602.3	4626.4	1708.3	1445.6	1457.9	122.5	181.8	205.6	112.1	368.3	423.0	261.4	238.2	185.7
	10	4266.7	4162.0	3921.3	1045.7	1050.1	1811.8				327.8	532.6	198.1			
	15	4577.7	4520.2	4173.3	1510.9	1322.6	985.3							417.1	679.2	277.8
VOLUME (cu ft/acre)—TREES ≥ 9.6 INCHES D.B.H.																
30	20	3930.0	3720.4	4135.2	2965.1	2742.5	3198.8									
50	5	3067.4	4483.8	2937.9	1442.5	2853.8	1317.0	243.8	197.3	0.0	314.2	229.1	240.8	278.2	202.6	450.2
	10	4765.0	3839.1	3739.9	3114.2	2172.4	2188.8				339.5	529.3	570.6			
	15	3257.1	2927.7	3914.1	1635.2	1399.4	2266.1							627.9	679.4	731.1
70	5	4504.9	3671.0	3613.4	2242.0	2258.9	1405.3	282.3	0.0	244.9	210.6	551.9	248.0	401.0	362.0	420.2
	10	3751.6	3865.0	3914.7	1508.9	1604.2	1634.4				214.2	393.5	628.2			
	15	4338.5	4481.9	3600.3	1961.4	2206.2	1335.2							617.2	606.3	677.8
90	5	4421.3	4268.0	4259.9	1642.4	1363.7	1334.7	117.8	181.8	201.4	112.1	366.4	417.6	244.3	234.6	180.5
	10	3954.4	3885.4	3570.2	1007.4	986.6	1728.2				323.8	522.9	198.1			
	15	4304.9	4176.5	3904.3	1425.3	1250.9	910.4							406.9	651.7	274.1

Survivor growth—Growth on trees present at both the beginning and end of a measurement period within a given size class.

Ingrowth—Growth on trees that grew into the 4.6-inch d.b.h. class during a measurement period (new growing stock) or growth on trees that grew into the 9.6-inch d.b.h. class (new saw log tree).

Mortality—Volume or basal area of all trees that died during a measurement period.

Cubic foot volumes were obtained from composite volume tables for the Lake States (Gevorkiantz and Olsen 1955). Board foot volumes (Scribner rule) were obtained from local volume tables prepared for the Upper Peninsula Experimental Forest. Gross growth was calculated for each measurement period by adding survivor growth and ingrowth. Gross growth minus mortality equalled net growth.

Both residual stocking and structure affect growth, but it is often difficult to separate them in analyzing field experiments. To better test this interaction, Moser's (1974) growth model for northern hardwoods was applied to a variety of stocking levels and structures. The cutting studies reported by Eyre and Zillgitt (1953) provided the basic data for developing Moser's projection system. Tests using our study's 1951 data as initial conditions and projecting 1971 measurements show the model is a valuable predictive tool (Moser *et al.* 1979). The model provides estimates of basal area, volume, and number of trees by size classes for ingrowth, survivor growth, and mortality.

Stand structure can be characterized by size-class distribution, which in an ideal all-age forest, follows a simple geometric progression. The ratio between the number of trees in succeeding size classes is called q. The number of trees in a size class multiplied by q equals the number in the next smaller size class. A low q (1.1) describes a stand with proportionally more large trees, while a large q (1.5) describes a stand with proportionally more small trees. A q of 1.3 is generally recommended for northern hardwoods in the Lake States (Tubbs and Oberg 1978). A range of q values from 1.1 to 1.4 were tested in the model, each applied to the stocking levels (30, 50, 70, and 90) considered. A diameter distribution was calculated by 2-inch diameter classes (assuming a maximum diameter of 24 inches d.b.h.) for each q factor and stocking level combination. These data representing a variety of stand structures and stockings were used as initial conditions in a 20-year simulation.

RESULTS AND DISCUSSION

Basal Area Growth

Length of cutting cycle affected growth rates, although differences were small and statistically nonsignificant. Survivor growth increased and mortality decreased with decreasing cutting cycle, resulting in net annual basal area growth averaging 2.05, 1.96, and 1.89 square feet per acre for the 5-, 10-, and 15-year cycles, respectively (table 2). Mortality differences among cutting cycles were more evident at the lower stockings (50 and 70 square feet), while survivor growth differences were more evident at the higher stocking (90 square feet). More frequent entry into the stand reduced competition and allowed removal of high risk trees. No differences were evident for ingrowth by cutting cycle. In all cases, the variation within each cutting cycle was substantial, and differences in net growth among cycles did not differ at the 95 percent level of probability.

The lack of significant responses by cutting cycles allowed the pooling of data for considering the impact of residual stocking level on growth (table 3). The 30 square foot stocking level/20-year cutting cycle was also added to the comparisons in table 3. Results indicate average annual net basal area growth remained relatively constant over the range of residual basal areas. At 30, 50, and 70 square feet of residual basal area, net growth for trees 4.6 inches d.b.h. and larger was similar, averaging 2.08 to 2.09 square feet/acre/year, and was slightly less, 1.73 square feet/acre/year, at 90 square feet of basal area. For sawtimber-size trees, net growth ranged from 1.50 to 1.77 square feet/acre/year across the range of stocking levels. A uniform response showed in the study's 5-year results (Church 1960), and net growth uniformity across a wide range of stocking levels has been reported for second-growth hardwoods in the Lake States (Erdmann and Oberg 1973), the Northeast (Solomon 1977), and the Appalachians (Trimble 1968).

The net growth range for the mature stands treated in this study was below the 2.32 to 3.22 square feet of annual basal area growth (trees 4.6 inches d.b.h. and larger) recorded for six cutting treatments made in northeastern Wisconsin over 15 years in second-growth stands dominated by sugar maple, basswood, yellow birch, and white ash (Erdmann and Oberg 1973). Comparative values are expected to converge after several mature stand cuts decrease the proportions of large over-mature trees and increase the representation of fast growing poletimber and small saw logs. In fact, net growth values during the last measurement period at 50 and 70 square feet of residual basal area were within the range of values cited by Erdmann and Oberg (1973) for second growth forests.

Based on a composite of studies, Jacobs (1968) cited an average gross basal area of 2.5 square feet/acre/year (in trees 4.6 inches d.b.h. and larger) for selection stands on the Upper Peninsula Experimental Forest. This is very close to the gross production rate recorded for this study's last measurement period at 30, 50, and 70 feet of residual stocking. Jacobs (1968) further stated that "with continued management, as the small trees develop and the overstory vigor improves, basal area growth may reach 3 square feet/acre/year." The maximum gross rate recorded for any combination of treatments and measurement period in our study was 2.99 square feet/acre/year (N = 108). Thus, 3 square feet would seem a valid upper bound for the stand and site conditions studied here, but average figures are substantially lower.

Table 2.—*Average annual basal area growth in square feet per acre (trees 4.6 inches d.b.h. and larger) and standard deviations by growth component, stocking level, and cutting cycle (Mean values are based on three replications and four measurement periods, N = 12)*

SURVIVOR GROWTH

Cutting cycle (years)	Residual stand density (sq ft/acre) 50	70	90	$\bar{x}$ (SD)
5	1.82	1.95	1.78	1.85(0.34)
10	1.83	1.89	1.75	1.82(0.28)
15	1.82	1.91	1.70	1.81(0.23)
$\bar{x}$ (SD)	1.82(0.33)	1.92(0.27)	1.74(0.22)	
INGROWTH				
5	0.43	0.43	0.25	0.37(0.15)
10	0.45	0.37	0.27	0.37(0.13)
15	0.40	0.34	0.27	0.35(0.13)
$\bar{x}$ (SD)	0.43(0.15)	0.38(0.11)	0.27(0.10)	
GROSS GROWTH				
5	2.25	2.38	2.03	2.22(0.42)
10	2.28	2.28	2.02	2.19(0.35)
15	2.22	2.25	1.97	2.15(0.31)
$\bar{x}$ (SD)	2.25(0.40)	2.30(0.33)	2.01(0.27)	
MORTALITY				
5	0.10	0.15	0.25	0.17(0.18)
10	0.19	0.22	0.26	0.23(0.22)
15	0.20	0.28	0.31	0.26(0.33)
$\bar{x}$ (SD)	0.16(0.22)	0.22(0.31)	0.28(0.23)	
NET GROWTH				
5	2.15	2.23	1.78	2.05(0.52)
10	2.09	2.04	1.76	1.96(0.49)
15	2.02	1.97	1.66	1.89(0.52)
$\bar{x}$ (SD)	2.09(0.54)	2.08(0.54)	1.73(0.35)	

Although differences in average annual survivor growth were not significant ($P > 0.05$) among stocking levels, maximum survivor growth occurred at 70 square feet of stocking for all cutting cycles and the minimum occurred in all cases at 90 square feet (table 2). At 70 square feet, survivor growth ranged from 1.32 to 2.34 square feet/acre/year among replications, cutting cycles, and measurement periods (N = 36), compared to a range of 1.19 to 2.01 at 90 square feet of residual stocking. In comparison to the maximum at 70, the reduced levels of survivor growth at 90 square feet can be explained by increased competition, advanced age, and less opportunity to rid stands of poor growers. At 30 and 50 square feet, stands were initially understocked for survivor growth. By the last growth period, however, survivor growth at these stocking levels exceeded or equalled that measured at 70 square feet (fig. 1).

Table 3.—*Average annual gross and net basal area growth, survivor growth, ingrowth, and mortality for trees 4.6 inches d.b.h. and larger and for trees 9.6 inches and larger*

(In square feet of basal area/acre/year)

TREES 4.6 INCHES D.B.H. AND LARGER

Stocking level[1]	Survivor growth	Ingrowth[2]	Gross growth	Mortality	Net growth
30	1.77	0.56	2.33	0.25	2.08
50	1.82	0.43	2.25	0.16	2.09
70	1.92	0.38	2.30	0.22	2.08
90	1.74	0.27	2.01	0.28	1.73
TREES 9.6 INCHES D.B.H. AND LARGER					
30	1.02	0.66	1.68	0.18	1.50
50	1.16	0.71	1.87	0.14	1.73
70	1.37	0.55	1.92	0.14	1.78
90	1.34	0.42	1.76	0.26	1.50

[1] Unit: residual basal area, square feet/acre. Figures for 50, 70, and 90 square feet represent averages for three cutting cycles, 5, 10, and 15 years. At 30 square feet the cutting cycle was 20 years.

[2] Ingrowth represents sapling ingrowth into poletimber for 4.6 inches d.b.h. and larger, and poletimber ingrowth into sawtimber for 9.6 inches d.b.h. and larger.

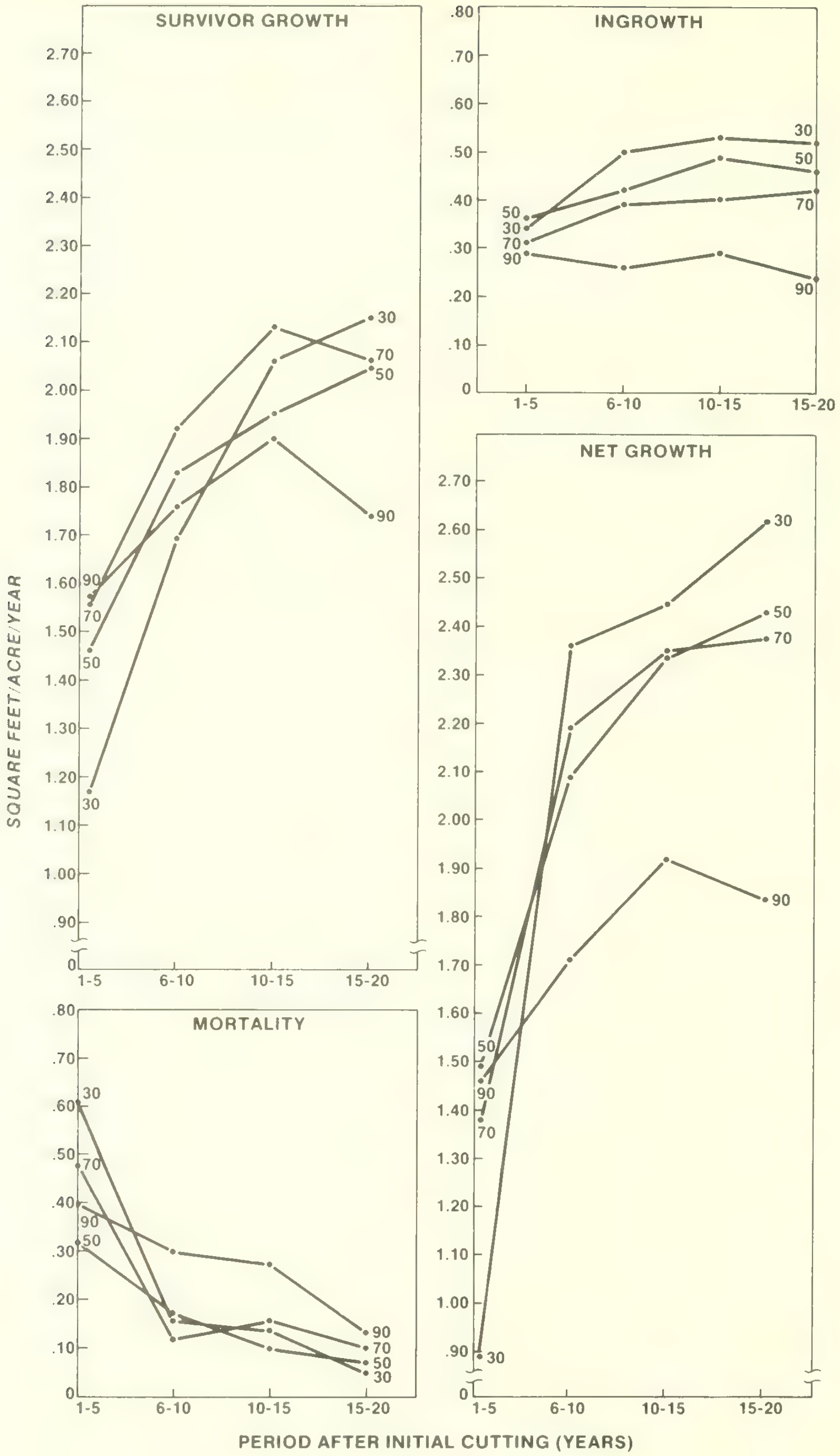

Figure 1.—*Average survivor growth, ingrowth, mortality, and net growth (trees ≥ 4.6 inches d.b.h.) expressed as basal area (square feet/acre/year) by measurement period. Averages based on N = 9 (three cutting cycles, three replications) for 50, 70, and 90 square feet; N = 3 (one cutting cycle, three replications) for 30 square feet.*

Ingrowth accounted for a declining proportion of net annual growth with increasing stocking. At 30 square feet, ingrowth represented 27 percent of net growth, compared to 16 percent at 90 square feet (table 3). Similar trends were noted for ingrowth into the sawtimber class. At 30 square feet, ingrowth into the saw log class was 44 percent of net growth. It declined to 28 percent at 90 square feet. The maximum value recorded for any measurement period, stocking level, cutting cycle combination was 1.23 square feet of ingrowth per acre per year at 30 square feet of stocking and 20-year cutting cycle.

Reduced mortality results from converting slow-growing unmanaged stands to thrifty, managed stands. In an unmanaged stand similar to those in this study, annual mortality averaged 1.23 square feet/acre and almost equalled growth (Eyre and Zillgitt 1953). In managed stands, partial cutting reduced this figure by more than two-thirds. Average study mortality rates increased at the lowest and highest stocking levels and were lowest in intermediate levels (table 3). Higher mortality at 90 square feet occurred when light cutting did not remove a majority of high-risk trees. Other differences are probably not closely related to stocking level. Additional mortality factors are discussed later.

Substantial changes did occur for most growth parameters during the four measurement periods (fig. 1). After a large second period net growth increase, smaller increments were recorded for several growth periods. Maximum gross and net growth rates occurred 10 to 15 years after the initial treatment, and steady increases continued for many individual plots throughout the 20 years of measurement. During the last growth period, net annual growth was inversely related to basal area stocking, with rates at 90 square feet significantly lower ($P < 0.01$) than those at 30, 50, and 70 square feet. The mean net growth recorded for 30, 50, and 70 square feet during the fourth growth period, 2.40 to 2.60 square feet/acre/year, probably best represents the average net annual growth than can be expected for these stands and sites under managed conditions.

Growth components changing the most were survivor growth and mortality. Survivor growth increased from an annual average (all stocking levels) of 1.53 square feet/acre during the first 5 years to 1.84 during the next 5 years, and reached a maximum value of 1.99 after 15 years. Slight declines occurred at 70 and 90 square feet during the last period. By the end of the study, survivor growth varied inversely with stocking level (fig. 1).

Maximum mortality rates were recorded during the first measurement period and declined thereafter (fig. 1). High mortality is not unusual following the first cut in unmanaged stands. During the study's first 5-year period, average annual mortality ranged from 0.32 to 0.62 square foot/acre. After the first period, however, mortality was essentially the same for 30, 50, and 70 square feet, and in the last period, mortality was relatively unimportant regardless of stocking (fig. 1).

Mortality figures for the first measurement period were greatly influenced by the 1953 windstorm and logging damage following the heavy initial cut in the treatment stands. Plot surveys following the initial cut and the 1953 storm identified mortality due solely to those factors. Summaries by stem number and basal area indicate over half of the total mortality and in some treatments as much as 90 percent during the first period was due to logging damage and windthrow (table 4). Data also indicate storm-associated mortality was not density dependent but was related to storm path proximity.

Ingrowth varied only slightly by measurement period (fig. 1). Although ingrowth rates were somewhat lower during the first period at 30, 50, and 70 square feet, they were not significantly different ($P > 0.05$) from subsequent rates. Little or no change occurred with time at 90 square feet.

These data showed the need for long-term measurements. Because rapid changes occurred in mortality and survivor growth during the study's first 10 years, erroneous conclusions and recommendations could easily result if based solely on early information. Nor do 20-year averages necessarily represent differences in stand response among treatments. Greater weight should be given those data from the last two measurement periods.

Cubic-foot Volume Growth

The trends for cubic foot volume (table 5) are similar to those for basal area growth. Twenty-year averages for net and gross cubic foot growth varied little by stocking level and cutting cycle. Average rates at 30, 50, and 70 square feet were almost identical and rates at 90 square feet were only slightly less.

Again, considering only 20-year averages can be misleading due to changes in volume increment with time. Variation by measurement period in mean annual volume growth (net) for trees 4.6 inches d.b.h. and larger can be seen in table 6. At the study's end, stocking level and net annual growth showed a clear relation.

Table 4.—*Factors responsible for poletimber and saw log mortality during the first measurement period (values are based on totals for three replications in each treatment)*

Factor	Number of trees	Percent of total	Basal area (sq. ft.)	Percent of total
		30/20[1]		
Windstorm	23	38	13.47	56
Logging damage	28	47	5.28	22
Other	9	15	5.36	22
		50/5		
Windstorm	20	47	8.15	55
Logging damage	18	43	5.78	39
Other	4	10	0.89	6
		50/10		
Windstorm	8	25	10.30	46
Logging damage	13	39	4.31	19
Other	12	36	7.92	35
		50/15		
Windstorm	9	23	8.14	34
Logging damage	20	50	10.06	42
Other	11	27	5.75	24
		70/5		
Windstorm	2	7	2.18	13
Logging damage	17	61	5.87	35
Other	9	32	8.72	52
		70/10		
Windstorm	15	47	18.92	79
Logging damage	10	31	3.59	15
Other	7	22	1.44	6
		70/15		
Windstorm	17	46	20.48	70
Logging damage	5	14	1.76	6
Other	15	40	7.02	24
		90/5		
Windstorm	9	26	12.52	47
Logging damage	17	50	5.33	20
Other	8	24	8.79	33
		90/10		
Windstorm	4	21	6.66	33
Logging damage	8	42	3.23	16
Other	7	37	10.29	51
		90/15		
Windstorm	13	36	14.67	55
Logging damage	13	36	3.40	13
Other	10	28	8.64	32

[1] Residual stocking (basal area in trees ≥ 9.6 inches d.b.h.)/cutting cycle.

Table 5.—*Average annual gross and net volume growth, survivor growth, ingrowth, and mortality for trees 4.6 inches d.b.h. and larger and for trees 9.6 inches d.b.h. and larger*

(In cubic feet/acre/year)

TREES 4.6 INCHES D.B.H. AND LARGER

Stocking level[1]	Survivor growth	Ingrowth[2]	Gross growth	Mortality	Net growth
30	59.08	14.43	73.51	7.74	65.77
50	60.93	11.16	72.09	5.25	66.84
70	64.14	9.80	73.94	6.95	66.99
90	58.20	6.94	65.14	9.02	56.12

TREES 9.6 INCHES D.B.H. AND LARGER

Stocking level[1]	Survivor growth	Ingrowth[2]	Gross growth	Mortality	Net growth
30	35.29	20.40	55.69	5.84	49.85
50	39.59	20.60	60.19	4.43	55.76
70	46.63	16.76	63.39	5.83	57.56
90	45.44	11.78	57.22	7.79	49.43

[1] Unit: residual basal area, square feet/acre. Figures for 50, 70, and 90 square feet represent averages for three cutting cycles, 5, 10, and 15 years. At 30 square feet the cutting cycle was 20 years.

[2] Ingrowth represents sapling ingrowth into poletimber for 4.6 inches d.b.h. and larger, and poletimber ingrowth into sawtimber for 9.6 inches d.b.h. and larger.

Table 6.—*Average annual net growth in cubic feet per acre and standard deviation for trees 4.6 inches d.b.h. and larger by stocking level and measurement period (Averages are based on N = 3 for 30 square feet and N = 9 for 50, 70, and 90 square feet.)*

Stocking Level (ft²e/acre)	Measurement Period 1	2	3	4
	$\bar{x}$ (SD)—ft³/acre/yr			
30	28.48(30.25)	73.17(4.86)	77.59(4.72)	83.84(3.57)
50	47.78(15.82)	66.87(14.80)	74.77(11.39)	77.91(10.22)
70	44.72(16.07)	70.80(8.20)	75.81(9.06)	76.59(11.05)
90	47.90(9.49)	55.43(14.02)	62.17(9.32)	59.79(4.27)

During the first measurement period, net annual cubic-foot volume growth varied from –6.15 to 70.52 among the various treatments and replications (N = 30). This compares to a range of 53.01 to 94.75 cubic feet/acre/year for the last period. Figures available for second-growth sugar maple stands are substantially higher. For example, Erdmann and Oberg (1973) reported a range from 102 to 123 cubic feet/acre/year (averages) for a cutting methods study in a sugar maple-dominated second growth forest.

Board-foot Volume Growth

The trends for board foot growth paralleled those of other units, except an optimum stocking is more obvious when dealing strictly with saw logs (table 7). The maximum net growth at 70 square feet confirmed the optimum stocking recommended by Eyre and Zillgitt (1953) based on their analysis of several cutting methods. The advantage at 70 square feet continued throughout the study (fig. 2). Most of the explainable differences in net board foot growth among treatments were due to survivor growth. At 30 and 50 square feet of residual stocking, stands were clearly understocked for sawtimber growth (fig. 2).

Ingrowth into saw log classes did not differ greatly because the initial stands were understocked with poletimber (fig. 2). Sapling numbers were greatly affected by the treatments (Tubbs 1968), but sapling growth rates were not large enough to affect saw log ingrowth. As management proceeds, ingrowth should vary substantially by treatment.

In mature stands, advanced age increases mortality risk during the initial management period, and at 90 square feet fewer opportunities to remove trees before they died and became unmerchantable resulted in higher mortality rates (table 7). With continued management, factors such as increasing tree vigor and declining average age minimized mortality differences among stocking levels (fig. 2).

Wide variation in net board foot growth among similarly treated replications was evident (table 8). The correlation coefficient relating stocking and net growth was r = 0.48, indicating that factors other than total stocking were important in determining board foot growth. Other possible factors are site quality, tree age and vigor, stand structure variations, species, and cutting cycle.

Table 7.—*Average annual growth in board feet per acre (Scribner rule) for trees 9.6 inches d.b.h. and larger*

Residual basal area	Survivor growth	Ingrowth	Gross growth	Mortality	Net growth
30	179	18	197	20	177
50	201	18	219	15	204
70	243	14	257	22	235
90	235	10	245	32	213

To further explore how stocking affects board foot growth, the best and worst gross growth for each replication during the 20 years (excluding the 30 square foot treatment) were plotted and fit with a polynominal curve (fig. 3). Average growth declined sharply in stands with stocking less than 60 square feet and more than 90 square feet. However, very good growth (300 board feet/acre) can occur between about 50 square feet and 90 square feet. The best possibility for optimum growth is at 60 to 80 square feet of residual basal area in trees over 10 inches d.b.h. (fig. 3). Stands growing at about 2.0 square feet of basal area net growth, with residual basal areas between 60 and 70 square feet, and cut at intervals between 5 and 15 years, should remain within the stocking level range producing maximum growth.

According to Eyre and Zillgitt (1953), a net average annual growth of 200 board feet/acre should be obtainable for managed northern hardwood stands on good Lake State upland sites. After the first measurement period, average net growth exceeded 200 board feet/acre/year for all treatments except the lowest stocking level (table 8). Growth rates after the first period at 70 square feet averaged 260 and 270 board feet (net) /acre/year and 300 to 320 board feet/acre/year were recorded for several growth periods in replications at 50, 70, and 90 square feet of residual stocking.

D.b.h. Growth

Results indicate partial cutting can sharply increase average stand diameter growth. Average 20-year diameter growth for sugar maple in unmanaged stands is usually approximately 2.0 inches (Jacobs 1968). Average study 20-year growth ranged from 4.28 inches for a 6-inch (beginning d.b.h.) tree at 50 square feet to 2.35 for a 6-inch tree at 90 square feet (table 9).

Average diameter growth of sugar maple generally declined from the smallest to largest trees, from the lightest residual stocking to the heaviest, and from the shortest to the longest cutting cyle. Yellow birch, the only associated species numerous enough to analyze, with a beginning diameter of 6 inches outgrew sugar maple with a similar beginning diameter, but larger yellow birch grew more slowly than sugar maple.

Maximum sugar maple growth rates were summarized to indicate diameter growth potential (table 9). Growth rates as high as 7 and 8 inches were recorded on 6-inch class trees for the 20-year period. Twelve-

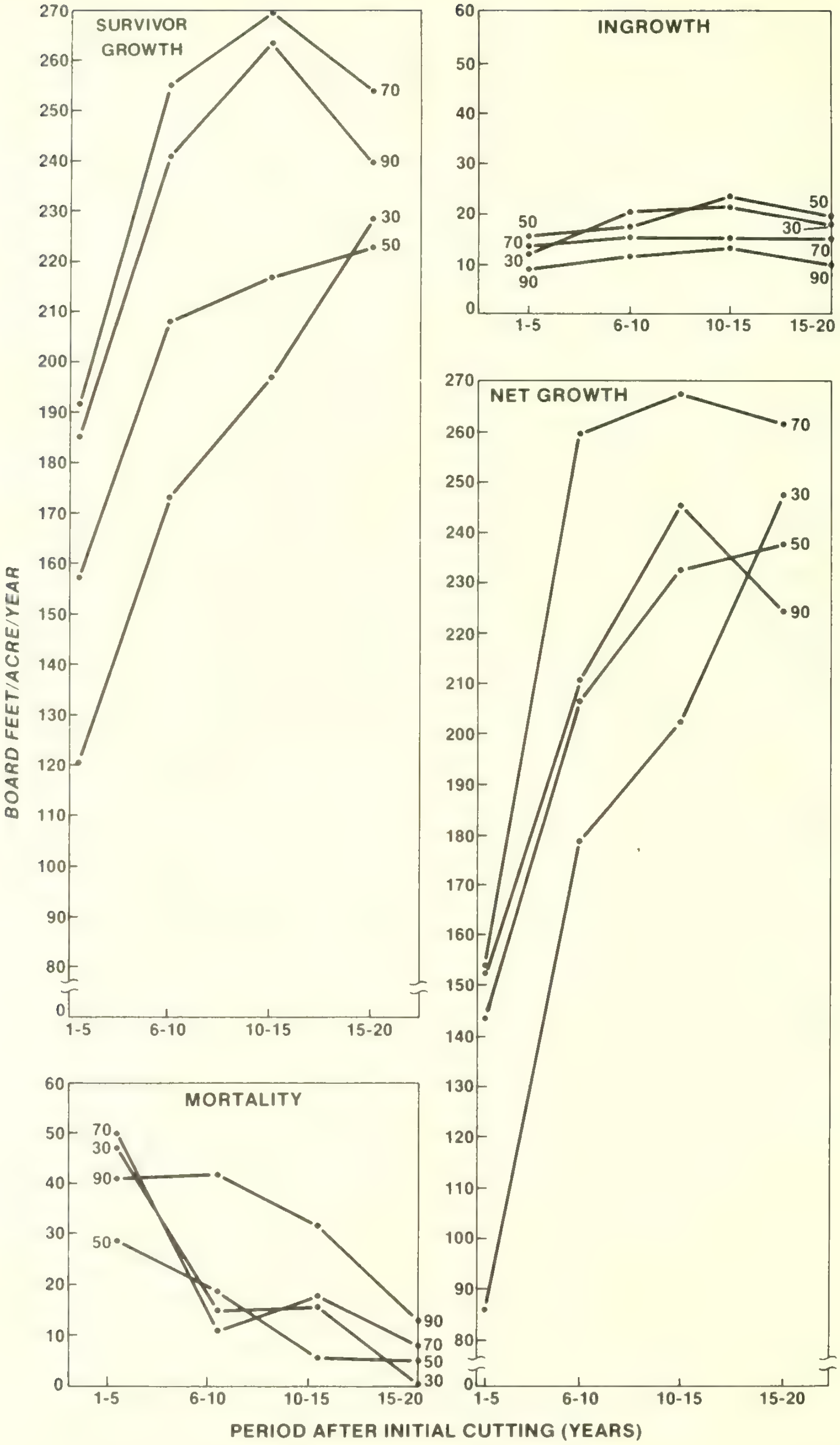

Figure 2.—*Average survivor growth, ingrowth, mortality, and net growth (trees ≥ 9.6 inches d.b.h.) expressed as board feet (Scribner Decimal C)/acre/year by measurement year. Averages based on N=9 (three cutting cycles, three replications) for 50, 70, and 90 square feet; N=3 (one cutting cycle, three replications) for 30 square feet.*

Table 8.—*Average annual board foot growth (net per acre and standard deviation for trees 9.6 inches d.b.h. and larger by stocking level and measurement period) (Averages are based on N = 3 for 30 and N = 9 for 50, 70, and 90 square feet.)*

Stocking Level (ft^2e/acre)	Measurement Period 1	2	3	4
	$\overline{x}$ (SD)—bd ft/acre/yr (Scribner rule)			
30	89(77)	178(42)	202(13)	247(26)
50	143(42)	206(52)	232(34)	237(44)
70	153(61)	259(39)	267(35)	261(41)
90	152(64)	210(76)	245(37)	224(40)

inch trees grew at maximum rates from 3.6 to 7.1 inches while 18-inch trees ranged from 4.2 to 5.8 inches d.b.h. growth. Value increase occurring from maximum growth rates could be substantially higher than those reported by Godman and Mendel (1978). Thus, the most vigorous trees should remain in the stand.

Jacobs (1968) illustrated the gradual diameter increase in similar stands over several decades of partial cutting. Average and perhaps maximum rates would be expected to change similarly in this study.

Cut vs. Growth

When board foot cut was compared with board foot growth (table 10), the cut was proportionately less in more heavily stocked stands and longer cutting cycles. Apparently, stands cut more heavily and at shorter intervals are becoming balanced more rapidly due to faster ingrowth and reduced saw log mortality. As management proceeds, all cycles and treatments should result in balanced stands capable of sustaining cuts nearly equal to growth; however, the more lightly cut stands on longer cycles will take longer to reach a balanced structure.

Board foot cut (no deduction for cull) tended to be greatest for stands under the 5-year cutting cycle (table 10). Those treatments with cuts of 175 board feet or less were due partly to undercutting, thus stands under 10- and 15-year cycles were nearly equal.

Stand Structure and Stocking

The hypothetical stands used to test the interaction of structure and stocking on growth are given in table 11. Projections for the total stand (≥ 4.6 inches d.b.h.) in figure 4A indicated declines in basal area growth with increasing stocking levels and q values. The growth trends with increasing stocking corroborated trends measured for trees 4.6 inches d.b.h. and larger during the last two study growth periods (fig. 1). At low stocking levels (30 and 50), maximum growth rates in the simulated stands occurred at 1.2 (q), although differences in growth rates were not great for q's of 1.1 to 1.3. At higher stocking levels (70 and 90), substantial declines in growth rates resulted at q values 1.3 and 1.4.

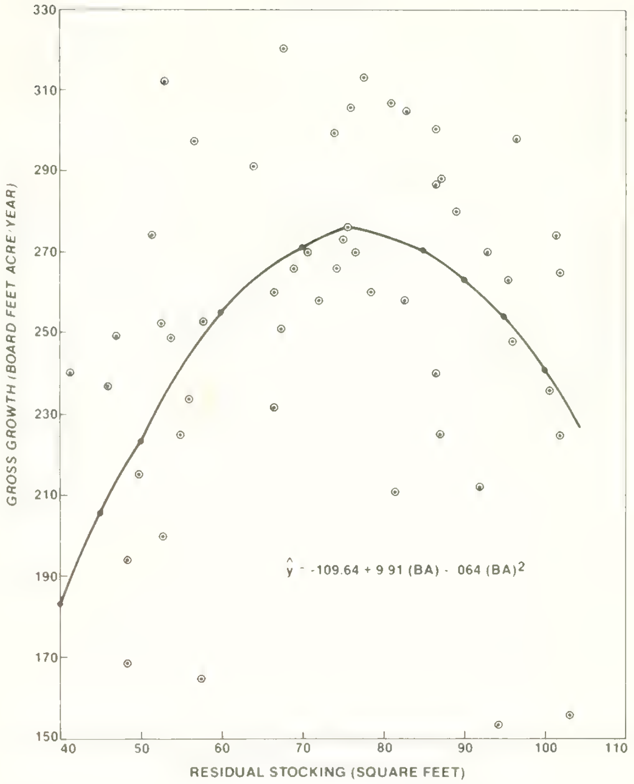

Figure 3.—*Plots of board foot gross growth for the best and worst growing periods (excluding the first period) for each replication. Curve represents best regression fit between residual basal area (square feet) and gross growth in board feet.*

Mortality was primarily responsible for differences in figure 4A. Mortality was especially heavy in the pole-timber class at 70 (1.4), 90 (1.3), and 90 (1.4), where smaller size classes suffered in overstory competition. A net growth decline resulted. As measured by number of trees, ingrowth increased substantially with lower stocking and q factor, but differences were not significant in terms of basal area during the 20-year simulation. Survivor growth varied little by q factor and stocking level.

Table 9.—*Average and maximum 20-year diameter growth of sugar maple under various densities, cutting cycles, and beginning diameters*
(In inches)

	Stocking density/acre (trees 9.6 inches d.b.h. and larger)											
	30			50			70			90		
	Beginning diameter (inches)											
Cutting cycle	6	12	18	6	12	18	6	12	18	6	12	18
	AVERAGE											
5				4.3	4.2	4.0	3.5	3.3	3.1	2.7	2.7	2.8
10				3.9	3.9	3.8	3.2	3.2	3.2	2.3	2.5	2.6
15				3.9	3.5	3.2	3.1	3.2	3.3	2.4	2.5	2.6
20	4.0	3.8	3.7									
	MAXIMUM											
5				6.9	6.1	5.8	5.7	5.1	4.6	8.4	5.1	4.0
10				6.3	6.5	5.0	5.8	7.1	5.0	5.6	4.9	3.7
15				7.1	5.6	4.2	7.1	5.7	4.6	3.9	3.6	5.1
20	7.0	6.8	3.8									

Table 10.—*Board foot harvest on an annual basis and board foot harvest as a percent of net growth by stocking level and cutting cycle*

	Stocking level (square feet/acre)		
Cutting cycle (years)[1]	50	70	90
	HARVEST (bd ft/acre/year (SCRIBNER RULE))		
5	198	251	188
10	188	171	151
15	174	183	134
	HARVEST AS PERCENT OF GROWTH		
5	96	100	61
10	95	74	69
15	79	70	52

[1] 5- and 15-year cycles for 15-year period. 10-year cycle for 10-year period.

When considering sawtimber growth only (fig. 4B), maximum growth rates were obtained at two different stocking levels—structures, 70 (1.3) and 90 (1.2). Differences in growth rates were small at 50, 70, and 90 square feet at q's of 1.2 and 1.3 (fig. 4B), but declines in simulated sawtimber growth occurred at structures represented by q's equal to 1.1 and 1.4 (table 11). The projected decline at 70 (1.4) in figure 4B was a combination of high mortality in pole-size trees and the lack of saw log class ingrowth. At 50 (1.4), mortality was substantially less than for 70 (1.4) and at 90 (1.4), sawtimber growth (survivor growth) exceeded that at 70 (1.4), thus compensating for mortality and lack of ingrowth. In researching uneven-aged stand management, the development and stocking of the small size class, i.e., the saplings and poles, and the relation of their development to long-term productivity should receive greater emphasis.

In the field studies, application of existing marking rules (Eyre and Zillgitt 1953, Arbogast 1957) produced variations in size class distribution and maximum tree size by stocking level. Leaving 90 square feet of basal area resulted in a structure close to q = 1.2, with the greatest basal area stocking in the largest trees (20 inches d.b.h. +). Residual stands of 70 square feet in saw log trees approximated (q ~ 1.3) the structure recommended by Eyre and Zillgitt (1953). These stands had the greatest stocking in medium-sized saw logs and produced the maximum board foot growth (table 7). Stands with 50 square feet of residual basal area developed larger q values, and few study plots had trees greater than 24 inches d.b.h.

Recommendations for stocking and structure depend on management objectives. Where the goal is maximum total stand production, low residual stocking levels (30 or 50 square feet of basal area in saw log classes) provide optimal growth rates. Simulation procedures further suggest a low q value (~ q = 1.2) for maximum stand growth. The distribution of trees and basal area by diameter class for 30 (1.2) is given in table 11.

Both field results and simulation indicated maximum sawtimber growth at the intermediate stocking

Table 11.—*Initial conditions used for testing the effects of stocking and structure on basal area growth (distributions were calculated using procedures outlined by Tubbs & Oberg (1978) assuming a maximum tree diameter of 24 inches)*

Size classes (inches)	q factors							
	1.1	1.2	1.3	1.4	1.1	1.2	1.3	1.4
	Number of trees/acre				Basal area (ft^2/acre)			
30/50[1]								
1.6- 4.5	14.7	27.5	46.2	72.2	0.8	1.4	2.4	3.5
4.6- 9.5	14.2	22.7	32.0	42.2	4.7	6.9	9.7	12.5
9.6-14.5	11.2	14.6	16.9	18.9	10.0	12.0	13.8	15.1
14.6-19.5	9.6	9.6	8.7	7.9	15.6	15.2	14.4	12.9
19.6-24.5	6.7	6.3	4.6	3.5	20.0	15.8	12.4	9.3
Stand total	56.4	80.7	108.4	144.7	51.1	51.3	52.7	53.3
50/70								
1.6- 4.5	20.6	38.5	64.7	101.0	1.1	2.0	3.3	5.0
4.6- 9.5	20.7	31.8	44.6	59.3	6.5	9.9	13.5	17.6
9.6-14.5	16.5	20.4	23.9	26.4	13.8	16.8	19.4	21.1
14.6-19.5	12.8	12.9	12.0	11.1	21.5	21.4	18.0	18.1
19.6-24.5	10.3	8.2	6.4	4.9	28.0	22.2	17.1	13.1
Stand total	80.9	111.8	151.6	202.7	70.9	72.3	71.3	74.9
70/90								
1.6- 4.5	26.5	49.5	83.2	129.9	1.4	2.6	4.2	6.4
4.6- 9.5	26.7	40.8	57.5	76.2	8.5	12.7	17.5	22.6
9.6-14.5	21.1	26.3	30.6	34.0	17.7	21.6	24.9	27.2
14.6-19.5	16.6	16.4	15.5	14.2	27.9	27.3	25.5	23.2
19.6-24.5	13.2	10.6	8.2	6.3	36.1	28.5	22.0	16.9
Stand total	104.1	143.6	195.0	260.0	91.6	92.7	94.1	96.3
90/110								
1.6- 4.5	32.4	60.5	101.7	158.7	1.7	3.1	5.2	7.8
4.6- 9.5	32.5	50.0	70.3	93.0	10.3	15.6	21.3	27.7
9.6-14.5	25.9	32.1	37.4	41.5	21.6	26.5	30.4	33.1
14.6-19.5	20.2	20.1	18.9	17.4	34.0	33.4	31.1	28.3
19.6-24.5	16.0	12.9	10.1	7.7	43.5	34.8	27.1	20.5
Stand total	127.0	175.6	238.4	318.3	111.1	113.4	115.1	117.4

[1] Basal area (square feet) in sawtimber-sized trees/total stand basal area (square feet)

levels and q values, with little difference in sawtimber growth at 50, 70, and 90 square feet and q's of 1.2 and 1.3. Maximum growth occurred at 70 (1.3) and 90 (1.2). Based on our field measurements, however, the recommended structure and stocking for sawtimber growth is q = 1.3, with 72 square feet in sawtimber and 94 feet in the total stand ≥ 4.6 inches d.b.h. (table 12). This recommendation agrees closely to that proposed by Eyre and Zillgitt (1953) for uneven-aged northern hardwoods, but does not support the proposed stocking based on Adams' and Ek's (1974) work.

Using Ek's (1974) growth model, Adams and Ek (1974) projected diameter distributions that maximized several parameters of tree value as well as cordwood and board foot volume growth. Regardless of the parameter, the distributions had many more trees in the smaller diameter classes and fewer trees in the larger classes than recommended by Eyre and Zillgitt (1953). Our projections suggest very high mortality rates in the sapling, pole, and small saw log classes with structures recommended by Adams and Ek (1974). Projected over 20 years, these rates severely decreased stand volume growth. Some of these

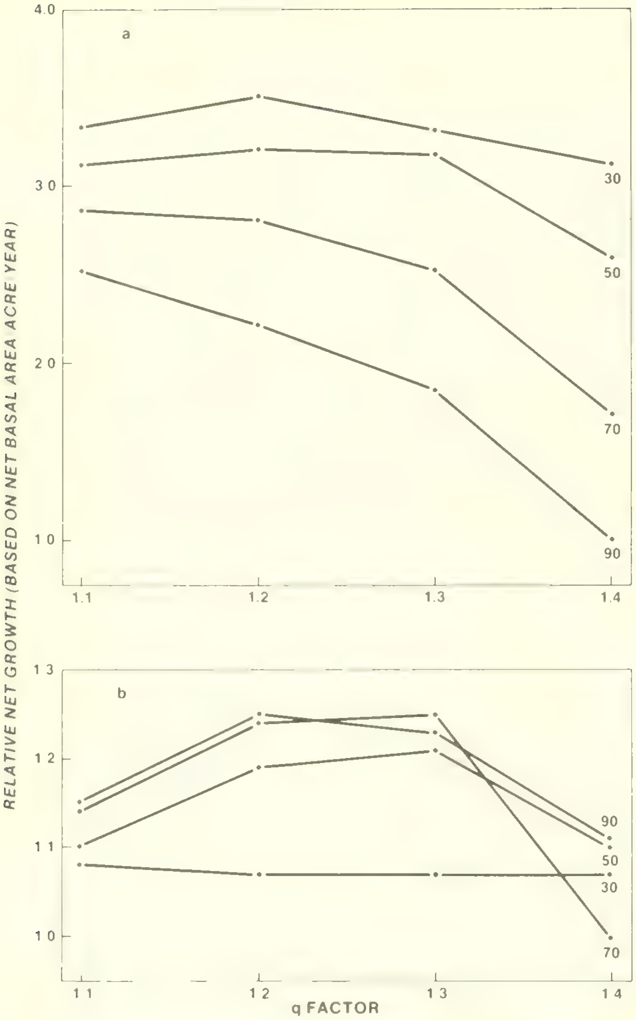

Figure 4.—*Optimization using a growth model to test the combined effects of stocking and structure on growth. Because predicted absolute growth rates were less important than the relative position of the response curves, values were plotted on a relative scale. (a) Average net annual basal area growth for all trees ≥ 4.6 inches d.b.h.; (b) Average net annual basal area growth for trees ≥ 9.6 inches d.b.h. Averages were based on a 20-year simulation; initial conditions for the model are given in table 11.*

differences are related to stand condition and composition. Ek's (1974) model was based on second-growth stands of at least 50 percent (basal area) sugar maple, along with yellow and white birch, aspen, northern red oak, and balsam fir. The mature stands in our study were predominantly sugar maple.

CONCLUSIONS

Our results suggest that stocking recommendations published by Eyre and Zillgitt (1953) are valid. Sugar maple stands on average or better sites (SI = 55 to 69) in northern Wisconsin and Michigan will produce saw logs at acceptable rates and develop a balanced structure when residual stocking is near 70 square feet in saw log trees (92 square feet for the entire stand) and harvest occurs every 10 years. At this stocking, annual growth rates should average 2.0 to 2.5 square feet of basal area/acre on average to better sites (trees ≥ 4.6 inches d.b.h.), 60 to 90 cubic feet/acre (trees ≥ 4.6 inches d.b.h.), and 200 to 300 board feet/acre (trees ≥ 9.6 inches d.b.h.).

Table 12.—*A comparison of growing stock distributions recommended for optimum sawtimber production in northern hardwood stands*

	Present study[1]		Eyre and Zillgitt (1953)		Adams and Ek (1974)[2]
D.b.h. class (inches)	Number of trees/acre	Basal area (sq ft/acre)	Number of trees/acre	Basal area (sq ft/acre)	Number of trees/acre
1.6-4.5	83.2	4.2	202	8	—
4.6-9.5	57.5	17.5	65	16	149.1
9.6-14.5	30.6	24.9	28	22	79.8
14.6-19.5	15.5	25.5	17	26	15.4
19.6-24.5	8.2	22.0	8	20	0.7
Stand total	195.0	94.1	320	92	245.0 (>6"d.b.h.)

[1] Obtain from diameter distribution for 70 square feet of residual stocking in trees 9.6 inches and larger with a q = 1.3.

[2] Diameter distribution for optimal 5-year board foot growth; values were derived from 2-inch d.b.h. classes from 6 to 18 inches d.b.h.

Optimal growth at 70 square feet was the result of rapid survivor growth and low mortality. Maximum survivor growth occurred at 70 square feet. Stands at 30 square feet were clearly understocked for survivor growth. The importance of survivor growth was especially evident when considering board foot growth (table 7). Mortality was an important factor early in the study. Under managed conditions at the end of the study, however, mortality varied little by stocking level. Ingrowth accounted for a declining proportion of net annual growth with increasing stocking, and partially compensated for trends observed in survivor growth and mortality.

Near optimal growth rates, however, were obtained over a wide range of treatments and several structural and stocking combinations resulted in satisfactory growth during the 20-year measurement period. These combinations 70 square feet (q = 1.3) and 90 square feet (q = 1.2) in saw log trees, provide different management options. The lower density (70) favors faster growth, while the higher density (90) favors tree quality and form (Godman and Books 1971).

A short cutting cycle (e.g., 5 years) allows the harvest of trees normally lost to mortality at 15- or 20-year cycles. However, differences in net growth for 5-, 10-, and 15-year cycles were small and selecting among these cutting cycles should be based on practical considerations.

Optimal stocking and structure in this study were based on growth rates. Optimization based on value and economic return could provide different results. Because size, quality, and value are closely related, the greatest economic return may be produced by those stands whose structures include the greatest number of large trees. The fact that differences in growth at 50, 70, and 90 square feet were not large in a practical sense provides additional support for economic rather than biological factors in deciding which stocking to use.

ACKNOWLEDGMENT

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The impacts of stocking, structure, and cutting cycle on basal area, cubic foot volume, board foot volume, and diameter growth are considered. Recommendations are provided for maximum growth in uneven-aged sugar maple stands.

KEY WORDS: *Acer saccharum*, uneven-age management, Lake States, stocking, stand structure, cutting cycle.

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HARVESTING WOOD FOR
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Rodger A. Arola and Edwin S. Miyata

North Central Forest Experiment Station
Forest Service, U.S. Department of Agriculture

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HARVESTING WOOD FOR ENERGY

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Houghton, Michigan

Although energy production is the greatest single world-wide use of wood, there has been relatively little interest in using wood for fuel in this country since the turn of the century. In the last few years, however, due to the spiraling fuel costs and the scarcity of petroleum fuels, there has been renewed interest in the use of wood fuel in the United States. Forest and mill residues, especially, have received considerable attention to supplement conventional fossil fuels.

Trade journals repeatedly cite case histories of forest industries which have converted to wood fuel; most of these facilities currently rely on primary and secondary mill residues. Mill residues, however, although they may presently be the most economical source of energy wood, will not be sufficient to satisfy the increasing industrial wood fuel demands of the future. A far greater potential lies in the large volumes of currently unutilized wood fiber in existing forest stands.

This potential can be at least partially realized through conventional harvesting operations with existing equipment and technology. Some of the benefits, in addition to more efficient use of the resource, would include reduction of logging slash, thinning of overcrowded stands, and conversion of low-quality, understocked stands. To illustrate the potential of harvesting wood for industrial energy, we have detailed the results of five harvesting operations.

CASE STUDIES

There is a lack in the literature of well documented information on the costs and productivity of timber harvesting with various types of commercial logging equipment. Since each logging operation is different, each must be analyzed independently, taking into account the equipment used, the stand conditions, and other considerations.

The objective of this paper is to present pertinent cost and productivity data for several harvesting operations. These operations were not all conducted to provide wood fuel, but the information is still of value to those considering the harvest of wood for energy.

The case studies are based on the following harvesting operations:

- Two mechanized thinning operations in pole-sized hardwoods.
- One hardwood land-clearing operation (for agricultural land).
- One hardwood land-clearing operation (for site conversion).
- One relogging operation of hardwood tops and limbs resulting from a saw log harvest.

All of the studies were conducted between 1974 and 1978. For convenience and uniformity, all harvesting costs have been converted to 1980 dollars.

CASE I—MECHANIZED THINNING OF POLE-SIZED HARDWOODS

Stand Description

In 1974, a 50-acre, predominantly pole-sized stand of mixed northern hardwoods containing a few saw log trees on the Mishwabic State Forest in Michigan's Upper Peninsula was selected for mechanized thinning trials (fig. 1)(Biltonen *et al.* 1976). The soil was a sandy loam and the terrain had only minor changes in elevation. Approximately one-half mile of existing woods haul road was improved to facilitate chip-van transport. Landings were located 1,650 feet apart at each end of the woods haul road.

The stand contained 13 cords of hardwood pulpwood per acre and close to 2,700 board feet of sawtimber per acre in trees 10 inches diameter breast height

Figure 1.—*Typical pole-sized hardwood stand before thinning—Case I.*

(d.b.h.) and larger. Basal area was about 100 square feet per acre in trees 6 inches d.b.h. and larger. Ring counts of the larger trees revealed that the virgin hardwood timber had been heavily cut in the late 1920's and early 1930's. Tree diameters at the time of harvest ranged from less than 2 inches d.b.h. to a maximum of 28 inches, with an average of slightly less than 6 inches. The stand was dominated by red maple (55 percent) and sugar maple (25 percent). Pole-sized trees (5 to 9 inches d.b.h.) accounted for 63 percent of the 217 trees per acre greater than 5 inches d.b.h. The initial stand, counting trees of all sizes, contained approximately 350 trees per acre. The stand was overcrowded, of poor quality, and in need of timber stand improvement.

Operation and Equipment

The purpose of this case study was to determine the costs of using a completely mechanized system to thin a northern hardwood pole stand, chip the harvested trees, and transport the chips to the mill. The goal was to demonstrate that mechanized hardwood timber stand improvement (TSI) could be done profitably without prohibitively damaging the residual stand. The thinnings were converted to pulp chips because of an existing market, but could as well have been used as fuel chips.

Conventional, selective thinning by chain saw, besides being wasteful, is labor-intensive and costly. In Michigan, TSI costs for such thinnings typically range from \$35 to \$48 per acre (average \$42 per acre[1]). This study demonstrated that given the proper equipment and market, TSI in northern hardwoods can be transformed from a labor-intensive, costly practice into an operation providing immediate monetary return to the landowner and logger.

Five thinning treatments, four fully mechanized, with two replications per treatment, were tested. The four mechanized treatments were: (1) clearcut strip only; (2) clearcut strip with selection thinnings between strips; (3) selection thinning only; (4) shelterwood cut. The fifth treatment was a conventional chain saw thinning in which the selectively felled trees were left as forest floor residue.

The stand was thinned from a density of 100 square feet of basal area per acre to a residual density of 65 square feet (with the exception of the shelterwood cut, in which a 70-percent crown cover was left).

Harvesting and wood processing were done with three major pieces of equipment: a Rome shear[2] with accumulator top clamp mounted on a John Deere 544 loader; a Clark Ranger 667 GS grapple skidder; and a Trelan D-60 whole-tree chipper (fig. 2).

The chips were transported 22 miles to a pulpmill. Two truck-tractor units were used in combination with four chip vans. Auxiliary equipment consisted of one loader to feed the chipper, one maintenance truck, one fuel truck, one chain saw, and a landing truck for spotting vans. Five men were required for the operation—four equipment operators alternated every 3 or 4 hours between machines to reduce operator fatigue.

Time studies of all operations were done to determine cost and productivity. The equipment, the estimated purchase price, plus fixed and operating costs are listed in table 1.

Results

Although four mechanized treatments were used, specific results are presented only for the two most promising ones—the clearcut strip with selection thinning between strips (fig. 3) and the shelterwood (fig. 4). Average results are presented for all the mechanized treatments (table 2).

Including all delays, the feller buncher cut an average of 89 stems per hour to produce 17.5 green tons per hour. It handled about three stems per cycle in preparing skidder bunches, each containing about 11 stems. The grapple skidder averaged 72 stems per hour, or almost 17 green tons per hour. Load per skidder turn was approximately 2.3 green tons (11 stems). Average skid time, including delays, ranged from 8.6 to 9.4 minutes; average skid distance, including woods and road, ranged from 1,100 to 2,000 feet. Over the entire study, the chipper produced, including delays, an average of 17 green tons per hour. Without delays, average productivity would be nearly 35 green tons per hour. At an average of 1.6 stems per chipping cycle, it took 84 minutes to fill a van with chips. Each van load contained approximately 24 green tons (116 stems at an average weight of 413 pounds per stem). An average of 47 green tons per acre were removed in each of the four mechanized treatments (table 3).

As previously indicated, the costs from this 1974 study have been converted to 1980 dollars. Felling,

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[1] *Information obtained by telephone from Michigan Department of Natural Resources.*

[2] *Mention of trade names does not constitute endorsement of the product by the USDA Forest Service.*

Figure 2.—*Major equipment used—Case I: (left) John Deere 544 feller/buncher with Rome accumulator shear; (center) Clark Ranger 667 grapple skidder; and (right) Trelan D-60 whole-tree chipper.*

Table 1.—*Harvesting equipment and machine rate for 1974 thinning study—Case I*

(In January 1980 dollars)

Equipment	Estimated purchase cost[2]		Machine rate[1] without labor	
			Fixed cost	Operating cost
1 John Deere 544 with Rome shear	80,000	(39,900)	17.24	15.87
1 Clark Ranger 667 grapple skidder	85,000	(38,943)	24.17	17.92
1 Trelan chipper	70,725	(34,000)	13.87	10.22
1 Barko loader	33,500	(17,122)	9.08	4.85
5 Chip Vans @ $12,000 ea.	60,000	(25,980)	.12/mi	.06/mi.
2 Truck-tractors @ $45,000 ea.	90,000	(56,100)	.37/mi	.39/mi.
1 Maintenance van	2,000	(2,000)	.28/SH[3]	.02/mi.
1 Fuel truck	2,000	(1,500)	.55	2.50
1 Landing truck	6,000	(2,500)	2.38	4.24
1 Chain saw	312	(280)	.66	.86
Total Investment Cost	429,537	(218,815)	—	—

[1] Machine rates are based on productive hours.
Fuel cost is assumed to be $1.00 per gallon.

[2] 1974 dollars are shown in parentheses.

[3] Scheduled hours.

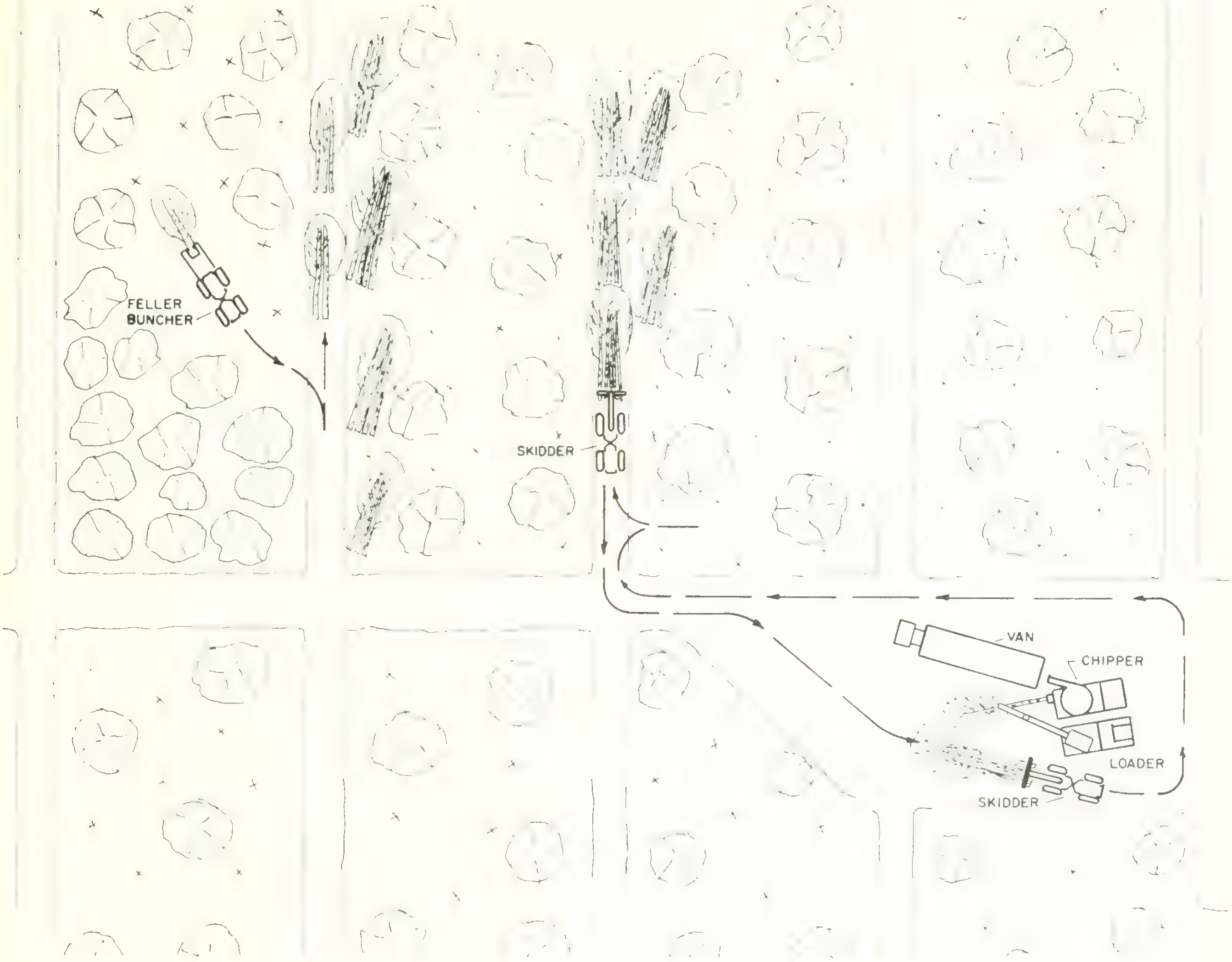

Figure 3.—*Simplified schematic of clearcut strip with selection thinning—Case I.*

Table 2—*Productivity by thinning treatment—Case I*

Thinning treatment		**Feller/buncher**		**Skidder**		**Chipper**	
		Stems/hr	**Tons/hr**	**Stems/hr**	**Tons/hr**	**Stems/hr**	**Tons/hr**
Strip	(without delays)	139.7	24.0	121.3	22.3	154.4	29.4
	(actual)	89.6	16.4	87.4	16.0	93.7	18.2
Shelterwood	(without delays)	133.8	25.0	133.2	28.8	185.2	36.1
	(actual)	87.4	17.2	71.2	15.9	77.1	15.0
Selective	(without delays)	137.2	29.7	143.0	36.9	174.9	37.6
	(actual)	79.7	17.3	61.8	16.1	75.7	16.3
Strip with selective	(without delays)	129.1	26.7	143.4	31.3	170.6	37.2
	(actual)	85.7	21.5	75.2	17.0	88.2	19.3
Average	(without delays)	133.3	27.2	135.0	31.3	172.3	34.8
(weighted)	(actual)	88.8	17.5	72.5	16.8	82.2	17.2

Table 3.—*Summary of material removed with best two thinning treatments—Case I*

Treatment	Area	Chips removed	Saw logs removed	Total removed	Total removed per acre	Stems removed per acre
	Acres	*Tons*	*Bd. ft.*	*Green tons*		*Number*
Shelterwood	9.61	470	2,670	486	50.6	255.0
Clearcut strip with selective thinning	9.50	513	2,830	531	55.9	263.9

skidding, chipping, and transport accounted for over 80 percent of the $13.27 per green ton (including labor) required to produce whole-tree chips from the recovered thinnings (table 4). Transport costs alone over the 22-mile haul was $3.66 per ton, or 27 percent of the total.

Figure 4.—*Pole-sized hardwood stand following shelterwood harvest.*

CASE II—MECHANIZED THINNING OF POLE-SIZED HARDWOODS

Stand Description

In August of 1978, a mechanized thinning study was conducted on 13 acres of pole-sized hardwoods in Alger County, Michigan, approximately 26 miles southeast of Marquette (Johnson *et al.* 1979). The study, which took place on State forest land, was a cooperative effort between Michigan Technological Univeristy, the Michigan Department of Natural Resources, the Marquette Board of Light and Power, and the USDA Forest Service.

The stand, which was predominantly pole-sized with a scattering of saw log trees, consisted of 73 percent sugar maple and 22 percent American elm and the remaining five percent was basswood, quaking aspen, and black cherry. The topography was level and the soil sandy. The precutting stocking was 254 trees per acre, with 116 square feet of basal area. Because of the presence of Dutch elm disease, all of the elm was harvested. This precluded uniform residual stocking, but also increased the yield.

Table 4.—Breakdown of costs—Case I[1]

(In January 1980 dollars)

Item	Dollars per green ton			Percent of total
	Equipment	Labor[2]	Total	
Feller/buncher	1.93	.99	2.92	22
Skidder	2.55	.97	3.52	27
Chipper	1.35	—	1.35	10.2
Loader	.78	.97	1.75	13.2
Truck-tractor	1.40	1.93	3.33	25
Chip van	.33	—	.33	2
Maintenance van	.03	—	.03	.2
Fuel truck	.01	—	.01	.1
Landing truck	.02	—	.02	.2
Chain saw	.01	—	.01	.1
TOTAL	8.41	4.86	13.27	100

[1] Average of all thinning treatments on 40 acres.

[2] Crew members: five operators @ $10 per hour, including all fringe benefits.

Operation and Equipment

The purposes of the study were: (1) to further test and evaluate mechanized strip thinning in a pole-sized hardwood stand and (2) to provide whole-tree chips for a trial burn in a coal-fired electrical generating plant. Based on findings of the previous case study, the thinning method consisted of clearcutting narrow strips and selectively thinning the alternating "leave" strips. Following the marking of leave trees (they were painted with rings that could be easily seen from all directions), feller/buncher routes were laid out by locating east-west compass lines 55 feet apart and perpendicular to the access road. As the feller/buncher proceeded into the stand, the operator cut a nominal 15-foot-wide strip and selectively removed all unmarked trees up to 20 feet on both sides of the strip (fig. 5). The operator formed bunches between the standing trees in the selectively thinned strips on both sides of the clearcut strips. Trees were placed butts toward the clearcut strips to facilitate skidding (fig. 6). On egress from the stand, the feller/buncher operator laid the bunches of trees behind the machine with all butts pointing in the direction of skidding. Following this felling pattern, the thinned stand contained 40-foot bands of selectively thinned stand bordered by 15-foot clearcut strips. Residual stocking was 68 square feet of basal area per acre in the selectively thinned strips and 55 square feet per acre overall.

Harvesting and wood processing were done with a tracked Drott 40 feller/buncher, a John Deere 740 grapple skidder, and a Morbark Chipper (fig. 7, table 5).

Results

Based on data from 744 felling cycles, the average production rate of the Drott 40 feller/buncher, including all delays, was 72 trees per hour. (A felling cycle is defined as the sum of the motions a feller/buncher performs in reaching for trees, positioning, shearing, lifting, swinging and bunching, and traveling to the next group to be harvested.) The average numbers of trees per cycle and bunch were 1.3 and 11.0, respectively. It should be noted that the accumulator arm was not functioning for a major portion of the study which required the feller/buncher to work 30 percent longer each day to keep up with the skidder.

Skidder distances were reduced by moving the chipper to stations about every 300 feet along the

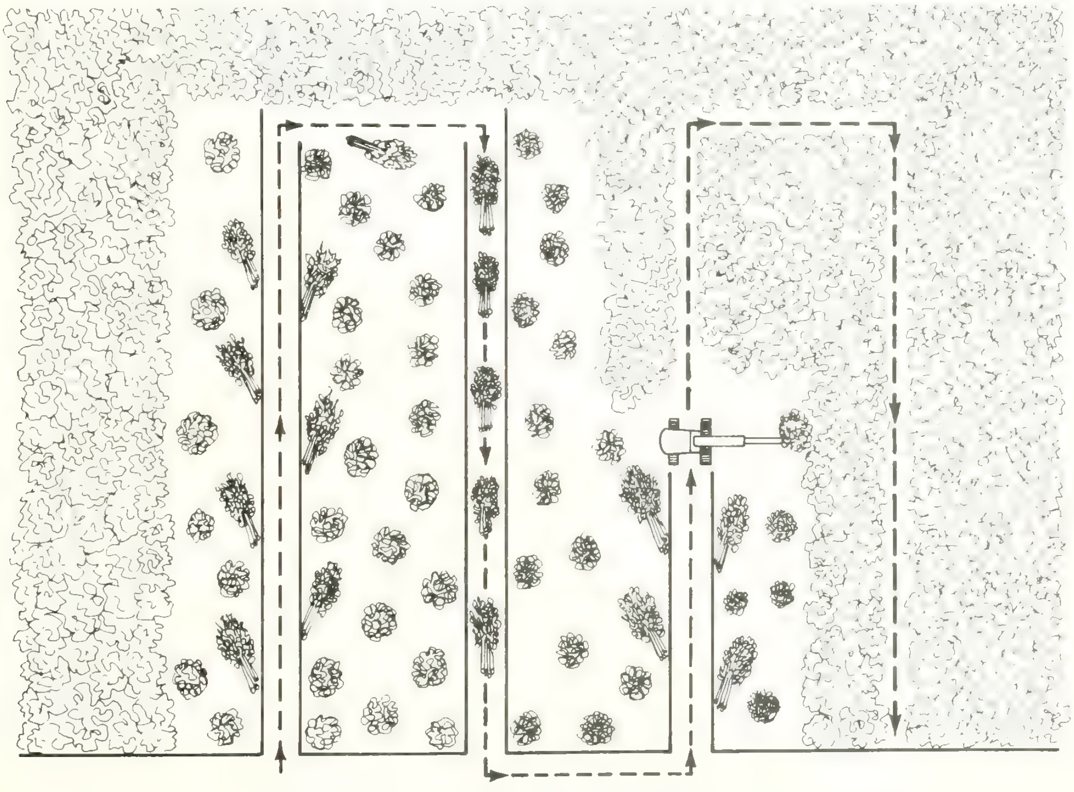

Figure 5.—*Simplified schematic of clearcut strip with selection thinning—Case II (15-foot strips, 40 feet between strips).*

Figure 6.—*Prebunched trees prepared by Drott 40 feller/buncher during travel into the stand—Case II.*

access road. This resulted in average distances of 320 feet, enabling one skidder to supply the chipper. The average skidder production was 11.4 stems (4.2 green tons) per turn and cycle time was 5.1 minutes. The skidder was periodically used for dozing, clearing slash, and grading.

Skid bunches, which were dropped to either side of the chipper, were converted to whole-tree chips and blown into waiting 25-ton-capacity vans at an average rate of 41.5 green tons per productive hour. This rate was achieved by chipping an average of 1.6 stems per chipper cycle. (A chipping cycle is defined as the sum of the motions a chipper performs in reaching for trees, positioning and grappling, lifting, swinging and feeding, and processing.) It took an average of 69 stems or 6 skidder loads to fill a van. Although the chipper was scheduled to do 33 hours of productive work, 25 percent of this time was recorded as delay. Waiting for vans was the principal cause of delay. A single-lane access road and rain adversely affected transportation efficiency.

The Marquette Board of Light and Power wanted only 1,000 green tons of chips for their trial with energy wood. With 25-ton-capacity chip vans, 40 van

Figure 7.—*Major equipment used—Case II: (A) Drott 40 feller/buncher; (B) John Deere 740 grapple skidder; and (C) Morbark 22-inch chipper.*

Table 5.—*Equipment costs for 1978 mechanized thinning study—Case II*

(In January 1980 dollars)

Equipment[1]	Purchase cost (f.o.b. delivered cost)
1 Drott 40 LC feller/buncher	$139,000
1 John Deere 740 grapple skidder	95,000
1 Morbark chipper	152,500
5 Truck/tractors @ $45,000 ea.	225,000
5 Chip vans @ $12,000 ea.	60,000
TOTAL INVESTMENT COST	$671,500

[1] The crew included a feller/buncher operator, a skidder operator, a chipper operator, and five truck drivers.

loads were required to achieve this amount. The 13 acres harvested yielded an estimated 2,740 trees averaging 730 pounds per tree, for a per-acre yield of 78.1 green tons.

This yield was considerably greater than the 46.8 green tons per acre from the Case I study, primarily due to the large harvest of elm trees. Because contractor cost data were not available, independent cost analyses were made which required certain assumptions (table 6).

The capital cost of equipment in 1980 dollars was $671,500 (table 5). Based on field-recorded production data and the assumptions made, the estimated total cost for felling, skidding, and chipping was $5,140; the transporting cost was $3,610. Thus, for a production of 1,000 green tons, the unit cost was $5.14 per green ton for all logging operations and $3.61 per green ton for transport. By including $0.60 per green ton for stumpage plus a conservative allowance of 15 percent for overhead, the total average delivered cost was estimated at $10.66 per green ton.

Table 6.—*Assumptions[1] for cost analysis—Case II*

Equipment	Estimated economic life	Working days per year	Scheduled hrs. or mi./yr.	Machine utilization
	Years	*Number*		*Percent*
Feller/buncher	5	250	2,000 hr.	65
Skidder	3	250	2,000 hr.	67
Chipper	5	250	2,000 hr.	75
Truck-tractor	4	250	40,000 mi.	—
Chip vans	8	250	20,000 mi.	—

[1] Other assumptions included: Stumpage at $0.60 per green ton, based on "Forest Residues Energy Program" USDA—Forest Service, 1978; overhead at 15 percent; and labor cost at $10.00 per hour including fringe benefits.

CASE III— NORTHERN HARDWOOD LAND CLEARING OPERATION

Stand Description

In August of 1978, a land clearing operation was conducted in a 25-acre northern hardwood stand located north of the town of Ontonagon in Michigan's Upper Peninsula. The stand consisted mainly of large-diameter aspen (9-inch average d.b.h.) with small amounts of red maple and black cherry. The terrain was flat to gently rolling. The soil was a loose, dry clay.

Operation and Equipment

The landowner wished to convert this northern hardwood stand to pasture. Although the operation was a commercial clearcut (fig. 8) only stems 4 inches d.b.h. or greater were chipped. The whole-tree chips were sold to Champion International Paper Mill in Ontonagon, Michigan. One-way haul distance was approximately 10 miles. The equipment and the estimated purchase costs (1980 dollars, f.o.b. delivered) are summarized in table 7. Personnel from the U.S. Forest Service's Houghton Laboratory conducted work measurement studies to establish system cost and productivity.

Table 7.—*Itemized cost of harvesting equipment for 1978 clearcutting study—Case III*

(In January 1980 dollars)

Equipment[1]	Purchase cost (f.o.b. delivered)
2 Drott 40 LC feller/bunchers @ $139,000 ea.	$ 278,000
2 John Deere 740 grapple skidders @ $95,000 ea.	190,000
1 Morbark 22-inch chipper	152,500
1 Pettibone chain flail PM850	90,000
1 Caterpillar D7G bulldozer	150,000
4 Truck-tractors @ $45,000 ea.	180,000
5 Chip vans @ $12,000 ea.	60,000
1 Maintenance van	2,000
1 Fuel truck	2,000
2 Chain saws @ $312 ea.	624
TOTAL CAPITAL INVESTMENT	$1,105,124

[1] The crew included two feller/buncher operators, two skidder operators, one chipper operator, one operator for bulldozer and chain flail, and three truck drivers.

Figure 8.—*Drott 40 feller/buncher in a northern hardwood land clearing operation—Case III.*

Results

The shear with accumulator load ranged from one to eight stems, depending on tree size. Bunches ranging from 4 to 18 stems were skidded to an intermediate landing for chain flailing prior to chipping (fig. 9). The purpose of the chain flailing was to remove the majority of small branches and twigs, which yield inferior chips and cause handling and conveyence problems.

Chain flailing took 2 to 8 minutes, depending on the bunch size and bulkiness of the tops. After flailing, bunches were skidded to either side of the chipper, which was equipped with a knuckle-boom and grapple. The chips were blown directly into 25-ton-capacity chip vans; fill time averged 20 minutes (fig. 10). The average transportation speed from chipper (landing) to mill was 45 miles per hour. Trucks and vans spent an average of about 45 minutes at the mill, depending on mill traffic. Although the dozer was used principally to clear the landing area, it was also used to move bunches at the chipper and maintain the haul road. The two feller/bunchers were scheduled to operate 10 hours a day and to work 1 day prior to start-up of other equipment to maintain supply. Other equipment averaged 9 scheduled hours per day. Over the 2-week study period, production reached a mill quota of 60 vans per week, and productivity ranged from 11 van loads to 16 van loads per day. To establish costs from the time study data, the following assumptions were made (table 8):

A stumpage price of $0.60 per green ton; an overhead cost of 15 percent of logging and transportation cost was assumed for overhead; a labor cost of $10.00 per hour including fringe benefits. Based on the recorded data and assumptions made, the production costs ($/green ton) for a range of daily production rates were summarized (table 9).

The hauling distance of 10 miles is less than the typical site-to-mill transport distance. Therefore, to expand the usefulness of these data, the effects on production cost of hauling distances of 20, 30, and 40 miles were projected (table 10). For each haul distance, two or three alternative transportation systems are presented to carry the tabulated amount of chips. For example, for the 20-mile haul distance with a daily productivity of 11 or 12 van loads, three truck-tractors and four chip vans would do the job at the cost of $14.26 and $13.53 per green ton, respectively. However, if the productivity increased from 13 to 16 van loads, four truck-tractors and five chip vans would be required at a cost range of $12.41 to $11.07 per green ton, respectively.

Figure 9.—*Landing site showing chain flailing of trees prior to whole-tree chipping—Case III.*

Figure 10.—*Whole-tree chipping and chip van loading—Case III.*

CASE IV—WHOLE-TREE HARVESTING OF LOW-VALUE HARDWOODS FOR STAND CONVERSION

Stand Description

In 1978, a 20-acre, predominantly low-value stand of pole-sized northern hardwoods located on the Mishwabic State Forest in Michigan's Upper Peninsula was selected for fully mechanized whole-tree chip harvesting and subsequent stand conversion. The terrain was essentially flat, and the soil was a sandy loam. The area contained usable logging roads and was bordered by a blacktop highway.

A preliminary survey indicated that the predominant species were red maple, sugar maple, yellow birch, and cherry, with lesser amounts of oak, white pine, and hemlock. The stand, which was about 50 years old, contained 803 stems per acre in trees 1 inch to 12 inches d.b.h., and a basal area of 118 square feet per acre. A preharvest estimate indicated a potential yield of about 100 tons of chips per acre.

Table 8.—*Cost analysis and machine rate assumptions—Case III*

(In January 1980 dollars)

Equipment	Economic life	Scheduled hours/yr.	Utilization	Productive hours/yr.	Interest, insurance and taxes[1]	Repair cost multiplier	Machine rate[3] Fixed Cost	Machine rate[3] Operating cost
	Years		*Percent*		*Percent*			
Feller/buncher	5	2,000	65	1,300	21	100[2]	$32.38	$24.18
Skidder	3	2,000	67	1,340	21	60[2]	27.31	20.87
Chipper	5	2,000	75	1,500	21	60	30.38	20.60
Chain flail	5	2,000	60	1,200	21	60	21.20	13.16
Bulldozer	5	2,000	60	1,200	21	100[2]	37.85	28.07
Maintenance van	5	2,000	—		19	5	.28/SH[4]	.02/mi.
Fuel truck	5	2,000	50	1,000	19	100	.55	2.50
Chain saw	1	2,000	25	500	16	100[2]	.66	.86
Truck-tractor	4	40,000/mi.	—	—	21	50	.37/mi.	.39/mi.
Chip vans	8	20,000/mi.	—	—	21	10	.12/mi.	.06/mi.

[1] Rate of interest = 15 percent, insurance = 3 percent, and taxes = 3 percent. (Maintenance van and fuel truck: rate of interest = 15 percent, insurance 2 percent, and taxes 2 percent.)

[2] The percentage rate by which the hourly depreciation is multiplied to estimate hourly repair costs. (See Warren, B. Jack. 1977. Logging cost and production analysis. Timber Harvesting Report 4, 42 p. LSU/MSU Logging and Forestry Operation Center, Bay St. Louis, Miss.)

[3] Based on productive hours and a fuel cost of $1.00 per gallon.

[4] Scheduled hours.

Table 9.—*Daily production costs for a one-way hauling distance of 10 miles (based on 75 percent chipper utilization)—Case III*

(In dollars)

Number of van loads[1]	Tons	Logging cost	Transportation cost	Stumpage	Overhead[2]	Total
11	275	9.35	1.73	.60	1.66	13.34
12	300	8.57	1.65	.60	1.53	12.35
13	325	7.91	1.58	.60	1.42	11.52
14	350	7.35	1.52	.60	1.33	10.80
15	375	6.86	1.47	.60	1.25	10.18
16	400	6.43	1.43	.60	1.18	9.64
17	425	6.05	1.39	.60	1.12	9.16

[1] Van capacity = 25 tons.

[2] Fifteen percent of logging and transportation cost.

Table 10.—*Daily production costs for one-way hauling distances of 20, 30, and 40 miles—Case III (based on 75 percent chipper utilization)*

(In January 1980 dollars)

Number of van loads	Green tons	Logging cost	Transportation cost	Subtotal	Stumpage	Overhead (15 percent)	Total
20 MILES							
11[1]	275	9.35	2.53	11.88	.60	1.78	14.26
12[1]	300	8.57	2.67	11.24	.60	1.69	13.53
13[2]	325	7.91	2.36	10.27	.60	1.54	12.41
14[2]	350	7.35	2.46	9.81	.60	1.47	11.88
15[2]	375	6.86	2.57	9.43	.60	1.41	11.44
16[2]	400	6.43	2.67	9.10	.60	1.37	11.07
30 MILES							
11[2]	275	9.35	2.72	12.07	.60	1.81	14.48
12[2]	300	8.57	2.88	11.45	.60	1.72	13.77
13[2]	325	7.91	3.04	10.95	.60	1.64	13.19
14[3]	350	7.35	2.75	10.10	.60	1.52	12.22
15[3]	375	6.86	2.88	9.74	.60	1.46	11.80
16[3]	400	6.43	3.01	9.44	.60	1.42	11.46
40 MILES							
11[2]	275	9.35	3.30	12.65	.60	1.90	15.15
12[2]	300	8.57	3.51	12.08	.60	1.81	14.49
13[3]	325	7.91	3.17	11.08	.60	1.66	13.34
14[3]	350	7.35	3.34	10.69	.60	1.60	12.89
15[4]	375	6.86	3.09	9.95	.60	1.49	12.04
16[4]	400	6.43	3.23	9.66	.60	1.45	11.71

[1] Three truck-tractors and four chip vans match the chipper's production and transportation round trip time.

[2] Four truck-tractors and five chip vans match the chipper's production and transportation round trip time.

[3] Five truck-tractors and six chip vans match the chipper's production and transportation round trip time.

[4] Six truck-tractors and seven chip vans match the chipper's production and transportation round trip time.

Operation and Equipment

Two feller/bunchers equipped with accumulator shear heads felled the trees and placed them in skidder-sized bunches with all butts facing toward a centrally located landing. A grapple skidder transported the bunches from the felling area to the landing. Prior to chipping, all skid bunches were delimbed with a chain flail. The chips were blown into chip vans and transported to the mill. Because the site has not been replanted, total conversion costs cannot be presented. The equipment used and the labor force were as follows:

Equipment

Drott 40 LC feller/bunchers with accumulator shear
1 John Deere 740 grapple skidder
1 Morbark Chiparvester (22-inch)
1 Pettibone PM850 chain flail
1 Caterpillar D7G bulldozer
4 truck-tractors
13 chip vans
1 maintenance van
1 fuel truck

Crew

2 feller/buncher operators
1 chipper operator
1 skidder operator
1 chainflail and dozer operator
4 truck drivers

Results

Because most trees were less than 10 inches d.b.h., the accumulator shear head was especially efficient. The felling rate was 132 trees per scheduled hour (155 trees per productive hour). The average skidding distance to the chain-flail site was about 370 feet. The skidding time was 4.25 minutes per turn including all delays, or 3.64 minutes per turn without delays. The average number of stems per skid load was 20.

Removal of twigs and small branches by chain flailing took from 2 to 7 minutes, depending upon the size of the skid load and bulkiness of the tops. Chain-flailed bunches were skidded to either side of the chipper with loader. The chips were blown directly into waiting vans. Including delays, the chipping rate was 43.5 green tons per scheduled hour; without delays, it was 53.1 green tons per hour.

The gross production data for this land clearing operation are summarized below (tonnages are based on actual mill scale weights):

• Total chipper productive hours	28
• Total green tons delivered to the mill	1,479
• Number of van loads	52
• Average van load (green tons)	28
• Total area harvested (acres)	20
• Yield per acre (green tons)	74
• Total trees harvested	9,600
• Average number of trees per ton	6.5
• One-way hauling distance (miles)	22

The yield of 74 tons per acre was significantly less than the preharvest estimate of 100 tons per acre. Chain flailing removed perhaps 15 to 20 percent of the total above-ground biomass, and an additional 5 to 10 percent may have been left as harvesting residue. Had chain flailing not been required, perhaps 85 to 90 tons per acre might have been recovered.

The costs (in 1980 dollars) associated with this clearcut operation were calculated on the basis of equipment scheduled and productive hours (tables 11-13). Based on the total green chip production of 1,479 tons, the combined cost of logging and transportation was estimated at $8.66 per green ton (table 14). Adding an assumed $1.20 per green ton for stumpage and 15 percent for overhead, the total cost per green ton was estimated at $11.16.

Table 11.—*Scheduled and productive hours for equipment used—Case IV*

Equipment	Scheduled hours	Productive hours	Utilization
			Percent
2 Feller/bunchers	73	62.0	85
1 Skidder	34	29.1	86
1 Chipper	34	27.8	82
1 Chain flail	34	27.6	81
1 Bulldozer	34	3.4	10 (est.)
1 Maintenance van	34	—	—
1 Fuel truck	34	13.6	40 (est.)

Table 12.—*Cost analysis assumptions—Case IV*

Equipment	**Economic life**	**Scheduled hours/yr.**	**Utilization**	**Productive hours/yr.**	**Interest, insurance and taxes[1]**	**Repair cost multiplier[2]**
	Years		*Percent*		*Percent*	
Feller/buncher	5	2,000	65	1,300	21	100[2]
Skidder	3	2,000	67	1,340	21	60[2]
Chipper	5	2,000	75	1,500	21	60
Chain flail	5	2,000	60	1,200	21	60
Bulldozer	5	2,000	60	1,200	21	100[2]
Truck-tractor	4	40,000 mi.	—	—	21	50
Chip van	8	20,000 mi.	—	—	21	10
Fuel truck	5	2,000	50	1,000	19	100
Mainentance van	5	2,000	—	—	19	5

[1] Rate of interest = 15 percent, insurance = 3 percent, and taxes = 3 percent (Maintenance van and fuel truck. rate of interest 15 percent, insurance 2 percent, and taxes 2 percent.)

[2] The percentage rate by which the hourly depreciation is multiplied to estimate hourly repair costs. (See Warren, B. Jack 1977 Logging cost and production analysis. Timber Harvesting Rep. 4, 42 p. LSU/MSU Logging and Forestry Operation Center, Bay St. Louis, Miss.)

Table 13.—*Equipment costs—Case IV*

(In January 1980 dollars)

Equipment	**Purchase cost**	**Machine rate without labor cost[1]**	
		Fixed cost	**Operating cost**
2 Drott 40 LC feller/bunchers @ $139,000 ea.	$ 278,000	32.38	24.18
1 John Deere 740 grapple skidder	95,000	27.31	20.87
1 Morbark 22-inch Chiparvester	152,500	30.38	20.60
1 Pettibone chain flail PM850	90,000	21.20	13.16
1 Caterpillar D7G bulldozer	150,000	37.85	28.07
4 Truck tractors @ $45,000 ea.	180,000	.37/mi.	.39/mi.
13 Chip vans @ $12,000 ea.	156,000	.12/mi.	.06/mi.
1 Fuel truck	2,000	.55	2.50
1 Maintenance van	2,000	.28/SH[2]	.02/mi.
Total cost	$1,105,500		

[1] Based on productive hours and a fuel cost of $1.00 per gallon.

[2] Scheduled hours.

Table 14.—*Calculation of logging and transportation costs—Case IV (Based on productive hours)*

(In January 1980 dollars)

Equipment	Time on job		Machine rate		Fixed cost	Total operating cost	Total labor cost[4]	Total machine with labor cost	Cost per ton	Percent of total
	Scheduled hours	Productive hours	Fixed cost	Operating cost						
2 Feller/bunchers	73	62	32.38	24.18	2,007.56	1,499.16	730	4,236.72	2.86	33
1 Skidder	34	29.1	27.31	20.87	794.72	607.32	340	1,742.04	1.18	14
1 Chipper	34	27.8	30.38	20.60	844.56	572.68	340	1,757.24	1.19	14
1 Chain flail	34	27.6	21.20	13.16	585.12	363.22	303	1,251.34	.84	10
1 Maintenance van[1]	34		.28/SH[2]	.02/mi.	9.52	.88	—	10.40	.01	(5)
1 Fuel truck	34	13.6	.55	2.50	7.48	34.00	—	41.48	.03	(5)
1 Bulldozer	34	3.4	37.85	28.07	128.69	95.44	37	261.13	.18	2
13 Chip vans[3]	—	—	.12/mi.	.06/mi.	274.56	137.28	—	411.84	.28	3
4 Truck-tractors[3]	—	—	.37/mi	.39/mi.	846.56	892.32	1,360	3,098.88	2.09	24
Total cost	—	—	—	—	5,498.77	4,202.30	3,110	12,811.07	8.66	100

[1] Maintenance van fixed cost = \$0.28/scheduled hr. × 34 scheduled hours = \$9.52; operating cost = \$0.02/mi. × 44 mi. = \$0.88.

[2] Scheduled hours.

[3] Transportation: 22 miles (one-way distance) and 52 loads or round trips.

[4] Labor cost: \$10 per scheduled hour for each operator, including all fringe benefits.

[5] Less than 0.5 percent.

CASE V—RECOVERY OF HARDWOOD SAW LOG TOPS AND LIMBS

Stand Description

Significant volumes of tops and limbs are left in the forest each year after harvesting of hardwood saw logs (fig. 11). In 1978, a 21-acre northern hardwood stand at Michigan Technological University's Ford Forestry Center, about 10 miles south of L'Anse, Michigan, was selected for a unique trial in topwood recovery. The preharvest inventory indicated a volume of 7,000 board feet (net Scribner) and 6 cords of pulpwood per acre with a basal area stocking of 116 square feet per acre. The soil was classified as Alouez—a well-drained, coarse, gravelly loam. The tract was on level terrain and traversed by an all-weather road.

Previous selective logging operations had been conducted in 1938 and 1967. Sugar maple and American elm were the major species, with basswood, yellow birch, red maple, and hemlock contributing minor volumes. The 1977 selective harvest removed 1,800 board feet per acre (net Scribner) and 5.1 tons of pulpwood per acre. Fifty-two percent of the saw log volume harvested was sugar maple, 38 percent American elm, 4 percent basswood, and the remaining 6 percent yellow birch, red maple, and hemlock. This reduced the basal area from 116 square feet to 80 square feet per acre in trees 5 inches d.b.h. and larger. A total of 304 trees were felled on the 21-acre study area, averaging 14.5 trees per acre. Of these, 237 (78 percent) were saw log trees and 67 (22 percent) were pulpwood trees (less than 11 inches d.b.h.). In preparation for this case study all residue tree tops were marked prior to recovery.

Operation and Equipment

The objectives of this case study were: (1) to test the capability of an experimental topwood processor designed and built by the Forestry Sciences Laboratory, Houghton, Michigan; and (2) to evaluate the economic feasibility of recovering hardwood saw log tops and limbs.

The crew and equipment used were:

- 1 prototype topwood processor (12-inch-diameter shear head)
- 1 Clark Ranger 667 grapple skidder
- 1 Morbark chipper
- 1 chain saw
- 4 men—a topwood processor operator, a skidder operator, a chipper operator, and a sawyer.

The experimental topwood processor was designed to reduce bulky tops to a manageable size in the woods, thus permitting skidding to roadside without damaging the residual stand (figs. 12 and 13). Small

Figure 11.—*Residue hardwood tops and limbs following saw log removal—Case V.*

tops not large enough to cause residual stand damage when skidded intact were not processed with this experimental device. All tops delivered to the landing site were chipped and blown into a pile at the landing (fig. 14). A time study established costs and productivity.

Results

The prototype topwood processor was used to process 115 tops. A maximum of seven limbs per top were severed, with a mean of about two. Limb diameters ranged from 2 to 11 inches, with an average of 6.5 inches. The average time required to process the tops was 4 minutes without delays, and slightly under 6 minutes including delays. Productivity of the topwood processor was 10.2 tons or 14.6 tops per hour without delays.

Two skidding methods were tried: (1) direct skidding of processed and unprocessed tops from the woods to the landing, and (2) "shuttle" skidding, in which the skidder built larger loads from individual tops at the service road before skidding the remaining distance to the landing. The purpose of trying "shuttle" skidding was to determine the productivity and costs for a multiple skidder system. Using the shuttle skidding, the average payload was 1.12 tons,

Figure 12.—*Experimental topwood processor used for compacting hardwood saw log tops and limbs prior to skidding—Case V.*

Figure 13.—*Hardwood saw log top (A) before and (B) after compaction with the experimental topwood processor—Case V.*

Figure 14.—*Major equipment used—Case V: (A) experimental topwood processor; (B) Clark Ranger 667 grapple skidder; and (C) Morbark 22-inch chipper.*

compared with 0.84 tons for direct skidding. Productivity, without delays, was 14.8 tons, or 21.1 tops per hour for the shuttle method, and 6.3 tons or 8.9 tops per hour for direct skidding.

Chipper productivity was very low because only one skidder was used. Productivity for direct skidding was less than 5 tons per hour due to the delay involved in waiting for tops and the need to sever limbs and short protruding stubs made by the topwood processor. The shuttle skidding method increased chipper productivity to 25.7 tons per hour (from 17.5 tons with direct skidding method) because the skidder loads were larger, allowing the chipper operator to increase the size of grapple loads when feeding the chipper.

Due to inadequacies in the topwood processor, there was still a need to sever some of the remaining limb stubs which could not be fed into the chipper. This in itself was not time consuming, but resulted in added chipper delay. The chain saw cost was $0.30 per green ton (see fig. 15 for cost assumptions). An improved topwood processor would remove limbs closer to the main stem and eliminate the short stubs. The productivity data and cost data showed that the weakest link in the operation was skidding—chipping averaged 1 ton of material in 2.3 minutes or 26 tons per hour, compared with skidding a green ton in 4.1 minutes. Total production cost, excluding transportation, ranged between $10.00 to $16.50 per green ton depending on skidding method used. The reader is cautioned that these costs should be tempered by the fact that they are the result of a single case study with an experimental machine.

Post-harvest inspection showed damage to the residual stand to be relatively minor. This was partially because of the deep snow which acted as a cushion, and also because skidding was done during winter when the bark was tight. We did learn some things in this first attempt at recovering hardwood tops and limbs with an experimental topwood harvester. For example, we found it was much easier to skid small tops intact rather than cutting them up, because small severed limbs occasionally slipped out of the grapple when the load shifted. A skidder with a constant pressure grapple would lessen this problem.

Data on the weight of typical sugar maple tops and limbs for trees of various diameters (fig. 16) were obtained from independent residue studies. With this information, we can determine the potential heat energy available in hardwood tops and limbs. For example, a typical top from a 20-inch d.b.h. sugar maple tree weighs 1,800 pounds (green) (fig. 17). Assuming 40-percent moisture content and an oven-dry heat value of 8,500 BTU's/lb., the as-fired heat value is about 5,100 BTU/lb. Thus, the 1,800-pound top has a heat potential of 9.2 million BTU's. This is equivalent to slightly less than one 42-gallon barrel of oil.

CONCLUSIONS

Companies, researchers, and others investigating the potential of forest resources as a source of energy need better information on the costs and productivity of various harvesting operations. While it is impossible to cover all harvesting situations and variety of equipment, documentation of the type provided here will be useful for estimating systems performance and costs involved in recovering energy from our underutilized forest resources. It is hoped that others follow this lead and similarly document costs and productivity of logging operations.

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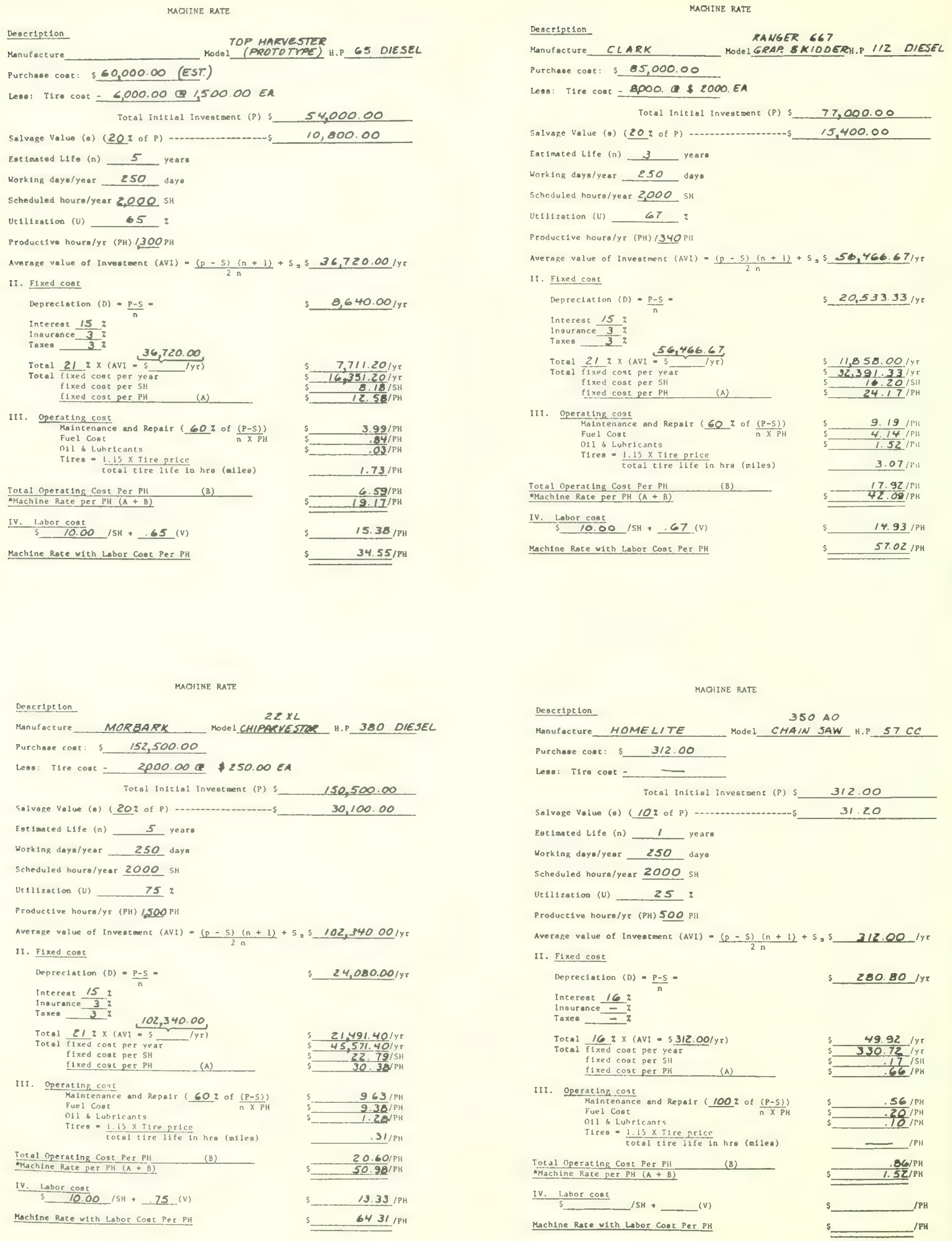

MACHINE RATE

Description

Manufacture ____ Model TOP HARVESTER (PROTOTYPE) H.P 65 DIESEL

Purchase cost: $ 60,000.00 (EST.)

Less: Tire cost - 6,000.00 @ 1,500.00 EA

Total Initial Investment (P) $ 54,000.00

Salvage Value (s) (20 % of P) -------------------$ 10,800.00

Estimated Life (n) 5 years

Working days/year 250 days

Scheduled hours/year 2,000 SH

Utilization (U) 65 %

Productive hours/yr (PH) 1,300 PH

Average value of Investment (AVI) = $\frac{(p - S)\ (n + 1)}{2\ n}$ + S = $ 36,720.00 /yr

II. Fixed cost

Depreciation (D) = $\frac{P-S}{n}$ =	$ 8,640.00/yr
Interest 15 %	
Insurance 3 %	
Taxes 3 %	
Total 21 % X (AVI = $ 36,720.00 /yr)	$ 7,711.20/yr
Total fixed cost per year	$ 16,351.20/yr
fixed cost per SH	$ 8.18/SH
fixed cost per PH (A)	$ 12.58/PH

III. Operating cost

Maintenance and Repair (60 % of $\frac{(P-S)}{n \times PH}$)	$ 3.99/PH
Fuel Cost	$ .84/PH
Oil & Lubricants	$ .03/PH
Tires = $\frac{1.15 \times \text{Tire price}}{\text{total tire life in hrs (miles)}}$	1.73/PH
Total Operating Cost Per PH (B)	6.59/PH
*Machine Rate per PH (A + B)	$ 19.17/PH

IV. Labor cost

$ 10.00 /SH ÷ .65 (V)	$ 15.38/PH
Machine Rate with Labor Cost Per PH	$ 34.55/PH

MACHINE RATE

Description

Manufacture CLARK Model RANGER 667 GRAP. SKIDDER H.P 112 DIESEL

Purchase cost: $ 85,000.00

Less: Tire cost - 8000. @ $ 2000. EA

Total Initial Investment (P) $ 77,000.00

Salvage Value (s) (20 % of P) -------------------$ 15,400.00

Estimated Life (n) 3 years

Working days/year 250 days

Scheduled hours/year 2,000 SH

Utilization (U) 67 %

Productive hours/yr (PH) 1340 PH

Average value of Investment (AVI) = $\frac{(p - S)\ (n + 1)}{2\ n}$ + S = $ 56,466.67/yr

II. Fixed cost

Depreciation (D) = $\frac{P-S}{n}$ =	$ 20,533.33 /yr
Interest 15 %	
Insurance 3 %	
Taxes 3 %	
Total 21 % X (AVI = $ 56,466.67 /yr)	$ 11,858.00 /yr
Total fixed cost per year	$ 32,391.33 /yr
fixed cost per SH	$ 16.20 /SH
fixed cost per PH (A)	$ 24.17 /PH

III. Operating cost

Maintenance and Repair (60 % of $\frac{(P-S)}{n \times PH}$)	$ 9.19 /PH
Fuel Cost	$ 4.14 /PH
Oil & Lubricants	$ 1.52 /PH
Tires = $\frac{1.15 \times \text{Tire price}}{\text{total tire life in hrs (miles)}}$	3.07 /PH
Total Operating Cost Per PH (B)	17.92 /PH
*Machine Rate per PH (A + B)	$ 42.09/PH

IV. Labor cost

$ 10.00 /SH ÷ .67 (V)	$ 14.93 /PH
Machine Rate with Labor Cost Per PH	$ 57.02 /PH

MACHINE RATE

Description

Manufacture MORBARK Model 22 XL CHIPARVESTOR H.P 380 DIESEL

Purchase cost: $ 152,500.00

Less: Tire cost - 2000.00 @ $ 250.00 EA

Total Initial Investment (P) $ 150,500.00

Salvage Value (s) (20 % of P) -------------------$ 30,100.00

Estimated Life (n) 5 years

Working days/year 250 days

Scheduled hours/year 2000 SH

Utilization (U) 75 %

Productive hours/yr (PH) 1,500 PH

Average value of Investment (AVI) = $\frac{(p - S)\ (n + 1)}{2\ n}$ + S = $ 102,340 00/yr

II. Fixed cost

Depreciation (D) = $\frac{P-S}{n}$ =	$ 24,080.00/yr
Interest 15 %	
Insurance 3 %	
Taxes 3 %	
Total 21 % X (AVI = $ 102,340.00 /yr)	$ 21,491.40/yr
Total fixed cost per year	$ 45,571.40/yr
fixed cost per SH	$ 22.79/SH
fixed cost per PH (A)	$ 30.38/PH

III. Operating cost

Maintenance and Repair (60 % of $\frac{(P-S)}{n \times PH}$)	$ 9 63 /PH
Fuel Cost	$ 9.38/PH
Oil & Lubricants	$ 1.28/PH
Tires = $\frac{1.15 \times \text{Tire price}}{\text{total tire life in hrs (miles)}}$	.31/PH
Total Operating Cost Per PH (B)	20.60/PH
*Machine Rate per PH (A + B)	$ 50.98/PH

IV. Labor cost

$ 10.00 /SH ÷ .75 (V)	$ 13.33 /PH
Machine Rate with Labor Cost Per PH	$ 64 31 /PH

MACHINE RATE

Description

Manufacture HOMELITE Model 350 AO CHAIN SAW H.P 57 CC

Purchase cost: $ 312.00

Less: Tire cost - —

Total Initial Investment (P) $ 312.00

Salvage Value (s) (10 % of P) -------------------$ 31.20

Estimated Life (n) 1 years

Working days/year 250 days

Scheduled hours/year 2000 SH

Utilization (U) 25 %

Productive hours/yr (PH) 500 PH

Average value of Investment (AVI) = $\frac{(p - S)\ (n + 1)}{2\ n}$ + S = $ 312.00 /yr

II. Fixed cost

Depreciation (D) = $\frac{P-S}{n}$ =	$ 280.80 /yr
Interest 16 %	
Insurance — %	
Taxes — %	
Total 16 % X (AVI = $ 312.00/yr)	$ 49.92 /yr
Total fixed cost per year	$ 330.72 /yr
fixed cost per SH	$ .17 /SH
fixed cost per PH (A)	$ .66 /PH

III. Operating cost

Maintenance and Repair (100 % of $\frac{(P-S)}{n \times PH}$)	$ .56 /PH
Fuel Cost	$ .20 /PH
Oil & Lubricants	$ .10 /PH
Tires = $\frac{1.15 \times \text{Tire price}}{\text{total tire life in hrs (miles)}}$	— /PH
Total Operating Cost Per PH (B)	.86/PH
*Machine Rate per PH (A + B)	$ 1.52/PH

IV. Labor cost

$ ____ /SH ÷ ____ (V)	$ ____ /PH
Machine Rate with Labor Cost Per PH	$ ____ /PH

Figure 15.—*Calculation of machine rate for equipment used in topwood harvesting operation.*

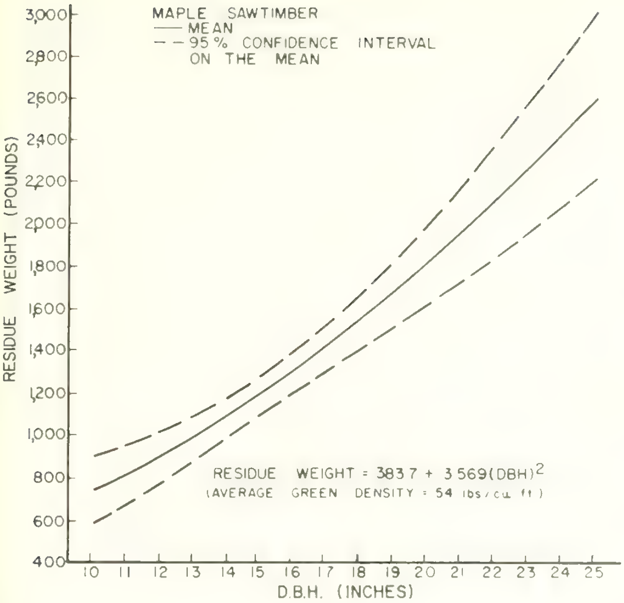

Figure 16.—*Residue weight of sugar maple sawtimber in terms of d.b.h.*

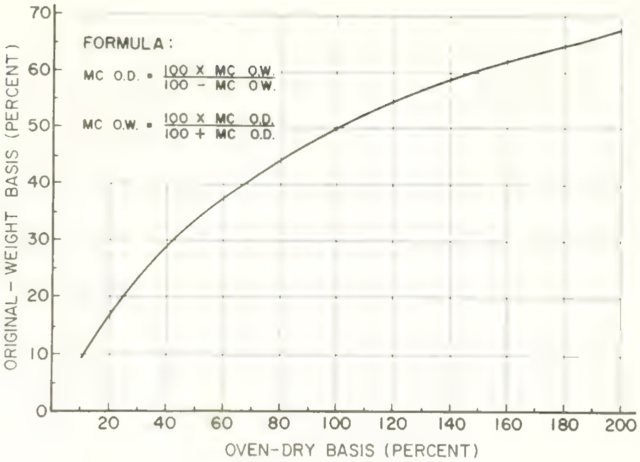

Figure 17.—*Moisture content comparison.*

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APPENDIX

ENERGY-RELATED INFORMATION

Heat value.—The oven-dry heating value of wood is presented (tables 15-17) along with those of conventional fossil fuels (table 18). Direct comparisons are difficult because heat values of solid fuels are typically expressed in Btu/lb., liquid fuels in BTU/gal., and gaseous fuels in Btu/cu. ft. (liquified gas, however, is usually expressed in Btu/gal). Many engineering manuals list the conversion factors, such as pounds per gallon for liquid fuels, making it simple to directly compare alternate fuels on a unit-value basis.

Rule of thumb equivalency.—Fossil fuel and wood or bark fuel equivalency can be easily calculated on a theoretical basis (100-percent efficiency) or by accounting for the differences in combustion efficiencies. However, for estimating purposes (accounting for differences in combustion efficiencies), a ton of green wood (50 percent moisture content—green weight basis) is approximately equivalent to 6,500 cu.ft. of natural gas, ¼ ton of coal, or a barrel of oil. If the wood is ovendry, the equivalency is about twice the above values.

Moisture content.—Moisture in wood-based fuels not only lowers the heat value and causes problems with combustion, it also causes confusion among people calculating moisture content. Moisture content of wood is expressed either on an ovendry basis or a green-weight basis. Combustion equipment people usually express it on a green-weight basis as follows:

$$\text{M.C. green-weight basis} = \frac{(\text{greenweight} - \text{ovendry weight}) \times 100}{\text{green weight}}$$

Table 15.—*Typical heating values for hardwoods*[1]

(In Btu per pound)

WOOD

Species	Heating value (dry) Average	Low	High
White ash		8,246	8,920
Beech		8,151	8,760
Birch, wood refuse	8,870		
Paper birch		8,019	8,650
Hickory		8,039	8,670
Elm		8,171	8,810
Maple		7,995	8,580
Maple, wood refuse	8,190		
Black oak		7,587	8,180
Red oak		8,037	8,690
White oak		8,169	8,810
Poplar		8,311	8,920

BARK

Species	Heating value (dry)
Red alder	7,947
Quaking aspen	8,433
Beech	7,640
Paper birch[2]	9,434
Paper birch[2]	10,310
Yellow birch	9,200
Blackgum	7,936
American elm	6,921
Elm, soft	7,600
Hard maple	8,230
Soft maple	8,100
Sugar maple	7,301
Northern red oak	8,030
White oak	6,995
Poplar	8,810
Sweetgum	7,450
Sycamore	7,403
Black willow	7,168

[1] See Arola 1976.

[2] Paper birch data obtained from two different sources.

To convert moisture content on an ovendry basis to a green-weight basis the following expression is used:

$$\text{M.C. green-weight basis} = \frac{100 \times \text{M.C. dry}}{100 + \text{M.C. dry}}$$

A conversion chart can be readily used to convert either way (fig. 17). Typical moisture contents on a green-weight basis of northern forest species is provided in table 19.

As-fired heating value.—The best indicator of any fuel is its "as-fired" heating value. With green wood or bark, the as-fired value is considerably lower than with oven-dry wood or bark. If the as-fired heating value for moisture-laden wood or bark is not available, it may be computed using the green moisture contents (table 19) and the oven-dry heating values (tables 15, 16, 17):

As-fired heating value =

$$\frac{(100 - \text{M.C. green weight basis})}{100} \times \text{ovendry heating value.}$$

Comparison of fuel values.—A convenient nomograph can be used to quickly show the relative value of wood or bark as a replacement for or supplement to fossil fuels (fig. 18). Comparing as-fired heating values alone is not sufficient. The most meaningful comparison between wood or bark and fossil fuels is not based on heat per unit of measure, but rather dollars per million Btu. The nomograph in figure 19 allows that comparison. For example, given the current delivered price for a particular fossil fuel, one can determine the comparable value of wood or bark. The nomograph is not a substitute for a detailed fuel analysis, but does allow a quick comparison of fuel values that will determine whether a detailed analysis is warranted. Use of the nomograph is illustrated in the following example:

Given:	The price of 12,000 Btu/lb. coal is $41.50 per ton; it can be combusted at 80-percent efficiency.
Problem:	What would be the dollar value of whole-tree chips as a replacement for this coal if the chips were combusted at

Table 16.—*Typical heating values for softwoods*[1]

(In Btu per pound)

WOOD

Species	Heating value (dry) Average	Low	High
White cedar		7,780	8,400
Western red cedar	9,700		
Cypress		9,234	9,870
Fir, Douglas[2]	9,050		
Fir, Douglas[2]		8,438	9,050
Fir, Douglas[2]	8,900		
Fir, white	8,200		
Hemlock, eastern	8,885		
Hemlock, western[2]	8,620		
Hemlock, western[2]		8,056	8,620
Pine sawdust	9,130		
Jack pine wood refuse	8,930		
loblolly pine stemwood	8,600	8,310	9,352
Pitch pine		10,620	11,320
Ponderosa pine	9,100		
White pine		8,308	8,900
Yellow pine		8,927	9,610
Redwood		8,498	9,040
BARK			
Balsam, all varieties	9,100	8,900	9,210
Balsam fir	8,861		
Douglas-fir	9,800		
Hemlock, eastern[2]	8,890		
Hemlock, eastern[2]	8,802		
Hemlock, western	9,400		
Western larch	8,204		
Jack pine	8,930	8,690	9,170
Lodgepole pine	10,190		
Ponderosa pine	9,100		
Slash pine	9,002		
Western white pine	8,085		
Black spruce	8,610	8,150	8,710
Engelmann spruce	8,359		
Pine spruce (1 ft. above ground)	8,985	8,870	9,140
Pine spruce (mid height)	8,825	8,650	8,910
Pine spruce (4 in. top)	8,700	8,550	8,825
Red spruce	8,630		
White spruce	8,530	8,340	8,630
Tamarack	9,010		

[1] See Arola 1976.

[2] Two or more entries per species indicate data obtained from different source.

60-percent efficiency at an as-fired heating value of 5,000 Btu/lb.?

Solution: Enter the nomograph at $41.50 per ton for coal along a vertical line to 12,000 Btu/lb. Then move horizontally to the 80-percent combustion efficiency. The cost of steam (on the top horizontal scale) is about $2.10 per million Btu. To determine the value of wood chips at this same $2.10 per million Btu of steam, follow a vertical line down to the 60-percent combustion efficiency for wood and then horizontally to an as-fired value of 5,000 Btu/lb. Then move vertically to the lower horizontal scale and read the value.

Answer: About $13 per ton as-fired.

Table 17.—*Typical oven-dry heating values of wood and bark*[1]

(In Btu per pound)

	Range	Average
Hardwoods		
Wood	7,590- 8,920	8,530
Bark	6,920-10,310	8,040
Softwoods		
Wood	7,780-11,320	8,910
Bark	8,200-10,190	8,950

[1] See Arola 1976.

Table 18.— *Typical fossil fuel heating values*[1]

COAL	Btu/pound
Anthracite	13,900
Bituminous	14,000
Sub-bituminous	12,600
Lignite	11,000
HEAVY FUEL OILS AND MIDDLE DISTILLATES	**Btu/gallon**
Kerosene (6.814 lb./gal.)	134,000
No. 2 burner fuel oil (7.022 lb./gal.)	140,000
No. 5 heavy fuel oil (7.612 lb./gal.)	144,000
No. 5 heavy fuel oil (7.676 lb./gal.)	150,000
No. 6 heavy fuel oil, 2.7% sulfur (8.082 lb./gal.)	152,000
No. 6 heavy fuel oil, 0.3% sulfur (7.401 lb./gal.)	143,800
GAS	
Natural	[2]1,000
Liquefied butane	103,300
Liquefied propane	91,600

[1] From Energy Conservation Program, Guide for Industry and Commerce, U.S. Chamber of Commerce, National Bureau of Standards Handbook No. 115, Washington, D.C., 1974.

[2] Btu/cu. ft.

Table 19.—*Approximate moisture contents of typical Northern forest species*[1]

(In percent, green weight basis)

Species	Wood	Bark
Bolewood:		
Aspen	50	47
Hard maple	36	38
Balsam fir	58	52
Jack pine	49	55
Red pine	51	55
White spruce	48	61
Topwood:		
Aspen	48	48
Hard maple	37	41
Balsam fir	56	55
Jack pine	55	66
Red pine	60	62
White spruce	55	64

[1] See Erickson 1972.

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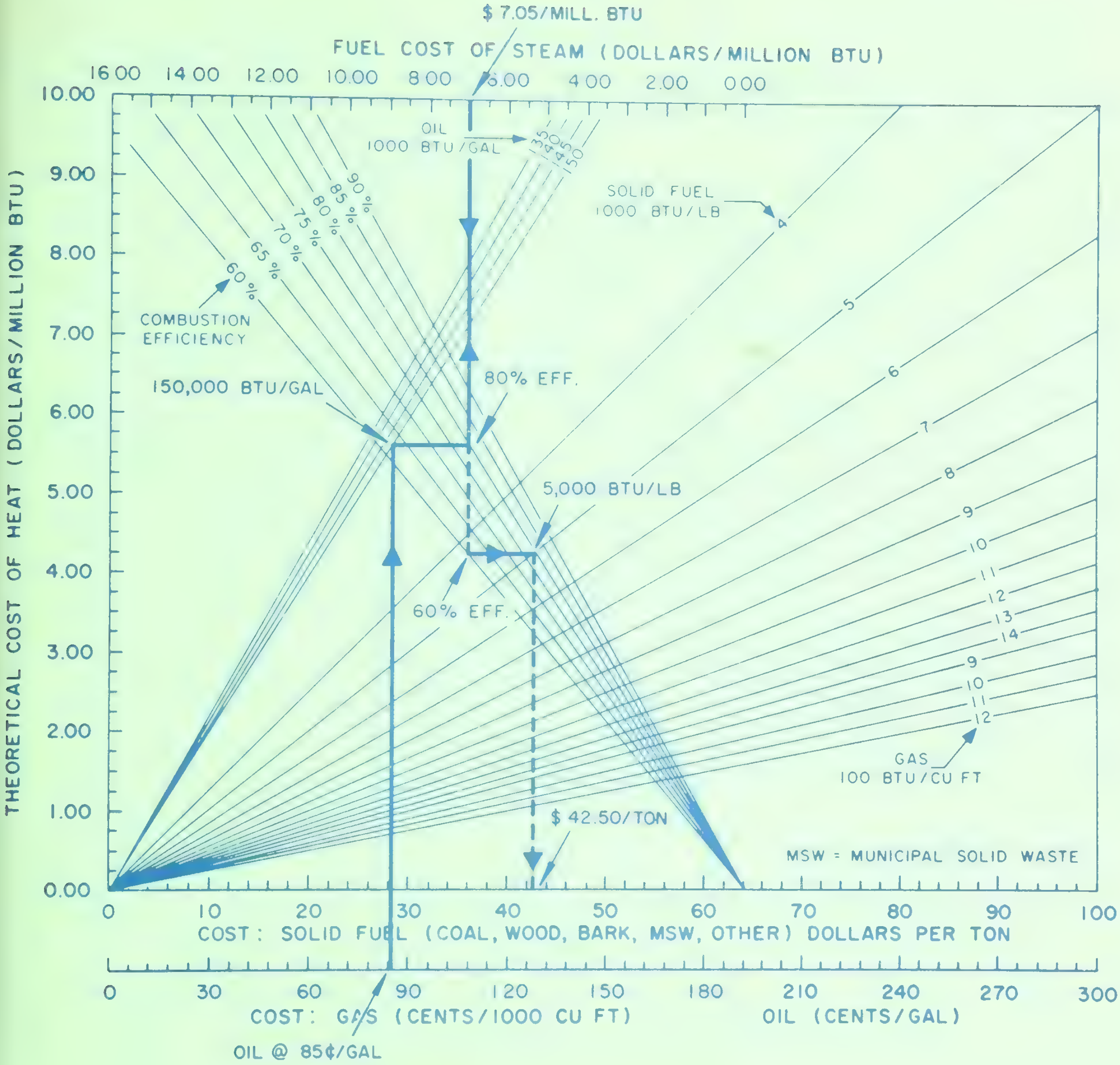

Figure 18.—*Fuel value nomograph.*

Arola, Rodger A., and Edwin S. Miyata.

1981. Harvesting wood for energy. U.S. Department of Agriculture Forest Service, Research Paper NC-200, 25 p. U.S. Department of Agriculture Forest Service, North Central Forest Experiment Station, St. Paul, Minnesota.

Illustrates the potential of harvesting wood for industrial energy, based on the results of five harvesting studies. Presents information on harvesting operations, equipment costs, and productivity. Discusses mechanized thinning of hardwoods, clearcutting of low-value stands, and recovery of hardwood tops and limbs. Also includes basic information on the physical and fuel properties of wood.

KEY WORDS: Logging, whole-tree chipping, fuelwood, mechanized thinning, clearcutting, residues.

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Clone expansion and competition between QUAKING & BIGTOOTH ASPEN SUCKERS after clearcutting

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CLONE EXPANSION AND COMPETITION BETWEEN QUAKING AND BIGTOOTH ASPEN SUCKERS AFTER CLEARCUTTING

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The ability of quaking and bigtooth aspens (*Populus tremuloides* Michx., *P. grandidentata* Michx.) to vegetatively regenerate dense stands of root sprouts (suckers) is well documented (Brinkman and Roe 1975). Tens of thousands of suckers per hectare are commonly produced when stands are killed by fire or removed by clearcutting.

Suckers from a common parent are genetically identical and form a multi-stemmed clone that is distinct from other clones (Barnes 1966, Steneker 1973). Clones can expand, intergrow with other clones, and coalesce, depending on rate of root expansion, inherent suckering ability, and degree of stand disturbance (Barnes 1966). Clone sizes are usually small, ranging from a few trees covering 0.004 ha up to 1.5 ha (Steneker 1973). However, two clones of 10.1 and 43.3 ha have been verified in Utah, and other central and southern Rocky Mountain clones may be at least 81 ha in size (Kemperman and Barnes 1976).

There is much inherent variation among aspen clones in productivity, stem quality, disease resistance, and other characteristics of interest to the land manager (Steneker 1973). By taking advantage of the root suckering characteristics of aspens, it may be possible to extend the area of clones having desirable characteristics. But little is known about the effective range of clone extension where competition is keen in a closed forest environment.

Described here are the extension, early growth, and competition between quaking and bigtooth aspen clones after a mature, fully stocked aspen stand was clearcut.

STUDY AREA

The study area is located 47° 40′N, 93° 59′W on the Chippewa National Forest, Minnesota. The area supported a fully stocked forest of mature, even-aged (44 years) quaking and bigtooth aspen in about equal mixture, with lesser amounts of other uneven-aged hardwoods (table 1). Shrubs were sparse due to the dense shade cast by the hardwoods, but a well developed herb layer characterized by *Polygonatum biflorum, Uvularia grandiflora,* and *Maianthemum canadense* was present. The topography is rolling to hilly moraine. The soil is a well drained calcareous glacial till, classified as Warba very fine sandy loam, and a good site for aspen (site index = 24.5 m at age 50). The climate is continental, with mean maximum July temperature of 27° C and mean annual precipitation of 61 cm.

METHODS

In July 1974, 0.08-ha (16-m radius) plots were established on the contact boundaries of adjacent pairs of five quaking and five bigtooth aspen clones. There was a sharp separation of aspen species, with no intermixing. All trees greater than 5 cm d.b.h. were mapped by plane table, identified by number, and recorded by species and d.b.h. Twenty-five trees

Table 1.—*Parent stand summary*[1]

Species	Number per hectare	Basal area (m^2/ha)	Mean d.b.h. (cm)	Mean stand height (m)
Quaking aspen	313	10.4	20.6	22.1
Bigtooth aspen	378	15.5	22.8	23.5
Other hardwoods[2]	362	5.4	13.8	—
Total stand	1,053	31.3	19.5	—

[1] For all stems exceeding 5 cm d.b.h. Aspen data adjusted to reflect equal area of quaking and bigtooth clones (actual area mapped: 43 percent bigtooth aspen; 57 percent quaking aspen).

[2] *Betula papyrifera* Marsh., *Acer saccharum* Marsh., *A. rubrum* L., *Quercus rubra* L., and *Tilia americana* L.

of each species 10 to 35 cm in diameter were measured for total height and cored for total age.

The stand was clearcut during the winter of 1974-1975 to provide excellent conditions for aspen suckering. In May 1975, before leaf-flushing, the stumps of all quaking and bigtooth aspens on the clonal boundaries were re-identified and labeled (fig. 1). This provided accurate referencing for later sampling and mapping of regeneration.

In August 1975, the intrusion of quaking aspen suckers into the bigtooth aspen clones was mapped (fig. 1). The mapping was repeated for bigtooth suckers into quaking aspen clones. In May 1979, regeneration fronts were remapped to include only 4-year-old suckers that had dominant or codominant crown positions. Also in 1979, the d.b.h.'s, heights, and densities of dominant and codominant (within species) suckers were inventoried by point sampling using nonoverlapping triangles (Loetsch *et al.* 1973).

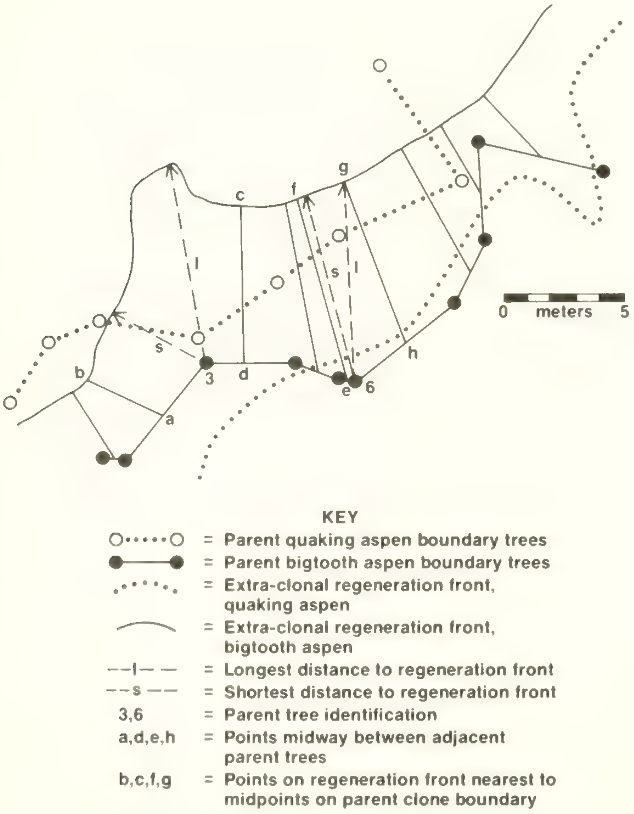

Figure 1.—*Map of quaking and bigtooth aspen clone boundary trees, regeneration fronts, and method to estimate regeneration reach by individual trees. For example, the putative area regenerated by bigtooth No. 3 is defined by a-b-c-d-3-a and for No. 6 is e-f-g-h-6-e. Regeneration reach is the mean of the long and short measurements from the parent tree to the regeneration front.*

Points were established at 3-m intervals on radii emanating every 45° from plot center. Thus there were 40 sample points (8 radii × 5 points per radius) in each of the five 0.08-ha plots.

The area added to each clone by extra-clonal suckering was determined from the maps by planimeter. Mean clone extension was then computed as:

$$\frac{\text{area added (m}^2\text{)}}{\text{length of parent contact boundary (m)}} = \text{clone extension (m)}$$

The clone extension attributed to each tree was also estimated from the 4-year data (fig. 1). These data were pooled for all clones within species and averaged by 5-tree, variable-interval, parent-d.b.h. classes.

The point sampling data were used to compute stem density, biomass (Perala 1973), and mean height [weighted by (d.b.h.)^2] of dominant and codominant suckers. These data were averaged within clone by species and outside of clone by 1-m distances from the nearest possible parent tree.

RESULTS

The two aspen species regenerated profusely both intra-clonally and extra-clonally. The extra-clonal extension of all suckers averaged 5.6 m for quaking aspen clones and 5.9 m for bigtooth aspen (table 2). Considering only dominants and codominants, quaking aspen clones extended an average of 5.1 m, compared with 3.3 m for bigtooth aspen.

The extra-clonal extension estimated for individual trees varied greatly (0.7 to 11.7 m for quaking, 0 to 9.5 m for bigtooth), but was largely accounted for by parent tree d.b.h. (fig. 2). Again, the species difference was pronounced, particularly in the smaller diameter classes, where bigtooth clone extension was much less than quaking aspen.

Quaking aspen produced suckers in greater numbers, total biomass, and mean weight than did bigtooth aspen (fig. 3). Moreover, quaking aspen extra-clonal sucker numbers and total biomass differed little from intra-clonal numbers and biomass up to 5 m away from the nearest possible parent before gradually declining. In contrast, bigtooth aspen suckers tended to decline continually in numbers and biomass as distance from nearest possible parent increased. The greatest contrast between the species is in mean sucker weight, which tended to increase with distance from nearest possible parent for quaking aspen and decrease with bigtooth. Despite these contrasts, mean height did not differ greatly between the species except at 7.5 m distance where quaking aspen was clearly taller.

Table 2.—*Quaking and bigtooth aspen parent trees and clone extension by suckering*

	Parent boundary trees			*Clone extension*	
Clone	**Number**	**Mean d.b.h. (cm)**	**Boundary length (m)**	**All[1] (m)**	**D&C[2] (m)**
		Quaking aspen			
1	16	17.4	71.4	(3)	3.40
2	9	22.1	35.9	7.09	6.39
3	9	24.1	19.6	(3)	6.46
4	29	21.0	97.8	4.10	4.10
5[4]	—	—	—	—	—
Mean	15.8	21.2	56.2	5.6	5.09
		Bigtooth aspen			
1	10	20.6	22.1	8.14	3.35
2	12	21.8	38.6	5.52	2.04
3	15	22.0	42.7	5.10	3.73
4	11	25.4	40.0	4.29	2.72
5	10	25.6	37.2	6.65	4.85
Mean	11.6	23.1	36.1	5.94	3.34

[1] All dominance classes, measured at age 1.

[2] Dominants and codominants only, measured at age 4.

[3] Not determined, suckering incomplete.

[4] This clone surrounded and regenerated completely across bigtooth clone 5. Therefore, maximum extension was unidentifiable.

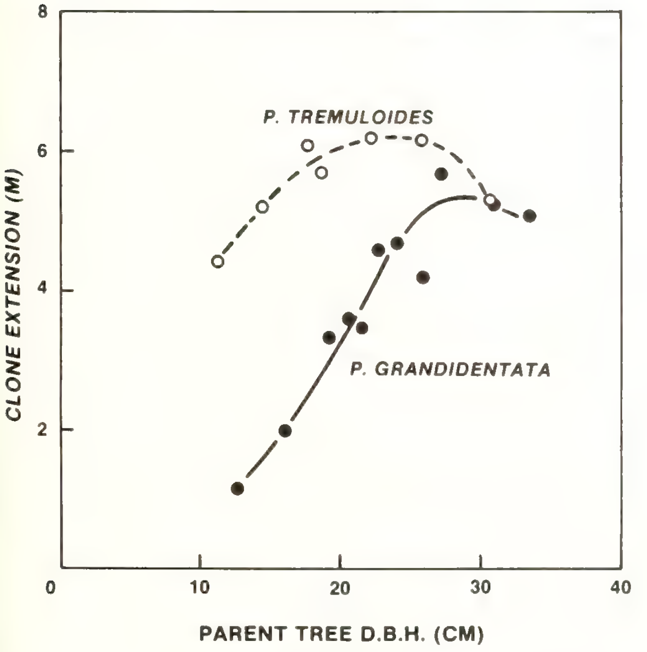

Figure 2.—*Clone extension of aspen in relation to species and d.b.h. of putative parent.*

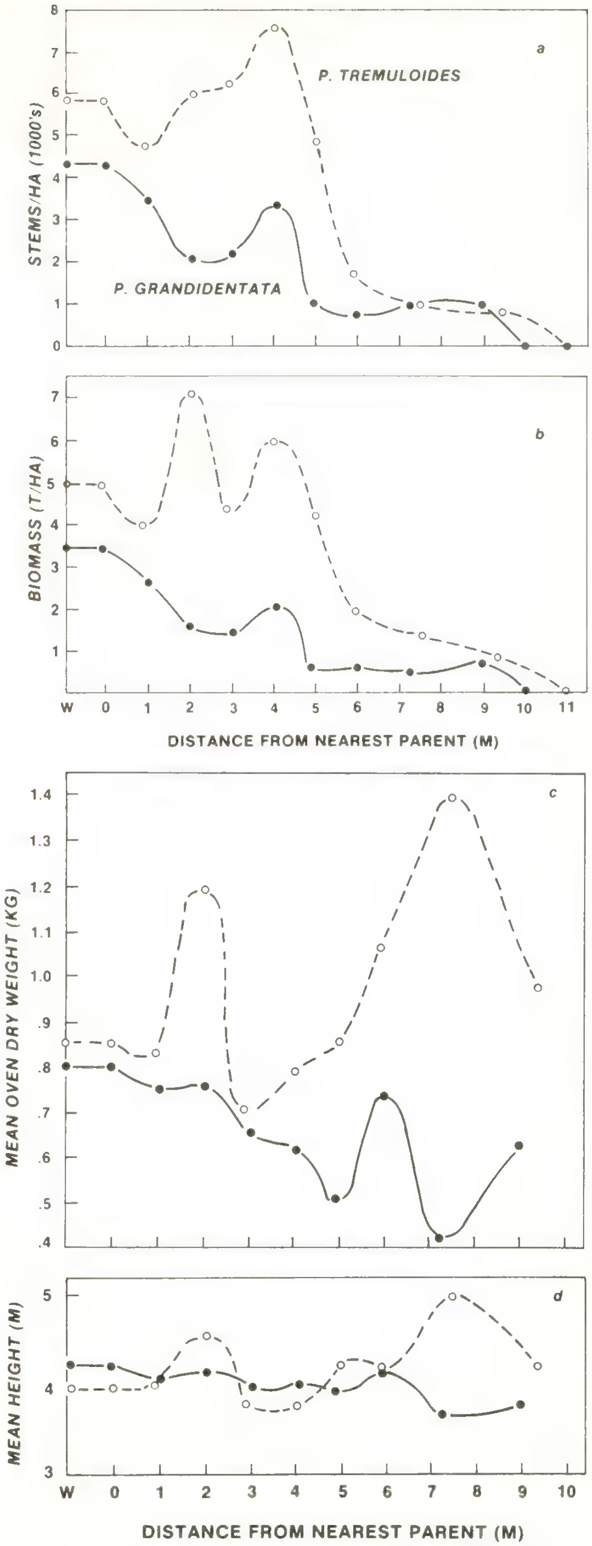

Figure 3.—*Characteristics of 4-year-old dominant and codominant (within species) trembling and largetooth aspen suckers in relation to distance from nearest putative parent; (a) stem density, (b) aerial ovendry biomass (except leaves, Perala 1973); (c) mean stem weight, and (d) mean stem height. W = within clone. Each data point is the mean of 10 to 17 observations, except for within clone with 69 (trembling aspen) and 36 (largetooth aspen) observations.*

DISCUSSION AND CONCLUSIONS

The extension of these competing aspen clones was much less than reports by Graham *et al.* (1963) and Beetle (1974) for aspen invading nonforested areas (up to 25 m), by Green (1961) for aspen invading deforested hardwoods (27 m), or what seems possible from excavated root systems (14.3 m reported by Day 1944 and 31.7 m reported by Buell and Buell 1959). Thus, the potential for enlarging favored aspen clones through silvicultural manipulation is modest.

Despite the ability of quaking aspen to regenerate greater sucker numbers and biomass than bigtooth aspen, the two species appear to coexist without great population changes in either. Rapid juvenile height growth to attain dominance is critical to both aspens' chances for survival. On that basis, neither species has demonstrated an early decided advantage.

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1981. Clone expansion and competition between quaking and bigtooth aspen suckers after clearcutting. U.S. Department of Agriculture Forest Service, Research Paper NC-201, 4 p. U.S. Department of Agriculture Forest Service, North Central Forest Experiment Station, St. Paul, Minnesota.

Quaking aspen clones expanded over more area, and regenerated greater sucker stem densities and biomass than did bigtooth aspen clones. However, sucker height growth was similar between the two species.

KEY WORDS: *Populus tremuloides, Populus grandidentata,* Minnesota, biomass regeneration, coppice.

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Northern Red Oak Regeneration

After Preherbicided Clearcutting and Shelterwood Removal Cutting

Paul S. Johnson and Rodney D. Jacobs

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NORTHERN RED OAK REGENERATION AFTER PREHERBICIDED CLEARCUTTING AND SHELTERWOOD REMOVAL CUTTING

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The failure of northern red oak (*Quercus rubra* L.) to regenerate in upland oak forests on good sites in southern Wisconsin and similar areas in adjacent States is a serious silvicultural problem (Johnson 1976). Unfortunately, reliable methods of obtaining adequate oak regeneration have not been developed yet (Sander 1979). Therefore, oak stands in this region with known histories of cutting and regeneration development are potentially important sources of information on the oak regeneration process.

This report documents the status of northern red oak reproduction after final harvest cutting in the Hardies Creek Timber Harvest Forest[1] in Trempealeau County, Wisconsin. Two of the stands were managed under two variations of the shelterwood system for 20 years preceding the final harvest; the third stand was clearcut after the understory was herbicided but received no cutting for 20 years preceding the final harvest.

FOREST CHARACTERISTICS

The 60-acre Hardies Creek Timber Harvest Forest lies within the unglaciated or "driftless" area of southwestern Wisconsin. The forest is situated on mainly east to northeast aspects, and slopes range from about 20 to 45 percent. The soil is Hixton loam formed on loamy sandstone residuum underlain by cemented sandstone bedrock; the solum ranges from 20 to 40 inches deep (Langton 1977). Site index for red oak is about 70.

The oldest stands in the forest were 106 years old at the time of the latest harvest (1974), even aged, and dominated by northern red oak. Black oak (*Quercus velutina* Lam.) and white oak (*Quercus alba* L.) dominated on some upper slopes. In the lower tree canopy, shagbark hickory (*Carya ovata* (Mill.) K. Koch) and black cherry (*Prunus serotina* Ehrh.) were the most important species; the latter occurred primarily as understory seedlings and saplings and few developed into sawtimber-size trees. Other subordinate tree species included American elm (*Ulmus americana* L.), mountain maple (*Acer spicatum* Lam.), boxelder (*Acer negundo* L.), and paper birch (*Betula papyrifera* Marsh.).

A dense shrub canopy is a conspicuous feature of much of the forest; predominant species are American hazel (*Corylus americana* L.), gray dogwood (*Cornus racemosa* Lam.), and common blackberry (*Rubus allegheniensis* Porter). In some areas, interrupted fern (*Osmunda claytonia* L.) and lady fern (*Athyrium felix-femina* L.) form a nearly continuous 3-foot tall ground layer. The possible origin, successional status, and other characteristics of southern Wisconsin oak forests have been discussed elsewhere (Curtis 1959, Auclair and Cottam 1971, Loucks and Schnur 1976, Braun 1967, Marks 1942).

In some unmanaged portions of the forest total basal area exceeds 130 square feet per acre, 80 percent or more of which is northern red oak. Mean stand diameters of the overstory range from about 14

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[1] *A State-owned tract on which demonstration and research projects are being carried on cooperatively by the Wisconsin Department of Natural Resources, the office of the Extension Forester at the University of Wisconsin, and the USDA Forest Service.*

to 16 inches d.b.h. Northern red oak is poorly represented or nonexistent in sapling and small pole-size diameter classes. Earlier studies of this forest have shown that although red oak seedlings under mature stands may exceed 7,000 per acre (Johnson 1974), few grow beyond 6 to 8 inches in height due to severe competition from ferns and shrubs (Scholz 1955). Thus, populations of small red oak rise and fall cyclicly, depending upon acorn crop and environmental conditions after seedfall. In the even-aged management of oaks, advance reproduction of this size has been considered inadequate for meeting stocking needs after final harvest cutting (Sander *et al.* 1976).

STAND HISTORIES

Shelterwood A.—Three shelterwood cuttings were made in this 5.4-acre stand prior to the final removal cut in 1974 at stand age 106. The first cut (preparatory cut) was made in 1952 at stand age 84 and reduced basal area from 123 to 103 square feet per acre (table 1). Mean stand diameter before and after this cut was between 14 and 15 inches d.b.h.

The second cut (seed cut) was made in 1962 at stand age 94 and reduced basal area to 75 square feet per acre. Just before this second cut, red oak reproduction averaged 1,500 stems per acre with 30 percent of milacre sample plots containing one or more seedlings; most of these were less than 1 foot tall. Number of seedlings of all other tree species averaged 3,480 per acre.

The third cut (second seed cut) was made in 1968 at stand age 100 because the first seed cut was too light. Basal area was reduced to 60 square feet per acre. In all three shelterwood cuts, removals were concentrated in the smaller diameter classes present. The final cut was made in the spring of 1974 during which all trees 2 inches d.b.h. and larger were felled or girdled. No inventory of reproduction was made immediately before the final removal cut.

Shelterwood B.—The combination preparatory/seed cut was made in this 6.5-acre stand in 1959 at stand age 91 and reduced basal area from 96 to 63 square feet per acre (table 1). Mean stand diameter was 16.0 and 16.5 inches d.b.h. before and after cutting, respectively. Most of the trees removed were in the smaller diameter classes present. In the final removal cut made early in 1968 at stand age 99, all trees 2 inches and larger were felled or girdled.

A reproduction survey just after the preparatory/seed cut in the spring of 1960 showed 552 seedlings per acre—all 18 inches or less in height. Tree reproduction of all other species averaged 396 per acre, with shagbark hickory and black cherry predominating. White oak, American elm, and paper birch were also present. The tallest reproduction was black cherry, American elm, and paper birch, which collectively averaged 57 inches in height. However, only 22 percent of milacre sample plots were stocked with any species of tree seedlings.

Seven growing seasons after the preparatory/seed cut, red oak reproduction averaged 2,600 trees per acre and were present on 58 percent of milacre plots. The average height of these trees was 10 inches and height ranged from 3 to 91 inches. All other tree reproduction averaged 417 stems per acre and were present on 38 percent of milacre plots. This reproduction averaged 69 inches in height and consisted mostly of shagbark hickory, black cherry, white oak, and paper birch.

Table 1.—*History of stand removals and basal areas*

Year	Stand age	Shelterwood A	Shelterwood B	Preherbicided clearcut	Type of removal
		Basal Area Per Acre (ft^2) Before/After Removals			
1951	83	—	—	137/103	Thinning
1952	84	123/103	—	—	Preparatory cut
1959	91	—	96/63	—	Preparatory/seed cut
1962	94	[1]*/75	—	—	Seed cut
1968	100	*/60	—	—	Seed cut
1968	100	—	*/0	—	Final Harvest
1972	104	—	—	(Herbicided)	Understory[2]
1973	105	—	—	(Herbicided)	Understory[2]
1974	106	*/0	—	*/0	Final Harvest

[1]* = unknown basal area.

[2]Shrubs and trees <2 inches d.b.h. were removed.

Preherbicided clearcut.—In 1951 at stand age 83, basal area was reduced in this 5.9-acre stand from 137 to 103 square feet per acre (table 1). Mean stand d.b.h. was 14 inches both before and after thinning.

The understory of this stand was treated with 2,4,5-T in late summer of 1972 and any surviving understory vegetation was treated again in 1973. The acorn crop was moderately good in the fall of 1973, and seedfall was complete before the stand was clearcut in early spring of 1974 at stand age 106. No information is available on parent stand characteristics at the time of the clearcut.

REGENERATION AFTER FINAL HARVEST CUTTING

Trees and shrubs were inventoried in early spring 1979 on 32 4.3-foot-radius plots in each of the three stands. A 1/735-acre plot size was used because it is the "minimum tree area" for a tree 4.5 inches d.b.h. (Gingrich 1967). In other words, a tree 4.5 inches d.b.h. requires a minimum of 1/735-acre (1.36 milacres) of growing space. It is assumed that dominant or codominant trees average 4.5 inches d.b.h. when mean stand diameter is 3 inches (Sander *et al.* 1976). At or beyond a mean stand diameter of 3 inches, more than one codominant or larger tree would not be expected to persist within a 1/735-acre sample space. When trees reach 3 inches in mean diameter, their utilization of growing space can be evaluated using the central hardwoods stocking guide (Roach and Gingrich 1968). Thus, a 1/735-acre plot is an appropriate sampling unit that can be used to express the number of "unit-growing-spaces" occupied by tree reproduction that can be related to future stocking criteria.

Shelterwood A.—Red oak seedlings and seedling-sprouts averaged 506 per acre and were present on 316 unit-growing-spaces per acre (43 percent of plots) five growing seasons after the final harvest cut (table 2). Most of them were more than 5 feet tall (table 3), with the largest red oak per stocked plot averaging 8.8 feet. Largest competitors averaged 10.3 feet in height and included black cherry, shagbark hickory, mountain maple, paper birch, and a few clumps of red oak stump sprouts. Red oak was codominant or larger (i.e., at least as tall as the largest competitor on a plot) on 28 percent of plots. Shrubs occurred on 60 percent of plots and the mean height of the shrub layer was 6.6 feet. American hazel and gray dogwood were the predominant species. Red oaks at or above the mean shrub canopy level occupied 279 unit-growing-spaces per acre (38 percent of plots).

Shelterwood B.—Red oak seedlings and seedling-sprouts averaged 804 per acre and were present on 316 unit-growing-spaces per acre (43 percent of plots) 11 growing seasons after the final harvest cut. Most of them were more than 5 feet tall (table 3), with the largest red oak per stocked plot averaging 16.6 feet in height. Codominant or larger competitors averaged 19.8 feet in height. Red oak was codominant or larger on 184 unit-growing-spaces per acre (25 percent of plots). Shrubs occurred on 41 percent of plots and the mean height of the shrub layer was 6.6 feet. American hazel and gray dogwood were the predominant shrub species. Red oaks at or above the mean shrub canopy level occupied 301 unit-growing-spaces per acre (41 percent of plots).

Preherbicided clearcut.—Red oak seedlings and seedling-sprouts averaged 2,872 per acre and were represented on 617 unit-growing-spaces per acre (84 percent of plots) five growing seasons after the clearcut. Most of these trees were less than 5 feet tall

Table 2.—*Northern red oak seedlings and seedling sprouts after final harvest cutting*

Stand	Northern red oaks	Unit growing spaces occupied by N. red oaks	Mean height of codominant or larger N. red oaks[1]	Unit growing spaces occupied by a codominant or larger N. red oak[2]	Unit growing spaces occupied by red oak at or above mean shrub canopy level
	(Mean no./acre)		(Feet)	(Mean no./acre)	
Shelterwood A[3]	506	316	8.8	206	279
Shelterwood B[4]	804	316	16.6	184	301
Clearcut[4]	2,872	617	3.6	301	162

[1] Based on red oaks as tall or taller than the largest competitor tree per plot.

[2] Based on chi-square—differences betweeen stands were not significant (0.05 level).

[3] Eleven years after final harvest cutting.

[4] Five years after final harvest cutting.

Table 3.—*Northern red oaks seedlings and seedling sprouts by stand and height class (time since harvest cutting is 5 growing seasons for Shelterwood A and the clearcut and 11 growing seasons for Shelterwood B)*

(In number/acre)

Stand	Tree height class (feet)					
	<1	1 to 1.9	2 to 2.9	3 to 3.9	4 to 4.9	⩾ 5
Shelterwood A	0	69	23	46	23	345
Shelterwood B	0	0	23	23	0	758
Clearcut	253	781	942	482	230	184

(table 3), with the largest red oak per stocked plot averaging 3.6 feet tall. Red oak was codominant or larger on 301 unit-growing-spaces per acre (41 percent of plots). However, with the sample size used, no between stand differences (0.05 level) in the proportion of plots stocked with codominant or larger red oaks could be demonstrated based on chi-square analysis.

Dominant competitors averaged 7.3 feet tall and their composition was similar to that of the shelterwood stands. However, in 1979, total density of competing trees and shrubs was visibly lower in the preherbicided clearcut than in either of the shelterwood-origin stands. Shrubs occurred on 38 percent of plots, and the mean height of the shrub layer was 5 feet. American hazel was the predominant species. Red oak seedlings and seedling-sprouts at or above the mean shrub canopy level occupied 162 unit-growing-spaces per acre (22 percent of plots).

The number of stump sprout clumps were not adequately inventoried after the final cut. However, they were expected to range from 18 in Shelterwood B to 46 in the clearcut, based on number of parent trees per acre before the final removal cut and the relation between frequency of sprouting and parent tree diameter (Johnson 1975).

DISCUSSION AND CONCLUSIONS

Neither shelterwood stand contained many red oaks less than 5 feet tall in contrast to the clearcut which contained a large population of red oaks less than 5 feet tall. Most of the red oak reproduction in the clearcut originated from the 1973 acorn crop. This suggests that the preherbicided clearcutting created more favorable conditions for seedling establishment and development than in Shelterwood A in which the final removal cut took place the same year. Moreover, the paucity of red oaks larger than 5 feet tall in the clearcut indicates that advance oak reproduction was either eliminated by the herbicide or was not present before herbiciding.

Minimum stocking required to regenerate these stands is 221 well distributed dominant or codominant trees per acre of acceptable species by the time the stand reaches 3 inches in mean d.b.h. (Sander *et al.* 1976). In the shelterwood-origin stands, this goal will not be attainable if total contributions to future stocking depend on the free-to-grow red oaks that are now present. However, other acceptable growing stock, including shagbark hickory and red oak stump sprouts, could compensate for deficiencies in advance red oak reproduction. Currently overtopped red oaks may be capable of emerging to positions of dominance but whether or not they will do so is unknown (Oliver 1978). The current number of codominant or larger red oaks per acre in the shelterwood-origin stands are nevertheless substantially higher than the number predicted to develop in an average clearcut at the same age (Johnson 1976).

An important ecological limitation to the shelterwood system as a method of increasing red oak regeneration in this region is the shrub layer, which increases in density as overstory density decreases (Auclair and Cottam 1971). In turn, as shrub density increases, tree seedling populations tend to decrease (Johnson 1976, Loucks and Schnur 1976). Thus, reducing overstory density by shelterwood cuttings might not create favorable conditions for establishment and development of oak reproduction unless the understory is also controlled (Sander 1979). This view is supported by the failure of red oak seedlings to develop in Shelterwood B following the large 1973 acorn crop.

In the preherbicided clearcut, adequate regeneration and ultimately complete utilization of growing space by red oaks may be potentially more realizable than in either shelterwood because of the reservoir of more than 1,500 2- to 4-foot tall seedlings per acre. Although relatively small, this reproduction is well distributed, and about 300 unit-growing-spaces per acre (41 percent of the plots) contain trees that are free to grow. Nevertheless, developmental success of red oak reproduction in this stand will depend on future growth rates of oaks in relation to growth rates and population density of competitors. If red oaks ultimately occupy an acceptable proportion of the stand, it may cause reconsideration of the assumption that obtaining red oak reproduction in advance of the final cut is necessary, at least in this ecological setting. However, such cuts would have to coincide with good acorn crops and competition would have to be controlled.

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Northern red oak (*Quercus rubra* L.) reproduction and competition are described 5 or 11 years after final removal cuttings in two shelterwoods and one preherbicided clearcut in southern Wisconsin.

KEY WORDS: *Quercus rubra* L., two-step shelterwood, four-step shelterwood, understory control, herbicide, 2,4,5-T.

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Felling and Bunching Small Timber on Steep Slopes

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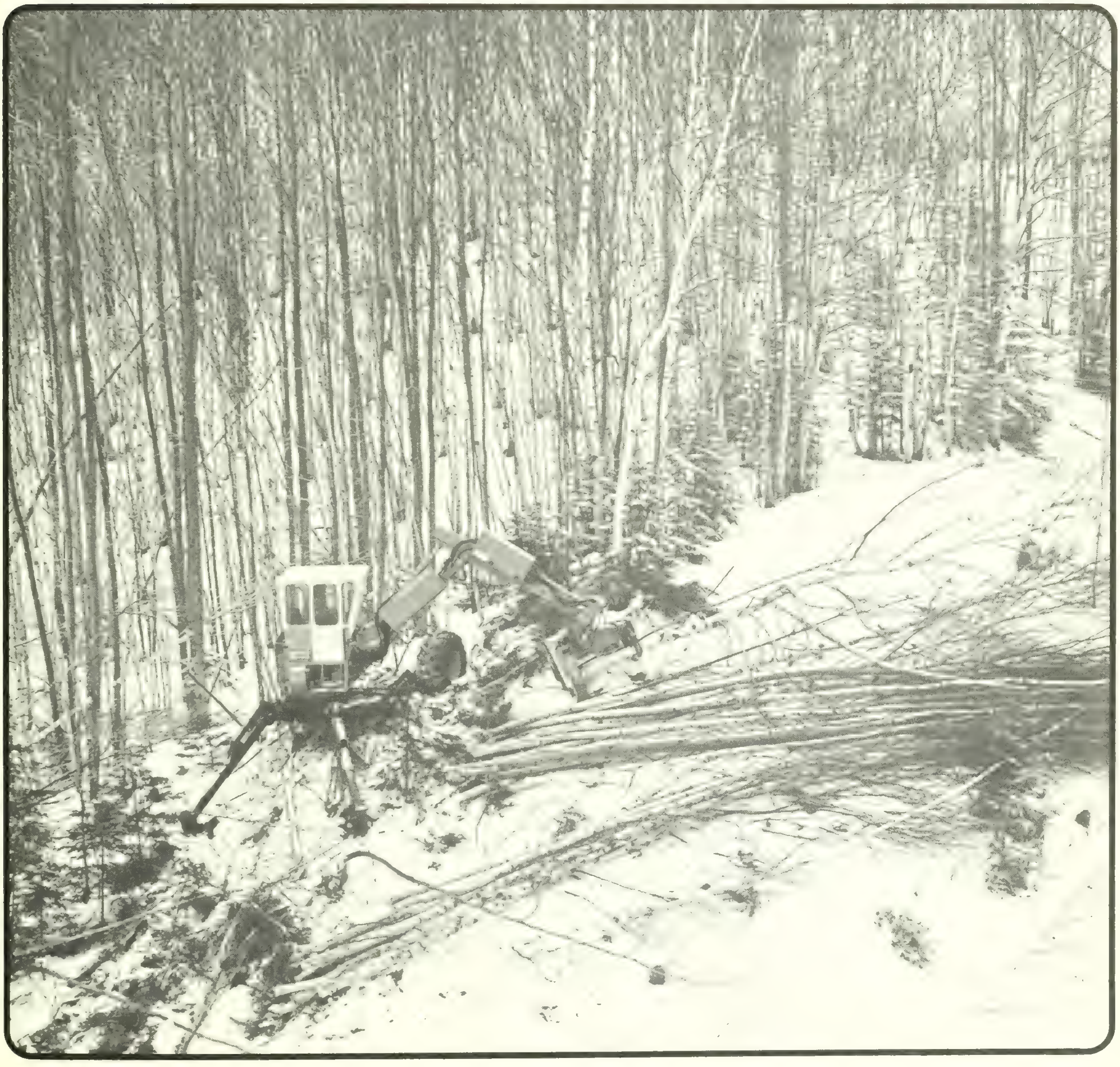

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FELLING AND BUNCHING SMALL TIMBER ON STEEP SLOPES

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The logging industry has long needed a small-tree, steep-terrain feller/buncher. Commercial feller/bunchers today generally cannot operate on slopes of more than 30 percent. On steep slopes containing large timber, trees can be directionally felled and bucked with a chain saw. The large volumes justify the use of chain saw felling and forwarding by cable systems or perhaps even the more elaborate helicopter and balloon systems. The economics become questionable when felling small trees on steep slopes. Trees felled by chain saw are left scattered over the hillside and economic recovery to a landing is a problem. However, if small trees could be felled and bunched so that the potential yarding payload is increased, the aggregate bunch volumes may improve justification of using cable or other systems for recovering small trees from steep slopes.

A machine called the Menzi Muck[1] appears to offer promise for harvesting small trees on steep-terrain. The Ernst Menzi AG[1] of Widnau, Switzerland, developed this unusual machine, which is capable of operating on steep slopes, in swamps, and under other conditions where conventional equipment often cannot work. The Menzi Muck machine, developed in the late 1960's as an excavator, has also been used for construction and mining. Its versatility is principally due to the hydraulically adjustable rear legs with wheels and front stabilizing legs with pads.

Because of the unusual potential of this machine for logging and forestry applications, Canadian Climbing Backhoe, Ltd.[2] of Edmonton, Alberta, a Canadian distributor for the Menzi Muck; Ernst Menzi AG, the manufacturer; and the North Central Forest Experiment Station of the USDA Forest Service cooperated to evaluate this machine as a small-tree, steep-terrain feller/buncher. Canadian Climbing Backhoe, Ltd. provided a Menzi Muck excavator (model 3000 EHA) to the USDA Forest Service Engineering Project in Houghton, Michigan. We modified the machine by fabricating and mounting a small prototype 12-inch shear (without an accumulator) to the end of the boom.

This publication presents preliminary results on the operation and performance of the Menzi Muck as a small-tree, steep-terrain feller/buncher. The reader is cautioned that the data presented are obtained from a limited period of testing. The detailed results are presented for the sole purpose of establishing baseline data that can be compared by other investigators or industry to subsequent tests. Such information can help pinpoint where improvements are needed.

TECHNICAL INFORMATION AND WORKING PRINCIPLES

The Menzi Muck is a fully hydraulic machine mounted on two adjustable stabilizer legs with pads and two adjustable legs with wheels. These wheels are free-rolling, receive no driving power, and have a rachet-type locking mechanism that can be manually activated if desired on steep slopes to allow them to roll in only one direction. A HATZ two-cylinder, four-stroke diesel engine, developing 40 hp at 3,000 rpm, powers the machine.

The knuckle or telescoping boom has a maximum lifting capacity of 4,629 pounds (2,100 kg). It is used to move the machine and also contains the working

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[1] *Mention of trade names does not consitiute endorsement of the products by the USDA Forest Service.*

[2] *Now Climbing Hoe of America, Ltd., Atlanta, Georgia.*

implement such as a shear or excavator bucket. An axial piston pump with horsepower regulator provides an operating hydraulic pressure of 2,850 p.s.i. (200 bar). The boom and cab can rotate 360° through the use of "Rothe Erde" ball races. The enclosed operator cab contains the controls for all operations such as tree felling and moving and leveling the machine. The machine is also equipped with a winch and cable to improve the stability of the machine on steep slopes and to aid in moving the machine.

The Menzi Muck has ground pressure of 4.84 p.s.i. (0.34 kg/cm^2 with standard equipment. Although this is higher than some conventional wheeled or tracked equipment, the wheels create little ground disturbance other than compaction. A special swamp package is available with a ground pressure of only 1.99 p.s.i. (0.14 kg/cm^2). The standard machine can operate on slopes up to 100 percent.

The machine is easily transported because it occupies a space of only 14 ft 9 in. by 6 ft 11 in. (4.5 m by 2.1 m) and weighs only 12,000 pounds (5,443 kg). It can load itself on a truck or trailer (fig. 1). The wheel base is hydraulically adjustable between 6 ft 6 in. (2.0 m) and 11 ft 6 in. (3.5 m). The maximum stabilizer leg base is 15 ft 1 in. (4.6 m). The machine can be pulled like a trailer for short distances. More complete manufacturer's specifications of the Menzi Muck are presented in Appendix I.

The Menzi Muck moves by means of the hydraulic boom (fig. 2). The shear head is lowered to the ground close to the machine (to push) or out ahead of the machine (to pull) and the stabilizers are raised so that the machine rests on only the shear head and the rear wheels. By applying hydraulic power to the boom, the machine advances or retreats "inch worm" fashion.

When in position to begin cutting, the stabilizer legs are lowered, and the legs and wheels are hydraulically adjusted to level the machine and attain maximum stability and operator comfort. To fell a tree the boom is extended and the shear is positioned at the base of the tree. The top clamps are closed on the tree, and it is sheared from the stump. The severed tree is lifted vertically and tilted back over the cab for stability, swung into position, and placed in bunches on the ground for skidding. (Skidding was not included in this study.) When all trees within reach are cut (it can harvest a 36-foot-wide swath), the machine is "inch wormed" to a new felling position. Because of the design and control of the two wheels and two stabilizing legs, the machine can accommodate a large variety of terrain conditions while operating up and down steep slopes or on side slopes. It can also climb over felled trees, stumps, large rocks, and other obstacles.

A part of the field test included use of the winch to improve the operability of the machine. Before moving straight up steep slopes, a cable from the power winch was run to the top of the hill and anchored. By maintaining cable tension, stability was improved and power could be applied to assist in moving the machine. This added assistance from the winch resulted in lower ground pressure under the heel of the shear so ground disturbance was reduced, which is especially important in sandy of soft soils. Ground disturbance can also be reduced by bottoming the shear on cut stumps.

Because the machine propels itself by pushing or pulling with the boom and the wheels receive no driving power, the tire life is expected to be substantially greater than conventional wheeled logging equipment.

FIELD TESTING

Two sites in the Six Mile Creek region of Baraga County, in the Upper Peninsula of Michigan were clearcut using the Menzi Muck. Both were too steep to harvest with conventional feller bunchers. One site was a pole-sized hardwood stand containing tree sizes and volumes similiar to those currently harvested on flat terrain in the Lake States area for whole-tree chips. The other site was a sapling-sized stand of hardwoods in which the trees were smaller, but much denser. Even though the volume per acre was low on the second site, it was selected to determine the shearing and bunching ability in a dense stand.

Both stands were inventoried before they were harvested to obtain the tree and stand factors necessary to describe the sites and to help evaluate the effect of stand on logging operations and productivity.

The areas were logged during the last half of November and the first half of December, 1979. Wet snow fell most of the time, and the ground was covered with 1 to 5 inches of snow over thick leaf litter.

Stop watch time study methods were used during the entire harvesting operation on both sites. The elements of the cycles were recorded as (1) travel, (2) reach and position, (3) shear, (4) lift and swing, (5) bunch, and (6) delay.

Following felling and bunching, data were collected on tree size, tree length, and bunch size. All felling and tree data were analyzed.

Figure 1.—*The Menzi Muck being loaded onto the bed of a transport vehicle (photos courtesy of Climbing Hoe of America, Ltd.).*

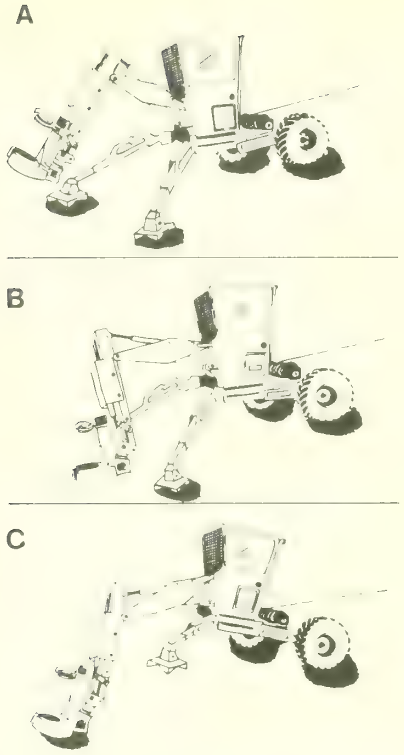

Figure 2.—*Simplified schematic illustrating movement of the machine up a slope. (A) Boom drawn towards machine. (B) Shear head bottomed on ground close to machine and downward pressure applied to lift the stabilizing pads from the ground. (C) Boom extended with shear head on the ground to push the machine up the slope. NOTE: The procedure can be reversed to pull the machine instead of push it.*

SITE DESCRIPTION

The pole stand contained white birch and red maple with small amounts of white pine, spruce, aspen, balsam, and red oak (table 1). Tree diameters ranged from 4 to 14 inches d.b.h. The basal area of trees ≥4 inches in diameter averaged 156 ft^2/acre. The number of trees ≥4 inches d.b.h. totaled 556/acre. The merchantable volume in trees ≥6 inches d.b.h. was 30 cords/acre. The soil was sandy and slopes ranged from 35 to 85 percent (fig. 3).

The preharvest cruise for the sapling stand indicated that white birch was the most prevalent species, followed by red maple and aspen (table 1). Individual tree diameters ranged from 1 to 9 inches d.b.h. Basal area of the trees ≥1 inch averaged 120 ft^2/acre and the trees ≥4 inches d.b.h. had a basal area of only 78 ft^2/acre. This stand contained more than 3,100 trees/acre ≥1 inch in d.b.h. The volume in trees ≥6 inches d.b.h. was only 3.5 cords/acre. The soil was sandy, and the slope was 80 percent (fig. 4).

RESULTS

The machine was initially used in the pole stand by working parallel to the slope. First, the crest of the slope was worked by felling and bunching all trees along a strip parallel to the contour line. Then, the machine was advanced to a lower elevation for each succeeding strip, still working parallel to the slope. On the second site, strips were cut at right angles to the contours, which proved to be more efficient, particularly on the steeper slopes. The machine was used working straight up and down the slope and the winch was used only when going up the slope.

After felling and bunching on each site, the butt diameters and tree lengths of the sheared trees plus the number of trees per bunch were recorded (table 2). Data on tree weights was estimated from work by Montieth 1979, and Steinhilb and Winsauer 1976. In the pole stand, the machine felled and bunched trees averaging about 7 inches in butt diameter and placed about seven trees in each bunch. The mean bunch was estimated to weigh about 2 green tons. In the sapling stand, average tree diameter at butt was less than 4½ inches, and the average bunch contained about 20 trees and weighed about 1.5 green tons.

The average cycle times in the pole and sapling stands were 1.27 minutes and 0.81 minutes, respectively (table 3). As shown in the following tabulation, the average number of trees sheared per cycle were 1.05 in the pole stand and 1.19 in the sapling stand.

Production data	**Pole stand**	**Sapling stand**
Trees cut (No.)	967	1,081
Scheduled hours (SH)	19.5	12.2
Productive hours (PH)	16.4	10.7
Machine utilization (U) (Percent)	84	87
Productivity per SH (No. trees)	49.7	88.3
(Tons)	13.9	6.2
Productivity per PH (No.trees)	58.9	100.9
(Tons)	16.5	7.1
Felling cycles (No.)	924	909
Trees/cycle (No.)	1.05	1.19
Average time/cycle (Min)	1.27	0.81
TOTAL YIELD (Tons)	271	76

Table 1.—*Number of trees and square feet of basal area per acre by species and diameter class*
POLE STAND

	White birch		Red maple		White pine		Aspen		Miscellaneous species		Total	
D.B.H. (inches)	Trees Trees	Basal area area	Trees Trees	Basal area area	Trees Trees	Basal area area		Basal		Basal		Basal
	No.	*ft²*	*No.*	*ft²*	*No.*	*ft²*	*No.*	*ft²*	*No.*	*ft²*	*No.*	*ft²*
4	68.76	6.00	68.76	6.00	—	—	—	—	—	—	137.52	12.00
6	111.98	22.00	40.72	8.00	30.54	6.00	—	—	10.18	2.00	193.42	38.00
8	74.36	25.96	28.60	9.98	17.16	6.00	—	—	11.44	4.00	131.56	45.94
10	54.90	29.94	—	—	—	—	3.66	2.00	—	—	58.56	31.94
12	23.32	18.31	—	—	2.54	1.99	5.08	3.99	2.54	1.99	33.48	26.28
14	—	—	—	—	—	—	1.88	2.01	—	—	1.88	2.01
Total	333.32	102.21	138.08	23.98	50.24	13.99	10.62	8.00	24.16	7.99	556.42	156.17
SAPLING STAND												
2	1,833.48	40.00	458.37	2.50	—	—	—	—	—	—	2,291.85	42.50
4	611.20	53.34	76.40	6.67	—	—	38.20	3.33	—	—	725.80	63.34
6	16.97	3.33	—	—	—	—	50.90	4.44	—	—	67.87	7.77
8	9.53	3.33	—	—	—	—	9.53	3.33	—	—	19.06	6.66
Total	2,471.18	100.00	534.77	9.17	—	—	98.63	11.10	—	—	3,104.58	120.27

Figure 3.—*The Menzi Muck as a small-tree feller/buncher operating parallel to the slope on the pole-sized steep site.*

Figure 4.—*The Menzi Muck as a small-tree feller/buncher operating straight up the slope on the sapling-sized steep site.*

Table 2.— *Sizes and green weights of trees and bunches for pole and sapling stands*

POLE STAND

Element	Mean	Standard deviation	Range
Butt diameter (inches)	7.14	2.84	1 to 14
Trees/bunch (Number)	6.93	4.46	1 to 22
Weight/tree (green tons)[1]	0.28	0.24	0.014 to 1.160
Weight/bunch (green tons)[1]	1.94	1.15	0.036 to 6.025

SAPLING STAND

Element	Mean	Standard deviation	Range
Butt diameter (inches)	4.31	1.76	1 to 11
Trees/bunch (Number)	20.06	8.44	6 to 38
Weight/tree (green tons)[1]	0.07	0.08	0.01 to 0.61
Weight/bunch (green tons)[1]	1.50	0.71	0.34 to 3.85

[1] More than 70 percent of the basal area of trees in the study areas were white birch. However, white birch weight tables were not available for this area, so we calculated all weights from sugar maple weight tables developed for Northern Michigan (Steinhilb and Winsauer 1976) because Montieth (1979) suggests that sugar maple tables can be used to obtain weights for white birch.

Table 3.—*Element time per cycle*
(In minutes)

POLE STAND[1]

Element	Mean	Standard deviation	Range
Reach and position	0.25	0.10	0.05 to 0.74
Shear	0.16	0.13	0.07 to 1.55
Lift and swing	0.15	0.09	0.02 to 0.89
Bunch	0.11	0.06	0.04 to 0.72
Travel	0.40	—	—
Delay	0.20	—	—
TOTAL	1.27		

SAPLING STAND[2]

Element	Mean	Standard deviation	Range
Reach and position	0.23	0.11	0.03 to 1.04
Shear	0.11	0.05	0.07 to 0.65
Lift and swing	0.12	0.06	0.03 to 0.70
Bunch	0.10	0.14	0.05 to 0.37
Travel	0.15	—	—
Delay	0.10	—	—
TOTAL	0.81		

[1] 556 trees per acre ≥ 4 inches d.b.h.

[2] 3,105 trees per acre ≥ 2 inches d.b.h.

The definitions of the time study elements are as follows: "*Reach and Position*"—begins when travel of the machine stops, or the shear head begins to move after dropping a tree onto a bunch and ends when the shear is in position to cut the next tree. "*Shear*"—begins when the shear blade moves to cut and ends when the tree is severed from the stump. "*Lift and Swing*"—begins after the tree is sheared and ends when the shearing head is in position to tilt the tree over the bunch. "*Bunching*"—begins after the shear head is in position to tilt the severed tree above the bunch and ends when the shear head drops the tree onto the bunch. "*Travel*"—begins when the last tree within reach of the machine is bunched, and ends when the machine has moved into a position to harvest uncut trees.

Delays for the Menzi Muck were grouped according to (1) *mechanical*—caused by malfunction or breakage of the machine; (2) *operational*—needed to plan and expedite the harvesting operation; (3) *service*—needed to fuel, grease, or service the machine; (4) personal—machine operator breaks; and (5) *other* (table 4). Most of the delays were operational and comprised 74 percent of the total delay time in the pole stand and 79 percent in the sapling stand.

Table 4.—Analysis of delays for the Menzi Muck in the pole and sapling stands

Cause of delay	Pole stand		Sapling stand	
	Minutes	*Percent*	*Minutes*	*Percent*
Mechanical				
Replace broken fitting	33.16	18	—	—
Operational[1]				
Remove obstacles	41.99	23	22.02	24
Plan action	7.83	4	0.46	1
Set brakes, winch, or pad	54.22	30	40.13	44
Instruct operator	26.75	15	2.9	3
Tree too large for shear	0.37	<1	—	—
Move to tree	4.18	2	6.32	7
Service				
Clean window	1.30	1	—	—
Fuel and grease	—	—	5.82	6
Sharpen shear	9.27	5	2.43	3
Personal	3.11	2	5.82	6
Other	0.59	<1	5.34	6
TOTAL	182.77	100	91.24	100

[1] Operational delays are those necessary to plan or expedite the harvesting operation—they are not related to equipment deficiency or failure.

Some of the delays are avoidable. The operator was not familiar with felling and bunching techniques so it was necessary to stop periodically to instruct him. An experienced operator would possibly have eliminated some of this delay. By the time the operator moved to the second site, he had developed more skill in felling and bunching with the net result that he required fewer instructions.

As shown in the following tabulation, the traveling speed of the the Menzi Muck ranged from 6.4 to 14.7 feet/minute.

	Terrain		
	Level	**Uphill**	**Downhill**
	------------- Speed	(feet/minute)	-------------
Pole stand	8.0	6.4	7.2
Sapling stand	11.1	7.0	14.7

In the soft, sandy soils of the study area, the machine sometimes had difficulty moving because the base of the shear would sink into the ground, thus creating holes. These "footprints" were more evident if the winch was not used when traveling uphill (fig. 5). The manufacturer rates the maximum speed of the machine at 4,000 feet/hour on flat, unobstructed terrain. When moving between shearing places, the machine traveled at rates ranging from 400 to 900 feet/hour. This lower speed is due to the steep terrain, soft ground with snow, obstacles, etc.

Figure 5.—*The Menzi Muck produces a line of "footprints" caused by pushing or pulling the machine with the boom and heel of the shear.*

The number of machine movements are affected by the number and spacing of the trees. In the pole stand, which contained more than 500 trees per acre, the machine moved 350 times to fell and bunch 967 trees. In the sapling stand, which contained more than 3,000 trees per acre, it moved only 200 times to harvest 1,081 trees.

Data from the pole stand revealed 967 trees, amounting to 271 green tons of wood, were harvested in 19.5 scheduled hours (including delays) or 16.4 productive hours (excluding delays). This yielded a production rate of 16.5 tons per productive hour or approximately 60 trees per productive hour. In the sapling stand, 1,081 trees or 76 tons of wood were harvested in 12.2 scheduled hours or 10.7 productive hours. The production rate was only 7.1 tons of wood per productive hour even though the tree felling and bunching rate in the sapling stand was close to 100 trees per productive hour.

Of major importance in this initial study was whether the machine could function as a small-tree feller/buncher on steep terrain. Of secondary importance was how well it functioned in terms of cost and productivity. Further testing of the machine for harvesting is needed to better define the range of operating conditions, strive for production performance, and isolate the improvements required before the machine can be developed as a commercial feller/buncher.

Costs for the Menzi Muck are difficult to determine because the machine has not previously been used for harvesting. However, based on the best information available, costs were calculated for the Menzi Muck when harvesting small trees on steep terrain on both sites using a single tree shear without an accumulator. The base machine and optional equipment cost information, together with a salvage value of 40 percent of purchase price, and a 10 year life for tires as provided by Climbing Hoe of America plus a machine life of 5 years (estimated by the authors) were used to calculate the hourly machine rate for the Menzi Muck on this test (Miyata 1980). Method of calculating this machine rate is shown in the following tabulation and results in a cost of $21.99 per productive hour excluding labor and $35.84 per productive hour including labor. Undoubtedly, future experience with the machine for logging will provide more accurate machine life, salvage, tire life, and maintenance and repair values, enabling a more realistic calculation of the machine rate.

MENZI-MUCK MACHINE RATE

Description

Purchase price (f.o.b. delivered)	$51,408	
Winch	6,000	
Shear head (estimated)	5,000	
Tire cost	-2,000	
Initial investment-P		= $60,408.00
Salvage value (40 percent of P)[3]-S		= $24,163.20
Estimated machine life-N	5 years	
Working days per year	250 days	
Scheduled hours-SH per year	2,000 hours	
Utilization-U	65 percent	
Productive time-PH per year	1,300 hours	

Average value of investment: $AVI = \frac{(P-S)(N+1)}{2N} + S$ = $45,910.08

Fixed cost

Depreciation cost: $D = \frac{(P-S)}{N} = \frac{\$60{,}408.00 - \$24{,}163.20}{5}$ = $ 7,248.96

Interest, insurance, taxes: = $11,018.42

IIT = (18 percent + 3 percent + 3 percent) x AVI

Yearly fixed cost: YFC = D + IIT = $18,267.38/yr.

Hourly fixed cost: HFC = YFC ÷ PH = $ 14.05/hr.

Operating cost

Maintenance and repair: $MR = (100\text{ percent of } \frac{D}{PH})$ = $ 5.58/hr.

Fuel cost: $F = \frac{1.65\text{ gal}}{\text{hr.}} \times \$1.02/\text{gal.}$ = $ 1.68/hr.

Oil and lubricant-L = $ .50/hr.

Tire: $T = \frac{1.15 \times \$2{,}000}{13{,}000/\text{hr.}}$ = $ .18/hr.

Hourly operating cost: HOC = MR + F + L + T = $ 7.94/hr.

Hourly machine cost: HMC = HFC + HOC = $ 21.99/hr.

Labor cost: LC = $9.00/SH x 2,000 SH ÷ 1,300 PH = $ 13.85/hr.

Hourly machine cost with labor:
HMCL = HMC + LC = $ 35.84/hr.

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[3] *Based on manufacturer's data when machine is used as an excavator.*

Based on the above hourly rate for productive hours, the cost of felling and bunching was estimated as \$2.17 per green ton (or \$0.60 per tree) in the pole stand and \$5.05 per green ton (or \$0.36 per tree) in the sapling stand.

These production figures are based on the nonaccumulating shear used in the study. Use of an accumulating shear would have reduced costs and increased productivity. For example, for trees averaging 7 to 7½ inches d.b.h., a shear with accumulator can produce about twice as many cords per hour as a shear without an accumulator (fig. 6) (Rome Industries 1974). The difference in production is even greater for smaller trees. Therefore, a recommendation is to equip the Menzi Muck with an accumulator shear in future small tree felling and bunching studies to determine if productivity could be increased and costs per ton and per tree reduced. Another recommendation is to use the Menzi Muck with the telescoping boom, which gives an added 3 feet 3 inches of reach over the knuckle boom. Thus, for a given setting, more trees would be within reach which should favorably influence productivity and cost per unit of production.

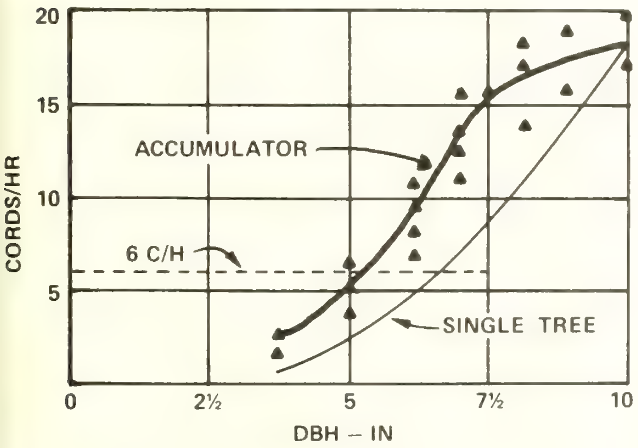

Figure 6.—*Productivity comparison of harvesting small diameter trees with a single tree shear versus a shear with a tree accumulating feature (Rome Industries 1974).*

CONCLUSIONS

This study demonstrated the potential of Menzi Muck to harvest small timber on steep slopes. Although the test covered only a short period of time and was limited in scope, these preliminary data can be used by other researchers or industry to compare with future tests of this machine. The productivity and cost results presented should be used with caution, because these figures are based on one machine operating for only 16.4 productive hours in a hardwood pole stand and 10.7 productive hours in a hardwood saping stand.

The Menzi Muck may have potential in felling and bunching small timber for cable yarding, strip thinning on steep slopes, and logging swampy areas. Included below is a partial list of other possible applications.

1. Bunching small trees or logs for a skyline system.
2. Placing tail hold anchors on steep slopes for skyline yarding systems.
3. Excavating ditches to drain swamps and roadways.
4. Recovering logging residue on steep slopes.
5. Chopping or shredding residue on steep slopes.
6. Harvesting stumps on swampy sites.
7. Constructing access roads or trails.

Further testing of this machine may solve other forestry and logging problems on adverse terrain.

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APPENDIX

MANUFACTURER'S SPECIFICATIONS

Hydraulic System

The model 3000 MENZI MUCK is a fully hydraulic excavator.

- The axial piston pump with HP regulator is directly flanged to the engine and has a capacity of 85 liters/minute (22.5 gal/min). This pump feeds the hydraulic system for both the working movements and the undercarriage.
- Cylinders and swing motor are operated through two control blocks.
- The working movements are controlled by a "Bosch" segment-type control unit with special precision-control leading edges. The main pressure-relief valve is adjusted to a working pressure of 200 bar (2,850 p.s.i.). In addition, safety elements with secondary safety valves are built into every segment.
- The stabilizing movements of the undercarriage (feet and wheels) are controlled through a "Parker" monoblock.
- All hydraulic cyliners are made by MENZI.
- A self-braking hydraulic piston swing motor turns the superstructure.
- Hydraulic oil is returned through the oil cooler to ensure a constant oil temperature of 70°C (158°F).
- Hydraulic oil is filtered in the return line to protect all high-precision parts.

Undercarriage

The adjustment stabilizer and wheels give the MENZI MUCK maximum stability.

- The wheels may be brought into the desired vertical position hydraulically, the control being infinitely variable. The wheel track may be horizontally adjusted hydraulically from 2 to 3.5 m (6½ to 11½ feet).
- The wheels run freely in the working direction. If desired, the wheels may be locked to prevent rotation in the opposite direction.
- High, wide-ribbed tires resist skidding and punctures, provide low ground pressure, and absorb shocks.
- The telescoping swivel feet are hydraulically adjustable in vertical direction and may be extended to 4.60 m (15 feet 1 inch) wide.
- The stabilizer claws give the excavator excellent stability. MENZI MUCK may be equipped with self-emptying steel claws, rubber pads, or swamp plates (diameter up to 1.25 m = 4 feet 1 inch).
- All hydraulic cylinders of the undercarriage automatically lock in case of pressure loss.

Superstructure

The superstructure is the main compact unit of the MENZI MUCK excavator.

- The built-in diesel is easily accessible for daily maintenance and service work. It is supported by four rubber blocks that absorb shocks and ensure that a minimum of vibration is transferred to the excavator.
- An all-around view cab gives unrestricted visibility on all sides. Canadian and U.S. machines are equipped with a Tubelok rollover structure and seatbelts conforming with U.S. and Canadian Safety Standards. The control levers and instruments are conveniently located.
- The windsheild may be easily removed. The roof may be opened for better aeration. An efficient hot air heater is included.
- The "Rothe Erde" ball race joins the undercarriage and superstructure. It makes an operational range of 360° possible. A grease cut ensures good lubrication. The superstructure may be bolted in two positions for transportation.

Boom

The boom of the MENZI MUCK is the actual working device. The MENZI MUCK makes use of its boom not only for digging, but also for moving itself.

- The digging arm is available in three different types:

Model EH—digging arm mechanically adjustable by 100 cm (3¼ feet).
Model T1—digging arm hydraulically adjustable by 100 cm (3¼ feet).
Model T2—digging arm hydraulically adjustable by 200 cm (6½ feet).

A large range of excavation buckets fit all types of booms.

Engineering Data

Engine

Air-cooled HATZ two cylinder four-stroke diesel engine, direct injection, with optional heater plug, deep sump oil pan for off-the-road operation. Output 40 hp at 3,000 rpm. Displacement 2,014 cm^2 (123 in.^3), BOSCH injection pump. BOSCH injection valves. Electrical equipment 12 V with alternator.
Optional: with electric motor 30 kw (40 hp).

Hydraulic system

Pump:	Axial piston pump with HP regulator. Operating pressure 200 bar.
Control unit:	BOSCH for working movements. PARKER for the adjustment of stabilizer feet and axles.
Hydraulic cylinders:	Manufactured by MENZI, hardened, impact-resistant chromium-plated piston rods, honed cylinders, supporting cylinders with protection against hose rupture.
Swing motor:	Self-braking hydraulic piston swing motor.
Hydraulic Oil:	120 l multi-grade oil, working temperature 70°C (158°F), oil cooler connected to return line oil filter for return lines.
Output	3 to 4 working cycles per minute. Climbing ability 100 percent.
Tires	20-20, 10-ply (1,270 mm high, 520 mm wide).

MISCELLANEOUS

Weight with 60 cm bucket	5,500 kg (12,125 lb)
Lifting capacity	2,100 kg (4,629 lb)
Tearing power, long bucket	3,000 kg (6,613 lb)
Tearing power, short bucket	3,500 kg (7,716 lb)
Breakout force, long bucket	5,500 kg (12,125 lb)
Breakout force, short bucket	10,000 kg (22,046 lb)
Ground pressure:	
Standard equipment	0.34 kg/cm^2 (4.84) p.s.i.
With swamp equipment	0.14 kg/cm^2 (1.99) p.s.i.
Measurements:	
Smallest horizontal clearance required	2,000 mm (6 ft 6 in.)
Smallest wheel base	2,000 mm (6 ft 6 in.)
Largest wheel base	3,500 mm (11 ft 6 in.)
Largest stabilizer base	4,600 mm (15 ft 1 in.)
Smallest space needed for transportation	4,500 by 2,100 mm (14 ft 9 in. × 6 ft 11 in.)
Height with cab	2,550 mm (8 ft 5 in.)
Height without cab	1,710 mm (5 ft 7 in.)
Maximum reach	6,400 mm (21 ft)
Maximum digging depth	4,200 mm (13 ft 9 in.)
Maximum dumping height:	
Chassis on the ground	3,200 mm (10 ft 6 in.)
Chassis in raised position	5,200 mm (17 ft 1 in.)
Boom extension mechanically adjustable	1,000 mm (3 ft 3 in.)
Smallest operational range	3,200 mm (10 ft 6 in.)
Overall height with smallest operational range	4,050 mm (13 ft 4 in.)

Arola, Rodger A., Edwin S. Miyata, John A. Sturos, and Helmuth M. Steinhilb.

1981. Felling and bunching small timber on steep slopes. U.S. Department of Agriculture Forest Service, Research Paper NC-203, 12 p. U.S. Department of Agriculture Forest Service, North Central Forest Experiment Station, St. Paul, Minnesota.

Discusses the results of a field test of the unique Menzi Muck machine for felling and bunching small trees on steep slopes. Includes the analysis of a detailed time study to determine the productivity, costs, and economic feasibility of this unusual machine.

KEY WORDS: Logging, rough terrain, productivity, costs, mechanized harvesting.

U.S. Government Printing Office: 1981—767-165/1 Region No. 6

United States Department of Agriculture

Forest Service

North Central Forest Experiment Station

Research Paper NC-204

Early Results of Planting English Oak in an Ozark Clearcut

Paul S. Johnson

Johnson, Paul S.

1981. Early results of planting English oak in an Ozark clearcut. U.S. Department of Agriculture Forest Service, Research Paper NC-204, 6 p. U.S. Department of Agriculture Forest Service, North Central Forest Experiment Station, St. Paul, Minnesota.

Shoot growth and survival of container-grown and 1-0 bare-root English oak (*Quercus robur* L.) seedlings are reported for a 3-year period after planting in a clearcut. Effects of mulching with black polyethylene are also reported.

KEY WORDS: *Quercus robur* L., shoot growth, polyethylene mulch, container-grown seedlings.

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1981

EARLY RESULTS OF PLANTING ENGLISH OAK IN AN OZARK CLEARCUT

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English oak (*Quercus robur* L.) belongs to the white oak group and is indigenous to Europe, Asia Minor, and northern Africa. In Europe, it occupies relatively moist and fertile sites and is grown for high quality timber on rotations of up to 400 years. Although English oak has been primarily planted as an ornamental in the United States, in southern Michigan forest plantations of it grew more than twice as fast in diameter as native white oak (*Quercus alba* L.) during the first 13 years (Wright *et al.* 1973). Thus, English oak may be of interest to North American silviculturists because of its rapid juvenile growth compared to the relatively slow growth of most North American oaks (Russell 1971).

The results of numerous oak planting trials on forest sites in the Oak-Hickory Region have generally shown that planted oaks survive well, but that their slow growth soon results in their suppression by more vigorous natural vegetation. Thus, there is a need for developing nursery and planting techniques that will produce seedlings that grow rapidly under forest conditions (Johnson 1979). This paper reports on the growth and survival of container-grown and bare-root English oak during the first three years after planting in a Missouri Ozark clearcut. Black polyethylene mulching placed around planted trees was also tested to evaluate its effectiveness in reducing competition and increasing planted tree growth.

METHODS

English oak acorns were collected in October 1975 from about six fastigiate-form trees on the University of Missouri campus at Columbia. The acorns were then stored in 0.1 mm thick plastic bags at 2 to 4° C until late January 1976, when about 500 acorns were removed from cold storage and germinated between layers of wet paper towels at greenhouse temperatures of 21 to 24° C. After one week, 404 acorns with radicles ½ to 3 cm long were potted in 294 cc (20 cm deep) Spencer Lemaire "Rootrainers"[1] with grooved side-walls and open bottoms. The open bottoms cause "air-pruning" of roots, which in turn, produces a fibrous root system. Containers were filled with a 1:1 mixture of peat and coarse vermiculite.

These 404 seedlings were grown in the greenhouse until early May when they were moved outdoors under 43 percent shade fabric. In both environments, seedlings were grown at a density of 330 trees per square meter during the 9 month propagation period. Container propagation methods were modified after Tinus (1974) and Matthews (1971). In late October, all container-grown seedlings less than 30 cm tall were rogued. The remaining seedlings (approximately 200) were kept under the outdoor shade frame in an apparently dormant state until planting time in November.

Bare-root stock was grown in a conventional nursery bed at the George O. White State Forest Nursery at Licking, Missouri, from about 1,500 acorns sown in early April 1976. Seedlings were grown at an average density of 36 trees per square meter. These seedlings were lifted on October 25, and "healed-in" in the nursery. On November 3, the seedlings were sorted and those with tops less than 30 cm long were discarded. Roots of the remaining trees were then pruned 25 cm below the root collar and packed in plastic bags with moist peat moss. In contrast to the container-grown seedlings, bare-root seedlings had few lateral roots.

On November 4, 384 seedlings were planted in a 0.4-hectare (1-acre) clearcut on the Sinkin Experimental Forest in southern Missouri. The clearcut occupied a 30 percent north-facing slope where the site index for black oak was 21.3 m (70 feet). Before planting, stumps of all overstory stems 4.1 cm (1.6 in.) d.b.h. and larger were treated with 2,4,5-T to

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[1] *Mention of trade names does not constitute endorsement of the products by the USDA Forest Service.*

prevent sprouting. Trees were planted in 12 blocks in a randomized block design. Each block contained two 8-tree rows of container-grown seedlings and two 8-tree rows of bare-root seedlings. Planting was done with mattocks at a 2.4- by 2.4-m (8- by 8-foot) spacing; soils were moist at time of planting. Container-grown seedlings were removed from containers with soil "plugs" intact and then planted.

After planting, two rows of each seedling-type per block were mulched with sheets of 0.1 mm thick black polyethylene film 91 by 91 cm. The polyethylene was held in place by U-shaped pins made of number 9 galvanized wire about 15 cm long that were pushed through the film and into the soil at the four corners of each sheet. Each corner was reinforced with nylon filament tape to prevent the film from tearing at the pinning points.

At the time of planting, measurements were made of seedling diameters (2 cm above the root collar) and seedling heights. On the average, stem diameters for bare-root seedlings were about 3 mm larger than for container-grown seedlings (table 1). Mean heights of planted trees by treatments ranged from 51.5 to 56.8 cm at time of planting. Measurements of total live heights of seedlings were also made at the end of each growing season; shoot dieback was measured after the first growing season. Also, on April 20 of the first growing season after planting, seedlings that had initiated shoot elongation were counted and flush lengths were measured. Net shoot elongation was calculated as the difference in live seedling height between two years. All heights and shoot lengths were measured to the nearest centimeter, and all stem diameters to the nearest millimeter.

RESULTS

Flushing was observed on some of the planted English oaks on April 20 of the first field growing season—several days before indigenous oaks at the planting site initiated flushing. By this date, 94 percent of the container-grown seedlings had initiated shoot elongation (90 unmulched and 91 mulched trees); the new shoots averaged 5 cm in length with the longest new shoot measuring 18 cm. Because of terminal shoot dieback, however, only 21 percent of those trees which had flushed by this date produced shoots that originated from the terminal bud cluster. In contrast to the high percent of flushing by the container-grown seedlings, only one of the 192 bare-root seedlings had initiated flushing by this date. This earlier initiation of growth by the container-grown seedlings may have been due to shading in the propagation bed the previous year—an effect similar to that of overstory canopy shading on northern red oak (*Quercus rubra* L.) seedlings as noted by McGee (1976).

During the first winter in the field there was much shoot dieback, and mean net shoot elongation for the first growing season was negative for all treatments. However, there was significantly more shoot dieback of bare-root seedlings than of container-grown seedlings, and significantly more dieback on mulched than on unmulched seedlings. Mean dieback was thus greatest for mulched bare-root trees (37.7 cm) and least for unmulched container-grown trees (13.7 cm) (table 2). By the end of the first year, container-grown trees were significantly taller than bare-root trees and unmulched trees were significantly taller than mulched trees. Live heights of unmulched container-grown trees were within 1 cm of their planted heights, and mulched bare-root seedlings were about 16 cm shorter than when they were planted. First-year survival averaged 89 percent, but was significantly higher for unmulched (99 percent) than mulched seedlings (82 percent). The difference in survival between types of nursery stock was not significant.

Table 1.—*Initial size of English oak nursery stock by treatments*

	Shoot diameter[1]			Height when planted		
Treatment	Mean	Standard deviation	Range	Mean	Standard deviation	Range
		mm			*cm*	
Bare root, unmulched	8.2	1.4	6-11	53.7	12.2	30-81
Bare root, mulched	8.3	1.5	5-12	51.5	12.6	30-80
Container-grown, unmulched	5.3	1.4	3-9	54.8	14.0	31-104
Container-grown, mulched	5.2	1.3	3-10	56.8	14.4	30-96

[1] Measured 2 cm above the root collar (nearest mm).

Table 2.—*Mean survival, shoot growth, shoot dieback, and significance level of treatment differences for planted English oaks*

	Response Variable								
	Survival	Shoot dieback	Net shoot elongation				Mean tree height after		
Treatment	Three-year	First year	First year	Second year	Third year	Three-year	First year	Second year	Third year
	Percent	*cm*[1]							
Bare root, unmulched	91	33.4	−7.9[2]	24.3	21.1	38.8	45.8	71.1	92.0
Bare root, mulched	75	37.7	−15.2	25.9	22.4	34.8	35.8	64.1	86.5
Container-grown, unmulched	97	13.7	−1.2	14.5	16.4	29.8	53.7	68.3	85.0
Container-grown, mulched	78	21.8	−8.5	15.0	16.3	24.3	48.9	65.5	81.8
	Significance Level of Treatment Differences[3]								
Comparison for a Given Response Variable									
Bare root vs. container-grown (S)	ns	.01	.01	.01	.05	ns	.01	ns	ns
Mulched vs. unmulched (M)	.01	.01	.05	ns	ns	ns	.01	ns	ns
S × M interaction	—	ns	ns	ns	ns	ns	ns	ns	ns
Replication	—	ns	ns	.05	.05	ns	ns	ns	.05

[1] Means are for survivors at the end of the year (field growing season) indicated.

[2] Negative values indicate that shoot dieback exceeded shoot elongation by the amount shown.

[3] ns = nonsignificant; for survival, significance is based on chi-square; for all other variables, significance is based on analysis of variance.

During the second growing season, mean net shoot elongation was positive for all treatments, and ranged from 14.5 to 25.9 cm. Net shoot elongation was significantly greater for bare-root than container-grown seedlings, despite the larger amount of shoot dieback of bare-root seedlings the first year. The second-year difference in net shoot elongation between mulching treatments was not significant nor did mean tree heights differ significantly among treatments. Frost in early May of the second year caused much dieback of new shoots; however, affected trees initiated new shoots shortly thereafter. During the first two growing seasons, most planted seedlings were subordinate to a cover of fireweed (*Erechtites hieracifolia* (L.) (Faf.)) of variable density but averaging about 2m in height. Thus, mulching was not very effective in reducing lateral shading of planted trees by competitors, although direct overhead shading was usually reduced.

During the third growing season, bare-root seedlings maintained their superiority over containerized seedlings in net shoot elongation. However, mulching effects were not significant the third year. Total live heights at the end of the third growing season did not significantly differ among treatments. Three-year survival by treatments ranged from 75 (mulched bare-root trees) to 97 percent (unmulched container-grown trees); 79 percent of total 3-year mortality occurred during the first growing season. Briars (*Rubus* spp.) and other woody plants emerged as the dominant vegetation during the third year and overtopped many planted trees. Even though the polyethylene film remained intact after three years, woody competitors were beginning to fill in the canopy "holes" created by mulching wherever planted trees did not already occupy a position of dominance or codominance.

Variability in net shoot elongation was high during the 3-year growth period. Although seedlings averaged 33 cm of net shoot elongation over the three growing seasons, about 20 percent of planted trees equaled or exceeded twice that amount. Among treatments, significant differences occurred in the percentage of trees that attained at least 40 cm of net shoot elongation (i.e., a minimum net shoot elongation of 40 cm); at or above 50 cm, minimum net shoot elongation percentages by treatments were not significantly different (fig. 1). Thus, 45 percent of unmulched bare-root trees attained at least 40 cm of net shoot elongation, while only 24 percent of mulched container-grown seedlings increased that much or more in height during the same 3-year period.

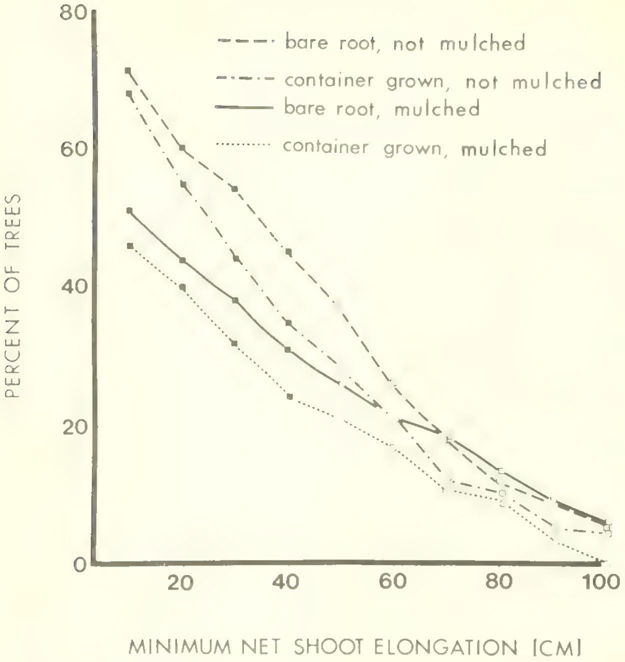

Figure 1.—*Percent of planted English oaks attaining a given minimum net shoot elongation after three field growing seasons by treatments. (Significance is based on chi-square; solid squares (■) indicate that significant differences ($p < .05$) occurred among treatments for a given minimum net shoot elongation.)*

Because average initial shoot diameters were smaller for container-grown than for bare-root seedlings, treatment effects were potentially confounded with seedling size effects. To overcome this problem, initial seedling cross-sectional area (2 cm above the root collar) was used together with minimum net shoot elongation percentages (fig. 1) as a predictor of the probability of net shoot elongation equaling or exceeding a given value. Based on these estimated probabilities for 3-year and 3rd year minimum net shoot elongation, combined effects of mulching and containerization in comparison to the "control" treatment (i.e., unmulched bare-root seedlings) were negative until an initial shoot diameter of a least 8 mm was reached (fig. 2, table 3).

Probability estimates indicated that above 8 mm shoot diameter, net shoot elongation of mulched container-grown trees may be superior to unmulched bare-root trees. However, the number of container-grown trees in the study that were above 8 mm in diameter was too small to reliably establish this relationship. The intersection of the two response surfaces for 3rd-year growth at about 8 mm (fig. 2) nevertheless suggests that net shoot elongation potentials for mulched-containerized trees 8 mm in diameter are about equal to those for unmulched bare-root seedlings; below 8 mm, combined effects of mulching and containerization are negative in comparison to the control treatment.

Based on the same regression models, comparison of probability response surfaces for mulched and unmulched container-grown seedlings (not shown) similarly indicated that mulching large diameter seedlings has a positive effect but that mulching small diameter seedlings has a negative effect on shoot growth. Comparison of response surfaces for unmulched and mulched bare-root seedlings (also not shown) indicated that mulching is likewise detrimental to small diameter trees but is not effective in increasing shoot growth of large diameter trees. Thus, the model indicates that only relatively large-diameter container-grown seedlings respond positively to mulching.

DISCUSSION AND CONCLUSIONS

Under greenhouse conditions, potential root growth of container-grown oaks has been shown to be superior to that of bare-root seedlings per unit of leaf area (Johnson 1979). In part, this may be due to the fibrous root systems of container-grown seedlings that provide relatively large numbers of sites for new root regeneration; in contrast, bare-root seedlings possess few lateral roots and the sites for root regeneration are confined primarily to the area around the root-pruning point. Nevertheless, figure 2 suggests that the possible advantages of containerization of English oak do not occur under field conditions until a minimum seedling diameter of 8 mm is attained. The slow growth of smaller plants may be related to the high density of seedlings in the container propagation bed which produced seedlings with spindly stems and small buds. Thus, wider container-bed spacing may be required to produce seedlings with large diameter stems, buds, and subsequent leaf areas that, in turn, will sustain a more efficient root and shoot feedback system (Borchert 1975).

First-year shoots died back primarily between time of planting and the onset of spring growth. Winter dessication of seedlings caused by limited root absorption is implicated as the primary cause of winter dieback of bare-root seedlings. In contrast, the relatively small amount of dieback of container-grown seedlings may have been attributable to the better root—soil contact provided by the container seedlings' intact root "plug". Despite more first-year

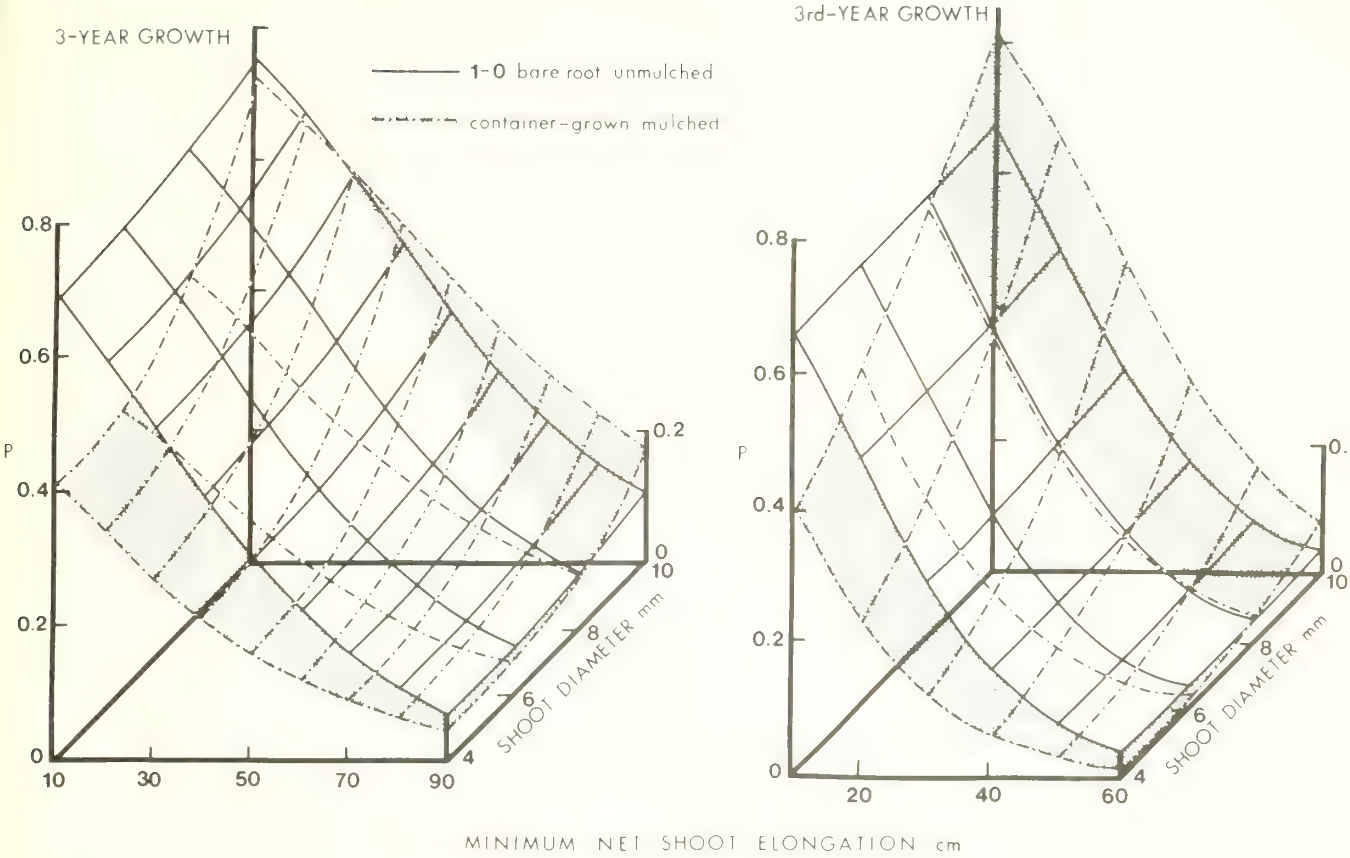

Figure 2.—*Response surfaces for estimated probabilities (P) of attaining at least the amount of net shoot elongation given on the horizontal axis in relation to initial shoot diameter 2 cm above the root collar. (Note that in both graphs, the response surface for container-grown, mulched (stipuled) intersects the other response surface at or above 8 mm shoot diameter. Regression equations and goodness-of-fit statistics are given in table 3.)*

shoot dieback, bare-root seedlings with stems less than 8 mm in diameter nevertheless tended to outgrow container-grown seedlings of equal diameter over the 3-year study period.

The reason for the negative effects from mulching on growth is unclear, but may be related to inadequate soil moisture recharge under the polyethylene mulch by light rainfalls during droughty periods as observed by Bowersox and Ward (1970). This may be particularly injurious to small planted seedlings with little potential for root growth and may explain the reduction in shoot elongation probabilities associated with mulching for trees of small diameter. However, for large seedlings with high root growth potentials, possible benefits from mulching might result from increased light over the mulch (due to a reduction in overhead shading from competitors) despite reduced soil moisture under the mulch. The early soil-warming effects of black polyethylene (Stephens 1965) apparently were nullified on the present study site by shading from competitors and a north aspect.

Average net 3-year shoot elongation of English oaks in the present study was about 2 to 2-½ times that of planted white oak, northern red oak, and black oak (*Quercus velutina* Lam.) measured in previous studies in the same area and under similar competition and site conditions.[2] In one comparison, 3-year minimum net shoot elongation percentages for English oak were approximately equal to 5-year percentages for northern red oak. Moreover, based on the reported growth of English oaks in southern Michigan (Wright *et al.* 1973), growth differences between English oak and native oaks might be expected to widen with tree age. Improvements in seedling production methods and seed source selection plus more intensive weed control might provide further gains. Given this potential, English oak

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[2] *Unpublished data on file, North Central Forest Experiment Station, Columbia, Missouri.*

should be further studied and evaluated for planting in the oak-hickory region.

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Table 3.—*Regression coefficients (B) for probability (P) equations represented by figure 2*[1]

	Model	
	3-year growth[2]	3rd-year growth
B_0	4.7250 $\times 10^{-1**}$	4.7055 $\times 10^{-1**}$
Independent variables[3] (B)		
X_1	−3.6097 $\times 10^{-1**}$	−7.7735 $\times 10^{-2**}$
X_2	6.3441 $\times 10^{-1**}$	7.3485 $\times 10^{-1**}$
X_3		1.4722^{**}
X_4	1.3532 $\times 10^{-2**}$	
X_5	1.2254 $\times 10^{-1*}$	2.3800 $\times 10^{-1**}$
X_6		-1.3799^{**}
X_7	−8.2990 $\times 10^{-3**}$	
X_8	−4.7780 $\times 10^{-3**}$	
Number of observations	3,456	2,304

[1] Equations are of the form: $P = \{1 + \exp[-(B_0 + B_1X_1 + \ldots B_nX_n)]\}^{-1}$ where P is the probability that net shoot elongation of a planted seedling equals or exceeds the amount set by the observed value of X_1.

[2] Significance levels are based on "t" tests (H_0: $B = 0$) and are: * = 0.05, ** = 0.01; $p<0.01$ for both regression F tests. Goodness-of-fit was also tested by chi-square for differences between observed and predicted numbers of seedlings with net shoot elongation equaling or exceeding the observed value of X_1 among probability intervals of width 0.05; both chi-square values were nonsignificant at the 0.05 level. This test was used because the customary measure of goodness-of-fit, the error mean square, is not appropriate when the dependent variable is dichotomous (Hamilton 1974).

[3] X_1 = the value of net shoot elongation (cm) that must be equaled or exceeded to yield an observed P of 1; smaller values of net shoot elongation yield observed P's of 0. For the 3-year growth model, values of P were observed for X_1 values of 10, 20, 30,...90; for the third-year model, values of 10, 20, 30,...60 were observed. X_2 = the orthogonally coded vector that compares mulched (−1) with unmulched seedlings (+1). X_3 = the cross sectional area of the seedlings stem at time of planting, measured 2 cm above the root collar (cm^2). $X_4 = (X_3)^2$. $X_5 = (X_2) \times$ (the orthogonally coded vector that compares bare-root (+1) with container-grown (−1) seedlings). $X_6 = (X_2) \times (X_3)$. $X_7 = (X_2) \times (X_4)$. $X_8 = (X_1) \times (X_2)$.

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Lifting Date Affects Black Walnut Planting Stock Quality

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LIFTING DATE AFFECTS BLACK WALNUT PLANTING STOCK QUALITY

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Instead of lifting hardwood planting stock in the spring, more and more forest tree nurserymen are lifting it in the fall and keeping it in cold storage overwinter. Lifting stock in the fall has several advantages: (1) soil conditions are often more favorable; (2) work loads can be spread over a longer period and steady work can be provided for fewer, better-trained employees; (3) earlier and more accurate inventory of available stock is possible; and (4) timing of deliveries with optimum planting periods is facilitated. All of these advantages improve efficiency and convenience of nursery operation. This trend creates a need for a better understanding of how fall lifting and overwinter storage affect seedling physiology so that consistently high quality planting stock can be produced.

If we are to optimize the physiological quality of hardwood nursery stock, we must have a method to measure the effects of various nursery cultural and storage treatments on physiological quality. Also, we need to know the relation between physiological quality of planting stock and field performance so we can set standards for stock grading. Finally, we need to know how the physiological quality of planting stock interacts with various silvicultural treatments —e.g. site selection, site preparation, weed control, and planting methods—so we can understand why some plantations are successful and others are unsuccessful. Root regeneration potential (RRP), a measure of the ability of seedlings to initiate and elongate new roots when planted in a favorable environment, has been used to assess the physiological condition of nursery stock and its suitability for outplanting (Stone and Schubert 1959, Stone and Jenkinson 1971, Webb and von Althen 1980). Measuring RRP has the advantage of assessing seedling growth potential in terms of the rapidity and amount of root regeneration, a factor regarded as highly important if transplanted seedlings are to survive and grow rapidly.

Effective physiological preconditioning of planting stock depends on lifting at the proper time, storing under appropriate conditions, and planting in an environment favorable to growth when seedling growth potential is highest. Although we know that seedlings must be cold-hardened before they are ready for lifting and overwinter storage, we do not know how much cold-hardening they need. Some nurserymen wait a period of time after leaf fall, some wait for the first hard frost, and others wait for a few frosts. Black walnut (*Juglans nigra* L.) is one of the first species to be lifted in the fall because leaf fall occurs early. However, leaf fall is only an indicator that dormancy has begun and is not an indicator of optimal lifting time. Thus, lifting and storing guidelines are needed based on convenient criteria for identifying seedling readiness.

This paper reports the results of a study on lifting date, storage duration, and field performance of black walnut. It includes an assessment of (1) RRP as a measure of the physiological quality of lifted and stored planting stock, and (2) the relation between physiological quality of planting stock and field performance.

METHODS

Eleven liftings of 1-0 black walnut seedlings were made between October 6, 1976 and April 25, 1977, from the Vallonia Forest Nursery near Brownstown, Indiana. The first lifting was about 7 days before leaf fall and the last one was about 10 days after flushing. Only those seedlings with a stem caliper ≥ 0.7 cm were used in the study, and roots were pruned to 22 cm. Twelve seedlings from each lifting date were potted and tested for RRP at each of the following times: immediately; 4, 8, and 12 weeks after lifting; and on December 8, March 8, and May 12. Seedlings that were not potted immediately were stored at 3°C.

Additionally, 25 seedlings lifted on each date were stored at 3°C until they were field planted on December 8, March 8, and May 12.

RRP was determined by a method similar to that of Stone and Schubert (1959). Potted seedlings were placed in a greenhouse for 4 weeks. In the greenhouse, air temperature varied seasonally (minimum 16°C), soil temperature was held at 24°C by pumping water maintained at that temperature through coiled tubing in each pot, and a 16-hour photoperiod was maintained by supplemental fluorescent and incandescent lighting. At the end of the 4 weeeks, the seedlings were unpotted and total shoot elongation, stem caliper 2.5 cm above root collar, ovendry weight of all new roots, and ovendry weight of the total root system were determined for each seedling. Differences in responses among lifting dates and storage treatments were tested for significance by analysis of covariance using total root dry weight as the covariable for root growth response and stem caliper as the covariable for shoot growth response.

The field planting was located on the Shawnee National Forest in southern Illinois on a deep, well-drained silt loam soil suitable for good black walnut growth. On each planting date the 25 stored seedlings from each lifting date were divided evenly among 5 randomized complete blocks and planted with KBC tree planting bars. Data collected were flushing date (December 8 and March 8 plantings only), initial shoot elongation, and total height at the end of the first and second growing seasons.

RESULTS AND DISCUSSION

Seasonal Pattern of RRP

Black walnut seedlings required exposure to cold temperatures for a minimum amount of time before any growth was observed. The seedlings that were lifted and potted immediately showed little growth response for any lifting date until late March when the growth response increased abruptly (fig. 1). Total shoot elongation and ovendry weight of new roots steadily increased with successive liftings during the spring and continued to increase beyond the time of flushing at the nursery. Our data showed two declines in shoot elongation but they were probably due to technique errors. Seedlings lifted on April 25 had as much as 10 cm of new shoot growth at the time of lifting but no new root growth. Existing new shoots died back during the RRP test, but shoot regrowth and root regeneration surpassed that of all previous lifting dates. Thus, no peak was found in RRP of freshly lifted seedlings. Note that these responses represent root and shoot growth potential under favorable growing conditions in a greenhouse. Seedlings lifted after flushing grew poorly in the field test.

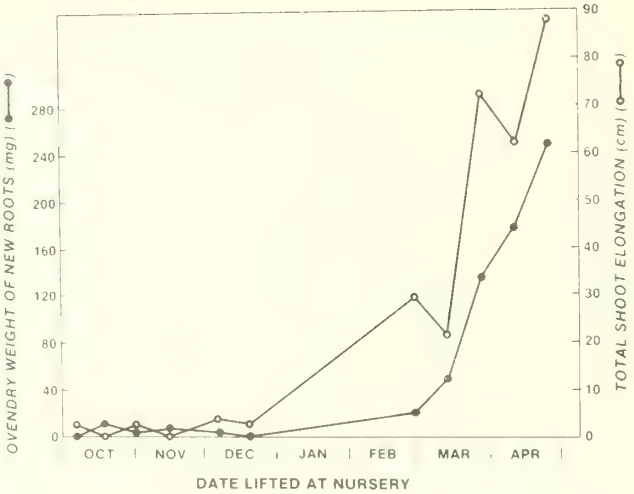

Figure 1.—*Total shoot elongation and ovendry weight of new roots for black walnut seedlings lifted on 11 dates in 1976-1977 and immediately tested for RRP under favorable conditions in a greenhouse.*

In the RRP tests, root growth was strongly related to shoot growth ($r = +0.95$, $P \leq 0.00001$)—root regeneration increased as shoot growth increased (fig. 1). Although active root and shoot growth occurred simultaneously, it is not apparent which process began first because the initiation of root growth was not observed.

RRP of Seedlings Lifted and Stored to Planting Time

Seedlings lifted between October 6 and December 8 and planted on December 8 had almost no RRP because of inadequate chilling. By March 8 chilling was minimal and RRP was low. In contrast, root regeneration and shoot growth of seedlings stored to May 12 were vigorous and differed significantly among lifting dates (fig. 2). Growth responses may be divided into two significantly distinct groups: (1) seedlings lifted on October 6 and 18 had low root and shoot growth during the 4-week test; and (2) seedlings lifted between November 1 and April 25 had high root regeneration and moderate shoot growth in fall-lifted and significantly higher shoot growth in spring-lifted seedlings. Thus, seedlings lifted before November 1 had reduced vigor when they were tested

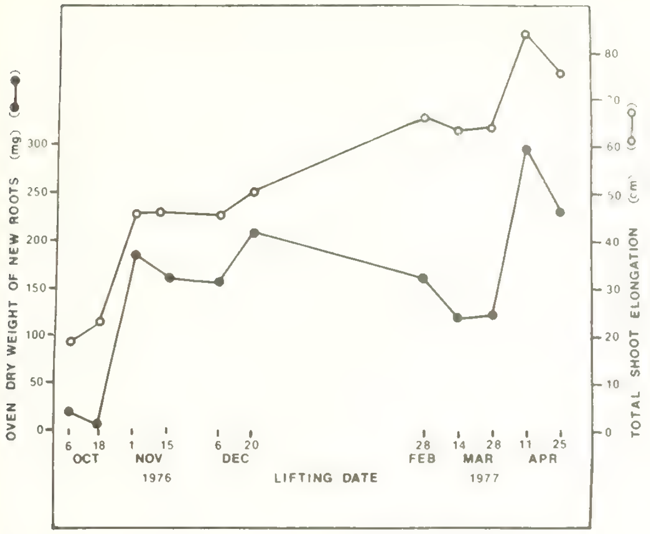

Figure 2.—*Mean 4-week root regeneration and shoot growth potential of black walnut seedlings lifted on different dates and stored to May 12, 1977. Each data point represents 12 seedlings.*

in late spring. Seedlings lifted after November 1 and stored overwinter had RRPs comparable to those of seedlings freshly lifted and tested on April 11 and 25 ($P \leq 0.05$) (fig. 1). This suggests that black walnut planting stock fall-lifted when sufficiently dormant has comparable physiological quality to spring-lifted stock. This finding agrees with the results of Webb and von Althen (1980) who found that RRP of black walnut, white ash (*Fraxinus americana* L.), sugar maple (*Acer saccharum* Marsh.), red oak (*Quercus rubra* L.), and paper birch (*Betula papyrifera* Marsh.) seedlings lifted on November 23 and cold-stored at 0.5 or 5°C to April was comparable to that of freshly lifted seedlings.

Both ovendry weight of new roots and total shoot elongation were strongly related to chilling time, $r = +0.82$ ($P \leq 0.05$) and $r = +0.90$ ($P \leq 0.01$), respectively. Seedlings lifted on November 1 and stored until March 8 had been stored at 3°C for approximately 3,100 hours, excluding exposure to cold temperatures in the nursery prior to November 1 (Rietveld and Williams 1978). This is the minimum amount of chilling required before any growth response occurred; the longer the seedlings remained in cold storage, the more rapidly they resumed growth and the greater the growth response during the 4-week test period. By May 12, after 4,600 hours at 3°C, the peak response had not yet been reached.

The extremely long chilling requirement of black walnut seedlings raises the question whether planting stock overwintered outside is adequately chilled during a mild winter. Growth could be sluggish the following growing season. It is known that maximum RRP varies from year to year and from nursery to nursery (Stone *et al.* 1963); this may be due in part to yearly differences in amount of effective chilling. There is generally thought to be a temperature threshold for chilling, below which any temperature is equally effective. On the other hand, extremely cold winters do not necessarily increase chilling. According to Samish (1954), the optimum temperature for breaking bud dormancy in most woody species is between 1 and 10°C, and extremely low temperatures may retard the process of breaking dormancy. Additional research is needed to determine the adequacy of natural chilling in mild winters and its effects on growth, compared with that of seedlings fall-lifted and cold-stored overwinter.

Freshly Lifted Versus Stored Seedlings for Spring Planting

Storage effects were evaluated for spring-planted seedlings only, by (1) comparing RRP of freshly lifted seedlings to that of seedlings that had been previously lifted (after February 28) and stored; and (2) comparing RRP of seedlings stored to later dates, up to late June, to that at lifting time.

The differences in RRP between seedlings freshly lifted during the period March 28 to April 25 and seedlings previously lifted and stored were not significant based on analysis of covariance (0.05 level). Seedlings stored for extended periods of time displayed variable, but acceptable, RRPs. Seedlings lifted on April 11 (just before bud swell) and stored, maintained the highest physiological quality in extended storage. Dry weight of new roots for April 11-lifted seedlings was 177 mg at lifting, 197 mg after 5 weeks of storage, and 311 mg after 8 weeks of storage. In contrast, dry weight of new roots for seedlings lifted on April 25 (after flushing) was 249 mg at lifting, 231 mg after 3 weeks of storage, and 118 mg after 8 weeks of storage. The lowest value would be considered "unacceptable" when compared to the average of 182 mg for seedlings lifted between November 1 and April 25 (fig. 2).

These results suggest that black walnut seedlings may be lifted in late winter or early spring and stored for late spring or early summer planting. The best time to lift and store for late planting appears to be just before the buds begin swelling.

Field Performance of Stored Seedlings

Bud burst.—For both December 8 and March 8 plantings, seedlings lifted earliest, and therefore stored longest before planting, were physiologically more responsive to favorable growing conditions in the spring.

Lifting date	Days to bud burst[1] Planted Dec. 8	Days to bud burst[1] Planted Mar. 8
Oct. 6	5.4	[2]6.7 a
Oct. 18	7.2	12.8 bc
Nov. 1	7.0	12.4 abc
Nov. 15	10.5	13.1 c
Dec. 6		14.7 c
Dec. 20		14.9 c
Feb. 28		11.7 abc
Mean	[3]6.1	12.3

Fall-planted seedlings that overwintered outside resumed growth approximately 1 week sooner than early spring-planted seedlings ($P \leq 0.01$). The reason for these responses is not clear. Seedlings overwintered in cold storage received more total chilling because they were continuously exposed to effective chilling temperatures. Thus, they would be expected to be more responsive in the spring, especially when compared to seedlings overwintered outside during a mild winter. However, seedlings overwintering outside during the winter of 1976-1977 were exposed to abnormally cold temperatures, which resulted in an unknown amount of effective chilling. This factor, counterbalanced by the fact that seedlings lifted and stored during mild fall weather between October 6 and November 1 received additional chilling, may account for the observed flushing pattern.

Survival.—Survival of fall-planted seedlings averaged 16 percent lower than spring-planted seedlings for the first 2 years after planting (table 1). This was mainly due to frost-heaving of fall-planted stock. Survival did not differ between the March 8 and May 12 plantings.

Differences in survival due to lifting date were not significant. Seedlings planted in early spring survived well regardless of lifting date, while seedlings lifted on October 6 and 18 and April 25 had lower survival when planted in late spring. Black walnut seedlings are tenacious and can survive difficult growing conditions, although they typically die back and grow poorly. Thus, in contrast to many coniferous species, seedling survival may not be a good criterion for distinguishing differences in vigor for black walnut seedlings.

Height growth.—Although fall-planted seedlings flushed earlier, mean terminal shoot elongation measured in mid-June did not differ significantly among the three planting times. First-year total height of seedlings planted December 8 was significantly higher than that of seedlings planted March 8, which in turn was significantly higher than that of seedlings planted May 12 (table 2). Second-year total height was significantly lower for the May 12 planting than for the other two plantings.

Analysis of variance of first and second year total height among lifting dates revealed no consistent significant differences within the three planting times (table 2). Seedlings planted in early spring grew well regardless of lifting date. Orthogonal comparisons of weighted mean total height within the May 12 planting of the October 6, October 18, and April 25 lifting dates versus the November 1 through April 11 lifting dates revealed no significant difference in the first year and a significant difference at the 0.05 level in the second year. The mean total heights for the two groups were 55.2 and 67.0 cm, respectively. Thus, seedlings lifted before November 1 and after April 11 generally grew less, when planted in late spring, than seedlings lifted within that period. This agrees with the RRP data and suggests that seedlings lifted too early or too late can physiologically deteriorate in storage (fig. 2). Additionally, planting in late spring under less favorable conditions appears to emphasize any differences in seedling vigor, resulting in a better evaluation of seedling quality in the field.

Based on overall survival and growth, early spring appears to be the best planting time. Lifting date did not affect survival and growth of seedlings planted in early spring. The principal disadvantage of late fall planting was lower survival caused by frost-heaving; seedlings that survived grew well. Spring frost-heaving may limit success of early-spring planting in some areas.

DETERMINING LIFTING TIME

Although seedlings lifted and stored before November 1, 1976, received more chilling than seedlings lifted later, RRP at planting time and field performance were significantly lower. This lack of vigor is clearly attributable to the seedlings being

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[1] *Time of bud burst is expressed as days after April 1; each value is the mean of 25 seedlings.*

[2] *Means followed by same letter are not significantly different (5 percent level) by multiple range tests.*

[3] *Means significantly different at 5 percent level.*

Table 1.—*First and second year survival of black walnut seedlings lifted on different dates and stored until planted on December 8, March 8, or May 12*
(In percent)

	Planting date					
	December 8		**March 8**		**May 12**	
Lifting date	**First year**	**Second year**	**First year**	**Second year**	**First year**	**Second year**
Oct. 6	72	64	100	92	[1]88 ab	84 ab
Oct. 18	84	84	96	84	80 ab	68 b
Nov. 1	76	68	96	96	96 a	92 a
Nov. 15	76	72	92	84	100 a	100 a
Dec. 6			84	84	92 ab	84 ab
Dec. 20			96	96	92 ab	88 ab
Feb. 28			100	92	92 ab	92 ab
Mar. 14					100 a	96 b
Mar. 28					96 a	96 a
Apr. 11					92 ab	92 ab
Apr. 25					76 b	68 b
Mean	[2]77**	72**	95	90	91	87

[1] Means within a column followed by same letter are not significantly different (5 percent level) by multiple range tests.

[2] **Means at bottom of columns significantly lower than comparable means at 1 percent level.

Table 2.—*First and second year total height of black walnut seedlings lifted on different dates and stored until planted on December 8, March 8, or May 12*
(In centimeters)

	Planting date					
	December 8		**March 8**		**May 12**	
Lifting date	**First year**	**Second year**	**First year**	**Second year**	**First year**	**Second year**
Oct. 6	31.6	65.7	[1]50.8 ab	74.0	38.6 c	58.2 c
Oct. 18	54.2	83.0	54.6 a	78.5	42.0 bc	54.7 c
Nov. 1	49.1	78.2	51.7 ab	72.7	52.8 bc	69.4 ab
Nov. 15	58.9	74.8	38.9 b	76.8	40.7 bc	65.6 abc
Dec. 6			45.9 ab	77.6	38.8 c	59.7 bc
Dec. 20			44.0 b	75.1	46.3 bc	61.5 bc
Feb. 28			46.0 ab	68.9	41.6 bc	65.9 abc
Mar. 14					59.5 a	
80.3 a						
Mar. 28					54.6 b	68.9 ab
Apr. 11					39.2 bc	65.0 abc
Apr. 25					33.6 c	52.7 c
Mean	[2]53.5**	75.4	47.4**	74.8	44.3**	63.8**

[1] Means within a column followed by same letter are not significantly different (5 percent level) by multiple range tests.

[2] **Means at bottom of columns significantly lower than comparable means at 1 percent level.

lifted before they were sufficiently cold-hardened. Therefore, lifting date is an important factor affecting physiological quality of black walnut planting stock. Because the time when seedlings are ready for lifting varies from year to year and from nursery to nursery, an independent criterion is needed to determine lifting date. Research is underway to develop these guidelines. In the meantime, an approximate criterion would be to lift black walnut seedlings 1 month after leaf fall.

RRP AS A MEASURE OF SEEDLING PHYSIOLOGICAL QUALITY

RRP appears to be a sensitive method to detect differences in seedling vigor resulting from various lifting and storage treatments of black walnut planting stock, providing the seedlings have been adequately chilled. For a vigorous and definitive RRP test, seedlings should be exposed to approximately 3,600 hours of 3°C temperatures. Additionally, the results of the late-spring field planting suggest that growing conditions that induce seedling stress may encourage expression of differences in vigor among treatments. In their proposed RRP-type vigor test of coniferous planting stock, Hermann and Lavender (1979) state that the physiological quality of seedlings becomes more apparent if the seedlings are stressed.

An inherent problem and confounding factor that introduces high variability into RRP tests of bare root seedlings is physiological shock—the disruption of seedling physiological processes caused by the multiple injuries sustained during lifting, storing, and planting. Such shock expresses itself as retarded root regeneration and minimal shoot growth or dieback. The severity of shock creates problems in regeneration research because we can account for it only as experimental error. The following methods can be used in RRP tests to reduce the variable effects of physiological shock: (1) chill seedlings well (at least 3,600 hours at 3°C); (2) use a testing environment favorable to growth and uniform within and among tests; (3) use well drained and well aerated growing medium; and (4) reduce the variation due to seedling size differences by grading seedlings to uniform size and using covariance analysis.

Three conspicuous problems with conducting RRP tests are: (1) they are costly—in terms of facilities, space, manpower, and money; (2) they are time consuming—4 weeks or longer are needed for the growth responses to occur, and thus for the results of the test; and (3) they are laborious—the growth responses are difficult to measure. A faster-developing, more conveniently measured variable is clearly needed. We have found that both days to bud-burst and total shoot elongation are highly related to root regeneration and will pursue developing a relation that incorporates these variables. Also, Webb and von Althen (1980) have reported that shoot xylem water potential is significantly related to RRP of hardwood seedlings at the time of removal from storage. Thus, shoot xylem water potential appears promising as a rapid measure of physiological quality.

RELATION BETWEEN RRP AT PLANTING AND FIELD PERFORMANCE

Seedlings lifted on October 6 and 18 had low RRP and below average survival, shoot elongation, and total height (fig. 3). These seedlings were not sufficiently hardened-off when lifted, so they deteriorated in storage and showed reduced vigor in RRP and field tests. RRP of seedlings lifted after November 1 increased markedly and field performance of these seedlings was generally acceptable. Second-year survival and height were similar to those of the first year, suggesting that seedling physiological quality at planting time determines subsequent growth (fig. 3).

In contrast to the similar pattern of RRP and field growth responses for fall-lifted seedlings, the opposite was true for spring-lifted seedlings (fig. 3). Seedlings lifted and stored during the period from February 28 through March 25 showed reduced RRP, followed by a marked increase just before bud-burst, then a decline in seedlings lifted after bud-burst. Field survival and growth showed just the opposite trend through March 28 or April 11 liftings, then declined sharply for the April 25 lifting. Shoot elongation potential was highest for the April 11 lifting date, while field survival and growth were highest for March 14 lifted seedlings.

Simple correlation coefficients for relations of ovendry weight of new roots or total shoot elongation in RRP tests of fall-lifted seedlings with field growth responses range between +0.45 and +0.79 (table 3). All are nonsignificant, probably because they are based on only six lifting dates. Thus, this study failed to establish a significant relation between RRP at planting time and field performance. More frequent sampling and larger numbers of seedlings will be

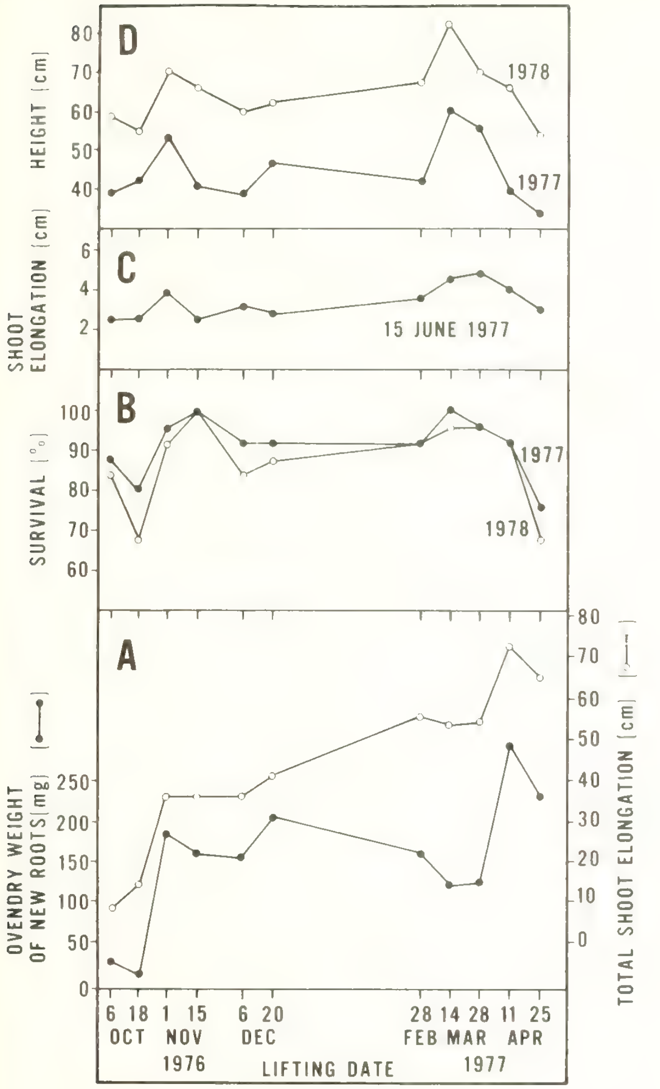

Figure 3.—*Comparison of several response variables for black walnut seedlings in relation to lifting date: (A) root and shoot regeneration potential; (B) survival at the end of the first and second growing seasons; (C) initial shoot elongation; and (D) mean total seedling height at the end of the first and second growing seasons. In all cases, seedlings were in cold storage between lifting date and May 12, 1977.*

required to establish a significant relation with predictive value between RRP and performance of field-planted trees.

It would be desirable to develop a method to routinely evaluate the physiological quality of hardwood planting stock before planting time so that low vigor stock can be culled. Such a method has been proposed for coniferous planting stock by Hermann and Lavender (1979). It is based on an RRP-type test in which seedlings are potted and days to bud burst and survival after a specified period of time are related to planting stock quality. A similar method could be devised for black walnut and other hardwoods, but the extremely long chilling requirement would present a problem. While most northern and western conifers require short periods of chilling, most eastern hardwood species require 2,500-3,500 hours before they will grow vigorously. Coniferous stock can easily be tested before planting time, however, hardwood planting stock cannot be completely chilled, tested for RRP, and graded in time for early spring planting. Unless a method can be devised to accelerate the chilling process in hardwood planting stock so that tests can be completed before the spring planting season, the usefulness of RRP tests for other than research purposes is questionable.

Table 3.—*Simple correlation coefficients among selected growth responses for six fall lifting dates*[1]

	Variable Y (field performance)				
	June 15	Total height		Survival	
Variable X (RRP)	shoot elongation	First year	Second year	First year	Second year
Ovendry weight of new roots	+0.53	+0.52	+0.75	+0.79	+0.72
Total shoot elongation	+0.48	+0.45	+0.68	+0.75	+0.66

[1] None of the correlation coefficients are significant at the 5 percent level; the minimum correlation coefficient required for significance is + 0.81.

CONCLUSIONS AND MANAGEMENT IMPLICATIONS

Fall-lifted and stored black walnut seedlings have a long chilling requirement—approximately 3,100 hours at 3°C—before growth will resume. This is a minimum value for any root regeneration to occur and growth rate increases markedly with additional chilling. Stored seedlings should be exposed to approximately 3,600 hours of chilling for a vigorous and definitive RRP test. Under greenhouse conditions, root growth is strongly related to shoot growth, so seedlings with rapidly elongating shoots can also be expected to have expanding root systems.

Lifting date affects the physiological quality of black walnut planting stock. The earliest date to lift seedlings for overwinter storage and early spring planting is approximately 1 month after leaf fall. Seedlings lifted from that time to the time of bud swell in spring maintain high RRP in storage. The best spring lifting date for extended storage is just before bud swell.

The best planting time appears to be early spring. Survival of fall-planted seedlings was significantly reduced by frost heaving, but surviving seedlings grew as well as early spring planted seedlings. Seedlings planted in late spring survived well, but growth was significantly lower than the other two planting times. Lifting date had no consistent effect on seedling survival and growth over the three planting times. Seedlings planted in early spring grew well regardless of lifting date, while seedlings lifted between November 1 and April 11 and planted in late spring grew significantly better than seedlings lifted earlier or later.

Root regeneration potential appears to be a good variable for assessing lifting and storage treatment effects on black walnut planting stock if the stock has been adequately chilled. Seedlings lifted early in the fall had low RRP in the spring, while those lifted when dormant had high RRP after chilling. Seedlings lifted just before and after flushing had the highest RRP at lifting, but the latter lost vitality in storage while the former did not. RRP of planting stock at planting time was positively, but not significantly, related to field survival and growth. Further research with more intensive sampling may establish a significant relation with predictive value. The usefulness of an RRP-type test to evaluate physiological quality of black walnut planting stock before planting is severely constrained by the long chilling requirement.

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1981. Lifting date affects black walnut planting stock quality. U.S. Department of Agriculture Forest Service, Research Paper NC-205, 8 p. U.S. Department of Agriculture Forest Service, North Central Forest Experiment Station, St. Paul, Minnesota.

Presents information for black walnut seedlings on storage chilling requirement, fall lifting for overwinter storage, spring lifting, planting times, use of root regeneration potential (RRP) to assess physiological quality of planting stock, and relation between RRP at planting and field performance.

KEY WORDS: *Juglans nigra*, nursery practices, cold storage, chilling, root regeneration potential, seedling survival, seedling growth.

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Growth of Hybrid Poplars, White Spruce, and Jack Pine

Under Various Artificial Lights

Pamela S. Roberts and J. Zavitkovski

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GROWTH OF HYBRID POPLARS, WHITE SPRUCE, AND JACK PINE UNDER VARIOUS ARTIFICIAL LIGHTS

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Supplemental greenhouse lighting is used for two main reasons: (a) to extend the photoperiod and prevent plant dormancy, and (b) to stimulate growth. Low light intensity (less than 1,000 lux) will satisfy the photoperiod requirements of various coniferous species, whereas high light intensity (above 10,000 lux) is necessary to increase photosynthesis and growth (Pollard and Logan 1975).

Cathey and Campbell (1975) studied the effectiveness of 5 lighting sources on growth of 22 species of ornamental plants and concluded that incandescent (INC) light with red/far-red ratio similar to that of sunlight and high pressure sodium (HPS) were best for plant growth. In a later study with 32 species of foliage and flowering plants, Cathey and Campbell (1979) suggested that most light sources can create a near optimum growing environment if they provide 21 to 42 W/m^2 within the visible region.

Selection of a supplemental light source for a greenhouse should be based on both biological and economic (or energy consumption) considerations. Some lamps are more efficient than others in converting electrical energy into photosynthetically active radiation (PAR) (Campbell *et al.* 1971, Bickford and Dunn 1972, Norton 1973, Cathey and Campbell 1974). Moreover, the information on biological effects of some of the recently introduced lamps, such as HPS, is largely restricted to ornamental plants (Cathey and Campbell 1979). Very little is known how different lamps affect growth and development of trees.

The objective of our study was to evaluate energy consumption and effects of fluorescent, incandescent, and high pressure sodium lamps on growth and dry matter production of two hybrid poplars, white spruce, and jack pine.

METHODS AND MATERIALS

The tests were conducted in 1978 and 1979 in a greenhouse covered with a double-layer of polyethylene. The 1978 tests ran from December 1978 to April 1979, and the 1979 tests from August 1979 to January 1980. The day temperature in the plastic greenhouse was maintained from 21 to 25°C (70 to 77°F) and the night temperature from 18 to 21°C (64 to 70°F) except for some sunny days in August and September 1979 when the day temperature reached or surpassed 32°C (90°F). A uniform 18-hour photoperiod was assured by supplemental lighting.

Supplemental Light

Three supplemental light sources were compared: the incandescent (INC), fluorescent in combination with incandescent (FLU), and high pressure sodium (HPS). These light sources were mounted in fixtures as for normal greenhouse use. Four 150W very wide flood lamps were mounted 45 cm (18 in) apart and suspended 90 cm (36 in) above the bench. Two 40W cool white fluorescent tubes and two 25W incandescent lamps were mounted on a white-painted fixture made of sheet metal. This FLU fixture was also located 90 cm above the bench. The 250W HPS lamps were mounted in a reflector with a plexiglass diffuser. The bottom of the diffuser was about 120 cm (48 in) above the bench. The three light sources were located adjacent to each other and the entire setup was replicated three times at different locations in the plastic greenhouse.

The photosynthetically active radiation, PAR, was measured with quantum sensors connected to a quantum meter for instantaneous readings or to an integrator for cumulative readings. Spectral distribution of the light sources was obtained with a spectroradiometer over a range from 380 to 1,550 nm.

The mean, standard deviation (SD), and coefficient of variation (CV) of PAR provided by the individual light sources at the bench level directly beneath the fixtures were as follows (in uE/m^2•sec):

Light source	1978			1979		
	Mean	SD	CV	Mean	SD	CV
			Percent			Percent
INC	62.7	8.9	14	46.5	5.7	12
FLU	22.3	2.8	13	20.0	1.8	9
HPS	17.8	1.5	8	46.8	4.1	9

The HPS PAR intensity was increased in 1979 by changing from 110V to 220V. The PAR intensity of the INC light in 1979 was adjusted to that provided by the HPS lamps by raising the INC fixtures.

In spectral distribution the INC lamps were poor in blue but rich in both the red and far-red wavelengths. The spectral distribution of the FLU light (without the INC lamps) peaked around 500 nm and sharply decreased to shorter and longer wavelengths. The blues and reds were balanced but the intensity of the far-red was low and had to be boosted by the two 25W INC lamps. The HPS lamps featured several peaks in the visible spectrum, the most conspicuous ones between 550 and 600 nm, and several small peaks in the 750 to 1,550 nm region. Blues and reds were well balanced but in general the HPS light was rich in greens, yellows, and orange hues.

Daylight

About 60 percent of the PAR in incoming solar radiation reached the benches in the plastic greenhouse. Spectral distribution of PAR in the plastic greenhouse was similar to that measured outside. Daylight interception by the INC and HPS fixtures was low but on clear days the bulky FLU fixture intercepted more light than was provided by the FLU itself. A similar problem was also reported by Bickford (1967).

In both years, most of the PAR was provided by daylight. For example, in the 1978 study, daylight accounted for 80, 85, and 60 percent of the total PAR under the FLU, HPS, and INC lights, respectively.

Plant Materials

White spruce (*Picea glauca*), jack pine (*Pinus banksiana*), and two hybrid poplars, *Populus* 'Tristis # 1,' a cross between *P. tristis* and *P. balsamifera*, and a cross between *P. nigra* var. *betulifolia* and *P. trichocarpa*, were used in the study. The conifers were produced from seeds and poplars from 20 cm (8 in) hardwood cuttings. The conifers were transplanted into Hillson rootrainers (volume 150 cm^3). The growing media was 3 parts peat and 1 part each medium grade perlite and medium grade vermiculite. The rootrainers were strapped together to form blocks with 24 seedlings. The poplar hardwood cuttings were planted directly into Tubepak[1] II planters (volume 265 cm^3) whose growing medium was adjusted with lime to a pH 6.5. The tubepaks were strapped into blocks of 25 plants. One block of each species was placed under each of the three light sources.

The duration of the studies was:

Species	**1978**	**1979**
	------(Days)------	
Whitespruce	131	170
Jackpine	131	111
Populus 'Tristis # 1'	64	43
Populus nigra var. *betulifolia* x *P. trichocarpa*	—	28

The plants were watered daily. Slow release fertilizer was added to the growing media at the time of mixing. Both macro- and micronutrients were added to each growing media. Additional fertilizer was added after 3 months to the conifers which were grown for a longer time.

RESULTS

The 1978 Tests

These tests were conducted during the winter months when low level supplemental light was needed to extend the photoperiod and prevent plants from going dormant. The percentage of total PAR provided by the supplemental light was the same for jack pine and white spruce plants and averaged 17, 37, and 14 percent under the FLU, INC, and HPS lamps, respectively. In tests with *Populus* 'Tristis # 1' the corresponding percentages were 21, 43, and 18.

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[1] *The use of trade names does not constitute endorsement by the USDA Forest Service.*

The PAR of the three light sources was not considered high enough to promote appreciable dry matter accumulation. However, contrary to expectation, dry weight of plants under the INC light was significantly higher than dry weight of seedlings under the FLU and HPS lamps (table 1). Also heights of jack pine and hybrid poplar plants were significantly greater under the INC lamps. Dry weight of plants under the FLU and HPS lamps, which provided similar PAR levels, were not different. Height growth was inconsistent: hybrid poplars grew more under the HPS lamp, jack pine under the FLU lamp, and heights of white spruce plants were identical under these two light sources (table 1). Finally, leaf area per plant of hybrid poplar was statistically not different under the three light sources.

The 1979 Tests

In tests with *Populus* 'Tristis # 1,' the supplemental light provided only 8 percent of the total PAR under the FLU lamps and about 17 percent under both the INC and HPS lamps. Not surprisingly, the

Table 1.—*Growth of several woody species under different sources of supplemental light*

Light source	Mean	1978 Height	1978 Top dry weight	1978 Leaf area	1979 Height	1979 Top dry weight	1979 Leaf area
		POPULUS 'TRISTIS #1'					
		cm	*g*	*cm*^{2}	*cm*	*g*	*cm*^{2}
FLU[1]	Mean	[2]26.7^{a}	1.85^{a}	311^{a}	36.0^{a}	2.35^{a}	504^{a}
	SD[3]	7.4	.77	85	9.2	1.03	239
INC[4]	Mean	33.2^{b}	2.50^{b}	343^{a}	40.8^{b}	2.71^{b}	594^{a}
	SD	9.3	.89	115	11.3	1.07	129
HPS[5]	Mean	28.6^{a}	2.03^{a}	360^{a}	40.0^{b}	3.01^{b}	502^{a}
	SD	6.7	.80	142	8.3	1.16	167
		P. NIGRA VAR. *BETULIFOLIA* x *P. TRICHOCARPA*					
FLU	Mean	not available			17.5^{a}	0.62^{a}	171^{a}
	SD				7.8	.47	61
INC	Mean	n.a.			27.5^{b}	1.61^{b}	230^{a}
	SD				8.5	1.16	96
HPS	Mean	n.a.			25.6^{b}	1.13^{c}	196^{a}
	SD				8.8	.65	114
		JACK PINE					
FLU	Mean	6.6^{a}	0.36^{a}	n.a.	8.5^{a}	0.14^{a}	n.a.
	SD	1.7	.17		3.0	.10	
INC	Mean	7.2^{b}	.43^{b}	n.a.	10.5^{b}	.26^{b}	n.a.
	SD	1.8	.20		4.1	.19	
HPS	Mean	5.7^{c}	.36^{a}	n.a.	8.9^{a}	.22^{b}	n.a.
	SD	1.3	.17		2.1	.11	
		WHITE SPRUCE					
FLU	Mean	7.0^{a}	0.21^{a}	n.a.	5.2^{a}	0.06^{a}	n.a.
	SD	1.3	.11		1.5	0.05	
INC	Mean	6.8^{a}	.30^{b}	n.a.	5.8^{ab}	.12^{b}	n.a.
	SD	1.5	.16		2.0	.11	
HPS	Mean	7.0^{a}	.21^{a}	n.a.	5.9^{b}	.11^{b}	n.a.
	SD	1.6	.11		1.7	.09	

[1] Fluorescent light (including two 25W incandescent lights) averaged 22.3 (± 2.8) and 20.0 (± 1.8) uE/m^2•sec in 1978 and 1979 tests, respectively.

[2] Values (in columns) followed by the same letter are not significantly different ($p = 0.05$).

[3] Standard deviation.

[4] Incandescent light averaged 62.7 (± 8.9) and 46.5 (± 5.7) uE/m^2•sec in 1978 and 1979 tests, respectively.

[5] High pressure sodium lamp provided 17.8 (± 1.5) and 46.8 (± 4.1) uE/m^2•sec in 1978 and 1979 tests, respectively.

difference between the FLU plants and plants grown under the INC and HPS sources, although significant for both height and dry weight, was modest and may have resulted from an excessive daylight shading by the bulky FLU fixtures.

The role of daylight was less evident in jack pine and white spruce plants primarily because supplemental light provided a higher percentage of total PAR: 11, 22, and 22 percent for the jack pine and 13, 25, and 25 percent for the white spruce under the FLU, INC, and HPS lamps, respectively. Dry weights of the FLU plants were significantly and substantially lower than dry weights of either the INC or HPS plants (table 1). The INC and HPS plants were statistically not different. Height growth, although less conclusive, also was better under the INC and HPS lamps.

In the tests with *P. nigra* var. *betulifolia* x *P. trichocarpa*, supplemental light accounted for 21, 38, and 38 percent of the total PAR under the FLU, INC, and HPS lamps, respectively. This was reflected in dry weights and heights (table 1). Dry weights and heights of the FLU plants were significantly smaller than dry weights and heights of the INC and HPS plants. Also in the 1979 tests, leaf area per plant was not significantly different under the three light sources (table 1).

DISCUSSION

Results of our studies indicated a positive relation between total quantity of supplemental light and growth of test plants. For hybrid poplars the relation was exceptionally good and explained 88 percent of total variability. At the same PAR level no light source was biologically more efficient than the other. In the 1978 tests, the FLU and HPS lamps provided about the same PAR intensity and dry weights in all three species. Heights were more variable: the hybrid poplars grew taller under the HPS lamps, jack pine grew taller under the FLU lamps, and white spruce plants averaged the same under both sources. In the 1979 tests, similar patterns of dry weight and height growth were observed under the INC and HPS lamps with almost identical PAR levels. Broadly, these results were consistent with conclusions reached by Cathey and Campbell (1979) that any supplemental light source may provide a suitable environment for plant growth if the intensity is high enough.

The positive and consistent effect of supplemental light was unusual in view of the low intensity and relatively small percentage (8 to 40 percent) of the total PAR. These supplemental PAR levels were much lower than the 10,000 lux (290 uE/m^2•sec) proposed by Pollard and Logan (1975) as the minimum needed to appreciably stimulate photosynthesis and dry matter production. However, in other studies supplemental PAR as low as 1 ft-c (about 0.25 uE/m^2•sec) significantly affected the growth of seedlings of a number of tree species (Cathey and Campbell 1975) and PAR levels of only 0.21 uE/m^2•sec significantly affected growth of eastern white and Japanese black pines (Struve and Blazich 1980). In Arnott's (1979) nursery study, at 8 PAR levels ranging from 0 to 220 lux (about 4.7 uE/m^2•sec), heights and dry weights of all species were positively affected even at PAR levels of 5 lux (0.1 uE/m^2•sec) in comparison to the control. Contrary to this positive evidence on the effects of small PAR levels on plants growth, Pollard and Logan (1975) found no or little effect of a supplemental PAR of 400 lux (about 11 uE/m^2•sec) on the dry weight of jack pine and white and black spruce.

In both experiments, leaf area per plant of hybrid poplar did not vary significantly under the three light sources. This could mean that production of leaves is less affected by the type and intensity of supplemental light. However, other factors such as high variability of the data, small sample size, and chance allocation of atypical plants for leaf area determination could also be involved.

CONCLUSION

We concluded that none of the three light sources was biologically more effective than any other with equal PAR. This would include the FLU source if PAR were increased to levels comparable to those of the INC and HPS lamps and if the bulky metal sheet fixture were replaced with fixtures designed to produce minimum shading and maximum light output (Bickford 1967).

Whereas the biological effects of the individual supplemental light sources may be argued and certain lighting types may be preferred, the question of energy savings and economics is clear. Our spectroradiometric measurements over the 380 to 1,550 nm range showed that the INC, HPS, and FLU (without the INC) lamps converted respectively, 15, 66, and 91 percent of the total energy in that range into PAR. The INC lamps were obviously the most wasteful and uneconomical whereas both the FLU and HPS lamps were very efficient. The same conclusion has been reached in other studies (Campbell *et al.* 1971, Bickford and Dunn 1972, Norton 1973, Cathey and

Campbell 1974). The HPS lamps have the additional advantage of a long lifespan which according to one manufacturer averages 24,000 hours.

To provide a reasonably uniform PAR distribution on a 120-cm (48-in) wide bench, the FLU and INC fixtures should be mounted crosswise (only 3 INC 150W floods per fixture) about 90 cm (36 in) above the bench and spaced about 100 to 120 cm (40 to 48 in) apart. The HPS fixtures would be mounted 120 cm (48 in) above the bench and be spaced 2 m (80 in) apart. Under these conditions the FLU lighting would provide 20 to 28 uE/m^2•sec, the INC about 40 to 60 uE/m^2•sec and the HPS about 45 to 60 uE/m^2•sec at the bench level. The electric energy drain per linear meter of bench would be 450, 110, and 140W for the INC, FLU (with two 25W INC lamps) and HPS lamps, respectively. The HPS lighting would reduce electricity consumption and cost to about one-third compared to an INC setup. Additional electricity and cost economy would be achieved with the FLU lighting but the PAR would be only half that provided either by the INC or HPS lamps.

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Roberts, Pamela S., and J. Zavitkovski.

1981. Growth of hybrid poplars, white spruce, and jack pine under various artificial lights. U.S. Department of Agriculture Forest Service, Research Paper NC-206, 5 p. U.S. Department of Agriculture Forest Service, North Central Forest Experiment Station, St. Paul, Minnesota.

Describes the energy consumption and biological effects of fluorescent, incandescent, and high pressure sodium lighting on the growth of poplars, white spruce, and jack pine in a greenhouse. At similar light levels the biological effects of all three light sources were similar. The incandescent lamps consumed several times more energy than the other two light sources.

KEY WORDS: Photosynthetically active radiation (PAR), height growth, dry matter production, plastic greenhouse.

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GROW—a Computer Subroutine

that Projects the Growth of Trees in Lake States' Forests

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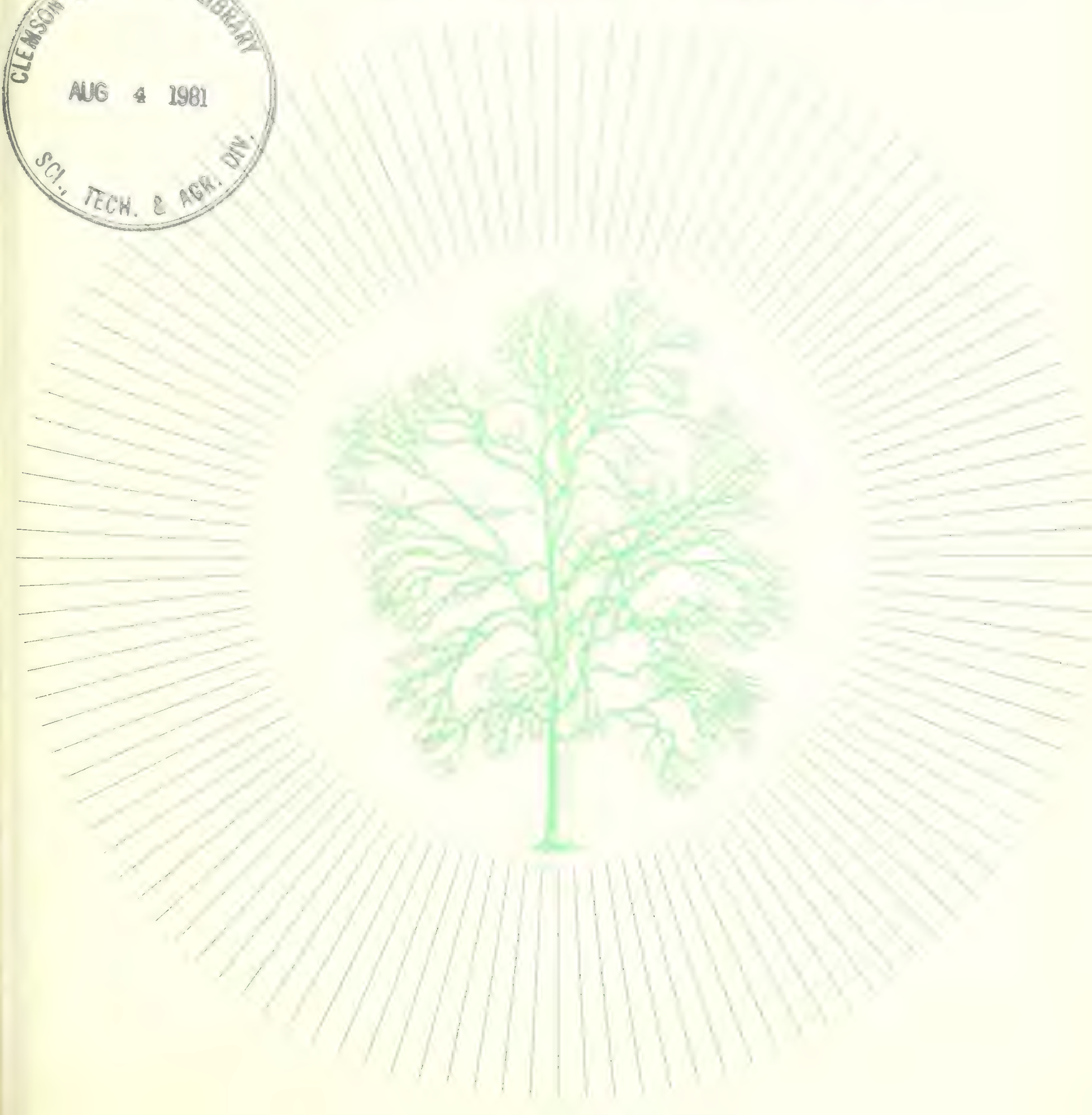

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"GROW"—A COMPUTER SUBROUTINE THAT PROJECTS THE GROWTH OF TREES IN LAKE STATES' FORESTS

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STEMS (Stand and Tree Evaluation and Modeling System) is comprised of two computer programs that simulate the growth, death, cutting, and regeneration of trees in Lake States' (Michigan, Minnesota, and Wisconsin) forests.[1] STEMS projects forest stands containing any mixture of tree species and sizes. The system was also designed to be flexible in the type of summary information it could provide. This flexibility is achieved by maintaining a tree list that describes the stand being projected. Examples of the type of summaries that can be produced from the tree lists are stand tables, stock tables, and yield tables.

The first program simulates growth, death, cutting, and regeneration. Its core component is a distance-independent, individual tree growth model that simulates both tree growth and mortality.[2] The second program summarizes the results of the projection in a variety of user-selectable ways.

Although STEMS can be used in many ways, a simpler system would be desirable in some situations. A small growth model could be an integral part of an analysis program whereas STEMS is too large to be included within another program. Secondly, a small model containing only the parts essential to growth would be easier to understand and evaluate. Thirdly, a smaller system would be cheaper to use.

I have developed a simpler version of STEMS called Grow that contains only the growth and mortality parts of STEMS. Grow contains two subprograms (fig. 1). The first is a subroutine that grows and kills trees. The second is a BLOCK DATA subprogram that contains all the coefficients for the functions in the model. Like STEMS, Grow will simulate growth and mortality for any size or species mixture encountered in the Lake States. Unlike STEMS, it does not simulate cutting or regeneration, read initial conditions, or produce summary tables. Therefore, the user must develop a main or calling program to read initial conditions, call Grow, and produce summaries.

To implement Grow the user must provide a tree list representing the stand to be projected and a computer program to read this list. A common tree list is a forest inventory plot from which tree species and diameters have been recorded. The tree characteristics required are d.b.h., species group code, status code, tree factor (the number of trees per acre the tree represents), and crown ratio code.[3] The stand site index is also required. Any tree list can be used as long as it has the information required.

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[1] *STEMS is the latest version of a series of computer programs designed to implement a generalized tree growth projection system. It was developed by a team of researchers at the North Central Forest Experiment Station. Included in the team were Jerold T. Hahn, David M. Belcher, Gary J. Brand, Roland G. Buchman, Stephen E. Fairweather, Margaret R. Holdaway, and Stephen R. Shifley. A description of STEMS is being written by David M. Belcher, Margaret R. Holdaway, and Gary J. Brand.*

[2] *The original growth model (U.S. Department of Agriculture, Forest Service. 1979. A generalized forest growth projection system applied to the Lake States Region. U.S. Department of Agriculture Forest Service, General Technical Report NC-49, 96 p. U.S. Department of Agriculture Forest Service, North Central Forest Experiment Station, St. Paul, Minnesota). was developed by a team of researchers at the North Central Forest Experiment Station. The team was led by Dr. Rolfe A. Leary and included Roland G. Buchman, Jerold T. Hahn, and Margaret R. Holdaway. This original model has since been modified and it is this modified version that is used in STEMS and Grow.*

[3] *Crown ratio code indicates the percent of the tree's total height that is in full live crown. A code of 1 means that between 1 and 10 percent of the total height is full live crown. Each additional 10 percent of full live crown increases the code by 1. Grow will calculate a crown ratio code for trees without a code using a function developed by Margaret R. Holdaway of the North Central Forest Experiment Station, St. Paul, Minnesota. This function is also used to produce a crown ratio code for each subsequent year of the projection.*

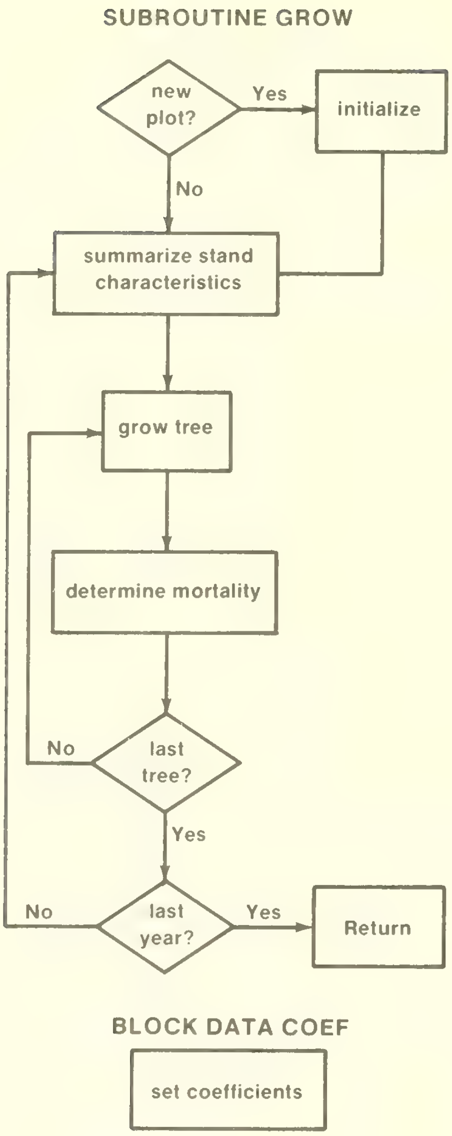

Figure 1.—Flow diagram of Grow.

The user's program must read tree characteristics into five arrays dimensioned to the longest expected tree list. Elements 1,2,...,n of each array correspond to characteristics of trees 1,2,...,n, where n is the number of trees in the list. A sixth array, dimensioned the same as the previous arrays, is needed to hold a crown ratio code correction. The correction is the difference between the observed and the predicted crown ratio code and is calculated by Grow. This correction is added to each subsequent calculation of crown ratio for each tree. Once the tree list is read into the arrays, the user selects the number of years the stand will be projected and the type of mortality desired.

To project the growth of the stand the user-written program must call subroutine Grow. The call contains the following variables (in this order):

number of years to project the stand,
number of trees in the tree list,
d.b.h. array,
species group code array,
status code array,
tree factor array,
crown ratio code array,
crown ratio code correction array,
stand site index (in feet, base age 50 years),
mortality code,
new plot flag (indicates this is the first
  call to Grow for the plot), and
error flag.

A more complete description of these variables is given in the Appendix.

Two types of mortality—deterministic and stochastic—can be calculated by Grow. The same mortality function is used for each type but it is applied differently. Deterministic mortality is indicated by a mortality code of 0. This type of mortality annually reduces the tree factor of a tree by an amount proportional to its calculated annual mortality rate. For example, if the tree factor was 10 trees per acre and the mortality rate was 0.05, the new tree factor would be 9.5 trees per acre (10 × (1–0.05)). Stochastic mortality is indicated by a mortality code of 1. With this option the calculated mortality rate is compared with a random number drawn from a uniform distribution from 0 to 1. If the random number is less than the mortality rate, the status code is set to dead. Stochastic mortality is also used for trees that have tree factors less than 1 when deterministic mortality is used.

Grow returns a projected tree list with updated diameters, status codes, tree factors, and crown ratio codes. These updated characteristics are contained in the same arrays that were passed to Grow. For instance, the new d.b.h. for the first tree is in the first position of the diameter array. The user must provide the appropriate computer statements to summarize the new tree list. If summaries of volume are desired, local volume equations must be incorporated. Repeated calls to Grow will produce additional projections of the stand.

To compare their storage requirements and costs, I projected a sample plot using both STEMS and Grow on a CDC Cyber 74 computer. Grow required 35 percent of the computer storage required by STEMS and the computing cost for Grow was 17 percent of the cost for STEMS. The larger program, however, produced both yield and components of growth summaries for basal area, number of trees, and volume. Grow produced only basal area and number of trees yield summaries. These differences may vary on other computer systems.

Grow provides a simple and inexpensive way to use the STEMS Lake States' growth model. To use Grow the user must write a program to read tree lists, call Grow, and summarize the results. A copy of Grow, a sample calling program, and a sample tree list punched on computer cards can be obtained from the author.

APPENDIX

```
      SUBROUTINE GROW (NYRS,NT,DBH,ISPG,ISTAT,TRFAC,CRC,CRD,
     1 SI,MORT,NUPL,IERR)
C
C
C                         WRITTEN BY:
C
C                  GARY BRAND
C                  NORTH CENTRAL FOREST EXPERIMENT STATION
C                  1992 FOLWELL AVENUE
C                  ST.  PAUL, MN 55108
C                  612-642-5276
C                  JUNE 10,1980
C
C  TO USE THIS SUBROUTINE THE FOLLOWING VARIABLES MUST BE SET IN
C     THE CALLING PROGRAM AND PASSED THROUGH THE CALL STATEMENT:
C
C   NYRS   - NUMBER OF YEARS IN PROJECTION
C   NT     - NUMBER OF TREES IN TREE LIST
C   DBH    - ARRAY OF DBH'S OF TREES
C   ISPG   - ARRAY OF SPECIES GROUP CODES OF TREES
C      1-JACK PINE       11-BLACK ASH     21-N.  RED OAK
C      2-RED PINE        12-COTTONWOOD    22-OTHER RED OAK
C      3-WHITE PINE      13-SILVER MAPLE  23-HICKORY
C      4-WHITE SPRUCE    14-RED MAPLE     24-BIGTOOTH ASPEN
C      5-BALSAM FIR      15-ELM           25-QUAKING ASPEN
C      6-BLACK SPRUCE    16-YELLOW BIRCH  26-PAPER BIRCH
C      7-TAMARACK        17-BASSWOOD      27-RED PINE PLANTATION
C      8-N. WHITE-CEDAR 18-HARD MAPLE     28-29 NOT USED
C      9-HEMLOCK         19-WHITE ASH     30-OTHER HARDWOODS
C     10-OTHER SOFT.    20-WHITE OAK      31-NONCOMMERCIAL
C
C   ISTAT  - ARRAY OF STATUS CODES OF TREES ( 1=LIVE 2=CUT 3=DEAD )
C   TRFAC  - ARRAY OF TREE FACTORS OF TREES (TREES/ACRE REPRESENTED BY
C             EACH TREE IN LIST)
C   CRC    - ARRAY OF CROWN RATIO CODES OF TREES (0-10%=1, 11-20%=2,..
C             81-90%=9, 91-100%=10)
C   CRD    - ARRAY OF DIFFERENCES BETWEEN OBSERVED AND PREDICTED CROWN
C             RATIOS OF TREES - RETURNED BY GROW
C   SI     - SITE INDEX (HEIGHT AT 50 YEARS)
C   MORT   - SELECTS TYPE OF MORTALITY,
C            MORT=0 DETERMINISTIC
C            MORT=1 STOCHASTIC
C   NUPL   - NEW PLOT INDICATOR SET TO ZERO BY THE CALLING PROGRAM WHEN
C             A NEW PLOT IS ENTERED
C   IERR   - ERROR FLAG RETURNED BY GROW ,
C             IERR=0 IF NO ERROR
C             IERR=1 IF NYRS IS LESS THAN 1
C             IERR=2 IF NT IS LESS THAN 1
C
C   PROJECTED TREE ATTRIBUTES ARE RETURNED AS THE SAME VARIABLES
C      THAT WERE SENT IN THE CALL
C
C   DBH, ISPG, ISTAT, TRFAC, CRC, AND CRD MUST BE DIMENSIONED IN THE
C      CALLING PROGRAM
```

```
C
C
      PARAMETER NSG=31
      COMMON /GROPAR/ CRP(4,NSG),PGP(5,NSG),PMP(5,NSG),GMPO(4,NSG),
     1 GMPB(2,NSG),GMPC(2,NSG)
      DIMENSION DBH(NT),ISPG(NT),ISTAT(NT),TRFAC(NT),CRC(NT),CRD(NT)
      DIMENSION RUNBA(10)
      NTREES=NT
C
C         NUPL EQUALS 0 WHEN A NEW PLOT IS STARTED
      IF(NUPL.EQ.0) THEN
C
C          CLEAR RUNNING AVERAGE BASAL AREA ARRAY.
        DO 5 I=1,10
    5   RUNBA(I)=0.0
      ENDIF
C
C          DO NOT PROJECT THE PLOT IF THERE ARE NO TREES OR YEARS
      IF(NYRS.LT.1.OR.NTREES.LT.1) THEN
        IF(NYRS.LT.1) IERR=1
        IF(NTREES.LT.1) IERR=2
      ELSE
        DO 400 IYR=1,NYRS
          AVDBH=0.0
          BA=0.0
          ALIVTR=0.0
          DO 10 I=1,NTREES
            IF(ISTAT(I).NE.1) GO TO 10
            IF(DBH(I).LE.0.0) GO TO 10
            ALIVTR=ALIVTR+TRFAC(I)
            AVDBH=AVDBH+DBH(I)*TRFAC(I)
            BA=BA+DBH(I)*DBH(I)*TRFAC(I)
   10     CONTINUE
C
C          CALCULATE RUNNING AVERAGE BA FOR UP TO THE PAST 10 YEARS
          BA=0.005454*BA
          AVDBH=AVDBH/ALIVTR
          BATOT=BA
          JBA=1
          DO 20 I=1,9
            IF(RUNBA(I+1).GT.0.0) THEN
              RUNBA(I)=RUNBA(I+1)
              JBA=JBA+1
              BATOT=BATOT+RUNBA(I)
            ENDIF
   20     CONTINUE
          RUNBA(10)=BA
          AV10BA=BATOT/FLOAT(JBA)
C
C          GROW THE LIVE TREES
          DO 50 I=1,NTREES
            IF(ISTAT(I).NE.1) GO TO 50
            ISG=ISPG(I)
C
```

```
C          CALCULATE THE CROWN RATIO
            CR=CRP(1,ISG)/(1.+CRP(2,ISG)*AV10BA)+CRP(3,ISG)*(1.-
     1        EXP(CRP(4,ISG)*DBH(I)))
            IF(NUPL.EQ.0.AND.IYR.EQ.1) THEN
C
C          CORRECT THE PREDICTED CROWN RATIO ACCORDING TO THE OBSERVED
C            CROWN RATIO AND STORE THE CORRECTION IN CRD
              IF(CRC(I).LE.0.0) CRC(I)=CR
              CRD(I)=CRC(I)-CR
            ELSE
              CRC(I)=CR+CRD(I)
              IF(CRC(I).LT..5) CRC(I)=.5
              IF(CRC(I).GT.10.0) CRC(I)=10.0
            ENDIF
C
C          CALCULATE THE POTENTIAL GROWTH
            PG=PGP(1,ISG)+PGP(2,ISG)*DBH(I)**PGP(3,ISG)+PGP(4,ISG)
     1        *SI*CRC(I)*DBH(I)**PGP(5,ISG)
C
C          CALCULATE THE MODIFIER OF THE POTENTIAL
C             RED PINE PLANTATION COEFFICIENTS ARE STORED IN GROUP 27.
C             IF THESE COEFFICIENTS ARE DESIRED USE JSG=27.
            JSG=ISG
            RATIO=DBH(I)/AVDBH
            OMEGA=GMPO(1,JSG)*(1.-EXP(GMPO(2,JSG)*RATIO))**GMPO(3,JSG)
     1        +GMPO(4,JSG)
            BETA=GMPB(1,JSG)*(AVDBH+1.)**GMPB(2,JSG)
            CHECK=GMPC(2,JSG)-BA
            IF(CHECK.LT.0.0) CHECK=0.0
            GM=GMPC(1,JSG)*(1.0-EXP(-OMEGA*BETA*SQRT(CHECK/BA)))
C
C          CALCULATE THE PREDICTED GROWTH
            DGRO=PG*GM
            IF(DGRO.LT.0.0) DGRO=0.0
            DBH(I)=DBH(I)+DGRO
C
C          CALCULATE THE PREDICTED MORTALITY RATE
            ARG=PMP(1,ISG)+PMP(2,ISG)*DGRO**PMP(3,ISG)+PMP(5,ISG)*
     1        DBH(I)
            IF(ARG.GT.740.2) ARG=740.2
            PM=1.0/(1.0+EXP(ARG))+PMP(4,ISG)
C
C       DRAW A RANDOM NUMBER FROM A UNIFORM DISTRIBUTION  (0 TO 1)
C         TO DETERMINE IF THE TREE WILL DIE (WHEN MORT=1 OR TREE
C         FACTOR IS LESS THAN 1.0)
            IF(MORT.EQ.1.OR.TRFAC(I).LT.1.0) THEN
C
C       IF NECESSARY, REPLACE RANF(0.0) WITH AN APPROPRIATE ROUTINE
C        THAT PRODUCES A RANDOM NUMBER UNIFORMLY DISTRIBUTED
C         BETWEEN 0 AND 1.
              RAN=RANF(0.0)
              IF(RAN.LE.PM) ISTAT(I)=3
C
C       REDUCE THE TREE FACTOR TO ACCOUNT FOR MORTALITY
```

```
          ELSE
            TRFAC(I)=TRFAC(I)*(1.-PM)
          ENDIF
 50     CONTINUE
400   CONTINUE
      IERR=0
    ENDIF
    NUPL=1
    RETURN
    END
    BLOCK DATA COEF

        ALL GROWTH COEFFICIENTS ARE SET IN THIS ROUTINE
    COMMON /GROPAR/ CRP(4,31),PGP(5,31),PMP(5,31),GMPO(4,31),
   1 GMPB(2,31),GMPC(2,31)

         CROWN RATIO COEFFICIENTS
    DATA ((CRP(I,J),I=1,4),J=1,16)/                                        ISPG
   C       .66400E+01  , .01350E+00 ,  .32000E+01  ,-.05180E+00 ,           01 JP
   C       .53500E+01  , .00530E+00 ,  .15280E+01  ,-.03300E+00 ,           02 RP
   C       .67900E+01  , .00580E+00 ,  .75900E+01  ,-.01030E+00 ,           03 WP
   C       .78400E+01  , .00570E+00 ,  .12720E+01  ,-.14200E+00 ,           04 WS
   C       .56300E+01  , .00470E+00 ,  .35230E+01  ,-.06890E+00 ,           05 BF
   C       .55400E+01  , .00720E+00 ,  .42000E+01  ,-.05300E+00 ,           06 BS
   C       .60000E+01  , .00530E+00 ,  .43100E+00  ,-.00120E+00 ,           07 TM
   C       .57100E+01  , .00770E+00 ,  .22900E+01  ,-.25300E+00 ,           08 NWC
   C       .57100E+01  , .00770E+00 ,  .22900E+01  ,-.25300E+00 ,           09 HEM
   C       .57100E+01  , .00770E+00 ,  .22900E+01  ,-.25300E+00 ,           10 OS
   C       .45000E+01  , .00320E+00 ,  .79500E+00  ,-.10500E+00 ,           11 BA
   C       .43500E+01  , .00460E+00 ,  .18200E+01  ,-.27400E+00 ,           12 COT
   C       .48500E+01  , .00500E+00 ,  .98100E+01  ,-.00990E+00 ,           13 SIL
   C       .43500E+01  , .00460E+00 ,  .18200E+01  ,-.27400E+00 ,           14 RM
   C       .44000E+01  , .00250E+00 ,  .10000E+01  ,-.09400E+00 ,           15 ELM
   C       .41800E+01  , .00250E+00 ,  .14100E+01  ,-.51200E+00 /           16 YB
    DATA ((CRP(I,J),I=1,4),J=17,31)/
   C       .44400E+01  , .00370E+00 ,  .20900E+01  ,-.06500E+00 ,           17 BW
   C       .34000E+01  , .00660E+00 ,  .28700E+01  ,-.43400E+00 ,           18 SM
   C       .44900E+01  , .00290E+00 ,  .12100E+01  ,-.06500E+00 ,           19 WA
   C       .58400E+01  , .00820E+00 ,  .32600E+01  ,-.04900E+00 ,           20 WO
   C       .42000E+01  , .00160E+00 ,  .27600E+01  ,-.02500E+00 ,           21 RO
   C       .50600E+01  , .00330E+00 ,  .17300E+01  ,-.06100E+00 ,           22 ORO
   C       .62100E+01  , .00730E+00 ,  .99900E+01  ,-.01000E+00 ,           23 HIC
   C       .41100E+01  , .00540E+00 ,  .16500E+01  ,-.11000E+00 ,           24 BTA
   C       .40000E+01  , .00240E+00 , -.28300E+01  , .02100E+00 ,           25 QA
   C       .50000E+01  , .00660E+00 ,  .49200E+01  ,-.02630E+00 ,           26 PB
   C       .40000E+01  , .00240E+00 , -.28300E+01  , .02100E+00 ,           27
   C       .40000E+01  , .00240E+00 , -.28300E+01  , .02100E+00 ,           28
   C       .40000E+01  , .00240E+00 , -.28300E+01  , .02100E+00 ,           29
   C       .40000E+01  , .00240E+00 , -.28300E+01  , .02100E+00 ,           30 OH
   C       .40000E+01  , .00240E+00 , -.28300E+01  , .02100E+00 /           31 NC

         POTENTIAL GROWTH COEFFICIENTS
    DATA ((PGP(I,J),I=1,5),J=1,16)/                                        ISPG
   C  .16062E-00,-.90000E-05, .36245E+01, .40000E-04, .10000E+01,           01
```

```
     C  .94460E-01,-.12000E-03, .20596E+01, .35000E-03, .24225E+00,       02
     C  .25578E-00,-.88000E-03, .17263E+01, .40000E-04, .10000E+01,       03
     C  .17056E-00,-.14516E-01, .10660E+01, .52000E-03, .27298E+00,       04
     C  .12200E-00,-.80000E-03, .19890E+01, .60000E-04, .10000E+01,       05
     C  .10713E+00,-.10700E-02, .20017E+01, .60000E-04, .91127E+00,       06
     C  .11147E-00,-.10000E-04, .30685E+01, .30000E-04, .10000E+01,       07
     C  .13403E-00,-.10000E-05, .36880E+01, .20000E-04, .10000E+01,       08
     C  .16872E-00,-.30000E-06, .35738E+01, .10000E-04, .10000E+01,       09
     C  .16062E-00,-.90000E-05, .36245E+01, .40000E-04, .10000E+01,       10
     C  .58807E-01,-.60000E-08, .50559E+01, .24000E-03, .31553E-00,       11
     C  .10948E-00,-.40000E-04, .22226E+01, .50000E-03, .66260E-01,       12
     C  .10948E-00,-.40000E-04, .22226E+01, .50000E-03, .66260E-01,       13
     C  .10948E-00,-.40000E-04, .22226E+01, .50000E-03, .66260E-01,       14
     C  .28496E-00,-.18200E-02, .15297E+01, .30000E-04, .10000E+01,       15
     C  .15155E-00,-.30000E-05, .33104E+01, .70000E-04, .57302E+00/       16
      DATA ((PGP(I,J),I=1,5),J=17,31)/
     C  .25402E-00,-.40000E-05, .29396E+01, .10000E-04, .10000E+01,       17
     C  .18772E-00,-.70000E-05, .25839E+01, .28000E-03, .83850E-01,       18
     C  .21167E-00,-.30000E-05, .33131E+01, .10000E-04, .12430E+00,       19
     C  .12654E-00,-.40000E-05, .27538E+01, .50000E-04, .62086E+00,       20
     C  .15535E-00,-.10000E-06, .35367E+01, .18000E-03, .25900E-00,       21
     C  .17358E-00,-.70000E-04, .24451E+01, .30000E-04, .95222E-00,       22
     C  .16471E-00,-.21610E-02, .13949E+01, .40000E-04, .71628E-00,       23
     C  .23490E-00,-.94200E-02, .11041E+01, .36000E-03, .15386E-00,       24
     C  .21645E-00,-.91000E-04, .26030E+01, .44000E-04, .10000E+01,       25
     C  .10971E-00,-.32000E-03, .20236E+01, .34000E-03, .21288E-00,       26
     C  .37510E-00,-.24790E-01, .96288E+00, .40000E-04, .10000E+01,       27
     C  .37510E-00,-.24790E-01, .96288E+00, .40000E-04, .10000E+01,       28
     C  .37510E-00,-.24790E-01, .96288E+00, .40000E-04, .10000E+01,       29
     C  .37510E-00,-.24790E-01, .96288E+00, .40000E-04, .10000E+01,       30
     C  .37510E-00,-.24790E-01, .96288E+00, .40000E-04, .10000E+01/       31
C
C            MORTALITY COEFFICIENTS
      DATA ((PMP(I,J),I=1,5),J=1,16)/                                    ISP
     C  .36767E+00, .60178E+02, .10727E+01, .00502E+00, .12220E+00  ,     01
     C  .10843E+01, .11012E+02, .58866E+00, .00020E+00, .48500E+00  ,     02
     C  .23507E+01, .33609E+02, .10088E+01, .00201E+00, .00000E+00  ,     03
     C  .28806E+01, .30774E+02, .12309E+01, .00396E+00, .00000E+00  ,     04
     C  .26976E+01, .30550E+02, .89963E+00, .00400E+00,-.23069E+00  ,     05
     C  .28774E+01, .43295E+03, .18576E+01, .00235E+00, .00000E+00  ,     06
     C  .36767E+00, .60178E+02, .10727E+01, .00502E+00, .12220E+00  ,     07
     C  .28774E+01, .43295E+03, .18576E+01, .00235E+00, .00000E+00  ,     08
     C  .28233E+01, .89560E+02, .10966E+01, .00320E+00, .00000E+00  ,     09
     C  .10843E+01, .11012E+02, .58866E+00, .00020E+00, .48500E+00  ,     10
     C  .14875E+01, .13338E+02, .54290E+00, .00018E+00, .00000E+00  ,     11
     C  .22405E+01, .56594E+02, .10392E+01, .00494E+00, .00000E+00  ,     12
     C  .22405E+01, .56594E+02, .10392E+01, .00494E+00, .00000E+00  ,     13
     C  .22405E+01, .56594E+02, .10392E+01, .00494E+00, .00000E+00  ,     14
     C  .19889E+01, .44541E+02, .10965E+01, .00899E+00, .00000E+00  ,     15
     C  .26705E+01, .63148E+02, .13819E+01, .00382E+00, .00000E+00  /     16
      DATA ((PMP(I,J),I=1,5),J=17,31)/
     C -.58612E+00, .10187E+03, .16493E+01, .00489E+00, .68398E+00  ,     17
     C  .81500E+00, .66937E+02, .15934E+01, .00435E+00, .75000E+00  ,     18
     C  .17821E+01, .23231E+03, .17267E+01, .00222E+00, .00000E+00  ,     19
```

```
C  .36946E+01, .95637E+02, .14517E+01, .00188E+00, .00000E+00  ,    20
C  .23092E+01, .69998E+04, .26615E+01, .00468E+00, .00000E+00  ,    21
C  .23092E+01, .69998E+04, .26615E+01, .00468E+00, .00000E+00  ,    22
C  .30626E+01, .63495E+02, .10498E+01, .00134E+00, .00000E+00  ,    23
C  .88050E+00, .56593E+02, .12154E+01, .01288E+00, .00000E+00  ,    24
C -.07855E+00, .21363E+03, .17126E+01, .02276E+00, .25812E+00  ,    25
C  .21808E+01, .11626E+02, .47500E+00, .00029E+00, .00000E+00  ,    26
C  .22339E+01, .29629E+02, .13427E+01, .00748E+00, .00000E+00  ,    27
C  .22339E+01, .29629E+02, .13427E+01, .00748E+00, .00000E+00  ,    28
C  .22339E+01, .29629E+02, .13427E+01, .00748E+00, .00000E+00  ,    29
C  .22339E+01, .29629E+02, .13427E+01, .00748E+00, .00000E+00  ,    30
C  .23581E+01, .11306E+03, .99930E+00, .01923E+00, .00000E+00  /    31

      MODIFIER OMEGA COEFFICIENTS
 DATA ((GMPO(I,J),I=1,4),J=1,16)/                                  ISPG
C   .1780E+01, -.3000E+01,  .1620E+02,  .2270E+00,                  01
C   .7190E+00, -.1090E+02,  .1688E+04,  .3750E+00,                  02
C   .1360E+01, -.2640E+01,  .1150E+02,  .3860E+00,                  03
C   .5000E+01, -.1010E+01,  .3640E+01,  .0        ,                 04
C   .1760E+01, -.1510E+01,  .2630E+01,  .2330E+00,                  05
C   .3800E+01, -.1520E+01,  .6540E+01,  .3480E+00,                  06
C   .1780E+01, -.3000E+01,  .1620E+02,  .2270E+00,                  07
C   .2540E+01, -.1140E+01,  .2260E+01,  .0        ,                 08
C   .1270E+01, -.1340E+01,  .1050E+01,  .0        ,                 09
C   .1360E+01, -.2640E+01,  .1150E+02,  .3860E+00,                  10
C   .5000E+01, -.5680E+00,  .1830E+01,  .6300E-01,                  11
C   .1400E+01, -.2030E+01,  .1040E+02,  .6940E+00,                  12
C   .1400E+01, -.2030E+01,  .1040E+02,  .6940E+00,                  13
C   .1400E+01, -.2030E+01,  .1040E+02,  .6940E+00,                  14
C   .5000E+01, -.9700E+00,  .4400E+01,  .2680E+00,                  15
C   .6790E+00, -.1097E+02,  .1568E+04,  .4830E+00/                  16
 DATA ((GMPO(I,J),I=1,4),J=17,31)/
C   .1590E+01, -.3270E+01,  .2670E+02,  .4120E+00,                  17
C   .1170E+01, -.4590E+01,  .2919E+02,  .4300E+00,                  18
C   .5000E+01, -.1380E+01,  .8260E+01,  .3260E+00,                  19
C   .1980E+01, -.9740E+00,  .1640E+01,  .0        ,                 20
C   .1980E+01, -.9740E+00,  .1640E+01,  .0        ,                 21
C   .1980E+01, -.9740E+00,  .1640E+01,  .0        ,                 22
C   .1660E+01, -.2620E+01,  .9970E+01,  .5150E+00,                  23
C   .1130E+01, -.4640E+01,  .1646E+03,  .6480E+00,                  24
C   .1080E+01, -.6600E+01,  .3461E+03,  .3950E+00,                  25
C   .1980E+01, -.1750E+01,  .3670E+01,  .2320E+00,                  26
C   .2310E+01, -.1670E+01,  .3940E+01,  .0        ,                 27
C   .1980E+01, -.9740E+00,  .1640E+01,  .0        ,                 28
C   .1980E+01, -.9740E+00,  .1640E+01,  .0        ,                 29
C   .1980E+01, -.9740E+00,  .1640E+01,  .0        ,                 30
C   .1980E+01, -.9740E+00,  .1640E+01,  .0        /                 31

      MODIFIER BETA COEFFICIENTS
 DATA ((GMPB(I,J),I=1,2),J=1,16)/                                  ISPG
C   .4020E+00,  .2300E+00,                                          01
C   .2030E+01, -.3540E+00,                                          02
C   .9700E-01,  .7550E+00,                                          03
C   .1507E+01, -.5200E+00,                                          04
```

```
     C   .9270E+00, -.2990E+00,                                            05
     C   .5220E+00,  .1730E+00,                                            06
     C   .3900E-01,  .1000E+01,                                            07
     C   .5260E+00,  .1360E+00,                                            08
     C   .4600E-01,  .1000E+01,                                            09
     C   .9700E-01,  .7550E+00,                                            10
     C   .2600E+00,  .4190E+00,                                            11
     C   .1810E+00,  .4450E+00,                                            12
     C   .1810E+00,  .4450E+00,                                            13
     C   .1810E+00,  .4450E+00,                                            14
     C   .1000E+00,  .6290E+00,                                            15
     C   .2020E+00,  .4540E+00/                                            16
      DATA ((GMPB(I,J),I=1,2),J=17,31)/
     C   .3530E+00,  .1820E+00,                                            17
     C   .1420E+00,  .5240E+00,                                            18
     C   .4530E+00,  .3400E+00,                                            19
     C   .5100E-01,  .1000E+01,                                            20
     C   .2780E+00,  .3650E+00,                                            21
     C   .1365E+01, -.2080E+00,                                            22
     C   .2800E+00,  .2280E+00,                                            23
     C   .9300E-01,  .1000E+01,                                            24
     C   .2090E+00,  .5430E+00,                                            25
     C   .1100E+00,  .6780E+00,                                            26
     C   .4410E+00,  .1730E+00,                                            27
     C   .2780E+00,  .3650E+00,                                            28
     C   .2780E+00,  .3650E+00,                                            29
     C   .2780E+00,  .3650E+00,                                            30
     C   .2780E+00,  .3650E+00/                                            31
C
C           MODIFIER CHECK COEFFICIENTS
      DATA ((GMPC(I,J),I=1,2),J=1,16)/                                    ISP
     C   1.     E 00,   .225 E 03,                                         01
     C   1.     E 00,   .300 E 03,                                         02
     C   1.     E 00,   .300 E 03,                                         03
     C   1.     E 00,   .350 E 03,                                         04
     C   1.     E 00,   .325 E 03,                                         05
     C   1.     E 00,   .300 E 03,                                         06
     C   1.     E 00,   .250 E 03,                                         07
     C   1.     E 00,   .350 E 03,                                         08
     C   1.     E 00,   .300 E 03,                                         09
     C   1.     E 00,   .300 E 03,                                         10
     C   1.     E 00,   .250 E 03,                                         11
     C   1.     E 00,   .250 E 03,                                         12
     C   1.     E 00,   .250 E 03,                                         13
     C   1.     E 00,   .250 E 03,                                         14
     C   1.     E 00,   .250 E 03,                                         15
     C   1.     E 00,   .250 E 03/                                         16
      DATA ((GMPC(I,J),I=1,2),J=17,31)/
     C   1.     E 00,   .250 E 03,                                         17
     C   1.     E 00,   .250 E 03,                                         18
     C   1.     E 00,   .250 E 03,                                         19
     C   1.     E 00,   .250 E 03,                                         20
     C   1.     E 00,   .275 E 03,                                         21
     C   1.     E 00,   .250 E 03,                                         22
```

```
C   1.     E 00,  .250 E 03,                                                   23
C   1.     E 00,  .250 E 03,                                                   24
C   1.     E 00,  .250 E 03,                                                   25
C   1.     E 00,  .275 E 03,                                                   26
C   1.     E 00,  .350 E 03,                                                   27
C   1.     E 00,  .275 E 03,                                                   28
C   1.     E 00,  .275 E 03,                                                   29
C   1.     E 00,  .275 E 03,                                                   30
C   1.     E 00,  .275 E 03/                                                   31
 END
```

Brand, Gary J.

1981. "Grow"—a computer subroutine that projects the growth of trees in Lake States' forests. U.S. Department of Agriculture Forest Service, Research Paper NC-207, 11 p. U.S. Department of Agriculture Forest Service, North Central Forest Experiment Station, St. Paul, Minnesota.

A computer subroutine, Grow, has been written in 1977 Standard FORTRAN to implement a distance-independent, individual tree growth model for Lake States' forests. Grow is a small and easy-to-use version of the growth model. All the user has to do is write a calling program to read initial conditions, call Grow, and summarize the results.

KEY WORDS: Growth model, mortality, FORTRAN.

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Logging System Cost Analysis

Comparison of Methods Used

Edwin S. Miyata and Helmuth M. Steinhilb

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LOGGING SYSTEM COST ANALYSIS: COMPARISON OF METHODS USED

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It has become increasingly difficult to plan logging operations to minimize costs and maximize profits. A variety of factors, including new harvesting equipment, smaller timber, scattered logging areas, lighter volumes per acre, inflation, and rising production and labor costs contribute to planning difficulties. Some of these factors are outside the control of logging management. However, a good knowledge of logging costs and their methods of calculation helps keep operations on a sound business basis.

Since cost analysis is vital to the success of logging operations, logging managers and others concerned with calculating machine rates and logging costs should become familiar with different cost analysis methods so that they may find one appropriate to their needs.

Choosing the right cost analysis method has been difficult because of the large number of methods—an incomplete literature review found 30 different ways of calculating machine rates and logging costs—and a lack of uniformity in defining the components used in the methods. If an inappropriate method is chosen or incorrect information is used in the calculations, the erroneous results may lead to poor decisions regarding the total logging operation.

In costing logging equipment, both the machine rate and cash flow approaches are used, although the machine rate method seems to predominate. To substantiate the charge that the lack of uniformity causes problems, it is noted that the machine rate method can employ either "scheduled hours" or "productive hours" or an erroneous combination of both.

To help managers best determine logging costs, this paper examines the use of three different cost analysis methods in determining the cost of a single piece of logging equipment and an entire logging system. Suggestions for using each of the three methods are given.

METHODS

Definitions of Terms

When discussing logging costs, a clear definition of all terms is important.

Total Time (TT) (Rolston 1968): The total elapsed time for the period under consideration. In 1 year the total time would be 365 24-hour days or 8,760 hours.

Scheduled Hours (SH): The total annual hours a machine is scheduled to do productive work. If a machine is intended to work 200 8-hour shifts, the scheduled hours would be 1,600.

Productive Hours (PH) (Rolston 1968): That scheduled time portion during which the machine actually works. If SH were 1,600 hours but the machine actually worked only 1,120 hours the PH would be 1,120 hours.

Machine Utilization (U) (Miyata 1980): The percentage of SH the machine actually works. In the above example, machine utilization is (1,120 ÷ 1,600) × 100, or 70 percent.

Fixed Costs (FC) (Miyata 1980): Costs incurred whether or not the machine is productively employed. They depend not on the amount of work done by the machine, but on the passage of time, and commonly include **Depreciation (D),** and **Interest, Insurance, and Taxes (IIT).**

Depreciation (D): The gradual decline in equipment value usually calculated for income tax purposes. Straight line depreciation is usually used for equipment machine rates and logging cost calculation.

Interest, Insurance, and Taxes (IIT): Interest is the cost of using funds—borrowed or taken from savings or equity—over a period of time. If the money comes from personal savings or established equity, an opportunity cost (the rate this money would earn if invested elsewhere, e.g., in U.S. savings bonds or a savings account), should be used as the interest rate. The equipment owner also pays property or usage taxes on his equipment as well as insurance premiums.

Operating Costs (OC) (Miyata 1980): Costs incurred because of the machine's productive activity. Such costs depended on PH and the number of units produced, and vary with hours of use. Typical OC include the cost of fuel, oil and lubricants, maintenance and repair necessary to keep a machine in good running condition and major supplies such as rigging and tires.

Hourly Machine Cost per PH (HMC/PH): Total hourly cost of owning and operating a machine based on productive hours and given by:

$$\text{HMC/PH} = \frac{\text{FC} + \text{OC}}{\text{PH}}$$

Hourly Machine Cost per SH (HMC/SH): Total cost of owning and operating a machine based on scheduled hours and given by:

$$\text{HMC/SH} = \frac{\text{FC} + \text{OC}}{\text{SH}}$$

The following formula expresses the relation between fixed and operating costs and it can be shown graphically as in figure 1.

$$\text{C} = \text{FC} + \text{OC}$$

Where: C = Total cost for any time period.
FC = Fixed cost for any time period.
OC = Operating cost for any time period or HOC × PH.
PH = Number of productive hours.
HOC = Operating cost per productive hour.

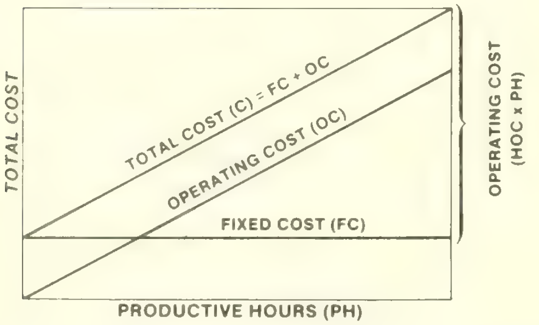

Figure 1.—*Relation between fixed and operating costs.*

Figure 1 shows that the greater the number of productive hours for any time period, the smaller the proportion of fixed cost is to total cost for that period. Conversely, the smaller the number of productive hours, the greater the proportion of fixed cost is to total cost.

FORMULAS USED

Methods of Calculating Hourly Machine Rate for Equipment

Three predominant methods have been chosen to calculate the hourly machine rate for equipment. They are described below:

Method 1: The sum of the fixed and operating cost per year is divided by the **scheduled** hours per year to obtain a machine rate per scheduled hour.

$$\text{Machine rate based on SH(\$/SH)} = \frac{\text{FC} + \text{OC}}{\text{SH}}$$

Method 2: The sum of the fixed and operating cost per year is divided by productive hours per year to obtain the machine rate per productive hour.

$$\text{Machine rate based on PH (\$/PH)} = \frac{\text{FC} + \text{OC}}{\text{PH}}$$

Both Method 1 and Method 2 are mathematically correct provided they are clearly labeled and understood by the user as being based on **either** scheduled hours or productive hours (Lussier 1965).

Method 3: The fixed cost of a machine per year is divided by the scheduled hours per year, and the operating cost per year is divided by the productive hours per year, and the sum of the results is used as the machine rate per hour.

$$\text{HMC/?} = \frac{\text{FC/year}}{\text{SH/year}} + \frac{\text{OC/year}}{\text{PH/year}}$$

Lussier (1965) emphasizes that Method 3 is incorrect for calculating an hourly machine rate from both a realistic and mathematical standpoint and can lead to very serious errors when used in logging cost analysis.

Modified Method 3: The $\frac{\text{FC/year}}{\text{SH/year}}$ is multiplied by the number of scheduled hours in the time period and the $\frac{\text{OC/year}}{\text{PH/year}}$ is multiplied by the PH in the time period and the sum of the products is the production cost for the time period. The production cost divided by the number of units of product produced during the time period gives the unit production cost.

Cost/Production Unit for any time period =

$$\frac{\left(\frac{\text{FC/year}}{\text{SH/year}} \times \text{SH in time period}\right) + \left(\frac{\text{OC/year}}{\text{PH/year}} \times \text{PH in time period}\right)}{\text{Number of units of Production in time period}}$$

The authors suggest that if a Modified Method 3 is used as above, **not** to find the equipment's hourly machine rate, but to obtain production cost per unit for short time intervals, (i.e., daily, weekly, monthly, etc.) it appears to calculate production cost more accurately and realistically than either Method 1 or 2, as illustrated below.

Discussion and Illustration—A Single Machine

To illustrate the discrepancies caused by the methods of calculating cost and machine rates, a hypothetical skidder can be used as an example. The following assumptions are made:

Scheduled hours (SH)	1,920/year
Productive hours (PH)	1,248/year
Fixed cost (FC)	$12,000/year
Operating cost (OC)	$13,000/year
Machine utilzation (U)	$\frac{\text{PH}}{\text{SH}} = \frac{1248}{1920} = .65$ or 65%
Total production	7,680 cd./yr @ 65% utilization
Cost per cord	$\frac{\$12{,}000 + \$13{,}000}{7{,}680 \text{ cd.}} = \$3.26/\text{cord.}$

Hypothetical monthly scheduled hours, productive hours, and monthly production volume for an entire year are summarized (table 1). Machine utilization varies from a January low of 25 percent to a June high of 84, with 65 percent average annual utilization. Monthly production ranges from 200 to 830 cords. Data from table 1 show how the monthly fixed and operating costs and the production cost per cord differ from month to month when calculated by Method 1, Method 2, and Modified Method 3.

Using Method 1

Hourly Machine Cost (HMC/SH)

$$= \frac{\text{Fixed Cost (FC)} + \text{Operating Cost (OC)}}{\text{Scheduled Hours (SH)}}$$

$$= \frac{\$12{,}000 + \$13{,}000}{1{,}920 \text{ hours}}$$

$$= \$13.02/\text{SH}$$

Then the total machine cost for January is $13.02/SH × 160 SH = $2,083.33. Cost per cord in January = $2,083.33 ÷ 200 cd. = $10.42 per cord. Fixed and operating costs and cost per cord are calculated for other months, and the results shown in columns 2 and 7 of table 2.

Table 1.—*Hypothetical monthly data scheduled hours (SH), productive hours (PH), machine utilization (U), and monthly production (P)*

Month	SH	PH	(Cumulative)	Machine utilization (U)	Production (P)
				Percent	*Cords*
January	160	40		25	200
February	160	72	(112)	45	465
March	160	115	(227)	72	732
April	160	120	(347)	75	830
May	160	130	(477)	81	781
June	160	135	(612)	84	740
July	160	130	(742)	81	790
August	160	118	(860)	74	600
September	160	124	(984)	78	800
October	160	104	(1,088)	65	714
November	160	84	(1,172)	53	628
December	160	76	(1,248)	48	400
Yearly Total	1,920	1,248		Ave.—65	7,680

Using Method 2

Hourly Machine Cost (HMC/PH)

$$= \frac{\text{Fixed Cost (FC)} + \text{Operating Cost (OC)}}{\text{Production Hours (PH)}}$$

$$= \frac{\$12{,}000 + \$13{,}000}{1{,}248 \text{ hours}}$$

$$= \$20.03/\text{PH}$$

For January, the total machine cost is $20.03 per PH × 40 PH = $801.20. Cost per cord is $801.20 ÷ 200 cd. = $4.01 per cord. Similarly, fixed and operating costs and cost per cord are calculated for the other months and the results shown in columns 3 and 8 of table 2.

Using Modified Method 3

With fixed cost based on scheduled time and operating cost based on productive time, the formula is:

Machine Cost per month

$$= \left(\frac{\text{FC}}{\text{SH}} \times \text{SH/month}\right) + \left(\frac{\text{OC}}{\text{PH}} \times \text{PH/month}\right)$$

$$= \left(\frac{\$12{,}000}{1{,}920} \times 160\right) + \left(\frac{\$13{,}000}{1{,}248} \times 40\right)$$

$$= (\$6.25 \times 160) + (\$10.42 \times 40)$$

$$= \$1{,}000.00 + \$416.67$$

$$= \$1{,}416.67 \text{ Total Machine Cost for January.}$$

Table 2.—*Fixed and operating cost and production cost of three alternative costing methods*

Month	Fixed and Operating Cost					Production Cost		
	First	Second	Modified Third Method			First	Second	Third
	Method	Method	Fixed	Operating	Total	Method	Method	Method
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	Dollars per month					Dollars per cord		
January	2,083.33	801.20	1,000	416.67	1,416.67	10.42	4.01	7.08
February	2,083.33	1,442.31	1,000	750.00	1,750.00	4.48	3.10	3.76
March	2,083.33	2,303.69	1,000	1,197.92	2,197.92	2.85	3.15	3.00
April	2,083.33	2,403.85	1,000	1,250.00	2,250.00	2.51	2.90	2.71
May	2,083.33	2,604.17	1,000	1,354.17	2,354.17	2.67	3.33	3.01
June	2,083.33	2,704.33	1,000	1,406.25	2,406.25	2.82	3.65	3.25
July	2,083.33	2,604.17	1,000	1,354.17	2,354.17	2.64	3.30	2.98
August	2,083.33	2,363.78	1,000	1,229.17	2,229.17	3.47	3.94	3.72
September	2,083.33	2,483.97	1,000	1,291.67	2,291.67	2.60	3.10	2.86
October	2,083.33	2,083.33	1,000	1,083.33	2,083.33	2.92	2.92	2.92
November	2,083.33	1,682.69	1,000	875.00	1,875.00	3.32	2.68	2.99
December	2,083.33	1,522.44	1,000	791.67	1,791.67	5.21	3.81	4.48
Yearly total[1]	25,000	25,000	12,000	13,000	25,000			

[1] Nearest full dollar.

Therefore, January production cost per cord is $1,416.67 ÷ 200 cd. = $7.08.

The fixed and operating costs and the cost per cord are similarly calculated for each other month as shown in columns 4, 5, 6, and 9 of table 2.

Although Modified Method 3 **cannot** be used to determine the machine rate per hour, unlike Methods 1 and 2, it **can** be used to determine total production cost for short intervals (daily, weekly, monthly, etc.), and when production cost for the interval is divided by the units produced during the interval, production cost per unit will be determined.

Examination of columns 7, 8, and 9 in table 2 shows marked differences in the cord cost calculated by each method. Cord production cost calculated by Method 1 shows the greatest range, from a low of $2.51 to $10.42. Cord cost calculated by Method 2 varied the least, from $2.68 to $4.0l. Cord production cost calculated by Modified Method 3 varied from $2.7l to $7.08. Loggers using any one of these methods (Method 1 and 2 are common) should get similarly differing costs. Since the figures vary so much, it is necessary to determine which are correct and how they should be used.

In October, when the monthly machine utilization corresponded to the yearly utilization of 65 percent, all three methods of calculation resulted in the same total cost and the same production cost per cord.

Total annual cost by each method ($25,000) divided by yearly volume (7,680 cords) results in a weighted average production cost per cord of $3.26. In bidding for timber, most operators would use the $3.26 annual average as their logging cost in calculating the bid price. However, table 2 shows that monthly skid cost per cord can vary greatly from the $3.26/cord average and thus this figure would be unreliable when used for periods of less than 1 year.

Figure 2 shows that Method 1 gives a total cost per month that is constant, and not affected by the number of Productive Hours or volume of production for any month. Total monthly machine cost calculated by Method 2 shows the widest monthly values range—it was the lowest of the three methods when machine utilization was below 65 percent and the highest when machine utilization for the month was above the yearly average utilization.

Total machine costs per month calculated by Modified Method 3 were midway between those of Method 1 and Method 2. Where the machine utilization for October is identical to the yearly machine utilization of 65 percent, total cost for all three calculation methods is the same.

Figure 3 shows that monthly per cord cost calculated by Method 1 is highest in the months of lowest machine utilization, and lowest in the months of higher than average machine utilization. Method 2 yields the lowest cost per cord with very low machine utilization and the highest cost with high machine utilization and production. Modified Method 3 gives an intermediate cost per cord.

Any of the three methods of calculation would produce the same average production cost per cord for the total yearly production, i.e., $3.26 per cord. However, if we use the $3.26 value to estimate equipment costs per cord for time periods shorter than a year, markedly different production costs per cord are obtained by the these methods (tables 1 and 2 and figs. 2 and 3). Therefore, the average yearly cost of production per cord is not recommended for estimating production costs for less than one year when production varies widely from month to month.

Method 1 has a constant total cost in every month regardless of the number of hours the machine is productively used or the volume of wood produced (table 2, fig. 2). Since operating costs **are** obviously incurred when the machine is utilized for production, equipment cost should not be constant for every month, but rather operating costs should be proportional to the productive hours.

In Method 2, unlike Method 1, all equipment costs were divided by total productive hours. In other words, equipment costs occur only when the equipment is used. The fixed costs however, should be charged whether or not the equipment is used. This method is currently used widely in North America. Method 2 is useful in making cost comparisons for two or more alternative machines. The biggest disadvantage of Method 2 is it cannot be applied when a machine is not in actual use.

Modified Method 3 best follows the true nature of cost in that the fixed cost is applied for all the scheduled hours, whether the machine works or not, while operating costs are calculated only for working hours.

By using Modified Method 3 to determine timber harvesting production costs, more realistic cost values are obtained for short time periods and under variable timber stand conditions. Use of Modified Method 3 also takes into account costs incurred by standby or when a machine is not in use.

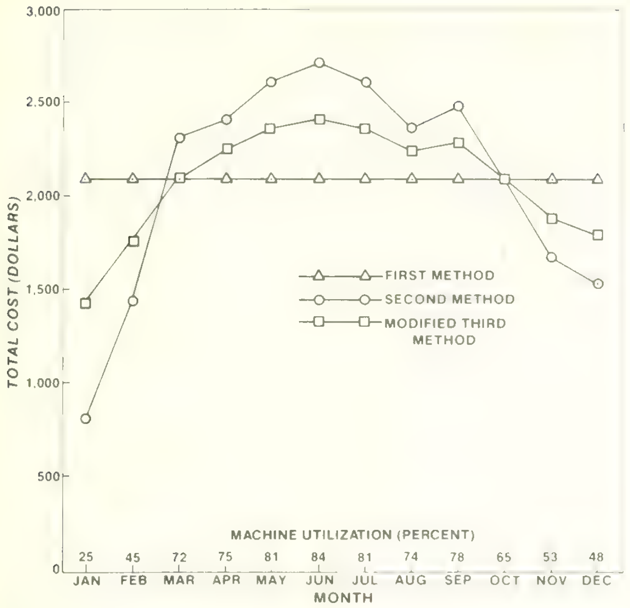

Figure 2.—*Total cost for each month as calculated by each of three methods.*

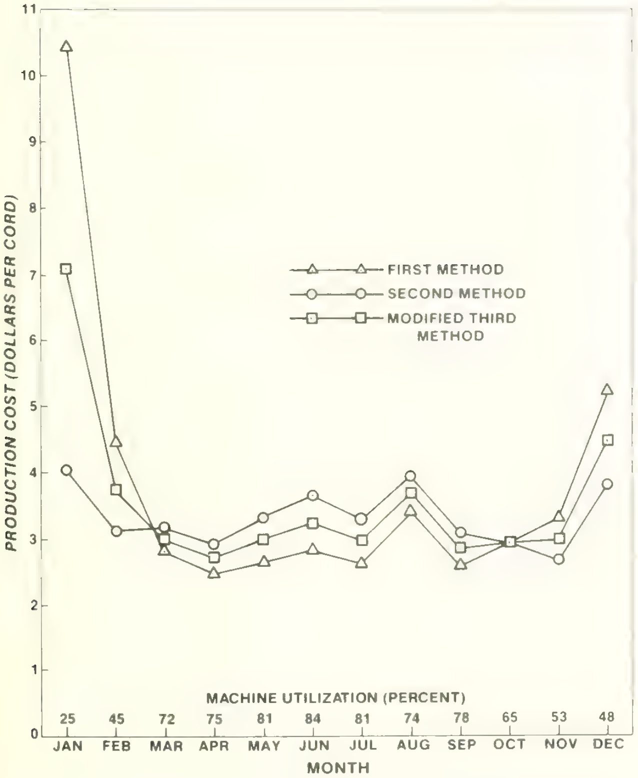

Figure 3.—*Production cost per cord for each month as calculated by each of three methods.*

Discussion and Illustration— A Logging System Case Study

When the three methods are applied to an entire logging system, similar results occur. The following assumptions are made:

A pole-sized stand of northern hardwoods is to be clearcut to create a debris-free planting site while maximizing raw-material recovery return. Wood from the present stand is to be sold as whole-tree chips. To clearcut the stand, two 5-day weeks at 10 hours a day, or 100 hours, are required. Two thousand tons of chips are produced from this stand. Hauling distance is 30 miles one way.

In the following calculations of production costs for each of the three methods, transportation costs (based on dollars per mile) are included because, though they do not affect the final comparisons of three methods, they are a part of the cost of production per ton of chips delivered at the mill.

The harvesting equipment and labor required are as follows:

Equipment:	**Labor:**
1 feller/buncher with accumulating head,	1 feller/buncher operator,
1 wheeled grapple skidder,	1 skidder operator,
1 standby wheeled grapple skidder,	1 chipper operator,
1 whole-tree chipper,	3 truck drivers,
3 truck-tractor units,	1 foreman
4 chip vans,	
1 fuel truck,	
1 maintenance van.	

The scheduled and productive hours, utilization of the equipment, and purchase price of the equipment are summarized on a yearly basis (table 3).

Table 3.—*Scheduled and productive hours for the equipment on a yearly basis*

Equipment	SH	PH	Machine Utilization (U)	Purchase price/unit
			Percent	*Dollars*
1 Feller/buncher	2,000	1,300	65	130,000
2 Skidders	2,000	1,340	67	85,000
1 Chipper	2,000	1,500	75	160,000
3 Truck units	40,000 mi/yr			45,000 ea
4 Chip vans	20,000 mi/yr			12,000 ea
1 Fuel truck	2,000	400	20	1,500
1 Maintenance vehicle	2,000	—	—	2,000

Table 4 presents the scheduled hours, productive hours, and utilization rate of the logging equipment used to complete this job. Machine rates of each piece of equipment are presented in the Appendix, page 9.

Calculation of cost of production per ton of chips at the mill:

Method 1	**Total cost**	**Cost/ton**
	------- *(dollars)*	-------
Feller/buncher ($27.97/SH × 100 SH)	2,797.00	1.40
Skidder ($27.90/SH × 100 SH)	2,790.00	1.40
Chipper ($43.50/SH × 100 SH)	4,350.00	2.17
Standby skidder ($14.95 FC/SH × 100 SH)	1,495.00	.75
Trucking ($0.73/mi × 4800 mi)	3,504.00	1.75
Chip van ($0.17/mi × 4800 mi)	816.00	.41
Fuel truck (($0.19/SH + $0.48/SH) × 100 SH)	67.00	.03
Standby maintenance vehicle ($0.27/SH × 100 SH)	27.00	.01
Total, excluding labor	15,846.00	7.92
Labor costs	5,800.00	2.90
Total, including labor	21,646.00	10.82

Table 4.—*Actual scheduled and productive hours for the equipment for the 2-week period required to clearcut the case study stand*

Equipment	SH	PH	U
			Percent
1 Feller/buncher	100	75	75
2 Skidders	100	80	80
1 Chipper	100	85	85
3 Truck units	4,800 miles		
4 Chip vans	4,800 miles		
1 Fuel truck	100	20	20
1 Maintenance vehicle	100	—	—

Labor cost: $8/SH for operator
Foreman cost: $10/SH for one foreman

Method 2	**Total cost**	**Cost/ton**
	------- *(dollars)*	-------
Feller/buncher ($43.02/PH × 75 PH)	3,226.50	1.61
Skidder ($41.64/PH × 80 PH)	3,331.20	1.67
Chipper ($58.01/PH × 85 PH)	4,930.85	2.47
Standby skidder[1]	—	—
Trucking ($0.73/mi × 4800 mi)	3,504.00	1.75
Chip van ($0.17/mi × 4800 mi)	816.00	.41
Fuel truck ($3.34/PH × 20 PH)	66.80	.03
Standby maintenance vehicle[1]	—	—
Total, excluding labor and standby vehicles	15,875.35	7.94
Total cost of standby skidder	1,495.00	.75
Total cost of maintenance vehicle	27.00	.01
Total, excluding labor	17,397.35	8.70
Labor costs	5,800.00	2.90
Total, including labor	23,197.35	11.60

Modified Method 3	**Total cost**	**Cost/ton**
	------- *(dollars)*	-------
Feller/buncher ($18.36/SH × 100) + ($14.78/PH × 75)	2,944.50	1.47
Skidder ($14.95/SH × 100) + ($19.33/PH × 80)	3,041.40	1.52
Chipper ($22.42/SH × 100) + ($28.11/PH × 85)	4,631.35	2.32
Standby skidder ($14.95/SH × 100) + (0/PH × 85)	1,495.00	.75
Trucking ($0.73/mi × 4800)	3,504.00	1.75
Chip van ($0.17/mi × 4800)	816.00	.41
Fuel truck ($0.19/SH × 100) + ($2.37/PH × 20)	66.40	.03
Maintenance vehicle	27.00	.01
Total, excluding labor	16,525.65	8.26
Labor costs	5,800.00	2.90
Total, including labor	22,325.65	11.16

Summarizing the total cost obtained by the three methods (costs for 10 days):

Method 1—
$10.82/ton × 2,000 tons = $21,640
Method 2—
$11.60/ton × 2,000 tons = $23,200
Modified Method 3—
$11.16/ton × 2,000 tons = $22,320

$1,560
$880
$680

There is a $1,560 difference in total costs between Method 1 and 2, an $880 difference between Method 2 and Modified Method 3, and a $680 difference between Method 1 and Modified Method 3 in this 10-day period. Therefore, it can be concluded that calculation of logging costs by Methods 1, 2, and Modified Method 3 have the same effect on cost differentials for a complete logging system as they have on a single piece of equipment.

CONCLUSION

Due to the intense competition of securing stumpage, loggers must accurately estimate production costs over short time intervals and for changing stand conditions in order to submit enough successful bids to be able to schedule harvest under favorable seasonal conditions insuring maximum profitability.

In this paper, three methods of equipment costing are discussed and the cost differentials resulting from Method 1, 2, and Modified Method 3, are demonstrated by calculating logging cost for a single piece of equipment and for an entire logging system. Methods 1 and 2 should be used to calculate the machine rate for equipment as long as it is clearly understood the rate is based upon either scheduled hours or productive hours. Modified Method 3 **cannot** be used to calculate an hourly machine rate, but is useful and realistic when used to calculate production costs for time periods of less than 1 year.

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[1] *Cannot be calculated by Method 2.*

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APPENDIX

MACHINE RATE

Based on yearly. Productive Hours (PH) and Scheduled Hours (SH)

I. Description

Type Track Type Feller/Buncher Model ______ H.P. 145

Purchase Cost: $ 130,000
Less: Tire Cost $ N.A.
TOTAL INITIAL INVESTMENT (P) = $ 130,000

Salvage Value (S) (20 % of P) = $ 26,000
Estimated Life (n) 5 years
Working days per year 250 days

Scheduled hours/yr (SH) 2,000 hr
Utilization (U) 65 %
Productive hours/yr (PH) 1,300 hr

Average Value of Investment (AVI) = $\frac{(P-S)(n+1)}{2n} + S$ = $ 88,400 /yr

II. Fixed Cost

Depreciation (D) = $\frac{P - S}{n}$ = $ 20,800 /yr

$\left.\begin{array}{ll}\text{Interest} & 12\ \% \\ \text{Insurance} & 3\ \% \\ \text{Taxes} & 3\ \% \end{array}\right\}$ IIT
Total = 18 % x AVI $ 88,400 /yr = $ 15,912 /yr

TOTAL FIXED COST PER PH = $\frac{D + IIT}{PH}$ = $ / 28.24 /PH /

TOTAL FIXED COST PER SH = $\frac{D + IIT}{SH}$ = $ / 18.36 /SH /

III. Operating Cost

Maintenance & Repair (50 % of $\frac{P - S}{nPH}$) = $ 8.00 /PH

Fuel Cost = 145 hp x 0.037 x $0.95 = $ 5.10 /PH

Oil & Lubrication (assume 33% of fuel cost) = $ 1.68 /PH

Tires = $\frac{1.15^{1/} \times \text{tire cost}}{\text{total tire life in hr}}$ = $ -

TOTAL OPERATING COST PER PH = $ / 14.78 /PH /

x U .65

TOTAL OPERATING COST PER SH = $ / 9.61 /SH /

1/ 15% labor cost to repair or replace tires

MACHINE RATE

Based on yearly. Productive Hours (PH) and Scheduled Hours (SH)

I. Description

Type Wheeled Grapple Skidder Model ________ H.P. 140

Purchase Cost: $ 85,000
Less: Tire Cost $ 10,000 @ $2,500 ea)
TOTAL INITIAL INVESTMENT (P) = $ 75,000

Salvage Value (S) (20 % of P) = $ 15,000
Estimated Life (n) 3 years
Working days per year 250 days

Scheduled hours/yr (SH) 2,000 hr
Utilization (U) 67 %
Productive hours/yr (PH) 1,340 hr

Average Value of Investment (AVI) = $\frac{(P-S)(n+1)}{2n} + S$ = $ 55,000 /yr

II. Fixed Cost

Depreciation (D) = $\frac{P - S}{n}$ = $ 20,000 /yr

$$\left.\begin{array}{ll}\text{Interest} & 12\ \%\\ \text{Insurance} & 3\ \%\\ \text{Taxes} & 3\ \%\end{array}\right\}\ \text{IIT}$$

Total = 18 % x AVI $ 55,000 /yr = $ 9,900 /yr

TOTAL FIXED COST PER PH = $\frac{D + IIT}{PH}$ = $ $\boxed{22.31 \text{ /PH}}$

TOTAL FIXED COST PER SH = $\frac{D + IIT}{SH}$ = $ $\boxed{14.95 \text{ /SH}}$

III. Operating Cost

Maintenance & Repair (60 % of $\frac{P - S}{nPH}$) = $ 8.96 /PH

Fuel Cost = 140 hp x 0.037 x $0.95 = $ 4.92 /PH

Oil & Lubrication (assume 33% of fuel cost) = $ 1.62 /PH

Tires = $1.15^{1/} \times \frac{\text{tire cost}}{\text{total tire life in hr}} = \frac{1.15 \times 10,000}{3,000}$ = $ 3.83

TOTAL OPERATING COST PER PH = $ $\boxed{19.33 \text{ /PH}}$

x U .67

TOTAL OPERATING COST PER SH = $ $\boxed{12.95 \text{ /SH}}$

1/ 15% labor cost to repair or replace tires

MACHINE RATE

Based on yearly. Productive Hours (PH) and Scheduled Hours (SH)

I. Description

Type Whole-tree Chipper Model ______ H.P. 380

Purchase Cost: $ 160,000
Less: Tire Cost $ 1,200 (8 tires @ $150 ea)
TOTAL INITIAL INVESTMENT (P) = $ 158,800

Salvage Value (S) (20 % of P) = $ 31,760
Estimated Life (n) 5 years
Working days per year 250 days

Scheduled hours/yr (SH) 2,000 hr
Utilization (U) 75 %
Productive hours/yr (PH) 1,500 hr

Average Value of Investment (AVI) = $\frac{(P-S)(n+1)}{2n}$ + S = $ 107,984 /yr

II. Fixed Cost

Depreciation (D) = $\frac{P - S}{n}$ = $ 25,408 /yr

Interest 12 %
Insurance 3 % } IIT
Taxes 3 %
Total = 18 % x AVI $ 107,984 /yr = $ 19,437.12 /yr

TOTAL FIXED COST PER PH = $\frac{D + IIT}{PH}$ = $ / 29.90 /PH /

TOTAL FIXED COST PER SH = $\frac{D + IIT}{SH}$ = $ / 22.42 /SH /

III. Operating Cost

Maintenance & Repair (60 % of $\frac{P - S}{nPH}$) = $ 10.16 /PH

Fuel Cost = 380 hp x 0.037 x $0.95 = $ 13.36 /PH

Oil & Lubrication (assume 33% of fuel cost) = $ 4.41 /PH

Tires = $\frac{1.15^{1/} \times \text{tire cost}}{\text{total tire life in hr}}$ = $\frac{1.15 \times 1200}{7500}$ = = $ 0.18

TOTAL OPERATING COST PER PH = $ / 28.11 /PH /

x U .75

TOTAL OPERATING COST PER SH = $ / 21.08 /SH /

1/ 15% labor cost to repair or replace tires

MACHINE RATE
Based on yearly Scheduled Hours (SH)

I. Description

Type Tractor-Truck Unit Model ______ H.P. 350

Purchase Cost: $ 45,000
Less: Tire Cost $ 1,600
TOTAL INITIAL INVESTMENT (P) = $ 43,400.00

Salvage Value (S) (20)% of P) = $ 8,680.00
Estimated Life (n) 4 yr
Working days per year ______ days
Total tire life 40,000 mi

Scheduled Hours/yr (SH) 2,000 hr
Operating Miles/yr (M) 40,000 mi/yr
Productive Hours/yr (PH) ______ hr
Average hauling distance (one way) ______ mi
Number of loads per day ______ /day

Average Value of Investment (AVI) = $\frac{(P-S)(n+1)}{2n} + S$ = $ 30,380.00 /yr

II. Fixed Cost

Depreciation (D) = $\frac{P - S}{n}$ = $ 8,680.00 /yr

Interest 12 %
Insurance 3 %
Taxes 3 %
} IIT
Total 18 % x AVI $ 30,380.00 /yr = $ 5,468.40 /yr

TOTAL FIXED COST PER MILE = $\frac{D + IIT}{M}$ = $ 0.35 /mi

TOTAL FIXED COST PER SH = $\frac{D + IIT}{SH}$ = $ 7.07 /SH

III. Operating Cost

Maintenance & Repair (50 % of $\frac{P \div S}{n \times M}$) = $ 0.11 /mi

Fuel Cost 4.53 mpg; $ 0.95 /gal = $ 0.21 /mi

Oil & Lubrication 800 mpg; $ 4.00 /gal = $ 0.01 /mi

Tires = $\frac{1.15^{1/} \text{ x tire cost}}{\text{total tire life in mi}}$ = $\frac{1.15 \times 1600}{40{,}000}$ = $ 0.05 /mi

TOTAL OPERATING COST PER MILE = $ 0.38 /mi

TOTAL OPERATING COST PER SH = $\frac{\text{Tot. op. cost/mi x M}}{SH}$ = $ 7.60 /SH

TOTAL COST PER MILE = $ 0.73 /mi

TOTAL COST PER SH $ 14.67 /SH

[1/] 15% labor cost to repair or replace tires

MACHINE RATE
Based on yearly Scheduled Hours (SH)

I. Description

Type Chip Van (25 ton cap.) Model ____ H.P. ____

Purchase Cost: $ 12,000
Less: Tire Cost $ 1,280
TOTAL INITIAL INVESTMENT (P) = $ 10,720.00

Salvage Value (S) (20)% of P) = $ 2,144.00
Estimated Life (n) 8 yr
Working days per year 250 days
Total tire life 40,000 mi

Scheduled Hours/yr (SH) 2,000 hr
Operating Miles/yr (M) 20,000 mi/yr
Productive Hours/yr (PH) ____ hr
Average hauling distance (one way) 30 mi
Number of loads per day ____ /day

Average Value of Investment (AVI) = $\frac{(P-S)(n+1)}{2n} + S$ = $ 6,968.00 /yr

II. Fixed Cost

Depreciation (D) = $\frac{P - S}{n}$ = $ 1,072.00 /yr

Interest 12 %
Insurance 3 % IIT
Taxes 3 %
Total 18 % x AVI $ 6,968.00 /yr = $ 1,254.24 /yr

TOTAL FIXED COST PER MILE = $\frac{D + IIT}{M}$ = $ 0.12 /mi

TOTAL FIXED COST PER SH = $\frac{D + IIT}{SH}$ = $ 1.16 /SH

III. Operating Cost

Maintenance & Repair (10 % of $\frac{P \div S}{nxM}$) = $ 0.005 /mi

Fuel Cost ____ mpg; $ ____ /gal = $ - /mi

Oil & Lubrication ____ mpg; $ ____ /gal = $ 0.001 /mi

Tires = $\frac{1.15^{1/} \text{ x tire cost}}{\text{total tire life in mi}}$ = = $ 0.04 /mi

TOTAL OPERATING COST PER MILE = $ 0.046 or 0.05/mi

TOTAL OPERATING COST PER SH = $\frac{\text{Tot. op. cost/mi x M}}{SH}$ = $ 0.46 /SH

TOTAL COST PER MILE = $ 0.17 /mi

TOTAL COST PER SH $ 1.62 /SH

1/ 15% labor cost to repair or replace tires

MACHINE RATE
Based on yearly Scheduled Hours (SH)

I. Description

Type Maintenance Truck Model ____ H.P. ____

Purchase Cost: $ 1,760
Less: Tire Cost $ ____
TOTAL INITIAL INVESTMENT (P) = $ 1,760.00

Salvage Value (S) (0)% of P) = $ -
Estimated Life (n) 5 yr
Working days per year 250 days
Total tire life 20,000 mi

Scheduled Hours/yr (SH) 2,000 hr
Operating Miles/yr (M) ____ mi/yr
Productive Hours/yr (PH) ____ hr
Average hauling distance (one way) ____ mi
Number of loads per day ____ /day

Average Value of Investment (AVI) = $\frac{(P-S)(n+1)}{2n} + S$ = $ 1,056.00 /yr

II. Fixed Cost

Depreciation (D) = $\frac{P - S}{n}$ = $ 352.00 /yr

Interest 12 %
Insurance 3 %
Taxes 3 %
Total 18 % x AVI $ 1,056.00 /yr
IIT = $ 190.08 /yr

TOTAL FIXED COST PER MILE = $\frac{D + IIT}{M}$ = $ / - /mi /

TOTAL FIXED COST PER SH = $\frac{D + IIT}{SH}$ = $ / 0.27 /SH /

III. Operating Cost

Maintenance & Repair (____% of $\frac{P \div S}{n \times M}$) = $ ____ /mi

Fuel Cost ____ mpg; $ ____ /gal = $ ____ /mi

Oil & Lubrication ____ mpg; $ ____ /gal = $ ____ /mi

Tires = $\frac{1.15^{1/} \text{ x tire cost}}{\text{total tire life in mi}}$ = = $ ____ /mi

TOTAL OPERATING COST PER MILE = $ / ____ /mi /

TOTAL OPERATING COST PER SH = $\frac{\text{Tot. op. cost/mi x M}}{SH}$ = $ / ____ /SH /

TOTAL COST PER MILE = $ / ____ /mi /

TOTAL COST PER SH $ / ____ /SH /

1/ 15% labor cost to repair or replace tires

MACHINE RATE
Based on yearly Scheduled Hours (SH)

I. Description

Type Fuel Truck Model H.P.

Purchase Cost: $ 1,500
Less: Tire Cost $ 240
TOTAL INITIAL INVESTMENT (P) = $ 1,260.00

Salvage Value (S) (0)% of P) = $ -
Estimated Life (n) 5 yr
Working days per year 250 days
Total tire life 20,000 mi

Scheduled Hours/yr (SH) 2,000 hr
Operating Miles/yr (M) 5,000 mi/yr
Productive Hours/yr (PH) 400 hr
Average hauling distance (one way) mi
Number of loads per day /day

Average Value of Investment (AVI) = $\frac{(P-S)(n+1)}{2n} + S$ = $ 756.00 /yr

II. Fixed Cost

Depreciation (D) = $\frac{P - S}{n}$ = $ 252.00 /yr

Interest 12 %
Insurance 3 %
Taxes 3 %
} IIT
Total 18 % x AVI $ 756.00 /yr = $ 136.08 /yr

TOTAL FIXED COST PER MILE = $\frac{D + IIT}{M}$ = $ / 0.08 /mi /

TOTAL FIXED COST PER SH = $\frac{D + IIT}{SH}$ = $ / 0.19 /SH /

TOTAL FIXED COST PER PH = $\frac{D + IIT}{PH}$ = $ / 0.97 /PH /

III. Operating Cost

Maintenance & Repair (100 % of $\frac{P \div S}{n \times M}$) = $ 0.05 /mi

Fuel Cost 8 mpg; $ 0.95 /gal = $ 0.12 /mi

Oil & Lubrication 400 mpg; $ 4.00 /gal = $ 0.01 /mi

Tires = $\frac{1.15^{1/} \text{ x tire cost}}{\text{total tire life in mi}} = \frac{1.15\ (240)}{20{,}000}$ = $ 0.01 /mi

TOTAL OPERATING COST PER MILE = $ / 0.19 /mi /

TOTAL OPERATING COST PER SH = $\frac{\text{Tot. op. cost/mi x M}}{SH}$ = $ / 0.48 /SH /

TOTAL OPERATING COST PER PH = $\frac{\text{Tot. op. cost/mi x M}}{PH} = \frac{.19 \times 5000}{400}$ = $ / 2.37 /PH /

TOTAL COST PER MILE = $ / 0.27 /mi /

TOTAL COST PER SH = $ / 0.67 /SH /
TOTAL COST PER PH = $ / 3.34 /PH /

1/ 15% labor cost to repair or replace tires

Miyata, Edwin S., and Helmuth M. Steinhilb.

1981. Logging system cost analysis: comparison of methods used. U.S. Department of Agriculture Forest Service, Research Paper NC-208, 15 p. U.S. Department of Agriculture Forest Service, North Central Forest Experiment Station, St. Paul, Minnesota.

Several methods of calculating machine rates, costs, and productivity for both single pieces of logging equipment and for logging systems are discussed.

KEY WORDS: Harvesting, productivity, machine rates, scheduled hours, productive hours, economics.

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A Simulated Inventory Update:

Wisconsin's 1979 Timber Resource

Gerhard K. Raile and W. Brad Smith

FOREWORD

This report presents Wisconsin's timber resource in 1979 as updated by the Forest Resources Evaluation Program (FREP). Current forest areas, timber volumes, growth, mortality, and removals are estimated and compared with the 1956 and 1968 surveys.

There are limits to the FREP's abilities. Although the system predicts mortality it has no mechanism for handling recent catastrophic changes in Wisconsin's forests. But the FREP model is still being developed and improved. This first attempt at updating a State inventory using FREP is not intended to take the place of a re-survey of Wisconsin; a new State inventory is scheduled to begin in 1981.

The following persons assisted in the Wisconsin update:

North Central Forest Experiment Station personnel:

Pamela Jakes, Associate Resource Analyst
Joan Stelman, Statistical Assistant
Patrick Peine, Statistical Assistant
Susan Krueger, Statistical Clerk

Wisconsin Department of Natural Resources personnel.

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A SIMULATED INVENTORY UPDATE: WISCONSIN'S 1979 TIMBER RESOURCES

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and
W. Brad Smith
Associate Mensurationists

BACKGROUND

Current facts about the Nation's forest resources such as area, timber volume, biomass, ownership, and prospective supply and demand are essential in the formation of management policies and practices. The Forest and Rangeland Renewable Resources Planning Act of 1974 specifically requires the Forest Service to make and keep current a comprehensive inventory and analysis of renewable forest and rangeland resources.

In the past, resource evaluation techniques have provided forest resource information that was often months, and, unfortunately, sometimes years, old before it was widely available for use. To meet the need for more current forest resource information, the North Central Forest Experiment Station (NCFES) began the Forest Resources Evaluation Program (FREP) in 1975.[1]

When fully developed, FREP will be a computerized resource evaluation system capable of evaluating economic, ecologic-environmental, and sociocultural aspects of timber, wildlife, recreation, water, forage, and special uses (Lundgren and Essex 1979). In an evaluation of FREP as an inventory tool, the 1968 Wisconsin forest survey (Spencer and Thorne 1972) was updated to the year 1979.

METHOD

A tree growth projection subsystem of FREP was used to update the 1968 Wisconsin survey to 1979. This subsystem of FREP is a distance-independent individual tree growth simulator (Munro 1974) of modular design. It consists of an executive program and a series of functional subroutines. Updated tree lists are generated through the simulation of growth and mortality. Management routines are available to prescribe and carry out silvicultural activities. A brief overview of FREP is available in "FREP 78: The Updated Tree Growth Projection System" (Hahn *et al.* 1979).

The Wisconsin update was conducted without the use of new field or photo-interpretive work. New inventory data from the Chequamegon (1976) and the Nicolet (1975) National Forests were used as a starting point for updating the National Forest data because the 1968 Wisconsin survey included National Forest data adjusted from 1967 and 1964 inventories to 1968. The term "update," as it is used here, is an estimate of current forest statistics derived by modeling the dynamic change in a forest from a known time in the past. The four major components that define this change are growth, mortality, regeneration, and removals.

Growth and Mortality

Growth and mortality functions[2] were calibrated and validated with data from throughout the Lake

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[1] *The FREP growth projection system was developed jointly by a team of researchers at the North Central Forest Experiment Station. Included were Rolfe A. Leary, Jerold T. Hahn, Roland G. Buchman, Gary Brand (working on a cooperative agreement through the University of Minnesota), Brad Smith, Margaret Holdaway, Jerrilyn LaVarre Thompson, and Linda Christensen.*

[2] *The derivations of the FREP growth functions (Hahn and Leary 1979, Leary and Holdaway 1979, Holdaway* et al. *1979) and mortality functions (Buchman 1979) are too long to present here.*

States (Christensen *et al.* 1979). Test projections made in Wisconsin over a wide range of forest conditions produced reliable results when compared with the previous Wisconsin data (Leary *et al.* 1979).

Regeneration

Although FREP regeneration routines[3] for the Lake States had not been developed by the time of the update, this did not significantly affect the projection. Most trees that became established on harvested land during the 11-year update period would not have grown to merchantable size. Tables showing number of trees in this report include trees below the 6-inch diameter class. Because there was no regeneration, these are trees that were in the original 1.0-to 4.9-inch sample and did not grow into the 6-inch diameter class.

Removals

Timber removals for the update fall into two categories, product and nonproduct. Timber removals for products was estimated using data collected by North Central's Renewable Resources Evaluation Project. Project staff collect pulpwood data annually, saw log data every 2 to 5 years, veneer log data every 2 years, and data on total removals (including poles, pilings, fuelwood, and an estimate of nonproduct removals) at the time of each State forest survey. For the update, pulpwood, saw log, and veneer data were compiled for each available year during the update period. Data for missing years were estimated by analyzing trends in wood consumption for the State (U.S. Department of Commerce, 1967-1978).

It was not possible to make an annual estimate of nonproduct removals — the timber removals from cultural operations and changes in land use. But estimates of removals caused only by changes in land use may be made by estimating the volume by forest type occurring on the commercial forest area lost since 1968. The area of commercial forest land in 1979 was assumed to be the same as a 1977 estimate made by the North Central Forest Experiment Station and the Wisconsin Department of Natural Resources (USDA Forest Service 1978). Area expansion factors used in the 1968 survey were adjusted for each forest type, so that the final updated acreage would coincide by type with the 1977 estimate of commercial forest area. Because stand-size class was determined by the projection, acres by size class will not agree with the 1977 estimate.

The current version of FREP has no provision for simulating actual removals. The system was modified to set removals during the update to the levels estimated above. Computerized Lake States guides (Brand 1979) were used in the projection system to select a subset of plots that were eligible for silvicultural treatment during the update period. Lake States guides were used in lieu of detailed information on Wisconsin timber management strategies. The FREP projection system was then modified by adding a special removals analysis algorithm. Each of the eligible plots was scanned by the algorithm to determine whether it would be cut. The volume from cut plots was accumulated until the estimated volume of growing-stock removals by species was reached.

Information on update costs and data requirements are outlined in "FREP: Application of the Tree Growth Projection System for Inventory" (Smith and Raile 1979).

UPDATE RESULTS

Area Trends

The total commercial forest area in Wisconsin has declined 3 percent since 1956 and will probably continue to decline in the near future. It is estimated that commercial forest land now accounts for 42 percent of all land in the State.

The aspen-birch[4] and maple-beech-birch forest types make up 29 and 25 percent of the commercial forest area, respectively. These types have dominated the forest area of Wisconsin as far back as the first official survey in 1936, although the percentage of northern hardwoods has been increasing while aspen-birch has been declining. The natural succession of aspen-birch stands to maple-beech-birch stands accounts for much of this shift. With the exception of aspen-birch, all hardwood types show modest increases in acreage during the update period (table 1).

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[3] *Buchman, R. G. Lake States tree recruitment for the north central generalized forest tree growth projection system. Unpublished Station study FS-NC-4252(78-04), on file at North Central Forest Experiment Station, St. Paul, Minnesota.*

[4] *In the 1956 survey the aspen and birch forest types were combined, so the 1968 and 1979 aspen and birch types were added together for comparison.*

Table 1. — *Area of commercial forest land by forest type, Wisconsin, 1956, 1968, and updated 1979*

Forest type	**1956**		**1968**		**1979**	
	Thousand acres	*Percent of total*	*Thousand acres*	*Percent of total*	*Thousand acres*	*Percent of total*
Jack pine	687	5	727	5	717	5
Red pine	146	1	310	2	332	2
White pine	172	1	178	2	159	1
Black spruce	207	1	236	2	215	1
Spruce-fir	352	2	628	4	601	4
Northern white-cedar	207	1	302	2	308	2
Tamarack	131	1	222	2	223	2
Oak-hickory	2,461	17	2,665	18	2,681	19
Lowland hardwoods	840	6	1,158	8	1,163	8
Northern hardwoods	2,634	18	3,522	24	3,551	25
Aspen-birch	4,684	31	4,219	29	4,202	29
Nonstocked	2347	16	370	3	326	2
All types	14,868	100	14,537	100	14,478	100

Table 2. — *Commercial forest land areas by stand-size class, Wisconsin, 1956, 1968, and updated 1979*

Stand-size class	**1956**		**1968**		**1979**	
	Thousand acres	*Percent of total*	*Thousand acres*	*Percent of total*	*Thousand acres*	*Percent of total*
Sawtimber	2,054	14	3,098	21	3,235	22
Poletimber	4,822	32	6,580	45	6,664	46
Seedling-Sapling	5,645	38	4,489	31	4,253	30
Nonstocked	2,347	16	370	3	326	2
All classes	14,868	100	14,537	100	14,478	100

The area of jack pine and white pine forest types has declined since 1968 — an apparent reversal of the trend noted between the 1956 and 1968 forest surveys. The red pine type, however, has shown a 127 percent increase since 1956. Much of this increase is the result of extensive plantings of red pine and the conversion of white pine sites to red pine because of blister rust. In the update, black spruce and spruce-fir types declined; northern white-cedar and tamarack types increased slightly.

Poletimber and sawtimber stands have shown a steady increase in area since the 1956 survey, but nonstocked and seedling-sapling stands have decreased. The 1979 update estimates 9.9 million acres of combined sawtimber and poletimber stands compared to 9.7 million acres in 1968 and 6.9 million acres in 1956. The area of nonstocked forest land has probably declined since the 1968 survey (table 2) although definition and procedural changes after the 1956 survey hinder interpretation of the decrease. A more detailed breakdown of the 1979 area data is given in tables 4 and 5.

Volume

Despite the decline in commercial forest area between 1968 and 1979, total growing-stock volume increased 16 percent — from 11 billion cubic feet in 1968 to 12.7 billion cubic feet in 1979 (table 3). Softwood growing-stock volume increased 36 percent and hardwood volume increased 10 percent. Softwoods continued to gain, jumping from 20 percent of all growing-stock volume in 1956 to an estimated 26 percent in 1979.

The maturing of Wisconsin's second-growth forests is shown by the upward trend in the area of sawtimber stands and the increase in sawtimber volume. Sawtimber volume has risen 44 percent since the 1968 survey and has almost doubled since the 1956 survey. Traditionally, hardwoods have been dominant, but softwoods have begun to make up an increasing percentage of the total sawtimber volume. They are now estimated to account for 33 percent of the sawtimber volume (table 3).

Table 3. — *Growing-stock and sawtimber volumes for Wisconsin, 1956, 1968, and updated 1979*

Species	**Growing-stock volume**						**Sawtimber volume**					
	1956		**1968**		**1979**		**1956**		**1968**		**1979**	
	Mil.cu.ft.	Percent	Mil.cu.ft.	Percent	Mil.cu.ft.	Percent	Mil.bd.ft.	Percent	Mil.bd.ft.	Percent	Mil.bd.ft.	Percent
Softwoods	1,670	20	2,475	23	3,368	26	4,783	30	6,497	30	10,318	33
Hardwoods	6,768	80	8,521	77	9,363	74	11,049	70	15,259	70	21,052	67
Total	8,438	100	10,996	100	12,731	100	15,832	100	21,756	100	31,370	100

Further evidence of the effects of Wisconsin's maturing forests is the increase in growing-stock volume per acre in all major forest types (fig. 1). A detailed breakdown of all numbers of trees and volume data is given in tables 6 through 12.

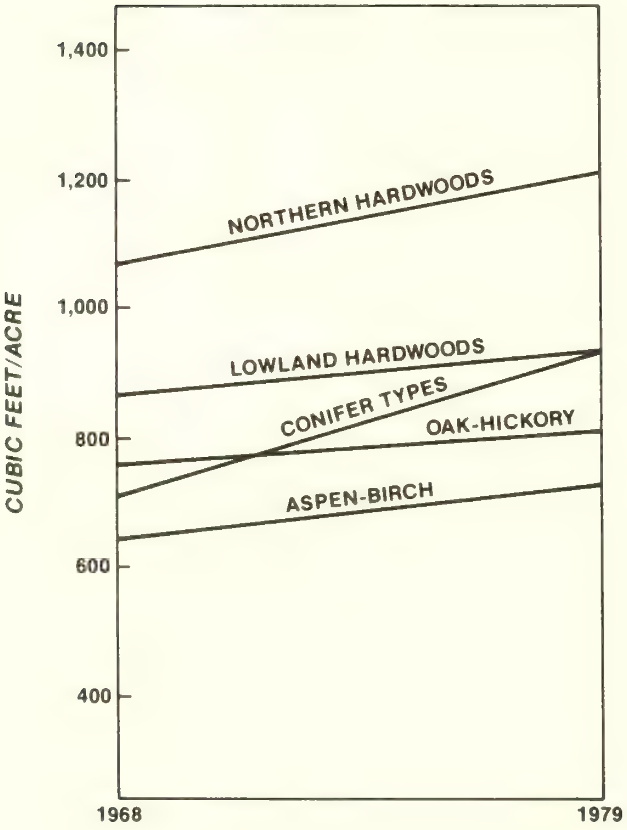

Figure 1. *Growing-stock volume trends for major types and type groups in Wisconsin, 1968 and updated 1979.*

Growth and Mortality

FREP's projected (1968-1979) average net annual growth of 346,500 cubic feet is an average annual growth rate of 3.1 percent. Net growth consists of survivor growth, ingrowth, growth on ingrowth, growth on removals, and growth on trees that die, minus mortality (tables 26-33):

Components of growth	**Thousand cubic feet**	**Percent of total net growth**
Survivor growth	312,326	90
Ingrowth	76,903	22
Growth on ingrowth	24,035	7
Growth on removals	33,525	10
Growth on mortality	24,192	7
Mortality	−124,425	−36
Total net growth	346,557	100

This projected net growth averages 24 cubic feet per acre per year for the update period compared with 34 cubic feet for 1967 and 20 cubic feet for 1955.[5]

Because there was no regeneration model in FREP at the time of this update and the original data only included d.b.h. measurements for trees 1 inch and larger, the ingrowth volumes may be slightly low over the 11-year period. The effects of no regeneration can be seen by looking at the original and current distributions of trees by diameter class in tables 7 and 8. The distributions by diameter class of mortality and removal trees are given in tables 10 and 11.

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[5] *This is the unadjusted 1955 net growth rate. The adjusted 1955 rate published in the 1968 survey is 26 cubic feet per acre per year.*

The predicted average annual growing-stock mortality is 124.4 million cubic feet — 1.1 percent of the original inventory or 8.6 cubic feet per acre per year. The 1967 estimate of 4.1 cubic feet per acre per year is about half this rate, and the unadjusted 1955 mortality is 11.4 cubic feet per acre per year. The projected mortality rates by forest type are as follows:

Forest type	Cubic feet/ acre/year	Projected mortality as a percent of inventory
Jack pine	3.4	0.66
Red pine	4.3	.54
White pine	6.8	.51
Black spruce	5.1	1.36
Balsam fir-white spruce	10.8	1.43
Northern white-cedar	10.7	1.10
Tamarack	6.7	1.58
Oak-hickory	7.1	.92
Elm-ash-cottonwood	8.9	1.05
Maple-beech-birch	10.4	.97
Aspen	10.5	1.72
Birch	5.0	.69
All types	8.6	1.11

All the components of net growth are summarized for both cubic feet and board feet in tables 26-33. These tables give both periodic and average annual values by forest type and species group.

Removals

Growing-stock removals for products have increased during the past 11 years (fig. 2), except for slumps in 1972 and 1975. The 1972 decline was due to a drop in products other than pulpwood — a pattern that continued through the early 1970's. In 1975, the recession reduced all domestic production. The estimated average annual removals of growing stock for products was 193 million cubic feet from 1968 through 1978, increasing an average of 2.5 percent per year. At this rate, the predicted removal of growing stock for products for 1979 is about 214 million cubic feet.

The tables of current statistics in the appendix show growing-stock removals for products on the 1979 commercial forest land base, but inadequate data prevented tracking other removals on a yearly basis. Removals from land use change are taken into account by an adjustment in area expansion factors and therefore do not appear in the tables.

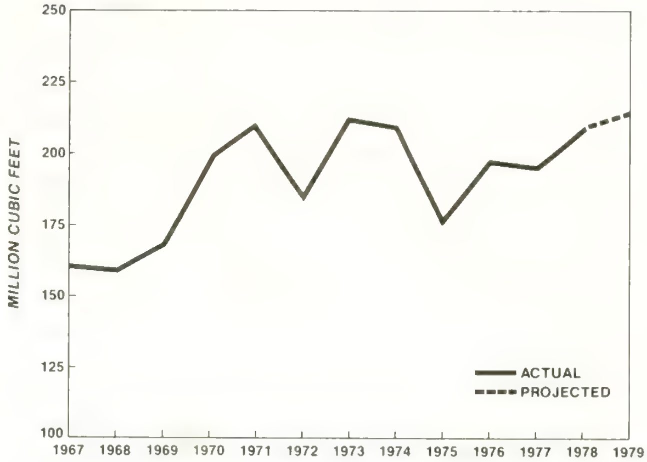

Figure 2. — *Estimated growing-stock removals for products in Wisconsin, 1967-1979.*

Biomass

Many of the equations for calculating individual tree biomass by species (Young 1976) could not be used in creating tables 34 and 35 because (1) usable equations are not available for many species in the State; (2) many equations use variables not available in the 1968 Wisconsin inventory data; and (3) some equations give unreliable estimates of biomass for large trees.

The following method was developed for estimating biomass in Wisconsin: first, the estimated net cubic foot volumes were converted to green tons by using weight conversion factors for each species (Markwardt 1930). Then, the weight of the bole bark was computed using bark correction factors for individual species and an average value of 37 pounds per cubic foot. Tops and limbs for trees 5 inches d.b.h. and over were estimated as a percent of gross bole volume. Above ground green tons for trees under 5 inches were computed from a regression equation fit to Young's tree weight table (Young *et al.* 1976). This regression equation uses d.b.h. to estimate total aboveground biomass as 80 percent of the above and belowground biomass.

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APPENDIX

DEFINITION OF TERMS

Land-Use Classes

Gross area.—The entire area of land and water as determined by the Bureau of Census, 1960.

Land area.—The area of dry land and land temporarily or partially covered by water such as marshes, swamps, flood plains, streams, sloughs, and estuaries. Canals less than 1/8-mile wide, and lakes, reservoirs, and ponds smaller than 40 acres are included as land area. These figures are from the Bureau of Census, 1960.

Forest land.—Land at least 16.7 percent stocked by forest trees of any size, or formerly having such tree cover, and not currently developed for nonforest use. Includes afforested areas. The minimum forest area classified was 1 acre. Roadside, streamside, and shelterbelt strips of timber must have a crown width of at least 120 feet to qualify as forest land. Unimproved roads and trails, streams, and clearings in forest areas were classed as forest if less than 120 feet in width.

Commercial forest land.—Forest land that is producing or is capable of producing crops of industrial wood and that is not withdrawn from timber utilization by statute or administrative regulation. This includes areas suitable for management to grow crops of industrial wood generally of a site quality capable of producing in excess of 20 cubic feet per acre of annual growth. This includes both inaccessible and inoperable areas.

Noncommercial forest land. —(a) **Unproductive** forest land incapable of yielding crops of industrial wood because of adverse site conditions, (b) **Productive-reserved**—forest land withdrawn from commercial timber use through statute or administrative regulation, or exclusively used for Christmas tree production.

Nonforest land.—and that has never supported forests, and land formerly forested where forest use is precluded by development for nonforest uses, such as cropland, improved pasture, residential areas, and city parks. Also includes improved roads and adjoining rights-of-way, powerline clearings, and certain areas of water classified by the Bureau of Census as land. Unimproved roads, streams, canals, and nonforest strips in forest areas must be more than 120 feet wide, and clearings in forested areas must be more than 1 acre in size, to qualify as nonforest land.

Tree Classes

All live trees.—Growing-stock, rough and rotten trees 1 inch d.b.h. and larger.

Growing-stock trees.—All live trees of commercial species except rough and rotten trees.

Desirable trees.—Growing-stock trees having no serious defects in quality limiting present or prospective use, and of relatively high vigor and containing no pathogens that may result in death or serious deterioration before rotation age. These are trees that would be favored by forest managers in silvicultural operations.

Acceptable trees.—Trees meeting the standards for growing stock but not qualifying as desirable trees.

Sawtimber trees.—Growing-stock trees of commercial species containing at least a 12-foot saw log or two noncontiguous saw logs, each 8 feet or longer. At least 33 percent of the gross volme of the tree must be sound wood. Softwoods must be at least 9 inches d.b.h. and hardwoods at least 11 inches.

Poletimber trees.—Growing-stock trees of commercial species at least 5 inches d.b.h. but smaller than sawtimber size and of good form and vigor.

Saplings.—Live trees of commercial species 1 to 5 inches d.b.h. and of good form and vigor.

Seedlings.—Live trees of commercial species less than 1 inch d.b.h. that are expected to survive according to regional standards (examples of seedlings not expected to survive are those that are diseased or heavily damaged by logging, browsing, or fire). Only softwood seedlings 6 inches and hardwood seedlings over 1 foot in height are counted.

Rotten trees.—Live trees (any size) of commercial species that do not contain a merchantable 12-foot saw log or two noncontiguous 8-foot or longer saw logs, now or prospectively, because of rot (that is, when more than 50 percent of the cull volume of the tree is rotten).

Rough trees.—Live trees that do not contain at least one merchantable 12-foot saw log or two noncontiguous 8-foot or longer saw logs, now or prospectively, because of roughness and poor form, as well as all live noncommercial species.

Short-log (rough) trees.—Sawtimber-sized trees of commercial species that contain at least one merchantable 8- to 11-foot saw log but not a 12-foot saw log.

Stocking

The degree of utilization of land by trees as measured in terms of basal area and/or the number of trees in a stand compared to the basal area and/or number of trees required to utilize fully the growth potential of the land.

A stocking percent of 100 indicates full utilization of the site and is equivalent to 80 square feet of basal area per acre in trees 5 inches d.b.h. and larger. In a stand of trees less than 5 inches d.b.h., a stocking percent of 100 would indicate that the present number of trees is sufficient to produce 80 square feet of basal area per acre when the trees do reach 5 inches d.b.h.

Stocking of all live trees, growing-stock trees, and desirable trees are recorded separately and stands are grouped into the following stocking classes.

Stocking Classes

Overstocked stands.—Stands in which stocking of trees is 133 percent or more.

Fully-stocked stands.—Stands in which stocking of trees is from 100 to 133 percent.

Medium-stocked stands.—Stands in which stocking of trees is from 60 to 100 percent.

Poorly-stocked stands.—Stands in which stocking of trees is from 16.7 to 60 percent.

Nonstocked areas.—Commercial forest land on which stocking of trees is less than 16.7 percent.

Stand-size Classes

Stand.—A growth of trees on a minimum of 1 acre of forest land that is stocked by forest trees of any size.

Sawtimber stands.—Stands at least 16.7 percent stocked with growing-stock trees, with half or more of this stocking in sawtimber or poletimber trees and with sawtimber stocking at least equal to poletimber stocking.

Poletimber stands.—Stands at least 16.7 percent stocked with growing-stock trees, and with half or more of this stocking in sawtimber and/or poletimber trees and with poletimber stocking exceeding that of sawtimber.

Sapling-seedling stands.—Stands at least 16.7 percent stocked with growing-stock trees and with saplings and/or seedlings comprising more than half of this stocking.

Nonstocked areas.—Commercial forest land on which stocking of growing-stock trees is less than 16.7 percent.

Other Classifications

Site index.—An expression of forest site quality based on the height of a free-growing dominant or codominant tree of a representative species in the forest type at age 50.

Site classes.—A classification of forest land in terms of inherent capacity to grow crops of industrial wood expressed in cubic-foot growth per acre per year.

Stand-age.—Age of the main stand. Main stand refers to trees of the dominant forest type and stand-size class.

Basal area.—The area in square feet of the cross section at breast height of a single tree. When the basal area of all the trees in a stand are summed, the result is usually expressed as square feet of basal area per acre.

Forest Types

A classification of forest land based upon the species forming a plurality of live-tree stocking. Major forest types in Wisconsin are:

Jack pine.—Forests in which pine species comprise a plurality of the live-tree stocking, with jack pine the most common. (Common associates include aspen, white birch, maple, balsam fir, cherry, and oak.)

Red pine.—Forests in which pine species comprise a plurality of the live-tree stocking, with red pine the most common. (Common associates include aspen, white birch, maple, balsam fir, and red oak).

White pine.—Forests in which pine species comprise a plurality of the live-tree stocking, with eastern white pine the most common. (Common associates include hemlock, aspen, white and yellow birch, and maple.)

Balsam fir-white spruce.—Forests in which balsam fir or white spruce, singly or in combination, comprise a plurality of the live-tree stocking. (Common associates include white-cedar, black spruce, tamarack, maple, birch, hemlock, and aspen.)

Black spruce.—Forests in which swamp conifers (black spruce, tamarack, and northern white-cedar) comprise a plurality of the live-tree stocking, with black spruce the most common.

Northern white-cedar.—Forests in which swamp conifers comprise a plurality of live-tree stocking, with northern white-cedar the most common.

Tamarack.—Forests in which swamp conifers comprise a plurality of live-tree stocking, with tamarack the most common.

Oak-hickory.—Forests in which upland oaks or hickories, singly or in combination, comprise a plurality of the live-tree stocking. (Common associates include aspen, cherry, balsam fir, elm, maple, and white birch.)

Elm-ash-cottonwood.—Forests in which lowland elm, ash, or cottonwood, singly or in combination, comprise a plurality of the live-tree stocking. (Common associates include maple, basswood, and river birch.) These forests may be subtyped cottonwood when it is the most common species.

Maple-beech-birch. — Forests in which maple, beech, yellow birch, or upland elm, singly or in combination, comprise a plurality of the live-tree stocking. (Common associates include hemlock, elm, basswood, white pine, and white and yellow birch.) Locally this type is called "northern hardwoods."

Aspen.—Forests in which a mixture of quaking or bigtooth aspen or balsam poplar, singly or in combination, comprise a plurality of the live-tree stocking. (Common associates include maple, white birch, balsam fir, red and northern pin oak, and cherry.)

Paper birch.—Forests in which paper birch comprises a plurality of the live-tree stocking. (Common associates include aspen, maple, balsam fir, red and northern pin oak, and cherry.)

Timber Volume

Volume of growing stock.—The volume of sound wood in the bole of growing-stock trees 5 inches d.b.h. and over, from a 1-foot stump to a minimum of 4-inch top diameter outside bark, or to the point where the central stem breaks into limbs. Growing-stock volumes are shown in cubic feet. Conversion to standard cords may be accomplished by a factor of 79 cubic feet per solid wood cord.

Volume of sawtimber.—Net volume of the saw log portion of live sawtimber trees in board feet, International 1/4-inch rule, from stump to a minimum 7 inches top diameter outside bark for softwoods and 9 inches for hardwoods.

Upper stem portion.—That part of the bole of sawtimber trees above the merchantable sawtimber top to a minimum top diameter of 4 inches outside bark or to the point where the central stem breaks into limbs.

Growth and Mortality

Net volume growth of growing stock.—The annual change in volume of sound wood in live growing-stock and sawtimber trees and total volume of trees entering these classes through ingrowth, less volume losses resulting from natural causes.

Net annual growth of sawtimber.—The annual change in volume of live sawtimber trees and the total volume of trees reaching sawtimber size, less volume losses resulting from natural causes.

Mortality of growing stock.—The volume of sound wood in growing-stock trees dying annually from natural causes. Natural causes include fire, insects, disease, animal damage, weather, and suppression.

Mortality of sawtimber.—The net board-foot volume of sawtimber trees dying annually from natural causes.

Timber Removals

Timber removals from growing stock.—The volume of sound wood in growing-stock trees removed annually for forest products (including roundwood products and logging residues) and for other removals. Roundwood products are logs, bolts, or other round sections cut and used from trees. Logging residues are the unused portions of cut trees plus unused trees killed by logging. Other removals are growing-stock trees removed but not utilized for products or trees left standing but "removed" from the commercial forest land classification by land use change — examples are removals from cultural operations such as timber stand improvement work, land clearing, and changes in land use.

Timber removals from sawtimber.—The net board-foot volume of live sawtimber trees removed for forest products annually (including roundwood products and logging residues) and for other removals.

Timber products output.—All timber products cut from roundwood, and byproducts of wood manufacturing plants. Roundwood products include logs, bolts, or other round sections cut from growing-stock trees, cull trees, salvable dead trees, trees on nonforest land, noncommercial species, sapling-size trees, and limbwood. Byproducts from primary manufacturing plants include slabs, edgings, trimmings, miscuts, sawdust, shavings, veneer cores and clippings, and pulpmill screenings that are used as pulpwood chips or other products.

Plant byproducts.—Wood products, such as pulpwood chips, obtained incidental to production of other manufactured products. Plant residues.—Wood materials from manufacturing plants not utilized for some product.

PRINCIPAL TREE SPECIES IN WISCONSIN

Softwoods:	
White and red pines	
Eastern white pine	*Pinus strobus*
Red pine	*Pinus resinosa*
Jack pine	*Pinus banksiana*
Spruce and balsam fir:	
White spruce	*Picea glauca*
Black spruce	*Picea mariana*
Balsam fir	*Abies balsamea*
Eastern hemlock	*Tsuga canadensis*
Other eastern softwoods:	
Tamarack	*Larix laricina*
Northern white-cedar	*Thuja occidentalis*
Other softwoods:	
Scotch pine	*Pinus sylvestris*
Eastern redcedar	*Juniperus virginiana*
Norway spruce	*Picea abies*
Hardwoods:	
White oaks:	
White oak	*Quercus alba*
Bur oak	*Quercus macrocarpa*
Chinkapin oak	*Quercus muehlenbergii*
Swamp white oak	*Quercus bicolor*
Select red oaks:	
Northern red oak	*Quercus rubra*
Other red oaks:	
Black oak	*Quercus velutina*
Northern pin oak	*Quercus ellipsoidalis*
Hickory:	
Bitternut hickory	*Carya cordiformis*
Shagbark hickory	*Carya ovata*
Yellow birch	*Betula alleghaniensis*
Hard maple:	
Black maple	*Acer nigrum*
Sugar maple	*Acer saccharum*
Soft maple:	
Red maple	*Acer rubrum*
Silver maple	*Acer saccharinum*
American beech	*Fagus grandifolia*
Ash:	
Black ash	*Fraxinus nigra*
White ash	*Fraxinus americana*
Green ash	*Fraxinus pennsylvanica*
Cottonwood and aspen:	
Balsam poplar	*Populus balsamifera*
Bigtooth aspen	*Populus grandidentata*
Quaking aspen	*Populus tremuloides*
Eastern cottonwood	*Populus deltoides*
American basswood	*Tilia americana*
Black walnut	*Juglans nigra*
Black cherry	*Prunus serotina*
American elm	*Ulmus americana*
Rock elm	*Ulmus thomasii*
Slippery elm	*Ulmus rubra*
Paper birch	*Betula papyrifera*
Butternut	*Juglans cinerea*
Other hardwoods:	
Hackberry	*Celtis occidentalis*
American sycamore	*Platanus occidentalis*
Red mulberry	*Morus rubra*
Blackgum	*Nyssa sylvatica*
Black willow	*Salix nigra*
Boxelder	*Acer negundo*
Honeylocust	*Gleditsia triacanthos*
Black locust	*Robinia pseudoacacia*
River birch	*Betula nigra*
Northern catalpa	*Catalpa speciosa*

Table 4.--Area of commercial forest land by forest type and stand-size class, Wisconsin, 1979[1]

(In thousand acres)

Forest type	All stands	Stand-size class			
		Sawtimber	Poletimber	Restocking	Nonstocked
Jack pine	717	38	373	306	--
Red pine	332	66	134	132	--
White pine	159	107	23	29	--
Black spruce	215	7	38	170	--
Balsam fir-white spruce	602	59	368	174	--
Northern white-cedar	308	47	187	74	--
Tamarack	222	5	92	126	--
Oak-hickory	2,681	1,033	1,059	590	--
Elm-ash-cottonwood	1,163	353	505	305	--
Maple-beech-birch	3,550	1,347	1,632	572	--
Aspen	3,652	155	1,891	1,606	--
Paper birch	550	20	361	169	--
Nonstocked	326	--	--	--	326
All types	14,478	3,235	6,664	4,253	326

[1] Table may not add to total due to rounding.

Table 5.--Area of commercial forest land by forest type and stand-age class, Wisconsin, 1979[1]

(In thousand acres)

Forest type	All classes	Stand-age class										
		0-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100	101-120	121+
Jack pine	717	120	131	173	217	55	15	6	0	0	0	0
Red pine	332	73	64	124	20	8	17	17	4	2	2	0
White pine	159	18	12	10	13	19	17	23	12	14	10	11
Black spruce	215	13	11	22	48	56	30	17	6	2	8	2
Balsam fir-white spruce	602	42	64	62	106	183	94	20	11	2	14	3
Northern white-cedar	308	16	12	12	15	51	54	35	21	47	23	23
Tamarack	222	40	35	17	11	41	39	19	12	3	5	0
Oak-hickory	2,681	270	155	137	374	410	317	233	187	183	326	89
Elm-ash-cottonwood	1,163	126	80	96	145	133	154	150	73	77	101	30
Maple-beech-birch	3,550	172	171	226	502	687	564	287	216	183	325	217
Aspen	3,652	939	539	502	1,032	480	116	27	8	4	4	2
Paper birch	550	83	51	78	132	120	58	17	2	7	1	0
Nonstocked	326	326	--	--	--	--	--	--	--	--	--	--
All types	14,478	2,238	1,326	1,459	2,613	2,243	1,475	851	553	526	820	374

[1] Table may not add to total due to rounding.

Table 6.--Number of live trees on commercial forest land by species and diameter class, Wisconsin, 1979[1]

(In thousand trees)

		Diameter class (inches at breast height)													
Species	All classes	1.0-2.9	3.0-4.9	5.0-6.9	7.0-8.9	9.0-10.9	11.0-12.9	13.0-14.9	15.0-16.9	17.0-18.9	19.0-20.9	21.0-22.9	23.0-28.9	29.0-38.9	39.0+
SOFTWOODS:															
White pine	64,831	(21,683)	(11,863)	8,172	7,012	3,981	3,652	2,363	1,915	1,385	1,166	687	779	171	3
Red pine	124,743	(12,942)	(30,928)	45,552	20,173	8,621	2,797	1,209	1,033	807	410	197	75	0	0
Jack pine	276,217	(47,128)	(88,171)	75,080	40,322	18,202	5,576	1,258	402	66	12	0	0	0	0
White spruce	35,147	(7,974)	(8,737)	6,676	5,088	3,055	2,041	807	531	168	37	22	8	2	0
Black spruce	168,451	(63,101)	(65,258)	30,775	7,413	1,487	363	35	7	12	0	0	0	0	0
Balsam fir	366,923	(162,084)	(92,840)	61,409	31,000	13,605	4,232	1,240	338	42	34	0	0	0	0
Hemlock	41,945	(10,534)	(7,057)	4,673	4,970	4,516	3,257	2,300	1,908	1,348	642	384	339	18	0
Tamarack	57,760	(9,146)	(18,024)	17,030	9,737	2,534	891	272	90	31	4	0	0	0	0
N. white-cedar	192,668	(50,332)	(42,822)	45,371	29,551	14,100	6,436	2,585	983	377	73	23	14	0	0
Other softwoods	968	(0)	(316)	379	153	92	15	13	0	0	0	0	0	0	0
Total	1,329,554	(384,923)	(366,016)	295,117	155,419	70,192	29,259	12,083	7,208	4,237	2,378	1,314	1,215	191	3
HARDWOODS:															
White oak	122,735	(33,300)	(25,187)	20,821	15,539	9,949	7,154	4,758	2,659	1,670	812	435	382	64	5
Select red oak	139,156	(16,238)	(16,361)	28,669	29,783	19,246	11,955	6,569	4,452	2,654	1,459	881	753	133	3
Other red oak	150,116	(23,330)	(32,983)	33,137	25,520	15,302	8,700	5,297	2,794	1,432	826	396	357	41	0
Hickory	44,907	(18,155)	(10,640)	6,112	4,988	2,523	1,600	579	241	51	10	7	0	0	0
Yellow birch	73,918	(25,824)	(17,937)	11,286	7,154	4,863	2,567	1,616	1,039	786	395	205	222	21	0
Hard maple	633,195	(249,899)	(190,190)	96,939	49,096	20,028	11,071	6,321	3,978	2,586	1,403	823	747	107	5
Soft maple	521,311	(224,942)	(144,381)	80,540	37,697	17,219	7,706	4,549	1,950	1,025	672	296	261	67	7
Beech	4,553	(2,631)	(221)	403	99	294	286	220	151	89	88	22	44	6	0
Ash	179,606	(55,315)	(41,377)	36,962	24,149	10,987	6,059	2,851	1,211	389	136	99	68	4	0
Balsam poplar	3,328	(666)	(675)	390	516	407	196	118	242	47	35	27	9	0	0
Cottonwood	1,586	(0)	(435)	374	217	120	116	134	47	44	13	23	30	27	4
Paper birch	364,664	(96,078)	(97,604)	82,508	55,733	22,241	7,490	2,156	636	153	28	22	15	1	0
Bigtooth aspen	75,441	(6,505)	(12,023)	(14,880)	17,748	13,406	7,073	2,567	901	246	67	18	6	0	0
Quaking aspen	434,933	(87,780)	(104,314)	(93,861)	70,960	43,755	22,122	8,172	2,881	864	186	33	6	0	0
Basswood	108,064	(3,141)	(20,188)	31,423	24,597	13,925	7,224	3,538	1,879	1,122	507	229	246	36	9
Butternut	3,345	(496)	(489)	186	710	505	545	260	89	46	16	0	3	0	0
Black walnut	874	(0)	(0)	133	164	300	143	58	15	44	10	0	7	0	0
Black cherry	50,582	(19,902)	(11,847)	9,611	5,455	2,274	981	350	100	40	12	4	5	0	0
Elm	150,345	(38,725)	(35,551)	25,544	17,798	12,416	7,749	4,695	3,380	1,931	1,096	619	672	151	18
Other hardwoods	9,331	(2,840)	(1,291)	1,536	1,218	1,014	617	339	241	148	36	29	21	2	0
Noncommercial species	266,056	(206,093)	(45,597)	10,639	2,636	729	294	62	0	7	0	0	0	0	0
Total	3,338,046	(1,111,861)	(809,291)	585,956	391,777	211,503	111,647	55,209	28,888	15,374	7,806	4,169	3,855	660	50
All species	4,667,600	(1,496,784)	(1,175,307)	881,072	547,196	281,695	140,906	67,292	36,095	19,611	10,184	5,482	5,070	851	53

[1] Table may not add to total due to rounding. Figures in parentheses may be misleading due to the lack of ingrowth.

Table 7.--Number of growing-stock trees on commercial forest land by species and diameter class, Wisconsin, 1968[1]

(In thousand trees)

Species	All classes	Diameter class (inches at breast height)												
		1.0-2.9	3.0-4.9	5.0-6.9	7.0-8.9	9.0-10.9	11.0-12.9	13.0-14.9	15.0-16.9	17.0-18.9	19.0-20.9	21.0-22.9	23.0-28.9	29.0-38.9	39.0+
SOFTWOODS:															
White pine	94,307	48,062	17,281	9,335	5,546	4,092	3,364	2,170	1,779	1,150	680	386	382	78	3
Red pine	143,480	50,316	47,743	23,883	10,811	5,107	2,193	1,587	979	536	229	64	31	0	0
Jack pine	314,073	123,710	88,367	63,960	28,284	7,417	1,781	472	64	18	0	0	0	0	0
White spruce	45,512	19,443	12,883	6,024	3,981	1,710	826	368	218	39	12	7	2	0	0
Black spruce	192,250	104,273	59,381	22,913	4,485	1,050	103	33	7	5	0	0	0	0	0
Balsam fir	586,133	325,102	152,817	73,184	25,753	7,226	1,561	421	69	0	0	0	0	0	0
Hemlock	51,976	16,599	8,378	6,615	6,125	4,613	3,474	2,397	1,714	1,065	484	259	239	15	0
Tamarack	119,555	53,368	37,876	18,857	7,359	1,424	563	66	42	0	0	0	0	0	0
N. white-cedar	232,681	89,038	68,084	41,554	19,914	9,007	3,354	1,100	455	113	42	14	8	0	0
Other softwoods	4,196	1,991	2,032	139	34	0	0	0	0	0	0	0	0	0	0
Total	1,784,161	831,901	494,842	266,463	112,291	41,646	17,219	8,614	5,326	2,926	1,446	730	662	94	3
HARDWOODS:															
White oak	104,079	26,830	28,592	18,342	11,345	7,822	5,164	2,885	1,663	821	321	149	137	9	1
Select red oak	185,709	36,090	42,120	38,902	28,022	17,186	8,904	6,279	3,836	1,962	1,311	552	485	60	0
Other red oak	105,647	23,828	29,875	22,570	13,046	7,155	4,145	2,468	1,209	637	367	175	154	17	0
Hickory	54,680	26,349	13,966	7,444	3,381	2,244	771	360	140	17	8	0	0	0	0
Yellow birch	84,633	37,002	20,316	11,574	6,400	3,939	2,224	1,188	942	540	223	148	121	17	0
Hard maple	888,418	543,655	198,031	78,540	34,235	15,167	7,753	4,578	2,870	1,634	1,010	470	434	41	0
Soft maple	709,795	396,719	195,655	70,268	26,087	11,539	4,730	2,543	1,099	546	365	103	117	20	4
Beech	10,977	8,917	510	422	206	253	231	123	134	97	36	30	18	0	0
Ash	315,602	155,954	75,929	45,004	22,027	9,264	4,290	1,949	762	232	86	65	38	3	0
Balsam poplar	12,634	7,166	1,747	1,591	744	663	308	243	75	46	27	22	4	0	0
Cottonwood	1,211	0	206	145	323	237	107	31	62	26	22	7	23	17	4
Paper birch	461,299	167,030	143,202	95,779	38,539	12,524	3,132	807	204	56	4	17	5	0	0
Bigtooth aspen	190,247	70,083	40,295	35,454	24,684	12,412	4,885	1,641	586	165	31	9	3	0	0
Quaking aspen	998,129	498,091	219,915	144,845	82,847	36,639	11,577	3,155	857	170	32	0	0	0	0
Basswood	176,312	46,889	49,023	37,429	21,629	11,771	4,736	2,506	1,234	597	256	136	100	5	0
Butternut	3,064	502	451	759	262	562	298	157	41	21	9	0	0	0	0
Black walnut	1,096	0	355	112	309	104	99	43	51	16	4	3	0	0	0
Black cherry	51,634	24,058	13,664	7,692	4,032	1,324	507	186	108	46	0	9	6	0	0
Elm	182,923	67,149	41,928	27,731	18,273	11,430	6,879	4,188	2,478	1,227	749	398	403	87	4
Other hardwoods	14,121	7,401	3,081	1,437	843	498	378	159	153	92	49	17	14	0	0
Noncommercial species	202	202	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	4,552,413	2,143,916	1,118,861	646,038	337,234	162,736	71,119	35,487	18,504	8,947	4,910	2,309	2,062	276	13
All species	6,336,574	2,975,817	1,613,703	912,501	449,524	204,382	88,338	44,101	23,830	11,873	6,356	3,039	2,724	370	16

[1] Table may not add to total due to rounding. Table includes data for the Nicolet and Chequamegon National Forests, from 1975 and 1976 respectively.

Table 8.--Number of growing-stock trees on commercial forest land by species and diameter class, Wisconsin, 1979[1]

(In thousand trees)

Species	All classes	Diameter class (inches at breast height)												
		1.0-2.9	3.0-4.9	5.0-6.9	7.0-8.9	9.0-10.9	11.0-12.9	13.0-14.9	15.0-16.9	17.0-18.9	19.0-20.9	21.0-22.9	23.0-28.9	29.0-38.9	39.0+
SOFTWOODS:															
White pine	58,081	(20,757)	(10,666)	6,650	6,060	3,293	3,100	2,057	1,672	1,311	1,062	599	699	152	3
Red pine	120,546	(11,770)	(29,817)	44,424	19,855	8,246	2,768	1,180	1,024	807	393	191	71	0	0
Jack pine	234,703	(37,206)	(75,773)	65,155	35,517	15,285	4,513	958	261	23	12	0	0	0	0
White spruce	34,297	(7,759)	(8,506)	6,454	5,088	3,013	1,955	783	520	148	37	22	8	2	0
Black spruce	152,424	(55,675)	(58,783)	28,838	7,270	1,440	363	35	7	12	0	0	0	0	0
Balsam fir	347,644	(149,438)	(89,057)	59,806	30,396	13,206	4,106	1,229	331	42	34	0	0	0	0
Hemlock	36,567	(8,373)	(6,440)	3,831	4,285	4,140	3,001	2,148	1,811	1,250	566	380	330	14	0
Tamarack	52,333	(7,352)	(15,967)	16,472	9,127	2,321	818	198	60	17	0	0	0	0	0
N. white-cedar	172,046	(44,158)	(39,770)	41,297	25,966	11,790	5,578	2,204	887	298	60	23	14	0	0
Other softwoods	790	(0)	(316)	379	61	34	0	0	0	0	0	0	0	0	0
Total	1,209,431	(342,489)	(335,095)	273,307	143,626	62,768	26,201	10,793	6,574	3,907	2,163	1,215	1,123	168	3
HARDWOODS:															
White oak	72,551	(13,693)	(13,722)	13,777	11,516	6,918	5,383	3,462	1,868	1,187	523	275	209	18	1
Select red oak	117,857	(10,266)	(11,565)	25,726	27,176	17,511	10,649	5,857	4,049	2,369	1,260	729	620	79	1
Other red oak	71,085	(7,997)	(10,396)	17,730	14,896	8,198	4,931	3,274	1,701	942	522	254	224	19	0
Hickory	33,597	(10,707)	(8,986)	5,418	4,337	2,148	1,284	472	189	43	10	3	0	0	0
Yellow birch	50,811	(16,982)	(11,260)	8,205	5,229	3,830	1,961	1,205	889	626	311	162	137	14	0
Hard maple	505,060	(187,886)	(155,336)	81,335	42,220	16,308	9,126	5,228	3,216	2,059	1,127	661	502	54	1
Soft maple	358,211	(127,666)	(106,869)	66,803	30,633	13,733	5,810	3,526	1,551	730	474	217	171	24	3
Beech	2,974	(1,908)	(0)	288	28	177	234	95	110	58	36	11	29	0	0
Ash	146,312	(37,931)	(32,800)	33,828	22,091	10,140	5,327	2,592	1,054	345	86	74	44	2	0
Balsam poplar	2,737	(444)	(675)	390	378	292	156	108	193	35	35	27	5	0	0
Cottonwood	984	(0)	(0)	258	217	120	102	115	47	44	13	23	18	22	4
Paper birch	313,435	(72,983)	(84,629)	74,508	51,658	20,468	6,674	1,820	522	125	24	14	12	0	0
Bigtooth aspen	69,308	(5,067)	(10,275)	(13,616)	17,023	12,988	6,789	2,455	829	208	38	15	6	0	0
Quaking aspen	367,383	(73,537)	(83,279)	(78,693)	63,638	39,011	19,324	6,835	2,306	621	121	20	0	0	0
Basswood	95,646	(1,555)	(16,769)	28,660	22,489	13,023	6,644	3,177	1,632	939	421	174	154	9	0
Butternut	1,776	(245)	(235)	53	520	258	299	101	31	29	6	0	0	0	0
Black walnut	574	(0)	(0)	63	133	172	91	46	15	44	10	0	0	0	0
Black cherry	21,481	(5,540)	(3,588)	5,998	3,803	1,529	676	225	79	27	12	0	3	0	0
Elm	103,179	(19,107)	(22,195)	20,569	14,860	10,165	6,428	3,798	2,663	1,513	833	477	473	86	11
Other hardwoods	5,336	(858)	(1,031)	1,159	833	538	385	187	189	98	30	19	9	0	0
Noncommercial species	0	(0)	(0)	0	0	0	0	0	0	0	0	0	0	0	0
Total	2,340,298	(594,372)	(573,609)	477,077	333,678	177,529	92,270	44,578	23,132	12,041	5,892	3,154	2,618	326	21
All species	3,549,729	(936,860)	(908,705)	750,384	477,304	240,297	118,471	55,371	29,706	15,948	8,055	4,369	3,741	494	24

[1] Table may not add to total due to rounding. Figures in parentheses may be misleading due to the lack of ingrowth.

Table 9.--Number of short-log trees on commercial forest land by species and diameter class, Wisconsin, 1979[1/]

(In thousand trees)

Species	All classes	Diameter class (inches at breast height)									
		9.0-10.9	11.0-12.9	13.0-14.9	15.0-16.9	17.0-18.9	19.0-20.9	21.0-22.9	23.0-28.9	29.0-38.9	39.0+
SOFTWOODS:											
White pine	335	15	75	103	53	10	29	29	16	6	0
Red pine	45	0	29	13	0	0	0	0	3	0	0
Jack pine	237	16	161	45	14	0	0	0	0	0	0
White spruce	7	0	0	0	0	7	0	0	0	0	0
Black spruce	16	16	0	0	0	0	0	0	0	0	0
Balsam fir	13	0	13	0	0	0	0	0	0	0	0
Hemlock	173	34	80	35	8	0	9	4	0	2	0
Tamarack	96	22	11	56	7	0	0	0	0	0	0
N. white-cedar	410	210	157	27	8	9	0	0	0	0	0
Other softwoods	0	0	0	0	0	0	0	0	0	0	0
Total	1,332	313	526	279	89	27	39	33	19	7	0
HARDWOODS:											
White oak	1,455	--	298	488	291	142	106	67	58	4	0
Select red oak	775	--	126	212	125	118	80	52	45	16	0
Other red oak	1,535	--	272	483	378	189	139	38	36	0	0
Hickory	100	--	39	52	8	0	0	0	0	0	0
Yellow birch	189	--	48	84	7	23	9	4	13	0	0
Hard maple	998	--	174	314	194	144	69	47	51	6	0
Soft maple	560	--	51	204	135	79	47	11	26	5	3
Beech	92	--	0	40	18	6	16	4	7	0	0
Ash	271	--	123	58	25	19	21	11	14	0	0
Balsam poplar	23	--	0	0	23	0	0	0	0	0	0
Cottonwood	30	--	0	19	0	0	0	0	9	2	0
Paper birch	297	--	120	125	41	7	0	3	0	0	0
Bigtooth aspen	101	--	41	29	19	7	5	0	0	0	0
Quaking aspen	287	--	13	156	85	33	0	0	0	0	0
Basswood	439	--	73	126	118	51	22	10	35	4	1
Butternut	75	--	0	55	10	5	5	0	0	0	0
Black walnut	11	--	0	11	0	0	0	0	0	0	0
Black cherry	85	--	34	33	7	7	0	4	0	0	0
Elm	1,097	--	25	359	290	194	106	51	52	21	0
Other hardwoods	81	--	0	68	0	11	0	0	2	0	0
Noncommercial species	0	--	0	0	0	0	0	0	0	0	0
Total	8,501	--	1,438	2,917	1,772	1,035	625	304	348	58	4
All species	9,833	313	1,964	3,196	1,861	1,061	663	337	367	65	4

[1/] Table may not add to total due to rounding.

Table 10.--Number of growing-stock mortality trees on commercial forest land by species and diameter class, Wisconsin, 1968-1979[1]

(In thousand trees)

Species	All classes	Diameter class (inches at breast height) 1.0-2.9	3.0-4.9	5.0-6.9	7.0-8.9	9.0-10.9	11.0-12.9	13.0 14.9	15.0-16.9	17.0-18.9	19.0-20.9	21.0-22.9	23.0-28.9	29.0-38.9	39.0+
SOFTWOODS:															
White pine	20,057	15,775	3,282	251	242	197	185	33	39	15	16	12	4	5	0
Red pine	5,691	4,477	855	241	71	39	0	9	0	0	0	0	0	0	0
Jack pine	44,854	29,045	9,229	3,873	1,818	688	157	37	8	0	0	0	0	0	0
White spruce	5,424	3,951	701	335	244	86	63	17	20	6	0	0	0	0	0
Black spruce	23,416	16,532	5,163	1,343	298	51	11	18	0	0	0	0	0	0	0
Balsam fir	152,624	101,608	32,300	11,924	4,919	1,371	319	155	27	0	0	0	0	0	0
Hemlock	8,459	6,412	940	227	281	175	134	125	73	60	17	4	8	2	0
Tamarack	61,519	39,924	16,128	4,103	1,081	172	89	23	0	0	0	0	0	0	0
N. white-cedar	33,107	22,366	7,498	1,957	892	231	136	9	0	12	4	3	0	0	0
Other softwoods	1,477	1,477	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	356,628	241,567	76,095	24,254	9,845	3,010	1,093	427	167	93	37	19	13	7	0
HARDWOODS:															
White oak	9,652	2,886	4,077	1,179	625	490	237	79	46	18	10	0	3	2	0
Select red oak	26,687	14,900	5,405	2,930	1,217	865	496	359	216	118	83	65	25	9	0
Other red oak	20,369	7,978	7,831	2,071	1,254	534	334	174	65	72	23	14	14	4	0
Hickory	7,962	5,332	1,679	771	108	14	48	10	0	0	0	0	0	0	0
Yellow birch	24,911	14,666	5,793	2,585	945	367	250	144	55	64	16	10	7	9	0
Hard maple	325,092	292,990	25,053	3,613	1,731	742	377	193	191	93	52	27	30	0	0
Soft maple	182,878	141,857	29,961	7,266	2,210	959	308	206	66	20	17	4	3	1	1
Beech	5,554	4,790	222	230	61	53	39	33	39	56	17	14	0	0	0
Ash	101,160	70,894	18,027	7,355	3,036	1,208	327	190	74	11	8	17	11	2	0
Balsam poplar	6,874	5,594	231	484	184	146	106	87	33	3	0	3	3	0	0
Cottonwood	55	0	0	0	26	0	13	0	5	6	0	0	3	2	0
Paper birch	49,399	31,393	11,667	4,029	1,757	427	121	0	6	0	0	0	0	0	0
Bigtooth aspen	78,209	48,501	12,449	7,474	4,985	2,664	1,236	550	243	94	4	7	0	0	0
Quaking aspen	473,831	331,056	74,903	35,114	18,506	9,160	3,468	1,209	301	111	4	0	0	0	0
Basswood	70,664	39,528	24,121	4,273	1,451	623	331	143	120	15	34	10	13	2	0
Butternut	588	0	0	122	101	158	98	62	16	22	9	0	0	0	0
Black walnut	497	0	278	77	47	0	47	18	23	0	4	3	0	0	0
Black cherry	20.863	11,274	4,911	2,543	1,448	372	154	83	35	33	0	9	3	0	0
Elm	49,778	32,196	7,748	4,728	2,100	1,003	860	525	244	181	88	56	38	11	0
Other hardwoods	7,977	5,252	1,984	205	197	91	159	8	13	30	29	0	8	0	0
Noncommercial species	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	1,463,000	1,061,087	236,339	87,048	41,988	19,874	9,007	4,075	1,793	945	398	240	162	43	1
All species	1,819,629	1,302,654	312,435	111,302	51,834	22,884	10,100	4,501	1,960	1,039	435	259	175	50	1

[1] Table may not add to total due to rounding. Table includes data for the Nicolet and Chequamegon National Forests, from 1975 and 1976 respectively

Table 11.--Number of growing-stock removal trees on commercial forest land by species and diameter class, Wisconsin, 1968-1979[1]

(In thousand trees)

Species	All classes	Diameter class (inches at breast height)												
		1.0-2.9	3.0-4.9	5.0-6.9	7.0-8.9	9.0-10.9	11.0-12.9	13.0-14.9	15.0-16.9	17.0-18.9	19.0-20.9	21.0-22.9	23.0-28.9	29.0-38.9	39.0+
SOFTWOODS:															
White pine	16,169	7,087	3,566	1,438	1,173	916	599	566	257	246	148	52	93	22	1
Red pine	17,242	3,009	4,790	4,036	2,703	1,082	491	536	350	173	45	21	15	0	0
Jack pine	34,516	2,170	5,382	12,005	9,948	3,698	971	277	54	11	0	0	0	0	0
White spruce	5,792	2,396	1,806	955	340	143	108	25	10	5	4	0	0	0	0
Black spruce	16,410	3,844	9,074	2,446	895	128	24	0	0	0	0	0	0	0	0
Balsam fir	85,865	44,202	25,301	9,635	4,612	1,577	477	55	7	0	0	0	0	0	0
Hemlock	6,950	1,167	1,030	1,228	1,305	840	635	325	169	141	54	36	19	2	0
Tamarack	5,703	803	4,353	275	218	22	13	19	0	0	0	0	0	0	0
N. white-cedar	27,528	13,337	13,656	162	172	157	31	4	9	0	0	0	0	0	0
Other softwoods	1,929	514	1,415	0	0	0	0	0	0	0	0	0	0	0	0
Total	218,102	78,528	70,362	32,179	21,366	8,563	3,349	1,806	856	575	250	114	127	24	1
HARDWOODS:															
White oak	21,877	7,560	10,185	1,389	633	772	650	262	220	144	25	24	14	0	0
Select red oak	41,165	8,656	18,034	4,773	2,576	1,927	1,343	1,274	1,106	617	406	228	195	28	1
Other red oak	14,193	4,121	8,843	696	180	194	92	48	15	0	0	3	0	0	0
Hickory	13,122	9,082	3,696	70	153	70	25	19	7	0	0	0	0	0	0
Yellow birch	8,911	2,703	3,653	817	559	540	233	195	90	70	8	20	22	1	0
Hard maple	58,266	32,424	11,536	5,622	4,132	2,660	565	501	309	192	138	60	101	26	0
Soft maple	168,706	101,339	54,314	7,063	4,032	1,267	363	171	55	54	30	11	5	2	0
Beech	2,449	1,997	222	92	66	16	21	25	0	5	0	3	2	0	0
Ash	68,131	39,986	21,485	3,790	1,528	925	246	72	54	32	8	0	5	0	0
Balsam poplar	3,023	222	1,206	583	431	314	153	64	28	13	2	3	4	0	0
Cottonwood	172	0	0	0	84	61	0	11	8	6	0	0	2	0	0
Paper birch	98,464	43,950	39,364	8,629	4,447	1,701	282	77	14	0	0	0	0	0	0
Bigtooth aspen	42,730	9,680	14,315	7,424	6,658	3,037	1,225	295	71	21	4	0	0	0	0
Quaking aspen	156,914	16,186	47,262	36,920	32,058	16,410	5,938	1,610	474	45	4	7	0	0	0
Basswood	10,002	2,151	1,510	1,727	2,583	1,376	256	213	109	33	16	14	14	0	0
Butternut	699	257	217	85	21	90	15	8	6	0	0	0	0	0	0
Black walnut	25	0	0	0	25	0	0	0	0	0	0	0	0	0	0
Black cherry	9,289	4,658	3,457	219	676	210	44	9	15	0	0	0	0	0	0
Elm	29,967	8,840	5,456	4,383	3,710	3,091	2,003	1,173	545	292	198	127	129	17	1
Other hardwoods	808	475	216	0	48	21	12	6	11	14	3	3	0	0	0
Noncommercial species	202	202	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	749,115	294,489	244,972	84,284	64,597	34,680	13,467	6,033	3,137	1,537	843	503	496	74	2
All species	967,217	373,017	315,334	116,463	85,963	43,243	16,817	7,840	3,994	2,111	1,093	617	623	98	3

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[1] Table may not add to total due to rounding. Table includes data for the Nicolet and Chequamegon National Forests, from 1975 and 1976 respectively. Data presented are growing-stock removals for products.

Table 12.--Net volume of all live trees on commercial forest land by species and diameter class, Wisconsin, 1979[1]

(In thousand cubic feet)

Species	All classes	Diameter class (inches at breast height) 5.0-6.9	7.0-8.9	9.0-10.9	11.0-12.9	13.0-14.9	15.0-16.9	17.0-18.9	19.0-20.9	21.0-22.9	23.0-28.9	29.0-38.9	39.0+
SOFTWOODS:													
White pine	525,006	19,812	32,777	31,985	49,665	49,606	56,860	57,308	62,298	46,682	81,624	34,754	1,635
Red pine	453,147	106,092	94,596	75,498	41,228	27,590	33,290	34,924	21,258	12,655	6,017	0	0
Jack pine	616,064	183,726	189,809	143,515	67,305	21,576	8,446	1,217	470	0	0	0	0
White spruce	155,152	18,208	27,924	28,533	31,107	18,789	17,984	7,344	2,339	1,882	774	269	0
Black spruce	147,030	88,318	38,614	13,589	5,042	716	183	569	0	0	0	0	0
Balsam fir	552,472	164,294	159,449	122,800	63,119	28,013	11,061	1,775	1,960	0	0	0	0
Hemlock	366,835	11,033	21,770	34,949	41,240	44,966	55,340	54,379	33,564	29,112	37,140	3,343	0
Tamarack	148,925	51,252	52,044	23,669	13,045	5,360	2,438	948	168	0	0	0	0
N. white-cedar	500,544	115,807	129,085	99,285	70,639	43,371	24,595	11,709	3,235	1,377	1,441	0	0
Other softwoods	2,332	1,193	443	496	77	124	0	0	0	0	0	0	0
Total	3,467,508	759,734	746,511	574,319	382,466	240,111	210,197	170,174	125,290	91,709	126,996	38,366	1,635
HARDWOODS:													
White oak	544,778	48,771	67,999	72,826	85,551	82,911	61,581	50,067	29,503	19,417	21,375	4,173	604
Select red oak	1,115,306	96,130	163,556	169,049	157,659	127,331	120,186	94,982	65,792	48,833	57,010	14,289	489
Other red oak	600,068	82,180	100,283	92,552	82,528	77,019	56,174	38,959	29,800	17,080	20,242	3,253	0
Hickory	133,873	27,538	37,493	27,971	22,777	10,878	5,337	1,344	294	242	0	0	0
Yellow birch	233,347	20,970	25,388	33,349	29,055	27,232	27,058	27,139	17,060	10,581	13,453	2,062	0
Hard maple	1,264,949	245,858	229,310	155,021	137,829	119,906	105,669	91,702	65,832	48,915	55,131	9,463	314
Soft maple	903,752	233,540	187,722	141,503	95,202	84,455	52,486	34,463	29,213	16,195	19,735	7,533	1,705
Beech	24,985	962	500	2,138	3,611	3,207	3,888	2,732	3,362	1,035	3,332	218	0
Ash	567,116	127,249	136,119	98,490	82,044	57,421	34,008	14,738	5,717	5,742	5,230	360	0
Balsam poplar	24,586	1,451	2,975	4,157	2,904	2,696	6,205	1,461	1,352	984	400	0	0
Cottonwood	26,486	1,608	1,422	1,225	1,543	2,568	1,386	1,697	766	1,692	2,937	7,213	2,432
Paper birch	974,797	261,695	319,390	213,978	108,635	44,625	17,604	5,723	1,334	866	792	153	0
Bigtooth aspen	506,412	46,941	107,433	142,005	113,769	58,204	26,155	8,274	2,320	929	381	0	0
Quaking aspen	1,762,798	297,911	426,607	434,403	329,074	165,199	75,034	26,418	6,756	1,196	201	0	0
Basswood	701,185	99,450	138,931	131,690	103,845	74,286	52,998	40,938	23,692	12,855	18,058	2,815	1,627
Butternut	23,891	829	4,018	4,120	6,507	4,319	2,036	1,348	544	0	171	0	0
Black walnut	9,859	533	1,010	2,568	1,903	1,118	488	1,438	455	0	346	0	0
Black cherry	102,006	32,098	28,326	17,903	12,435	6,128	2,622	1,300	590	255	350	0	0
Elm	796,920	86,264	99,274	106,294	99,272	89,095	88,127	67,586	50,162	35,334	52,373	19,173	3,965
Other hardwoods	43,369	4,526	5,838	6,599	6,612	5,486	5,767	4,397	1,494	1,376	1,014	258	0
Noncommercial species	38,976	24,848	8,580	3,192	1,802	458	0	95	0	0	0	0	0
Total	10,399,459	1,741,352	2,092,175	1,861,033	1,484,555	1,044,543	744,808	516,800	336,037	223,529	272,531	70,963	11,134
All species	13,866,967	2,501,085	2,838,686	2,435,351	1,867,021	1,284,653	955,005	686,974	461,327	315,238	399,527	109,330	12,769

[1] Table may not add to total due to rounding.

Table 13.--Net volume of growing stock on commercial forest land by species and diameter class, Wisconsin, 1968[1]

(In thousand cubic feet)

Species	All classes	Diameter class (inches at breast height) 5.0-6.9	7.0-8.9	9.0-10.9	11.0-12.9	13.0-14.9	15.0-16.9	17.0-18.9	19.0-20.9	21.0-22.9	23.0-28.9	29.0-38.9	39.0+
SOFTWOODS:													
White pine	419,605	25,888	27,812	36,539	49,004	46,900	55,196	49,372	37,880	28,992	43,209	17,646	1,169
Red pine	292,901	51,766	52,932	45,689	32,895	36,440	31,503	22,658	12,170	4,303	2,544	0	0
Jack pine	414,151	171,075	142,772	64,217	24,502	9,200	1,803	581	0	0	0	0	0
White spruce	88,091	17,494	22,388	16,545	12,565	8,332	7,270	1,921	836	516	224	0	0
Black spruce	100,746	65,198	23,219	9,653	1,497	670	252	257	0	0	0	0	0
Balsam fir	417,751	190,006	128,980	64,179	22,593	9,573	2,187	0	0	0	0	0	233
Hemlock	351,941	17,650	29,908	37,918	45,963	48,982	50,964	44,052	28,084	19,662	25,689	3,069	0
Tamarack	118,697	53,397	40,523	13,683	8,328	1,474	1,291	0	0	0	0	0	0
N. white-cedar	349,224	106,462	92,050	69,516	40,875	20,466	12,145	4,029	2,047	960	674	0	0
Other softwoods	441	271	170	0	0	0	0	0	0	0	0	0	0
Total	2,553,549	699,208	560,754	357,939	238,223	182,038	162,612	122,871	81,016	54,432	72,340	20,715	1,402
HARDWOODS:													
White oak	408,583	48,011	57,800	68,961	70,835	56,575	45,077	28,728	14,376	8,055	9,221	811	133
Select red oak	1,029,599	128,042	159,143	158,398	126,997	128,817	108,974	73,845	63,327	33,200	40,465	8,392	0
Other red oak	372,999	61,868	63,735	59,419	52,859	45,434	29,980	21,105	15,961	9,395	11,034	2,209	0
Hickory	113,192	35,115	26,624	27,751	12,174	7,236	3,571	447	275	0	0	0	0
Yellow birch	217,789	24,566	27,653	31,148	29,796	24,470	27,396	20,994	11,127	8,717	9,573	2,350	0
Hard maple	987,331	210,700	168,320	129,700	104,966	93,377	83,735	65,147	53,562	31,715	40,066	6,043	0
Soft maple	683,158	218,397	143,740	106,745	68,368	53,280	31,924	21,644	18,271	6,732	10,316	2,753	988
Beech	24,038	1,368	1,271	2,476	3,247	2,637	3,800	3,926	1,862	1,775	1,676	0	0
Ash	512,806	153,894	125,816	85,920	61,203	40,762	22,174	9,385	4,789	4,349	3,772	742	0
Balsam poplar	32,580	4,668	4,664	7,027	5,203	5,324	2,046	1,636	989	863	159	0	0
Cottonwood	20,708	622	1,933	2,265	1,565	687	1,699	973	1,213	544	2,655	4,513	2,039
Paper birch	712,693	290,921	222,986	123,418	48,137	17,810	6,003	2,181	146	753	337	0	0
Bigtooth aspen	529,056	106,389	149,457	130,285	79,691	37,689	17,325	6,099	1,448	489	185	0	0
Quaking aspen	1,613,260	452,216	498,483	377,532	182,507	70,354	24,895	5,888	1,383	0	0	0	0
Basswood	563,451	110,546	120,504	112,076	71,179	55,034	37,491	24,245	13,021	8,967	9,686	703	0
Butternut	18,769	2,710	1,519	4,991	4,124	3,112	1,179	741	393	0	0	0	0
Black walnut	7,620	308	1,744	959	1,406	893	1,401	554	183	170	0	0	0
Black cherry	75,287	24,781	22,234	11,887	7,048	3,809	2,972	1,744	0	403	408	0	0
Elm	736,343	98,679	108,413	106,840	97,388	86,350	71,316	48,448	38,571	26,331	38,302	14,502	1,202
Other hardwoods	34,265	4,491	4,768	4,610	5,288	3,385	4,341	3,300	2,248	903	932	0	0
Noncommercial species	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	8,693,525	1,978,292	1,910,806	1,552,408	1,033,982	737,037	527,299	341,028	243,145	143,363	178,788	43,017	4,362
All species	11,247,074	2,677,499	2,471,560	1,910,347	1,272,204	919,075	689,911	463,899	324,161	197,795	251,127	63,732	5,764

[1] Table may not add to total due to rounding. Table includes data for the Nicolet and Chequamegon National Forests, from 1975 and 1976 respectively.

Table 14.--Net volume of growing stock on commercial forest land by species and diameter class Wisconsin, 1979[1]

(In thousand cubic feet)

Species	All classes	Diameter class (inches at breast height) 5.0-6.9	7.0-8.9	9.0-10.9	11.0-12.9	13.0-14.9	15.0-16.9	17.0-18.9	19.0-20.9	21.0-22.9	23.0-28.9	29.0-38.9	39.0+
SOFTWOODS:													
White pine	496,926	18,987	31,653	30,174	46,711	46,248	53,116	56,066	59,302	43,593	77,147	32,294	1,635
Red pine	449,961	105,302	94,115	74,658	40,996	27,332	33,237	34,924	21,032	12,507	5,858	0	0
Jack pine	585,871	177,108	183,184	136,166	62,182	19,182	6,797	783	470	0	0	0	0
White spruce	154,238	18,113	27,924	28,476	30,879	18,682	17,904	6,996	2,339	1,882	774	269	0
Black spruce	145,699	87,258	38,495	13,438	5,042	716	183	569	0	0	0	0	0
Balsam fir	549,473	163,253	158,822	122,095	62,679	27,963	10,925	1,775	1,960	0	0	0	0
Hemlock	358,173	10,666	21,018	34,102	40,027	43,939	54,393	53,233	32,138	28,930	36,820	2,908	0
Tamarack	145,344	50,882	51,362	23,057	12,735	4,509	2,040	760	0	0	0	0	0
N. white-cedar	480,298	112,970	124,905	93,968	66,999	41,191	23,750	10,683	3,014	1,377	1,441	0	0
Other softwoods	1,757	1,193	263	301	0	0	0	0	0	0	0	0	0
Total	3,367,741	745,732	731,740	556,434	368,248	229,762	202,346	165,789	120,254	88,288	122,040	35,471	1,635
HARDWOODS:													
White oak	453,099	39,532	59,598	61,900	74,748	70,097	50,909	42,002	23,110	14,901	14,542	1,624	137
Select red oak	1,047,957	88,012	156,266	161,977	149,790	120,478	114,857	89,391	60,949	44,105	51,453	10,394	285
Other red oak	444,307	50,411	73,677	68,170	63,106	60,221	43,033	30,724	22,796	13,627	16,069	2,472	0
Hickory	125,806	26,539	35,503	26,572	20,947	9,749	4,802	1,243	294	157	0	0	0
Yellow birch	210,754	18,424	22,239	30,762	26,658	24,437	25,878	24,975	15,664	9,613	10,426	1,679	0
Hard maple	1,143,674	221,750	212,090	140,130	125,739	108,633	94,714	82,244	59,622	44,254	46,520	7,725	254
Soft maple	803,888	213,997	169,769	127,844	84,122	74,709	46,483	29,041	24,284	13,901	15,509	3,413	815
Beech	18,530	735	167	1,686	3,354	1,928	3,277	2,265	1,950	557	2,612	0	0
Ash	537,933	120,290	129,466	95,053	77,074	55,154	32,450	13,913	4,777	5,204	4,258	294	0
Balsam poplar	21,876	1,451	2,366	3,530	2,695	2,583	5,348	1,358	1,352	984	210	0	0
Cottonwood	23,427	1,034	1,422	1,225	1,393	2,233	1,386	1,697	766	1,692	1,909	6,239	2,432
Paper birch	921,356	243,345	305,412	205,641	102,885	40,805	15,572	5,181	1,213	653	648	0	0
Bigtooth aspen	493,820	44,228	105,316	140,135	111,736	57,076	24,950	7,562	1,652	786	381	0	0
Quaking aspen	1,634,232	257,283	401,290	413,898	311,895	153,272	68,268	22,242	5,233	852	0	0	0
Basswood	650,199	88,971	129,141	126,798	99,785	70,285	48,957	37,860	21,766	11,446	14,005	1,185	0
Butternut	14,221	213	2,935	2,514	4,291	2,163	950	936	220	0	0	0	0
Black walnut	7,136	206	789	1,477	1,355	927	488	1,438	455	0	0	0	0
Black cherry	73,280	19,939	21,577	13,687	9,497	4,656	2,139	999	590	0	196	0	0
Elm	702,585	75,176	89,299	96,423	91,549	79,257	77,359	58,500	43,130	30,822	43,924	14,259	2,886
Other hardwoods	34,591	3,814	4,839	4,802	5,324	3,740	5,234	3,648	1,391	1,143	658	0	0
Noncommercial species	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	9,362,672	1,515,352	1,923,160	1,724,223	1,367,941	942,400	667,053	457,217	291,214	194,695	223,321	49,285	6,810
All species	12,730,413	2,261,085	2,654,900	2,280,657	1,736,190	1,172,162	869,400	623,006	411,468	282,984	345,361	84,757	8,444

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[1] Table may not add to total due to rounding.

Table 15.--Net volume of sawtimber on commercial forest land by species and diameter class, Wisconsin, 1968[1]

(In thousand board feet)[2]

Species	All classes	Diameter class (inches at breast height) 9.0-10.9	11.0-12.9	13.0-14.9	15.0-16.9	17.0-18.9	19.0-20.9	21.0-22.9	23.0-28.9	29.0-38.9	39.0+
SOFTWOODS:											
White pine	2,192,377	214,836	276,800	267,110	319,682	293,698	236,688	179,120	280,459	116,224	7,758
Red pine	1,137,018	313,167	198,386	208,796	176,475	128,106	70,001	26,017	16,070	0	0
Jack pine	492,946	319,490	116,948	44,316	9,019	3,172	0	0	0	0	0
White spruce	232,845	80,120	58,302	38,700	35,110	9,937	4,418	3,837	2,422	0	0
Black spruce	59,899	47,142	6,894	3,458	1,161	1,243	0	0	0	0	0
Balsam fir	463,570	297,104	99,313	41,958	9,936	0	0	0	0	0	15,259
Hemlock	1,742,745	217,638	259,312	275,524	287,920	250,229	160,844	114,498	156,324	20,457	0
Tamarack	100,854	54,642	34,138	6,243	5,831	0	0	0	0	0	0
N. white-cedar	761,676	337,577	210,489	109,645	63,476	22,199	10,390	4,959	2,941	0	0
Other softwoods	0	0	0	0	0	0	0	0	0	0	0
Total	7,183,930	1,881,718	1,260,583	995,750	908,610	708,584	482,341	328,431	458,216	136,681	23,017
HARDWOODS:											
White oak	1,168,804	--	402,124	285,419	210,592	125,427	63,270	36,264	41,708	3,325	675
Select red oak	2,942,320	--	721,533	671,830	540,074	348,920	288,565	149,881	181,704	39,814	0
Other red oak	944,690	--	299,854	234,239	144,048	96,566	72,357	40,202	48,596	8,828	0
Hickory	105,545	--	53,373	31,410	17,032	2,277	1,452	0	0	0	0
Yellow birch	652,073	--	139,251	113,686	128,597	100,543	55,573	45,129	54,732	14,563	0
Hard maple	2,459,335	--	502,076	471,235	435,443	345,365	286,594	169,271	216,359	32,992	0
Soft maple	1,062,558	--	368,436	269,682	153,656	99,800	82,296	28,501	42,613	12,179	5,395
Beech	95,695	--	17,245	13,294	18,776	19,195	9,207	9,130	8,849	0	0
Ash	761,171	--	331,002	211,430	112,566	45,035	21,842	19,352	15,837	4,106	0
Balsam poplar	93,124	--	24,134	27,402	11,706	11,015	7,972	8,496	2,400	0	0
Cottonwood	65,220	--	8,738	3,533	8,516	4,872	5,483	2,053	10,794	15,261	5,970
Paper birch	373,077	--	229,386	88,997	30,902	12,394	1,287	6,556	3,554	0	0
Bigtooth aspen	707,206	--	375,018	187,215	94,459	35,867	9,719	3,603	1,324	0	0
Quaking aspen	1,373,915	--	842,774	349,088	135,562	36,968	9,522	0	0	0	0
Basswood	1,116,390	--	363,481	277,166	189,336	123,270	65,944	46,519	47,314	3,362	0
Butternut	50,626	--	21,920	16,615	5,880	4,117	2,094	0	0	0	0
Black walnut	22,628	--	7,500	4,412	6,604	2,502	824	786	0	0	0
Black cherry	81,091	--	33,770	18,668	15,176	8,871	0	2,232	2,374	0	0
Elm	2,176,778	--	502,596	449,145	378,706	255,090	202,864	134,320	188,574	61,851	3,632
Other hardwoods	105,878	--	28,536	16,683	21,990	17,031	11,609	4,899	5,130	0	0
Noncommercial species	0	--	0	0	0	0	0	0	0	0	0
Total	16,358,122	--	5,272,746	3,741,149	2,659,622	1,695,124	1,198,473	707,195	871,861	196,281	15,671
All species	23,542,052	1,881,718	6,533,328	4,736,899	3,568,232	2,403,708	1,680,813	1,035,626	1,330,077	332,962	38,688

[1] Table may not add to total due to rounding. Table includes data for the Nicolet and Chequamegon National Forests, from 1975 and 1976 respectively.

[2] International 1/4-inch rule.

Table 16.--Net volume of sawtimber on commercial forest land by species and diameter class, Wisconsin, 1979[1]

(In thousand board feet)[2]

Species	All classes	Diameter class (inches at breast height) 9.0-10.9	11.0-12.9	13.0-14.9	15.0-16.9	17.0-18.9	19.0-20.9	21.0-22.9	23.0-28.9	29.0-38.9	39.0+
SOFTWOODS:											
White pine	2,740,019	172,455	261,722	262,354	307,273	338,021	370,434	286,358	504,210	226,832	10,361
Red pine	1,533,777	510,726	247,943	153,996	185,091	196,262	124,285	76,356	39,118	0	0
Jack pine	1,109,810	678,521	297,068	92,738	34,876	3,870	2,737	0	0	0	0
White spruce	528,835	139,775	143,288	87,781	87,380	35,900	13,465	12,011	5,346	3,891	0
Black spruce	96,958	65,670	23,552	3,950	1,056	2,730	0	0	0	0	0
Balsam fir	1,027,422	563,395	273,416	122,381	49,295	8,809	10,128	0	0	0	0
Hemlock	1,878,634	195,628	226,252	246,066	307,689	302,055	185,895	169,239	226,146	19,664	0
Tamarack	174,167	89,184	52,507	19,448	9,045	3,984	0	0	0	0	0
N. white-cedar	1,226,987	450,960	348,573	214,042	126,542	58,144	15,104	6,991	6,631	0	0
Other softwoods	1,130	1,130	0	0	0	0	0	0	0	0	0
Total	10,317,740	2,867,443	1,874,319	1,202,756	1,108,246	949,774	722,048	550,955	781,451	250,386	10,361
HARDWOODS:											
White oak	1,439,872	--	423,319	352,171	238,477	184,429	99,655	65,894	67,144	8,065	718
Select red oak	3,216,434	--	845,283	626,364	563,340	423,990	278,593	198,120	228,774	50,727	1,244
Other red oak	1,272,287	--	364,162	313,348	206,992	145,524	100,872	60,640	71,609	9,140	0
Hickory	162,880	--	88,554	42,496	22,788	6,545	1,699	798	0	0	0
Yellow birch	679,738	--	123,981	114,429	122,426	120,643	79,241	49,658	58,894	10,466	0
Hard maple	2,946,387	--	604,969	553,431	495,198	439,062	320,116	242,539	248,626	40,902	1,544
Soft maple	1,442,997	--	453,152	382,113	221,807	133,409	108,498	59,892	64,489	15,179	4,458
Beech	81,010	--	17,625	9,792	16,369	11,002	9,581	2,960	13,681	0	0
Ash	992,048	--	414,765	286,861	160,613	67,738	21,496	22,748	16,938	888	0
Balsam poplar	90,774	--	12,723	13,374	31,367	9,066	11,143	10,446	2,656	0	0
Cottonwood	80,837	--	7,838	11,799	6,761	8,119	4,015	7,319	6,812	21,102	7,073
Paper birch	821,713	--	489,922	202,844	83,103	25,917	6,920	5,906	7,101	0	0
Bigtooth aspen	999,069	--	514,519	282,817	135,526	46,417	11,136	5,833	2,820	0	0
Quaking aspen	2,734,997	--	1,433,979	751,604	368,136	138,149	35,925	7,203	0	0	0
Basswood	1,555,976	--	508,626	357,683	249,594	191,399	114,915	57,139	70,369	6,253	0
Butternut	44,043	--	23,006	10,707	4,787	4,552	991	0	0	0	0
Black walnut	22,725	--	7,099	4,666	2,396	6,507	2,057	0	0	0	0
Black cherry	90,266	--	46,763	23,465	10,736	5,132	3,034	0	1,135	0	0
Elm	2,269,495	--	471,937	410,704	408,320	311,486	225,908	158,842	212,594	59,285	10,420
Other hardwoods	108,636	--	28,736	19,168	25,418	18,010	7,395	6,326	3,583	0	0
Noncommercial species	0	--	0	0	0	0	0	0	0	0	0
Total	21,052,186	--	6,880,957	4,769,839	3,374,156	2,297,095	1,443,191	962,260	1,077,225	222,007	25,457
All species	31,369,926	2,867,443	8,755,277	5,972,595	4,482,402	3,246,869	2,165,239	1,513,214	1,858,676	472,393	35,818

[1] Table may not add to total due to rounding.

[2] International 1/4-inch rule.

Table 17.--Net volume in short-log trees on commercial forest land by species group and diameter class, Wisconsin, 1979[1/]

(In thousand cubic feet)

Species	All classes	Diameter class (inches at breast height)									
		9.0-10.9	11.0-12.9	13.0-14.9	15.0-16.9	17.0-18.9	19.0-20.9	21.0-22.9	23.0-28.9	29.0-38.9	39.0+
SOFTWOODS:											
White pine	8,708	211	945	1,828	1,397	334	1,130	1,348	974	541	0
Red pine	529	0	232	137	0	0	0	0	159	0	0
Jack pine	2,295	101	1,354	588	251	0	0	0	0	0	0
White spruce	200	0	0	0	0	200	0	0	0	0	0
Black spruce	106	106	0	0	0	0	0	0	0	0	0
Balsam fir	117	0	117	0	0	0	0	0	0	0	0
Hemlock	2,249	235	678	492	145	0	381	182	0	135	0
Tamarack	1,190	155	98	761	177	0	0	0	0	0	0
N. white-cedar	3,719	1,442	1,507	356	140	273	0	0	0	0	0
Other softwoods	0	0	0	0	0	0	0	0	0	0	0
Total	19,113	2,250	4,933	4,162	2,109	808	1,511	1,530	1,133	676	0
HARDWOODS:											
White oak	28,781	--	3,376	6,967	5,569	3,538	3,262	2,503	3,201	365	0
Select red oak	20,451	--	1,545	3,340	2,784	3,382	2,845	2,399	2,631	1,526	0
Other oak	30,704	--	2,857	7,077	7,323	5,060	4,742	1,691	1,954	0	0
Hickory	1,332	--	403	755	174	0	0	0	0	0	0
Yellow birch	3,874	--	542	1,155	137	635	301	203	902	0	0
Hard maple	27,237	--	2,246	6,336	4,933	4,663	2,792	2,330	3,413	524	0
Soft maple	16,087	--	634	3,687	3,193	2,475	1,852	615	1,971	827	834
Beech	2,764	--	0	665	374	142	768	321	494	0	0
Ash	5,093	--	1,710	900	426	493	565	314	685	0	0
Balsam poplar	556	--	0	0	556	0	0	0	0	0	0
Cottonwood	1,635	--	0	334	0	0	0	0	866	434	0
Paper birch	4,463	--	1,346	1,926	917	148	0	126	0	0	0
Bigtooth aspen	1,733	--	495	426	400	253	160	0	0	0	0
Quaking aspen	6,180	--	166	2,973	1,912	1,129	0	0	0	0	0
Basswood	12,180	--	854	2,112	2,695	1,557	857	483	2,422	450	751
Butternut	1,601	--	0	956	214	188	243	0	0	0	0
Black walnut	192	--	0	192	0	0	0	0	0	0	0
Black cherry	1,515	--	379	495	198	187	0	255	0	0	0
Elm	31,574	--	263	6,033	6,426	5,931	4,420	2,516	3,797	2,187	0
Other hardwoods	1,439	--	0	1,095	0	253	0	0	90	0	0
Noncommercial species	0	--	0	0	0	0	0	0	0	0	0
Total	199,392	--	16,816	47,426	38,232	30,034	22,805	13,756	22,425	6,313	1,585
All species	218,505	2,250	21,749	51,589	40,341	30,842	24,316	15,286	23,558	6,988	1,585

[1/] Table may not add to total due to rounding.

Table 18.--Net board foot volume in short-log trees on commercial forest land by species group and diameter class, Wisconsin, 1979[1]

(In thousand board feet)[2]

Species	All classes	Diameter class (inches at breast height)									
		9.0-10.9	11.0-12.9	13.0-14.9	15.0-16.9	17.0-18.9	19.0-20.9	21.0-22.9	23.0-28.9	29.0-38.9	39.0+
SOFTWOODS:											
White pine	23,065	432	2,558	4,490	2,961	821	2,823	3,498	3,026	2,456	0
Red pine	2,037	0	983	555	0	0	0	0	499	0	0
Jack pine	8,517	464	5,326	1,929	798	0	0	0	0	0	0
White spruce	499	0	0	0	0	499	0	0	0	0	0
Black spruce	434	434	0	0	0	0	0	0	0	0	0
Balsam fir	445	0	445	0	0	0	0	0	0	0	0
Hemlock	7,524	974	2,589	1,530	409	0	924	519	0	580	0
Tamarack	3,932	653	354	2,478	447	0	0	0	0	0	0
N. white-cedar	13,634	5,947	5,419	1,137	397	735	0	0	0	0	0
Other softwoods	0	0	0	0	0	0	0	0	0	0	0
Total	60,087	8,904	17,673	12,118	5,012	2,055	3,746	4,017	3,525	3,037	0
HARDWOODS:											
White oak	72,792	--	8,967	18,912	13,795	8,363	7,752	5,867	8,046	1,090	0
Select red oak	49,784	--	5,060	9,568	6,793	7,668	6,120	5,200	5,743	3,632	0
Other red oak	81,267	--	11,787	23,016	19,985	11,358	9,316	2,759	3,045	0	0
Hickory	4,762	--	1,739	2,572	450	0	0	0	0	0	0
Yellow birch	10,022	--	1,988	3,942	390	1,389	634	336	1,343	0	0
Hard maple	56,979	--	7,212	14,435	10,739	9,087	5,004	3,912	5,633	956	0
Soft maple	38,133	--	1,932	9,366	7,134	4,975	3,579	885	3,897	2,674	3,690
Beech	3,173	--	0	405	528	133	991	351	765	0	0
Ash	14,098	--	4,378	2,330	1,243	1,243	1,664	1,127	2,113	0	0
Balsam poplar	1,228	--	0	0	1,228	0	0	0	0	0	0
Cottonwood	4,390	--	0	723	0	0	0	0	2,035	1,632	0
Paper birch	13,319	--	4,777	5,626	2,204	424	0	288	0	0	0
Bigtooth aspen	4,272	--	1,198	1,330	949	415	380	0	0	0	0
Quaking aspen	14,409	--	544	7,373	4,495	1,997	0	0	0	0	0
Basswood	25,174	--	2,950	5,735	6,317	3,148	1,533	807	3,432	611	640
Butternut	3,792	--	0	2,590	495	334	373	0	0	0	0
Black walnut	519	--	0	519	0	0	0	0	0	0	0
Black cherry	1,699	--	167	771	126	378	0	257	0	0	0
Elm	53,273	--	1,021	11,725	10,749	8,577	5,814	3,595	5,763	6,030	0
Other hardwoods	1,770	--	0	1,028	0	227	0	0	514	0	0
Noncommercial species	0	--	0	0	0	0	0	0	0	0	0
Total	454,852	--	53,721	121,968	87,617	59,717	43,160	25,385	42,328	16,625	4,331
All species	514,938	8,904	71,394	134,086	92,629	61,772	46,907	29,402	45,853	19,661	4,331

[1] Table may not add to total due to rounding.

[2] International 1/4-inch rule.

Table 19.--Net growing-stock volume of mortality trees on commercial forest land by species and diameter class, Wisconsin, 1968-1979[1]

(In thousand cubic feet)

Species	All classes	Diameter class (inches at breast height) 5.0-6.9	7.0-8.9	9.0-10.9	11.0-12.9	13.0-14.9	15.0-16.9	17.0-18.9	19.0-20.9	21.0-22.9	23.0-28.9	29.0-38.9	39.0+
SOFTWOODS:													
White pine	12,585	885	1,247	2,041	2,632	665	1,263	684	1,028	751	383	1,007	0
Red pine	1,866	970	341	350	0	206	0	0	0	0	0	0	0
Jack pine	28,506	10,544	8,821	5,816	2,429	703	193	0	0	0	0	0	0
White spruce	5,401	920	1,400	855	922	394	648	262	0	0	0	0	0
Black spruce	6,792	3,958	1,761	520	150	403	0	0	0	0	0	0	0
Balsam fir	77,836	30,995	25,125	12,375	4,737	3,507	864	0	0	0	0	0	233
Hemlock	15,126	647	1,362	1,563	1,763	2,734	2,185	2,426	945	270	879	352	0
Tamarack	20,553	11,287	5,785	1,581	1,447	453	0	0	0	0	0	0	0
N. white-cedar	13,979	5,054	4,316	1,977	1,466	197	0	470	259	239	0	0	0
Other softwoods	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	182,643	65,259	50,157	27,078	15,546	9,262	5,153	3,842	2,232	1,260	1,262	1,359	233
HARDWOODS:													
White oak	18,257	3,174	3,339	4,202	3,254	1,593	1,227	638	410	0	217	202	0
Select red oak	61,306	9,731	6,946	8,261	7,009	7,326	6,293	4,399	4,105	3,947	1,949	1,341	0
Other red oak	31,384	5,608	6,259	4,397	4,281	3,289	1,687	2,428	1,060	829	980	567	0
Hickory	5,840	3,681	970	212	774	203	0	0	0	0	0	0	0
Yellow birch	25,894	5,526	3,793	3,061	3,472	2,930	1,471	2,397	821	612	545	1,265	0
Hard maple	51,207	9,910	8,804	6,716	5,164	3,866	5,610	3,732	2,823	1,839	2,743	0	0
Soft maple	56,459	22,759	11,606	8,911	4,401	4,149	1,945	860	927	225	274	212	191
Beech	7,922	839	304	525	535	767	1,123	2,212	844	773	0	0	0
Ash	69,111	26,122	17,413	10,890	4,776	3,967	2,196	437	525	1,221	1,115	448	0
Balsam poplar	8,557	1,494	912	1,450	1,574	1,929	861	90	0	80	168	0	0
Cottonwood	1,523	0	206	0	213	0	155	213	0	0	346	390	0
Paper birch	29,226	12,366	10,365	4,306	2,022	0	168	0	0	0	0	0	0
Bigtooth aspen	127,726	23,222	31,125	28,002	20,856	13,058	7,315	3,608	199	340	0	0	0
Quaking aspen	416,645	109,819	115,776	95,932	55,583	26,651	8,722	4,006	156	0	0	0	0
Basswood	42,377	12,435	7,860	5,876	4,884	3,155	3,883	624	1,517	639	1,200	305	0
Butternut	7,009	487	567	1,528	1,486	1,300	442	795	404	0	0	0	0
Black walnut	2,485	200	318	0	633	387	590	0	184	173	0	0	0
Black cherry	26,239	8,025	7,949	3,404	2,195	1,704	1,057	1,267	0	422	215	0	0
Elm	90,022	17,544	12,698	9,371	12,456	10,530	7,070	6,912	4,505	3,501	3,426	2,010	0
Other hardwoods	8,595	596	1,091	982	2,351	177	376	1,152	1,368	0	502	0	0
Noncommercial species	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	1,087,783	273,538	248,299	198,026	137,919	86,983	52,192	35,771	19,847	14,601	13,680	6,739	191
All species	1,270,427	338,797	298,456	225,104	153,465	96,245	57,345	39,613	22,079	15,861	14,942	8,098	423

[1] Table may not add to total due to rounding. Table includes data for the Nicolet and Chequamegon National Forests, from 1975 and 1976 respectively.

Table 20.--Net growing-stock volume of removals on commercial forest land by species and diameter class, Wisconsin, 1968-1979[1]

(In thousand cubic feet)

Species	All classes	Diameter class (inches at breast height) 5.0-6.9	7.0-8.9	9.0-10.9	11.0-12.9	13.0-14.9	15.0-16.9	17.0-18.9	19.0-20.9	21.9-22.9	23.0-28.9	29.0-38.9	39.0+
SOFTWOODS:													
White pine	84,460	4,417	5,683	7,891	9,022	12,028	7,998	10,613	8,525	4,070	8,686	5,131	395
Red pine	74,418	9,798	11,887	9,911	7,419	12,154	10,947	7,255	2,420	1,373	1,254	0	0
Jack pine	138,000	34,124	50,151	32,882	13,630	5,435	1,420	358	0	0	0	0	0
White spruce	9,130	2,366	1,848	1,509	2,004	635	305	236	227	0	0	0	0
Black spruce	13,789	7,512	4,731	1,104	442	0	0	0	0	0	0	0	0
Balsam fir	73,593	26,423	24,007	14,551	7,154	1,230	228	0	0	0	0	0	0
Hemlock	51,561	3,243	6,568	6,827	8,507	6,788	5,207	5,811	3,329	2,831	2,101	351	0
Tamarack	2,713	728	1,111	234	211	428	0	0	0	0	0	0	0
N. white-cedar	3,398	504	744	1,361	421	102	267	0	0	0	0	0	0
Other softwoods	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	451,061	89,116	106,730	76,271	48,810	38,799	26,370	24,273	14,500	8,273	12,041	5,482	395
HARDWOODS:													
White oak	42,282	3,347	3,226	6,858	9,193	5,143	6,050	5,182	1,047	1,247	990	0	0
Select red oak	204,812	14,593	15,313	18,424	19,471	26,975	32,112	23,354	19,804	13,879	16,368	4,254	264
Other red oak	7,194	2,095	941	1,539	1,102	960	389	0	0	168	0	0	0
Hickory	3,056	264	1,125	756	370	363	178	0	0	0	0	0	0
Yellow birch	25,613	1,988	2,741	4,381	3,198	4,137	2,648	2,697	418	1,220	2,045	139	0
Hard maple	120,454	15,634	21,642	22,604	7,941	10,566	9,215	7,834	7,305	4,295	9,683	3,733	0
Soft maple	74,324	23,501	22,761	11,873	5,498	3,827	1,657	2,209	1,596	693	480	228	0
Beech	2,471	292	307	161	357	585	0	226	0	243	300	0	0
Ash	39,564	12,918	8,884	8,657	3,632	1,557	1,565	1,346	414	0	591	0	0
Balsam poplar	13,064	1,767	2,524	3,450	2,333	1,403	757	408	89	116	217	0	0
Cottonwood	2,146	0	552	656	0	187	212	249	0	0	289	0	0
Paper birch	77,563	26,842	27,041	17,309	4,312	1,658	402	0	0	0	0	0	0
Bigtooth aspen	126,702	24,653	41,275	31,157	19,550	6,930	2,084	841	210	0	0	0	0
Quaking aspen	619,234	114,600	192,781	167,784	92,812	35,281	13,700	1,761	176	339	0	0	0
Basswood	51,165	5,483	15,288	12,937	3,895	4,925	3,569	1,585	776	1,000	1,708	0	0
Butternut	1,874	328	152	860	195	158	180	0	0	0	0	0	0
Black walnut	159	0	159	0	0	0	0	0	0	0	0	0	0
Black cherry	7,817	690	3,860	2,014	653	186	414	0	0	0	0	0	0
Elm	183,302	15,315	22,524	28,694	28,851	24,776	16,068	11,602	10,831	8,667	13,075	2,628	269
Other hardwoods	2,054	0	328	169	175	187	347	497	176	174	0	0	0
Noncommercial species	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	1,604,847	264,310	383,424	340,283	203,538	129,804	91,549	59,792	42,842	32,041	45,747	10,983	533
All species	2,055,908	353,426	490,155	416,554	252,348	168,603	117,919	84,065	57,342	40,314	57,788	16,465	928

[1] Table may not add to total due to rounding. Table includes data for the Nicolet and Chequamegon National Forests, from 1975 and 1976 respectively. Data presented are growing-stock removals for products.

Table 21.--Net volume of growing stock on commercial forest land by species and forest type, Wisconsin, 1979[1]

(In thousand cubic feet)

		Forest type												
Species	All types	Jack pine	Red pine	White pine	Black spruce	Balsam fir-white spruce	Northern white-cedar	Tamarack	Oak-hickory	Elm-ash-cottonwood	Maple-beech-birch	Aspen	Paper birch	Nonstocked
SOFTWOODS:														
White pine	496,926	6,604	41,791	167,877	11,439	16,891	5,467	5,910	27,352	25,254	122,257	54,195	11,890	0
Red pine	449,961	27,914	290,667	22,012	3,898	2,579	188	855	20,708	524	8,924	65,210	6,480	0
Jack pine	585,871	436,176	12,263	5,751	1,041	178	522	184	67,925	1,542	1,505	55,819	2,447	517
White spruce	154,238	0	2,729	2,618	2,593	64,714	3,577	2,099	903	12,191	13,430	42,992	5,751	640
Black spruce	145,699	909	1,152	799	62,278	23,671	16,034	19,737	0	3,592	2,551	13,828	1,149	0
Balsam fir	549,473	301	3,249	2,712	3,662	249,412	11,132	10,128	0	40,542	90,918	116,282	20,789	345
Hemlock	358,173	0	623	1,378	0	10,084	5,596	393	442	14,142	320,100	3,115	2,301	0
Tamarack	145,344	0	493	982	7,955	6,080	19,484	75,585	1,839	8,413	2,947	15,633	5,095	839
N. white-cedar	480,298	0	480	3,387	1,720	65,226	243,115	2,660	0	75,570	63,434	17,070	7,636	0
Other softwoods	1,757	301	0	0	0	0	0	0	952	0	263	241	0	0
Total	3,367,741	472,205	353,447	207,516	94,586	438,835	305,115	117,551	120,121	181,769	626,330	384,386	63,539	2,341
HARDWOODS:														
White oak	453,099	277	0	956	0	348	245	0	348,701	16,605	55,461	25,348	4,768	390
Select red oak	1,047,957	2,046	5,924	4,039	666	826	0	249	678,302	11,998	221,420	93,625	28,650	212
Other red oak	444,307	11,486	2,730	1,942	0	0	0	0	386,139	2,003	15,984	20,478	2,160	1,386
Hickory	125,806	0	0	0	0	0	157	0	91,863	904	30,813	913	781	376
Yellow birch	210,754	0	0	0	175	6,472	2,716	0	606	16,823	177,826	3,864	1,838	435
Hard maple	1,143,674	0	863	637	199	6,302	205	303	26,307	16,880	1,041,947	39,832	9,671	528
Soft maple	803,888	0	3,411	4,870	1,368	24,194	3,708	680	64,690	203,231	378,078	93,130	26,526	0
Beech	18,530	0	0	0	0	0	0	0	0	189	18,341	0	0	0
Ash	537,933	0	0	1,135	0	11,261	7,872	0	19,862	270,374	187,543	33,719	4,723	1,445
Balsam poplar	21,876	0	0	0	0	1,394	532	0	983	5,572	3,658	8,387	1,351	0
Cottonwood	23,427	0	0	776	0	0	0	0	1,464	15,626	2,582	2,455	524	0
Paper birch	921,356	2,868	3,610	5,571	3,428	35,151	15,360	5,307	103,959	36,194	203,270	227,577	278,476	586
Bigtooth aspen	493,820	7,450	1,519	2,045	1,023	2,000	0	0	98,261	6,468	48,333	313,002	13,718	0
Quaking aspen	1,634,232	15,273	18,143	14,483	11,439	28,424	11,025	3,772	91,446	58,716	210,545	1,121,711	44,151	5,103
Basswood	650,199	46	0	0	0	1,506	1,070	0	27,792	27,325	565,140	23,186	4,135	0
Butternut	14,221	0	0	0	0	0	0	0	3,550	264	8,468	1,733	206	0
Black walnut	7,136	0	0	0	0	0	0	0	5,595	0	1,540	0	0	0
Black cherry	73,280	0	0	0	0	2,566	0	255	25,339	2,432	25,820	15,778	1,090	0
Elm	702,585	249	0	2,332	0	5,424	7,369	791	43,996	164,454	436,596	34,551	5,139	1,687
Other hardwoods	34,591	0	715	0	0	0	0	0	4,624	16,230	4,307	5,364	3,351	0
Noncommercial species	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	9,362,672	39,694	36,914	38,786	18,299	125,868	50,259	11,356	2,023,479	872,287	3,637,672	2,064,654	431,257	12,148
All species	12,730,413	511,898	390,361	246,302	112,885	564,703	355,374	128,907	2,143,599	1,054,056	4,264,003	2,449,040	494,796	14,489

[1] Table may not add to total due to rounding.

Table 22.--Net volume of sawtimber on commercial forest land by species and forest type, Wisconsin, 1979[1]

(In thousand board feet)[2]

		Forest type												
Species	All types	Jack pine	Red pine	White pine	Black spruce	Balsam fir-white spruce	Northern white-cedar	Tamarack	Oak-hickory	Elm-ash-cottonwood	Maple-beech-birch	Aspen	Paper birch	Nonstocked
SOFTWOODS:														
White pine	2,740,019	38,082	188,645	952,833	57,527	90,416	30,904	35,010	154,895	143,068	686,085	301,267	61,287	0
Red pine	1,533,777	44,960	890,957	110,688	19,735	15,822	1,115	5,359	67,051	3,689	49,540	288,846	36,015	0
Jack pine	1,109,810	693,752	31,382	20,375	3,897	896	0	0	174,942	5,804	3,375	164,216	11,172	0
White spruce	528,835	0	6,143	10,759	12,385	196,475	9,971	6,431	0	44,559	56,194	158,437	24,137	3,345
Black spruce	96,958	0	689	0	24,584	26,875	4,003	19,426	0	10,553	3,585	7,241	0	0
Balsam fir	1,027,422	0	8,165	11,125	2,810	412,511	6,152	16,957	0	92,603	203,829	234,938	36,816	1,518
Hemlock	1,878,634	0	743	3,073	0	46,835	26,540	2,263	2,739	68,110	1,706,691	10,201	11,437	0
Tamarack	174,167	0	1,786	2,068	3,399	7,170	18,764	73,634	5,234	24,671	1,433	31,133	3,726	1,148
N. white-cedar	1,226,987	0	1,895	13,808	5,042	193,340	506,935	8,907	0	201,220	253,349	25,788	16,703	0
Other softwoods	1,130	1,130	0	0	0	0	0	0	0	0	0	0	0	0
Total	10,317,740	777,925	1,130,406	1,124,728	129,378	990,341	604,385	167,987	404,861	594,277	2,964,081	1,222,069	201,293	6,011
HARDWOODS:														
White oak	1,439,872	0	0	3,315	0	0	1,029	0	1,083,491	65,847	213,380	53,128	17,632	2,050
Select red oak	3,216,434	6,152	1,763	11,162	0	2,169	0	0	2,055,143	44,326	810,971	194,884	88,810	1,054
Other red oak	1,272,287	28,884	7,598	6,588	0	0	0	0	1,091,404	5,658	55,213	65,093	5,802	6,048
Hickory	162,880	0	0	0	0	0	798	0	106,537	751	51,655	977	2,162	0
Yellow birch	679,738	0	0	0	801	23,579	7,572	0	1,932	40,670	594,325	6,437	4,423	0
Hard maple	2,946,387	0	1,084	2,859	1,101	17,094	0	1,630	62,011	35,681	2,779,404	27,714	15,464	2,346
Soft maple	1,442,997	0	0	9,237	1,685	45,229	12,960	1,078	73,959	525,949	695,311	54,923	22,665	0
Beech	81,010	0	0	0	0	0	0	0	0	965	80,045	0	0	0
Ash	992,048	0	0	3,405	0	14,028	5,749	0	29,838	501,447	398,135	31,981	4,882	2,583
Balsam poplar	90,774	0	0	0	0	2,596	2,351	0	2,757	30,556	20,243	25,587	6,684	0
Cottonwood	80,837	0	0	0	0	0	0	0	4,106	55,676	9,862	9,223	1,970	0
Paper birch	821,713	0	4,139	5,453	0	26,921	14,538	4,115	89,006	49,484	291,942	141,492	194,622	0
Bigtooth aspen	999,069	16,876	4,767	4,176	3,646	3,106	0	0	238,721	16,351	119,224	558,382	33,821	0
Quaking aspen	2,734,997	6,349	46,501	35,730	20,061	45,985	13,309	1,131	132,732	134,220	559,591	1,639,354	92,021	8,013
Basswood	1,555,976	0	0	0	0	3,509	4,378	0	63,411	74,278	1,377,176	27,654	5,570	0
Butternut	44,043	0	0	0	0	0	0	0	7,214	1,196	31,637	3,996	0	0
Black walnut	22,725	0	0	0	0	0	0	0	20,759	0	1,966	0	0	0
Black cherry	90,266	0	0	0	0	4,763	0	0	44,338	2,507	24,546	14,111	0	0
Elm	2,269,495	1,026	0	6,548	0	17,457	17,451	3,653	115,202	562,324	1,443,187	85,262	9,704	7,681
Other hardwoods	108,636	0	3,572	0	0	0	0	0	7,457	62,003	15,790	15,739	4,074	0
Noncommercial species	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	21,052,186	59,287	69,424	88,473	27,294	206,438	80,134	11,607	5,230,019	2,209,890	9,573,601	2,955,936	510,307	29,774
All species	31,369,926	837,212	1,199,829	1,213,201	156,672	1,196,778	684,519	179,594	5,634,880	2,804,167	12,537,683	4,178,005	711,600	35,786

[1] Table may not add to total due to rounding.

[2] International 1/4-inch rule.

Table 23.--Net volume of growing stock on commercial forest land by forest type and stand-age class, Wisconsin, 1979[1]

(In thousand cubic feet)

Forest type	All classes	Stand-age class (years)									
		0-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100	101-120	121+
Jack pine	511,898	14,548	67,549	139,472	220,780	51,764	11,486	6,299	0	0	0	0
Red pine	390,361	17,880	80,585	158,457	26,569	13,078	38,466	38,649	3,749	5,743	7,185	0
White pine	246,302	838	7,725	7,867	13,075	30,465	25,132	49,240	17,841	25,391	29,910	38,819
Black spruce	112,885	794	4,378	8,081	19,208	34,079	22,354	18,687	3,464	1,080	759	0
Balsam fir-white spruce	564,703	17,903	40,227	55,077	105,877	178,651	107,047	24,031	14,169	3,429	16,285	2,006
Northern white-cedar	355,374	3,365	8,543	5,176	16,535	44,489	70,337	45,765	25,295	59,371	35,906	40,592
Tamarack	128,907	5,044	11,465	6,101	7,920	28,066	36,975	16,020	10,980	2,918	3,419	0
Oak-hickory	2,143,599	49,902	49,460	79,635	306,506	409,018	319,165	238,505	172,252	179,603	270,020	69,535
Elm-ash-cottonwood	1,054,056	28,983	28,488	61,650	129,028	134,981	179,563	156,122	77,959	103,252	124,392	29,635
Maple-beech-birch	4,264,003	61,170	94,862	182,039	521,172	874,108	757,040	359,626	285,838	226,146	494,340	407,662
Aspen	2,449,040	277,043	326,698	319,148	824,351	528,465	130,488	29,467	5,199	3,874	825	3,481
Paper birch	494,796	13,549	24,417	49,769	135,025	144,490	93,503	20,732	1,758	9,813	1,740	0
Nonstocked	14,489	14,489	--	--	--	--	--	--	--	--	--	--
All types	12,730,413	505,508	744,397	1,072,473	2,326,048	2,471,652	1,791,556	1,003,144	618,505	620,618	984,782	591,730

[1] Table may not add to total due to rounding.

Table 24.--Net volume of sawtimber on commercial forest land by forest type and stand-age class, Wisconsin, 1979[1]

(In thousand board feet)[2]

Forest type	All classes	Stand-age class (years)									
		0-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100	101-120	121+
Jack pine	837,212	15,265	78,231	176,982	336,368	150,881	53,984	25,502	0	0	0	0
Red pine	1,199,829	34,664	43,065	516,207	92,167	60,080	183,900	194,868	13,487	29,473	31,918	0
White pine	1,213,201	0	28,834	27,891	44,318	116,658	116,623	248,944	97,584	141,084	173,017	218,247
Black spruce	156,672	0	3,745	2,872	6,668	58,356	28,060	51,440	4,010	0	1,520	0
Balsam fir-white spruce	1,196,778	38,498	92,914	112,066	218,391	378,663	204,267	43,283	41,497	17,996	47,291	1,912
Northern white-cedar	684,519	1,172	9,927	4,180	43,912	79,374	87,529	53,216	45,485	115,987	92,303	151,435
Tamarack	179,594	3,895	10,074	5,564	6,795	29,936	60,503	31,812	19,218	4,787	7,010	0
Oak-hickory	5,634,880	98,406	61,872	75,354	455,675	743,035	831,980	759,448	607,818	690,752	1,043,621	266,920
Elm-ash-cottonwood	2,804,167	64,380	52,003	98,819	251,538	306,363	470,671	440,945	265,100	322,419	413,356	118,571
Maple-beech-birch	12,537,683	159,041	137,398	332,431	939,585	1,909,844	1,897,145	1,136,310	1,070,982	880,415	2,107,945	1,966,587
Aspen	4,178,005	430,227	369,271	483,683	1,282,592	1,117,751	380,532	74,562	13,104	16,300	1,211	8,771
Paper birch	711,600	4,520	26,481	59,644	137,071	218,705	169,646	47,141	4,614	37,961	5,817	0
Nonstocked	35,786	35,786	--	--	--	--	--	--	--	--	--	--
All types	31,369,926	885,852	913,815	1,895,690	3,815,080	5,169,647	4,484,842	3,107,472	2,182,899	2,257,175	3,925,010	2,732,443

[1] Table may not add to total due to rounding.

[2] International 1/4-inch rule.

Table 25.--Net volume of all live trees on commercial forest land by tree class and species, Wisconsin, 1979[1]

(In thousand cubic feet)

Species	All classes	Tree class: Desirable	Acceptable	Rough cull	Short-log cull	Rotten cull
SOFTWOODS:						
White pine	525,006	26,211	470,715	17,302	8,708	2,070
Red pine	453,147	16,641	433,319	2,405	529	253
Jack pine	616,064	5,353	580,517	26,029	2,295	1,869
White spruce	155,152	0	154,238	665	200	49
Black spruce	147,030	1,597	144,103	1,035	106	190
Balsam fir	552,472	1,335	548,138	2,453	117	429
Hemlock	366,835	19,041	339,132	3,891	2,249	2,522
Tamarack	148,925	1,535	143,810	1,735	1,190	657
N. white-cedar	500,544	4,255	476,043	9,366	3,719	7,161
Other softwoods	2,332	0	1,757	451	0	124
Total	3,467,508	75,968	3,291,773	65,332	19,113	15,322
HARDWOODS:						
White oak	544,778	12,087	441,012	58,156	28,781	4,742
Select red oak	1,115,306	66,721	981,236	39,331	20,451	7,567
Other red oak	600,068	9,163	435,144	115,039	30,704	10,018
Hickory	133,873	3,232	122,574	5,596	1,332	1,138
Yellow birch	233,347	8,577	202,177	8,589	3,874	10,131
Hard maple	1,264,949	38,245	1,105,429	70,896	27,237	23,141
Soft maple	903,752	20,472	783,416	67,433	16,087	16,344
Beech	24,985	498	18,032	2,484	2,764	1,207
Ash	567,116	20,886	517,047	21,252	5,093	2,838
Balsam poplar	24,586	1,781	20,095	1,080	556	1,074
Cottonwood	26,486	945	22,482	886	1,635	539
Paper birch	974,797	17,267	904,089	42,685	4,463	6,292
Bigtooth aspen	506,412	39,706	454,114	7,443	1,733	3,416
Quaking aspen	1,762,798	36,431	1,597,801	87,358	6,180	35,028
Basswood	701,185	51,087	599,112	30,999	12,180	7,807
Butternut	23,891	254	13,967	6,857	1,601	1,212
Black walnut	9,859	574	6,562	2,103	192	428
Black cherry	102,006	1,245	72,035	24,924	1,515	2,288
Elm	796,920	26,740	675,845	56,405	31,574	6,355
Other hardwoods	43,369	1,508	33,083	6,662	1,439	677
Noncommercial species	38,976	0	0	38,700	0	276
Total	10,399,459	357,419	9,005,253	694,877	199,392	142,518
All species	13,866,967	433,386	12,297,026	760,209	218,505	157,840

[1] Table may not add to total due to rounding.

Table 26.--Periodic growth of growing stock on commercial forest land by component and forest type, Wisconsin, 1968-1979[1]

(In thousand cubic feet)

Forest type	Component							
	Survivor growth	Growth on mortality	Growth on removals[2]	Growth on ingrowth	Ingrowth	Mortality	Net growth	Removals[2]
Jack pine	147,592	9,286	28,465	34,044	84,097	-26,390	277,093	132,295
Red pine	86,125	3,283	11,352	31,892	50,782	-11,415	172,018	45,127
White pine	67,553	1,742	4,522	1,524	5,715	-11,678	69,378	33,559
Black spruce	22,473	2,591	1,921	3,706	22,993	-9,576	44,109	11,004
Balsam fir-white spruce	158,741	11,006	10,825	12,845	50,975	-56,124	188,267	80,074
Northern white-cedar	65,057	4,378	1,003	3,477	27,842	-29,880	71,879	15,304
Tamarack	31,525	2,809	827	3,794	14,366	-15,117	38,204	3,274
Oak-hickory	466,324	29,117	36,286	17,832	63,198	-206,000	406,757	330,993
Elm-ash-cottonwood	248,791	17,424	18,904	10,653	42,626	-109,481	228,917	155,328
Maple-beech-birch	895,184	55,916	44,568	32,157	179,888	-362,137	845,576	389,240
Aspen	810,435	116,324	186,479	95,657	208,509	-402,121	1,015,284	779,949
Paper birch	133,823	6,777	15,791	11,942	35,607	-29,943	173,999	78,583
Nonstocked	4,220	132	289	1,352	2,337	-564	7,766	1,176
All types	3,137,843	260,785	361,232	260,877	788,936	-1,270,427	3,539,247	2,055,908

[1] Table may not add to total due to rounding. Table includes data for the Nicolet and Chequamegon National Forests, from 1975 and 1976 respectively.

[2] Data presented are growing-stock removals for products.

Table 27.--Periodic growth of growing stock on commercial forest land by component and species, Wisconsin, 1968-1979[1]

(In thousand cubic feet)

Species	Component							
	Survivor growth	Growth on mortality	Growth on removals[2]	Growth on ingrowth	Ingrowth	Mortality	Net growth	Removals[2]
SOFTWOODS:								
White pine	148,400	1,971	13,381	1,917	8,697	-12,585	161,781	84,460
Red pine	109,352	1,324	17,173	42,640	62,854	-1,866	231,477	74,418
Jack pine	173,483	9,896	31,210	33,911	89,725	-28,506	309,720	138,000
White spruce	54,979	1,639	3,463	8,679	11,919	-5,401	75,277	9,130
Black spruce	26,145	1,368	1,622	5,397	31,001	-6,792	58,742	13,789
Balsam fir	177,223	13,918	14,725	17,831	59,455	-77,836	205,315	73,593
Hemlock	65,328	1,588	4,773	176	1,055	-15,126	57,793	51,561
Tamarack	30,157	4,055	325	2,787	12,588	-20,553	29,360	2,713
N. white-cedar	108,831	3,004	372	4,989	31,255	-13,979	134,472	3,398
Other softwoods	365	0	0	207	745	0	1,316	0
Total	894,263	38,763	87,044	118,534	309,293	-182,643	1,265,253	451,061
HARDWOODS:								
White oak	92,478	2,495	3,946	948	5,188	-18,257	86,799	42,282
Select red oak	232,064	7,861	21,561	3,891	19,099	-61,306	223,169	204,812
Other red oak	90,784	3,371	1,108	2,540	12,084	-31,384	78,502	7,194
Hickory	17,764	687	194	308	2,557	-5,840	15,670	3,056
Yellow birch	36,184	2,791	2,159	657	2,680	-25,894	18,577	25,613
Hard maple	223,997	8,319	13,538	12,189	69,962	-51,207	276,797	120,454
Soft maple	155,233	8,654	9,254	11,270	67,102	-56,459	195,054	74,324
Beech	3,443	514	194	79	656	-7,922	-3,037	2,471
Ash	94,235	6,760	4,128	3,162	25,517	-69,111	64,692	39,564
Balsam poplar	6,114	1,959	2,422	162	259	-8,557	2,360	13,064
Cottonwood	5,169	212	231	62	714	-1,523	4,865	2,146
Paper birch	230,548	4,205	10,303	16,807	53,589	-29,226	286,226	77,563
Bigtooth aspen	151,505	20,190	24,482	8,048	14,967	-127,726	91,466	126,702
Quaking aspen	568,932	127,491	151,424	67,823	141,181	-416,645	640,206	619,234
Basswood	144,421	6,033	5,308	3,629	20,900	-42,377	137,913	51,165
Butternut	3,367	807	161	0	0	-7,009	-2,674	1,874
Black walnut	1,751	403	6	0	0	-2,485	-325	159
Black cherry	15,228	4,212	1,079	2,765	8,765	-26,239	5,810	7,817
Elm	162,194	14,399	22,453	7,732	32,789	-90,022	149,544	183,302
Other hardwoods	8,170	661	237	273	1,633	-8,595	2,379	2,054
Noncommercial species	0	0	0	0	0	0	0	0
Total	2,243,580	222,023	274,188	142,343	479,644	-1,087,783	2,273,994	1,604,847
All species	3,137,843	260,785	361,232	260,877	788,936	-1,270,427	3,539,247	2,055,908

[1] Table may not add to total due to rounding. Table includes data for the Nicolet and Chequamegon National Forests, from 1975 and 1976 respectively.

[2] Data presented are growing-stock removals for products.

Table 28.--Average annual growth of growing stock on commercial forest land by component and forest type, Wisconsin, 1968-1979[1]

(In thousand cubic feet)

Forest type	Component							
	Survivor growth	Growth on mortality	Growth on removals[2]	Growth on ingrowth	Ingrowth	Mortality	Net growth	Removals[2]
Jack pine	15,397	845	2,619	3,107	7,683	-2,413	27,237	12,684
Red pine	12,199	342	1,136	2,951	4,855	-1,416	20,068	5,125
White pine	6,141	158	411	139	520	-1,062	6,307	3,051
Black spruce	2,355	249	182	351	2,322	-1,088	4,371	1,151
Balsam fir-white spruce	16,492	1,058	1,124	1,195	4,998	-6,509	18,358	10,099
Northern white-cedar	7,364	420	127	333	3,141	-3,285	8,099	2,902
Tamarack	2,993	262	77	345	1,306	-1,487	3,496	324
Oak-hickory	43,292	2,672	3,309	1,621	5,745	-18,997	37,643	30,884
Elm-ash-cottonwood	23,189	1,593	1,729	968	3,875	-10,308	21,047	14,397
Maple-beech-birch	90,819	5,295	4,164	3,008	18,990	-36,837	85,439	36,182
Aspen	78,708	10,669	17,181	8,797	19,944	-38,198	97,101	74,502
Paper birch	12,994	618	1,439	1,096	3,312	-2,775	16,684	7,235
Nonstocked	384	12	26	123	212	-51	706	107
All types	312,326	24,192	33,525	24,035	76,903	-124,425	346,557	198,642

[1] Table may not add to total due to rounding. Table includes data for the Nicolet and Chequamegon National Forests, from 1975 and 1976 respectively.

[2] Data presented are growing-stock removals for products.

Table 29.--Average annual growth of growing stock on commercial forest land by component and species, Wisconsin, 1968-1979[1]

(In thousand cubic feet)

Species	Component							
	Survivor growth	Growth on mortality	Growth on removals[2]	Growth on ingrowth	Ingrowth	Mortality	Net growth	Removals[2]
SOFTWOODS:								
White pine	14,443	190	1,235	174	791	-1,234	15,598	7,948
Red pine	13,931	120	1,645	3,965	6,156	-170	25,648	7,323
Jack pine	17,732	900	2,862	3,083	8,157	-2,592	30,141	13,144
White spruce	6,154	166	335	798	1,279	-618	8,114	979
Black spruce	2,741	125	174	501	3,228	-680	6,088	2,307
Balsam fir	17,209	1,315	1,387	1,645	5,569	-8,576	18,550	8,100
Hemlock	6,734	158	442	16	96	-1,536	5,909	4,853
Tamarack	3,069	377	30	253	1,144	-2,043	2,830	250
N. white-cedar	11,250	286	41	465	3,133	-1,472	13,704	405
Other softwoods	33	0	0	19	68	0	120	0
Total	93,295	3,638	8,150	10,920	29,621	-18,923	126,701	45,309
HARDWOODS:								
White oak	8,407	227	359	86	472	-1,660	7,891	3,844
Select red oak	22,449	720	1,962	357	1,919	-5,692	21,714	18,660
Other red oak	8,253	306	101	231	1,099	-2,853	7,137	654
Hickory	1,615	62	18	28	232	-531	1,425	278
Yellow birch	3,928	275	200	60	244	-2,802	1,904	2,419
Hard maple	23,697	806	1,247	1,146	7,503	-5,444	28,955	11,432
Soft maple	15,261	799	848	1,035	6,884	-5,532	19,294	6,977
Beech	319	47	18	7	60	-720	-270	225
Ash	9,017	640	376	296	2,729	-7,149	5,910	3,677
Balsam poplar	564	178	223	15	24	-778	225	1,261
Cottonwood	470	19	21	6	65	-138	442	195
Paper birch	22,511	388	949	1,528	4,872	-2,876	27,371	7,523
Bigtooth aspen	14,642	1,894	2,258	752	1,450	-12,483	8,513	12,106
Quaking aspen	54,716	11,741	14,033	6,241	13,466	-39,922	60,275	60,874
Basswood	14,571	571	491	331	2,114	-4,274	13,805	4,857
Butternut	315	73	15	0	0	-637	-234	174
Black walnut	159	37	1	0	0	-226	-30	14
Black cherry	1,498	389	98	251	797	-2,531	503	711
Elm	15,897	1,322	2,138	720	3,206	-8,473	14,810	17,266
Other hardwoods	743	60	22	25	148	-781	216	187
Noncommercial species	0	0	0	0	0	0	0	0
Total	219,032	20,554	25,375	13,115	47,282	-105,503	219,856	153,333
All species	312,326	24,192	33,525	24,035	76,903	-124,425	346,557	198,642

[1] Table may not add to total due to rounding. Table includes data for the Nicolet and Chequamegon National Forests, from 1975 and 1976 respectively.

[2] Data presented are growing-stock removals for products.

Table 30.--Periodic growth of sawtimber on commercial forest land by component and forest type, Wisconsin, 1968-1979[1]

(In thousand board feet)[2]

Forest type	Component							
	Survivor growth	Growth on mortality	Growth on removals[3]	Growth on ingrowth	Ingrowth	Mortality	Net growth	Removals[3]
Jack pine	94,876	19,562	98,405	226,952	307,391	-34,692	712,494	271,599
Red pine	192,679	4,016	35,295	99,547	200,703	-15,476	516,764	137,241
White pine	321,019	6,546	28,411	45,563	57,989	-31,845	427,683	162,916
Black spruce	30,340	448	5,355	13,767	18,646	-6,151	62,405	24,093
Balsam fir-white spruce	219,266	27,633	40,481	191,136	264,314	-96,272	646,558	190,845
Northern white-cedar	106,151	5,230	3,287	63,087	85,370	-30,278	232,848	30,248
Tamarack	32,161	8,229	1,248	32,038	41,844	-15,664	99,855	3,638
Oak-hickory	782,534	78,334	133,709	514,233	654,479	-435,946	1,727,343	1,120,626
Elm-ash-cottonwood	505,305	45,024	80,952	263,702	338,280	-224,219	1,009,044	443,084
Maple-beech-birch	2,144,363	164,095	158,208	803,698	1,093,773	-866,736	3,497,400	1,073,898
Aspen	671,995	194,102	390,956	921,557	1,220,438	-413,928	2,985,121	935,889
Paper birch	117,909	9,580	39,769	124,655	161,513	-31,730	421,696	134,630
Nonstocked	7,524	593	2,468	5,564	7,081	-2,422	20,808	3,436
All types	5,226,122	563,391	1,018,544	3,305,498	4,451,821	-2,205,359	12,360,018	4,532,144

[1] Table may not add to total due to rounding. Table includes data for the Nicolet and Chequamegon National Forests, from 1975 and 1976 respectively.

[2] International 1/4-inch rule.

[3] Data presented are growing-stock removals for products.

Table 31.--Periodic growth of sawtimber on commercial forest land by component and species, Wisconsin, 1968-1979[1]

(In thousand board feet)[2]

Species	Component							
	Survivor growth	Growth on mortality	Growth on removals[3]	Growth on ingrowth	Ingrowth	Mortality	Net growth	Removals[3]
SOFTWOODS:								
White pine	827,831	12,813	90,436	64,716	83,104	-64,679	1,014,222	466,579
Red pine	271,044	1,795	67,462	132,338	249,406	-3,577	718,469	321,710
Jack pine	132,984	25,877	102,688	283,956	379,941	-44,911	880,534	263,669
White spruce	118,843	5,779	8,362	81,691	119,449	-15,095	319,029	23,039
Black spruce	10,475	193	2,032	15,293	21,464	-5,091	44,366	7,307
Balsam fir	163,907	25,140	35,808	239,624	315,814	-112,105	668,187	104,334
Hemlock	327,548	8,031	27,843	36,479	50,231	-75,153	374,979	239,091
Tamarack	30,541	3,268	525	25,146	32,064	-14,652	76,892	3,579
N. white-cedar	236,795	4,578	1,754	109,103	145,911	-22,974	475,167	9,855
Other softwoods	0	0	0	497	633	0	1,130	0
Total	2,119,968	87,472	336,911	988,843	1,398,017	-358,237	4,572,974	1,439,164
HARDWOODS:								
White oak	179,509	6,920	15,402	110,398	140,507	-39,412	413,323	142,255
Select red oak	476,982	27,555	81,576	277,903	362,976	-182,643	1,044,350	770,236
Other red oak	157,577	12,352	5,541	10[illegible]7	137,208	-77,554	342,930	15,333
Hickory	12,176	102	212	2[illegible]80	29,883	-4,196	61,658	4,322
Yellow birch	100,198	8,080	7,535	24,785	34,171	-67,080	107,690	80,025
Hard maple	510,110	28,474	36,930	151,219	203,552	-132,542	797,744	310,693
Soft maple	193,891	11,800	12,139	131,974	177,075	-67,627	459,253	78,814
Beech	11,781	1,507	561	4,604	6,837	-31,234	-5,944	8,741
Ash	117,261	7,388	4,548	98,166	124,939	-75,391	276,912	46,035
Balsam poplar	19,501	8,352	7,994	7,546	9,605	-26,091	26,908	29,258
Cottonwood	13,124	651	320	5,245	6,675	-6,002	20,013	4,396
Paper birch	96,300	4,686	8,416	164,692	215,402	-10,398	479,098	30,462
Bigtooth aspen	137,882	51,499	51,661	182,827	240,894	-229,460	435,303	143,440
Quaking aspen	379,277	219,308	326,299	690,200	905,416	-457,360	2,063,139	702,057
Basswood	238,035	18,785	10,811	143,360	199,607	-83,931	526,667	87,081
Butternut	5,075	2,389	181	5,667	7,213	-24,041	-3,517	3,065
Black walnut	3,201	2,778	0	1,685	2,145	-9,712	97	0
Black cherry	10,162	4,009	594	15,485	19,709	-34,614	15,345	6,171
Elm	429,275	54,706	109,904	159,790	217,491	-256,625	714,540	621,823
Other hardwoods	14,836	4,578	1,007	9,822	12,501	-31,210	11,533	8,774
Noncommercial species	0	0	0	0	0	0	0	0
Total	3,106,154	475,919	681,633	2,316,656	3,053,805	-1,847,122	7,787,044	3,092,980
All species	5,226,122	563,391	1,018,544	3,305,498	4,451,821	-2,205,359	12,360,018	4,532,144

[1] Table may not add to total due to rounding. Table includes data for the Nicolet and Chequamegon National Forests, from 1975 and 1976 respectively.

[2] International 1/4-inch rule.

[3] Data presented are growing-stock removals for products.

Table 32.--Average annual growth of sawtimber on commercial forest land by component and forest type, Wisconsin, 1968-1979[1]

(In thousand board feet)[2]

Forest type	Component							
	Survivor growth	Growth on mortality	Growth on removals[3]	Growth on ingrowth	Ingrowth	Mortality	Net growth	Removals[3]
Jack pine	9,495	1,781	9,043	21,374	33,291	-3,217	71,766	27,231
Red pine	27,738	449	3,621	12,010	36,157	-2,078	77,896	16,081
White pine	29,184	595	2,583	4,142	5,272	-2,895	38,880	14,811
Black spruce	3,601	99	488	1,297	1,931	-1,175	6,241	2,223
Balsam fir-white spruce	23,958	2,900	4,753	18,218	29,401	-11,537	67,692	23,764
Northern white-cedar	12,561	556	324	5,938	9,134	-3,851	24,663	3,387
Tamarack	3,087	770	123	2,955	4,028	-1,753	9,211	483
Oak-hickory	71,320	7,121	12,155	46,748	59,498	-39,631	157,212	101,875
Elm-ash-cottonwood	46,601	4,106	7,406	24,079	31,444	-21,317	92,319	41,751
Maple-beech-birch	215,553	15,384	14,400	75,899	116,859	-85,665	352,430	97,850
Aspen	65,745	17,721	35,973	85,680	123,331	-39,318	289,133	87,895
Paper birch	11,300	871	3,624	11,447	15,284	-2,885	39,640	12,475
Nonstocked	684	54	224	506	644	-220	1,892	312
All types	520,826	52,408	94,717	310,293	466,275	-215,543	1,228,975	430,138

[1] Table may not add to total due to rounding. Table includes data for the Nicolet and Chequamegon National Forests, from 1975 and 1976 respectively.

[2] International 1/4-inch rule.

[3] Data presented are growing-stock removals for products.

Table 33.--Average annual growth of sawtimber on commercial forest land by component and species, Wisconsin, 1968-1979[1]

(In thousand board feet)[2]

	Component							
Species	Survivor growth	Growth on mortality	Growth on removals[3]	Growth on ingrowth	Ingrowth	Mortality	Net growth	Removals[3]
SOFTWOODS:								
White pine	80,147	1,224	8,324	5,913	7,710	-6,347	96,971	43,888
Red pine	33,142	163	6,494	15,270	42,391	-325	97,135	32,156
Jack pine	12,916	2,352	9,402	26,556	39,886	-4,083	87,030	26,116
White spruce	13,088	587	817	8,046	14,109	-1,568	35,080	2,528
Black spruce	1,124	18	207	1,470	2,449	-463	4,805	1,125
Balsam fir	16,231	2,605	3,822	22,218	31,520	-13,773	62,624	11,474
Hemlock	33,895	803	2,577	3,468	5,365	-7,715	38,393	22,684
Tamarack	2,910	304	48	2,288	2,927	-1,552	6,926	325
N. white-cedar	25,698	508	211	10,201	15,195	-3,276	48,537	1,247
Other softwoods	0	0	0	45	58	0	103	0
Total	219,151	8,564	31,904	95,474	161,611	-39,100	477,604	141,543
HARDWOODS:								
White oak	16,319	629	1,400	10,036	12,773	-3,583	37,575	12,932
Select red oak	44,328	2,527	7,416	25,635	35,637	-17,263	98,279	70,021
Other red oak	14,325	1,123	504	9,801	12,473	-7,050	31,175	1,394
Hickory	1,107	9	19	2,135	2,717	-381	5,605	393
Yellow birch	10,500	956	704	2,358	3,746	-6,589	11,675	7,659
Hard maple	52,257	2,615	3,357	14,191	21,239	-12,564	81,095	28,245
Soft maple	18,907	1,084	1,104	12,362	18,539	-6,428	45,568	7,169
Beech	1,071	137	51	458	827	-2,839	-296	795
Ash	11,316	682	413	8,924	11,358	-7,565	25,128	4,185
Balsam poplar	1,785	759	1,052	686	873	-2,372	2,784	2,985
Cottonwood	1,193	59	29	477	607	-546	1,819	400
Paper birch	9,436	426	786	15,204	21,164	-945	46,070	3,328
Bigtooth aspen	13,322	4,689	4,739	16,949	24,241	-21,206	42,734	13,636
Quaking aspen	37,002	20,143	30,042	63,825	89,001	-45,058	194,955	67,682
Basswood	24,054	1,750	997	13,719	22,354	-8,616	54,257	8,124
Butternut	497	217	17	515	656	-2,186	-284	287
Black walnut	291	253	0	153	195	-883	9	0
Black cherry	1,012	371	54	1,408	1,792	-3,429	1,207	561
Elm	41,606	4,999	10,038	15,091	23,337	-24,103	70,968	58,000
Other hardwoods	1,349	416	92	893	1,136	-2,837	1,048	798
Noncommercial species	0	0	0	0	0	0	0	0
Total	301,675	43,843	62,813	214,818	304,663	-176,442	751,371	288,594
All species	520,826	52,408	94,717	310,293	466,275	-215,543	1,228,975	430,138

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[1] Table may not add to total due to rounding. Table includes data for the Nicolet and Chequamegon National Forests, from 1975 and 1976 respectively.

[2] International 1/4-inch rule.

[3] Data presented are growing-stock removals for products.

Table 34.--All live tree biomass on commercial forest land by species and component, Wisconsin, 1979[1]

(In thousand green tons)

Species	All components	Component				
		Growing-stock boles	Growing-stock tops and limbs	Cull boles	Cull tops and limbs	1- to 5-inch trees
SOFTWOODS:						
White pine	19,173	11,140	5,214	741	556	1,523
Red pine	22,354	11,991	6,582	122	141	3,517
Jack pine	37,851	17,383	8,280	1,202	1,368	9,619
White spruce	5,934	3,100	1,545	25	37	1,226
Black spruce	11,674	2,734	1,339	33	38	7,530
Balsam fir	33,155	14,108	6,817	105	147	11,978
Hemlock	15,112	9,157	4,356	296	319	983
Tamarack	8,098	3,769	2,075	107	145	2,002
N. white-cedar	18,943	8,079	4,276	434	484	5,670
Other softwoods	149	46	21	18	15	49
Total	172,442	81,508	40,504	3,083	3,250	44,097
HARDWOODS:						
White oak	32,954	16,246	7,245	3,667	2,807	2,990
Select red oak	60,561	37,025	16,951	2,611	2,027	1,946
Other red oak	37,682	16,013	7,372	6,126	4,435	3,736
Hickory	8,533	4,572	1,952	330	255	1,423
Yellow birch	14,127	6,845	3,377	880	953	2,072
Hard maple	83,817	36,346	16,864	4,224	3,325	23,058
Soft maple	54,849	22,064	10,071	2,999	2,311	17,404
Beech	1,217	539	239	208	149	81
Ash	29,731	15,545	7,400	943	784	5,059
Balsam poplar	990	529	270	73	56	62
Cottonwood	1,132	657	309	86	41	39
Paper birch	52,830	26,025	12,642	1,613	1,185	11,364
Bigtooth aspen	20,779	12,920	5,888	376	275	1,320
Quaking aspen	80,908	42,095	20,467	3,705	2,814	11,828
Basswood	29,237	17,071	7,489	1,453	912	2,311
Butternut	1,159	435	191	308	167	58
Black walnut	440	217	95	85	42	0
Black cherry	6,100	2,252	977	907	449	1,515
Elm	40,955	21,627	9,725	3,123	2,201	4,280
Other hardwoods	2,158	1,016	452	297	235	158
Noncommercial species	8,994	0	0	1,218	672	7,105
Total	569,155	280,040	129,977	35,233	26,093	97,812
All species	741,597	361,548	170,481	38,316	29,343	141,909

[1] Table may not add to total due to rounding.

Table 35.--All live tree biomass on commercial forest land by forest type and stand-age class, Wisconsin, 1979[1]

(In thousand green tons)

Forest type	All classes	Stand-age class (years) 0-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100	101-120	121+
Jack pine	34,437	1,837	6,345	9,711	13,055	2,618	597	274	0	0	0	0
Red pine	20,716	1,969	5,236	7,665	1,218	625	1,541	1,606	387	199	270	0
White pine	10,705	149	530	418	720	1,514	1,111	1,875	814	1,101	1,075	1,398
Black spruce	10,228	91	319	763	1,991	2,948	2,278	982	381	80	395	0
Balsam fir-white spruce	30,991	1,105	2,430	3,923	6,463	9,223	5,127	1,083	641	123	793	79
Northern white-cedar	18,131	367	634	501	1,017	2,698	3,917	2,306	1,084	3,109	1,355	1,143
Tamarack	7,703	455	1,055	593	508	1,599	1,943	804	523	110	113	0
Oak-hickory	131,644	4,721	4,952	5,836	18,174	22,821	22,417	15,889	9,602	10,473	13,365	3,394
Elm-ash-cottonwood	55,127	2,682	2,630	4,620	7,613	7,183	8,774	7,236	3,585	4,357	5,344	1,102
Maple-beech-birch	249,856	5,483	8,923	13,468	36,882	51,415	41,544	19,918	15,474	12,511	25,115	19,123
Aspen	140,103	21,382	24,471	17,405	41,620	26,452	6,754	1,446	228	164	33	148
Paper birch	28,136	1,337	2,399	3,064	7,618	7,369	4,753	993	56	463	83	0
Non-stocked	3,821	3,821	--	--	--	--	--	--	--	--	--	--
All types	741,597	45,400	59,925	67,969	136,879	136,464	100,755	54,412	32,774	32,690	47,940	26,388

[1] Table may not add to total due to rounding.

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Raile, Gerhard K., and W. Brad Smith.
1982. A simulated inventory update: Wisconsin's 1979 tim[illegible] U.S. Department of Agriculture Forest Service, Research Paper NC-209, 40 p. U.S. Department of Agriculture Forest Service, North Central Forest Experiment Station, St. Paul, Minnesota.

Presents Wisconsin timber resource statistics that were update[illegible] the tree growth projection subsystem of the Forest Resour[illegible]tion Program (FREP).

KEY WORDS: Lake States, volume, growth, mortality, [illegible], FREP.

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Fertilization of Black Spruce on Poor Site Peatland in Minnesota

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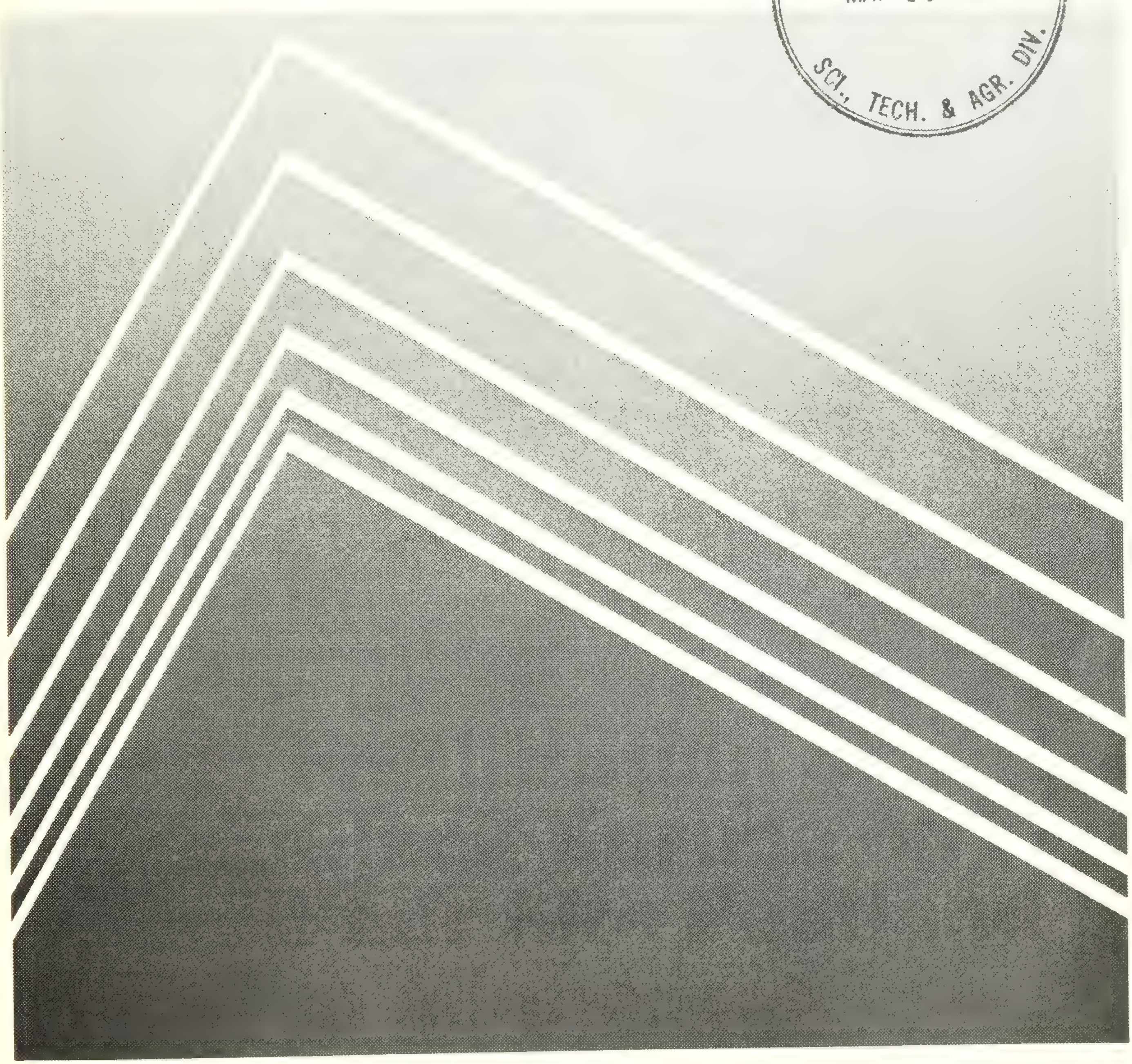

Alban, David H., and Richard F. Watt.

1981. Fertilization of black spruce on poor site peatland in Minnesota. U.S. Department of Agriculture Forest Service, Research Paper NC-210, 10 p. U.S. Department of Agriculture Forest Service, North Central Forest Experiment Station, St. Paul, Minnesota.

Fertilization of poor site black spruce on organic soil with various rates of nitrogen and phosphorus increased height and diameter growth from 2 to 4 times. The growth response declined with time but was still apparent 16 years after fertilization. Shrub biomass and coverage, and nutrient levels of spruce foliage were strongly affected by fertilization.

KEY WORDS: foliar nutrients, nitrogen, *Picea mariana,* phosphorus, shrubs.

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FERTILIZATION OF BLACK SPRUCE ON POOR SITE PEATLAND IN MINNESOTA

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As population pressures force forestry to the poorer sites, organic soils will become more important for forestry purposes in the United States. In northern Europe, Scandinavia, and Great Britian a significant portion of trees are already grown on organic soils (Holopainen 1967). These soils are often fertilized to increase forest growth, and in some cases, to convert nonproductive to productive forests (Heikurainen 1967, Baule and Fricker 1970).

On organic soils low levels of phosphorus (P) and potassium (K) most often limit growth, but levels of nitrogen (N) frequently are also low, particularly on low pH soils (Huikari 1973). It is not uncommon for two or more elements to be deficient on organic soils (Heikurainen 1967, O'Hare 1967), and drainage in combination with fertilization can result in significant growth increases (Braekke 1977).

Black spruce (*Picea mariana* (Mill.) B.S.P.) growth has been enhanced by fertilization on both organic soils (Haveraaen 1967, Watt 1966) and mineral soils (Weetman 1975, Van Nostrand 1979). The current study reports on the long term growth and nutrient response of black spruce and understory species to fertilization.

THE STUDY AREA

The two stands we studied are located in northern Minnesota (48° 22′N, 93° 46′W) about 24 km north of the town of Big Falls and were previously described by Watt (1966). They are separated by about 1.2 km and have nearly identical vegetation dominated by uneven-aged black spruce (mean age prior to treatment of 80 years but ranging up to 135 years). The site index is poor (only 4.6 m at age 50), and the stands are noncommercial. The ground is almost completely covered with sphagnum moss, and the predominant shrubs are *Ledum groenlandicum* Oeder (Labrador-tea) and *Chamaedaphne calyculata* (L.) *Moench* (leather-leaf) with lesser numbers of *Andromeda glaucophylla* Link. (bog-rosemary), *Kalmia polifolia* Wang (swamp laurel), and *Vaccinium oxycoccos* L. (small cranberry).

The vegetation is similar to that classified as the sphagnum-black spruce-leatherleaf community by Heinselman (1963). This community type typically has a convex land surface and occupies the central part of large peatlands where it is isolated from mineral soils and water tracks.

The study area is a nearly level lacustrine plain. The soils are woody peats about 150 cm thick over loamy mineral soil and are classified as the Moose lake series (*Typic Borohemists*), (Soil Survey Staff 1975). The bulk density of the peat ranges from 0.06 to 0.12 g/cc and the pH ranges from 3.2 (in 0.01M $CaCl_2$) near the surface to about 4.9 near the interface between peat and mineral soil.

In 1973 when the first mensurational measurements other than height growth were made, the trees on the control plots had the following characteristics: 3,980 trees/ha, mean d.b.h. 5.3 cm, mean height 4.4 m, and stand basal area 8.8 m^2/ha. The largest trees on the control plots were about 9 m tall and 12 cm d.b.h. Tree and stand characteristics a decade earlier (prior to fertilization) would not be a great deal different because of the extremely slow growth and low mortality.

METHODS

Plots of 0.04 ha with 3 m buffer strips were laid out and fertilized by hand during the growing season in two separate trials (table 1). The major objective of trial 1 was to determine if the trees would respond to N or P, which had been shown by foliar analysis to be the elements limiting growth (Watt and Heinselman 1965). There were 12 plots in trial 1—3 were used as controls, 3 received only N, 3 received only P, and 3 received both N and P. The plots were fertilized equally in 1962 and 1963 with ammonium nitrate and treble superphosphate. The major objective in trial 2 was to determine the optimum rate of N and P fertilization. The 24 plots in this trial were fertilized in 1964 with various rates of diammonium phosphate, phosphoric acid, and ammonium sulfate.

In October of the year of fertilization and for the next 4 or 5 years height growth of 10 sample trees on each 0.04 ha plot was measured to the nearest cm. Thereafter height growth was measured every other year until 1973, and a final measurement was taken (for trial 1 only) in March of 1980. Each time height growth was measured, about 2 grams of current-year foliage was collected from three additional trees per plot and used for physical measurements and chemical analysis.

In 1973, 36 trees (trial 1) and 48 trees (trial 2) representing the full range of heights and diameters were felled and 2 cm discs at b.h. were cut to determine age and diameter increment by 5-year intervals for the last 20 years. The current year's diameter growth was also measured but because of the very small increments, large errors are involved in this measurement.

Table 1.—*Fertilizer rates*[1]

Treatment	Plots	Nutrient added N	Nutrient added P
TRIAL 1			
	no.	*kg/ha*	*kg/ha*
Control	3	0	0
NP	3	672	294
N	3	672	0
P	3	0	294
TRIAL 2			
Control	6	0	0
P_1 N_1	3	56	49
P_1 N_2	3	112	49
P_1 N_3	3	336	49
P_2 N_1	3	56	122
P_2 N_2	3	112	122
P_2 N_3	3	336	122

[1] Trial 1 fertilized equally in 1962 and 1963 with ammonium nitrate and treble superphosphate; trial 2 fertilized in 1964 with diammonium phosphate, phosphoric acid, and ammonium sulfate.

In 1964 three and in 1973 four 1-m^2 subplots were established on each 0.04 ha plot on trial 1. Each understory shrub species was identified and its coverage estimated. All above-ground portions of the shrubs were clipped to determine oven-dry weight and nutrient content. On each understory plot, live and dead sphagnum coverage was estimated and a sample of sphagnum moss was collected for nutrient analysis.

All vegetation samples were dried at 75 C to determine oven-dry weight. Chemical analysis was by emission spectroscopy for P, Ca, Mg, K, Fe, Mn, Cu, Zn, and B. Nitrogen was digested by the Kjeldahl method followed either by titration or specific ion determination with an ammonia electrode. Foliage samples collected in 1980 were analyzed for metals by atomic absorption spectroscopy and N as before.

Statistical comparisons were by Duncan's new multiple range test and significance testing was all at the 5 percent level.

RESULTS AND DISCUSSION

Height Growth

Height growth responded rapidly and dramatically to fertilization on both trials (figs. 1 and 2). Maximum height growth response occurred in the first or second year following fertilization at which time the height growth for the maximum treatment in trial 1 (NP) was three times the control and in trial 2 was 2½ times the control. (The two P levels in trial 2 resulted in no significant differences—hence they are combined for all analyses.) In 1973, the NP and PN_3 treatments still had height growth rates two to three times greater than the controls and in 1980 the NP treatment of trial 1 shows little evidence of slow down in height growth.

Fertilization with N or P alone resulted in an initial height growth response about ½ as large as for the NP treatment but still significantly greater than the control (fig. 1). Within a few years the height growth of the N and P treatments fell to levels no different from the control and for N this low level of growth has continued up to the last measurement period. Initially, height growth surged in the P-treated plots, then it declined, and then steadily increased. By 1979, height growth on the NP and P plots do not significantly differ (fig. 1). Obviously, N availability increases slowly over a long time on the plots fertilized with P only. In the current study the long term increase in height growth on the P-treated plots is probably due to movement of N

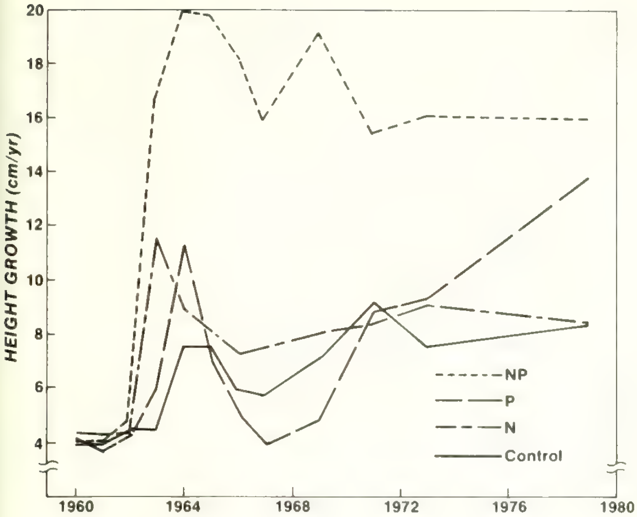

Figure 1.—*Black spruce height growth response to fertilization with nitrogen (N) and phosphorus (P)—trial 1.*

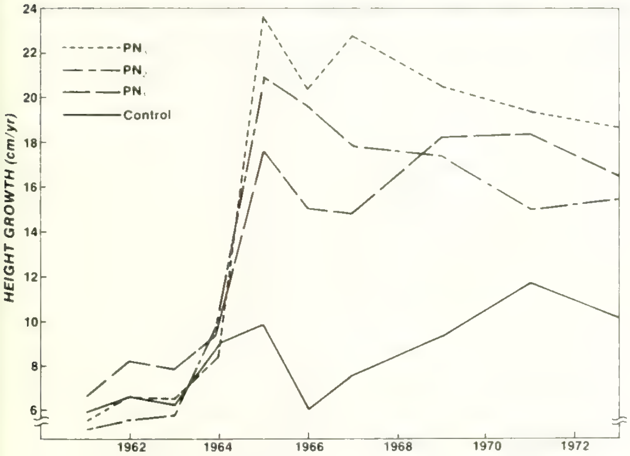

Figure 2.—*Black spruce height growth response to fertilization with nitrogen (N) and phosphorus (P)—trial 2.*

between the plots. By chance, every P plot was downslope from either a N or a NP plot. Thus, it is likely that N moved in the soil water and "contaminated" the P plots resulting in accelerated growth. Other possible sources of N increase on the P-only plots include increased N fixation or increased peat decomposition due to P addition. We have no measurements on these effects but it seems likely that each would be maximum soon after fertilization and decline thereafter. Thus these effects could play a role in the initial height growth increase on the P only plots but are probably not involved in the long-term height growth increase.

The initial height growth response of the P plots was 1 year later than the N or NP plots which again suggests movement of N across plot boundaries. One of the control plots was also immediately downslope from a NP plot and this control plot behaved similarly to the P plots, i.e., a 1 year delay in response and the magnitude of the initial Presponse was similar to that of the N or P plots. Because of its obvious contamination, we excluded this control plot from the analysis.

In trial 2 the initial response to N was directly related to the amount applied (fig. 2), although the differences between rates were less striking than between any of the rates and the controls. Part of the reason for the small differences between rates may be leakage between plots as was found in the P plots in trial 1. At the end of 9 years all three rates of N resulted in height growth still significantly greater than the controls.

For both trials we planned to use the control plots to show annual variations in height growth due to climatic factors. However, this effect may be masked by the nutrient leakage from plot to plot. In both trials height growth in the controls increased slightly shortly after fertilization followed by a decrease and then by a gradual increase. Part of this change may be climate related but most is probably due to contamination of the control plots from the fertilizer plots. Therefore, the height growth of the controls is greater than that of bonafide controls and the growth differential reported here between fertilizer and control plots is conservative.

The height of sample trees prior to fertilization was significantly related to annual height growth for the 3 years prior to fertilization. This relation was weakened by fertilization with N and P combined—the greater the amount of fertilizer applied, the poorer the relation. For the heaviest fertilizer treatment (NP trial 1) the height growth for any of the years 1963 through 1979 was not significantly related to height before fertilization. For lower levels of fertilization the relation was nonsignificant for the first few years following fertilization but became significant as the fertilizer effects began to lessen. With heavy fertilizer rates, all tree sizes responded equally (the longest single year's leader growth—49 cm—occurred on the NP treatment plot on a tree whose height before fertilization was only 2 m). With low fertilizer rates, height growth of the taller trees responded somewhat better than that of smaller trees.

Tree height and age were closely related (r = 0.70 trial 1, 0.79 trial 2), thus the height growth response was related to age in a manner similar to that for initial tree height. That is, heavy fertilization resulted in a height growth response that was not closely related to age. Young trees (about 40 years) responded as well as older trees (about 80 years). Therefore, fertilizers probably could have been used to increase growth at a much earlier age. With lower fertilizer rates or with time the height growth response of the older trees became larger than that of the younger trees.

Diameter Growth

Diameter growth on trial 1 was increased markedly by NP fertilization but no significant response occurred for N or P alone (fig. 3). Diameter growth on the NP plot was three times that of the controls during the first 5 years following fertilization. Thereafter it declined but even 10 years after fertilization the diameter growth of the NP plot was significantly greater than the controls. On trial 2 the maximum diameter growth response was somewhat less and the decline after the first 5 years was more rapid (fig. 4). Both PN_3 and PN_2 treatments resulted in diameter growth significantly greater than the controls for the first 5 years following fertilization, but only PN_3 was still significantly greater than the control after 9 years. Nine years after fertilization none of the fertilized treatments resulted in growth different from the controls (fig. 4). PN_2 had lower diameter growth than PN_1 prior to fertilization and a stronger response after the treatment. Both return to pretreatment levels by 9 years, however. It is clear that the maximum diameter growth response and its duration are directly related to the amount of N applied, increasing in the order PN_1, PN_2, PN_3 (trial 2) up to NP (trial 1). But the response to N only occurred when P was added also. Height growth followed a similar pattern but the duration of its response was longer.

Diameter growth of the control plots and all other plots prior to fertilization was directly related to d.b.h., but after fertilization such a relation no longer existed. Average diameter growth for 5 years after NP fertilization (trial 1) was 1.55 mm/yr irrespective of tree d.b.h., and the corresponding value for the PN_3 treatment was 2.00 mm/yr again irrespective of tree d.b.h.

Because basal area and volume are functions of diameter squared, it is obvious that the larger trees are increasing in these properties at a much faster rate than the smaller trees and that the heavily fertilized trees are increasing at rapid rates. For example, using the 1964 average and largest d.b.h. trees on trial 1, the 5-year volume growth after NP fertilization was 4½ times greater for the largest trees compared with the average trees (table 2).

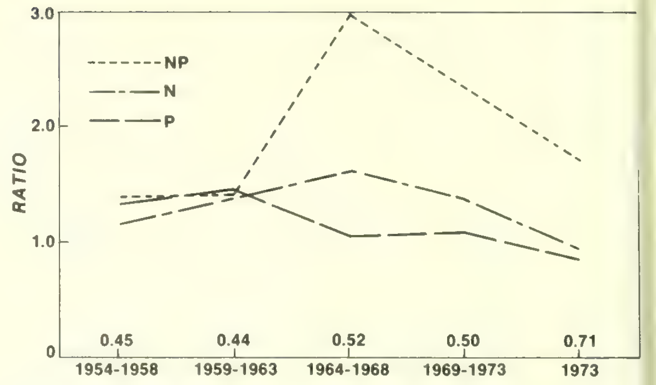

Figure 3.—*Ratio of diameter growth of black spruce on fertilized plots to that on controls (trial 1). The figures above the years are the diameter growth of the controls (mm/yr).*

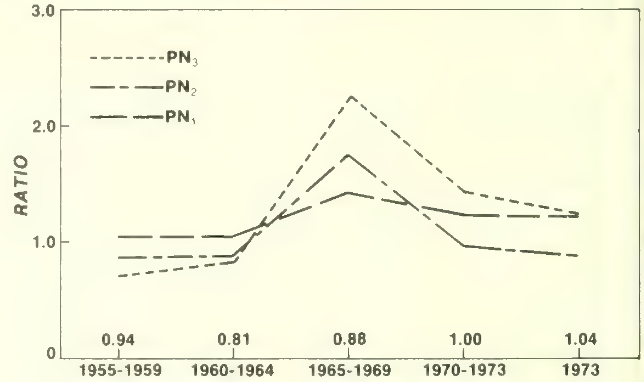

Figure 4.—*Ratio of diameter growth of black spruce on fertilized plots to that on controls (trial 2). The figures above the years are the diameter growth of the controls (mm/yr).*

For both fertilized and unfertilized trees volume growth is much greater for the larger trees than for the smaller. Assuming that the average d.b.h. tree represents average stand growth, volume growth for the first 5 years following maximum fertilization (NP or PN_3) increased 3 times over that of the controls on both trials. During the second 5-year period, height and diameter growth response to fertilization tapered off but because the increased growth is on larger trees, the final result is fertilization increasing volume growth by three and two times over the controls for trials 1 and 2, respectively.

Table 2.—*Five-year growth for average (4.8 cm) and largest (11.0 cm) d.b.h. trees on trial 1*

Treatment	Initial D.b.h.	Five-year growth 1964-1968 D.b.h.	Height	Volume
	cm	cm	m	dm^3
Control	4.8	0.26	0.38	0.7
	11.0	0.41	0.64	5.2
NP Fertilization	4.8	0.78	0.90	2.0
	11.0	0.78	0.90	8.9

Foliar Characteristics

In general, all fertilizer treatments in trial 2 and the NP treatment in trial 1 resulted in increased needle length and weight (table 3). In 1973 (10 and 9 years after fertilization for trials 1 and 2, respectively) foliage weight was still significantly greater than the controls for all plots fertilized with both N and P, and for trial 2 needle lengths were still significantly greater than the controls (table 3). Sixteen years after fertilization the NP treatment of trial 1 still had significantly larger and heavier needles than the controls (table 3). At this time the P-only fertilizer treatment had needles no different in length or weight than the NP treatment and this is probably due to N leakage into the P plots from upslope plots.

It was the relation between site index and foliar concentrations of N and P that initially suggested the possibility of nutritional deficiencies in poor site black spruce stands (Watt and Heinselman 1965). The application of fertilizers resulted in dramatic increases in foliar levels of these nutrients (figs. 5-8). In trial 1 application of NP or N alone significantly increased foliar N levels above those of the controls from 1963 to 1965; from 1966 onward foliar levels of all treatments were not significantly different (fig. 5). Foliar P levels were significantly greater than that of the controls for application of NP or P alone until 1973, but by 1979 only the NP treatment was still significantly greater than the controls (fig. 6).

For trial 2 foliar N level was directly related to rate of N application for the first 2 years following fertilization (fig. 7). In 1965, all three rates of N fertilization resulted in significantly higher N levels in black spruce foliage than the controls; by 1966 only at the two higher rates were foliar levels still above the controls and after that no differences were significant. P levels in the foliage were significantly higher than the controls for all fertilizer treatments from 1965 to 1973 (fig. 8).

Foliar levels of K, Ca, Mg, and Fe in 1973 were not significantly affected by fertilization but foliar levels of Mn, Cu, and Zn were all significantly lower than the controls (table 4). A similar depression of Mn, Cu, and Zn levels in Scotch pine (Pinus sylvestris L.) needles on peatlands was reported after fertilization with NPK (Veijalainen 1977). Addition of macronutrients may stimulate foliage growth and thereby reduce the level of micronutrients by simple dilution. But nutrient interactions may also be involved and high levels of foliar P (as found after fertilization in this study) are commonly associated with low levels of foliar B and Zn (Olsen 1972). Only rarely do micronutrients limit tree growth (Stone 1968) but

Table 3.—*Black spruce foliage characteristics*

TRIAL 1

Treatment[1]	Needle length 1964	1965	1966	1973	1979	Needle weight 1964	1965	1966	1973	1979
	mm					mg				
Control	7.5	7.0	7.3	6.3	5.4	1.38	1.35	1.32	1.29	1.62
NP	11.1[2]	10.2[2]	9.1[2]	6.8	6.9[2]	1.46	1.81[2]	1.49	1.42[2]	2.09[2]
N	6.8	7.4	6.8	5.9	5.9	1.08	1.51	1.20	1.21	1.71
P	8.3	7.1	6.8	6.5	6.7[2]	1.22	1.02[2]	1.05[2]	1.32	1.92[2]

TRIAL 2

Treatment[1]	Needle length 1964	1965	1966	1973	1979	Needle weight 1964	1965	1966	1973	1979
Control		6.7		6.1		1.54	1.37	1.40		
PN_3		10.7[2]		7.2[2]		2.26[2]	2.08[2]	1.65[2]		
PN_2		9.8[2]		7.1[2]		2.05[2]	1.45	1.65[2]		
PN_1		8.7[2]		7.0[2]		2.04[2]	1.62[2]	1.56[2]		

[1] See table 1 for fertilizer rates.

[2] Indicates values significantly different from the control at the 5 percent level.

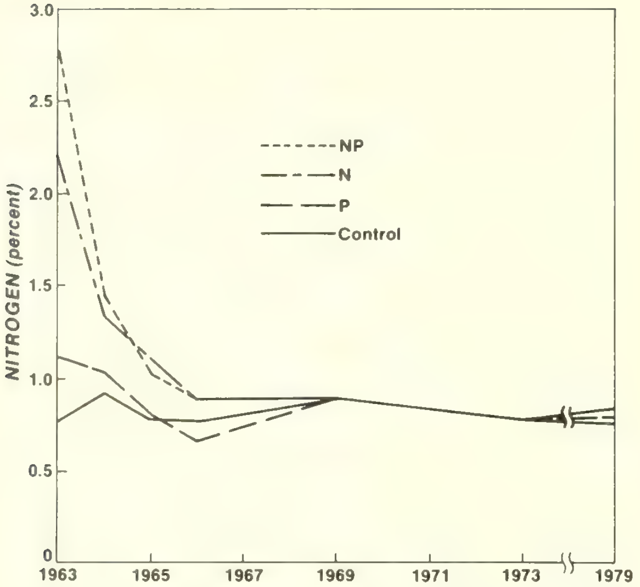

Figure 5.—*Foliar nitrogen concentration of black spruce on trial 1.*

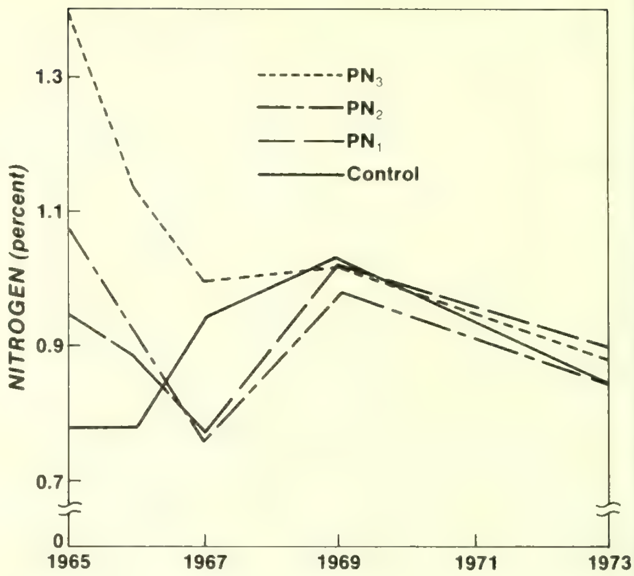

Figure 7.—*Foliar nitrogen concentration of black spruce on trial 2.*

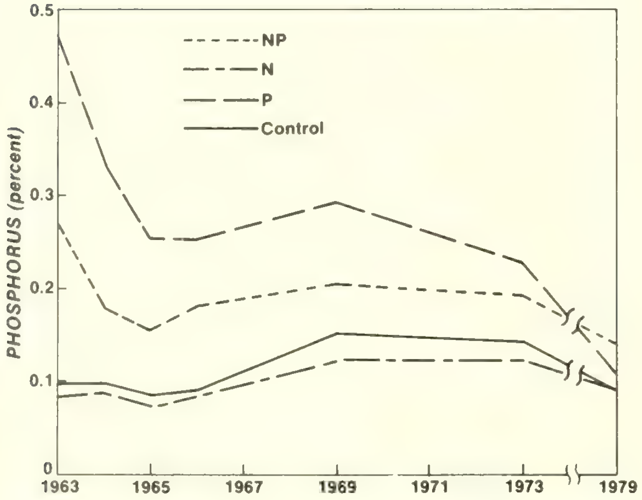

Figure 6.—*Foliar phosphorus concentration of black spruce on trial 1.*

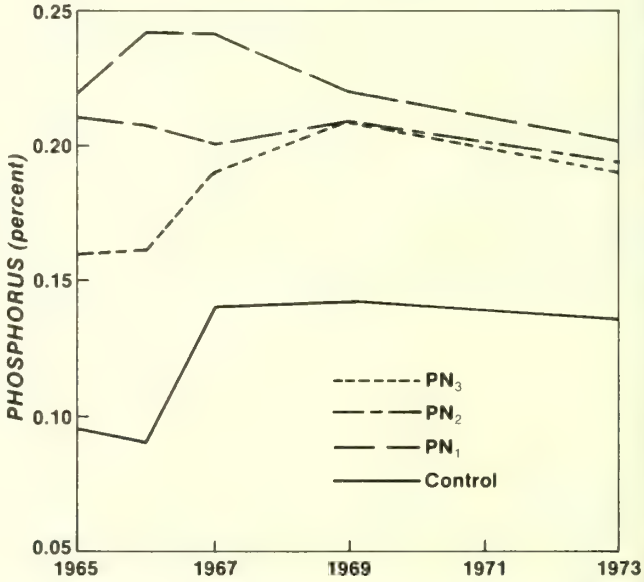

Figure 8.—*Foliar phosphorus concentration of black spruce on trial 2.*

Table 4.—*Black spruce foliage nutrient concentration in 1973*

(In ppm)

	Trial 1		Trial 2	
Element	Control	NP fertilizer treatment	Control	Mean of all fertilizer treatments
N	7,500	7,720	8,380	8,720
P	1,450	1,960[1]	1,350	1,960[1]
K	5,700	5,260	5,070	5,750
Ca	5,390	4,920	4,730	4,820
Mg	932	1,170	1,160	1,350
Fe	43	47	66	70
Mn	1,423	977[1]	1,282	909[1]
Cu	54	45[1]	52	40[1]
Zn	31	22[1]	28	21[1]

[1] Indicates values significantly different from the control at the 5 percent level.

when they do, it will be extremely difficult to diagnose by foliar analysis due to the strong effect macronutrients exert on foliage micronutrient levels (Veijalainen 1977).

For the control plots mean black spruce foliar concentrations (1963-1966) of N and P averaged 0.80 and 0.093 percent, respectively. These values indicate acute deficiency levels for these elements (Swan 1970). The other macronutrients (K, Ca, and Mg) were not measured until 1969 but because they showed no significant changes with time or between treatments, the average values (0.54, 0.51, 0.10) from 1973 (table 3) probably represent prefertilizer levels as well. These values indicate moderate deficiency of Mg but adequate levels of K and Ca (Swan 1970).

The low levels of N and P indicated a likely response to fertilization by these elements. But the accelerated growth due to fertilization has continued long after the foliar N concentrations returned to levels no different from the controls (figs. 5 and 7). Conversely, high foliar levels of P if not accompanied by N fertilization have not resulted in a long term growth response. The only plots showing a long term growth response were those fertilized with both N and P (although for trial 1 the P plots received their N inadvertently through seepage). Obviously, increased growth can continue without commensurate increases in the foliar concentration of the fertilizer element, and increased foliar nutrient levels are not necessarily translated into increased growth.

A major effect of fertilization is often to increase the foliage biomass (Fornes *et al.* 1970, Brix and Ebell 1969). The increased foliage is not only able to photosynthesize more carbohydrates but also contains more N and P which can be translocated to active growing regions of the tree. In the current study total foliage biomass was not measured but the longer, heavier needles suggest the likelihood of increased foliage biomass.

The Understory

Before fertilization live sphagnum moss covered 86 percent of the ground surface of trial 1. One year after fertilization with NP, N, and P live sphagnum covered 66, 39, and 37 percent, respectively. However, by 1973 sphagnum covered an average of 90 percent on all plots.

In trial 1 in 1964 shrub biomass was approximately double that of the controls on the NP and N fertilized plots but was the same as the controls on the P fertilized plots (table 5). By 1973 shrub biomass was still significantly greater on the NP fertilized plot than on the controls but more striking was the coverage response of *Ledum* and *Chamaedaphne*. On the NP and P fertilizer plots *Ledum* coverage was about three times as great as on the controls, while *Chamaedaphne* coverage was reduced to about ⅓ of the controls (table 5). Nitrogen fertilization alone did not significantly change the coverage of these shrub species but appeared to favor *Kalmia*.

Thus not only has NP fertilization significantly increased the shrub biomass, but it has also reversed the relative coverages of *Ledum* and *Chamaedaphne*. Heinselman (1963) found *Chamaedaphne* to be an indicator of black spruce site index because it occurred on the poorest peatlands but never occurred on the better ones. Therefore fertilization with NP has changed the understory species coverage from that indicating poor black spruce site to that indicating good black spruce site.

The chemical composition of the shrub leaves and the sphagnum still showed the effects of fertilization 10 years after treatment (table 6). Fertilization with NP or P resulted in higher levels of macronutrients than in the controls whereas N fertilization resulted in no significant differences from the controls. Levels of K, Ca, and Mg in understory tissue is consistently higher for the NP and P fertilizer treatment than for the controls or the N treatment indicating that the understory may be more responsive to fertilization than black spruce foliage.

Table 5.—*Shrub biomass and coverage, Trial 1*

Treatment[1]	Above-ground shrub biomass		Shrub coverage in 1973		
	1964	1973	Ledum groenlandicum	Chamaedaphne calyculata	Kalmia polifolia
	kg/ha		percent		
Control	153	532	12	38	4
NP	388[2]	841[2]	41[2]	12[2]	3
N	304[2]	698	17	36	9
P	161	790	39[2]	17[2]	3

[1] See table 1 for fertilizer rates.

[2] Indicates values significantly different from the control at the 5 percent level.

Table 6.—*Chemical composition of understory plants on trial 1 in 1973 (1964 values in parentheses)*

(In percent)

SPHAGNUM

Treatment[1]	Nutrient					
	N	P	K	Ca	Mg	Mn
Control	0.66(0.88)	0.09(.06)	0.43	0.39	0.08	0.076
NP	.80(1.40)[2]	.13(.30)[2]	.49	.48	.12[2]	.067
N	.66(1.46)	.08(.12)	.37	.35	.09	.067
P	.74(1.30)	.14(.28)[2]	.47	.50	.11[2]	.077
SHRUB LEAVES						
Control	1.13	0.14	0.37	0.58	0.12	0.16
NP	1.32	.17[2]	.42	.68[2]	.20[2]	.11[2]
N	1.24	.14	.37	.58	.13	.14
P	1.22	.18[2]	.40	.70[2]	.18[2]	.12[2]

[1] See table 1 for fertilizer rates.

[2] Indicates values significantly different from control at the 5 percent level.

Mn was the only micronutrient to show a significant change due to fertilization. This occurred in shrub leaves, but it should be realized that the shrub foliage data are confounded because species composition changed on fertilized plots. The lower Mn concentration in shrub foliage after NP or P fertilization agrees with the results from black spruce foliage. But the lower concentration of Mn is also due to the fact that *Chamaedaphne* foliage has much higher Mn concentrations than does *Ledum* (Gerloff *et al.* 1964) and *Chamaedaphne* decreased markedly after fertilization with NP or P. Micronutrient concentrations in the control plots were as follows:

	Micronutrient concentrations	
	Sphagnum	**Shrub leaves**
	(ppm)	
Fe	521	120
Zn	62	32
Cu	4.4	2.8
B	6.0	20.3

Part of the reason for the long-lasting effect of forest fertilization on tree growth may be because the added nutrients are incorporated into the nutrient cycling regime. Nutrient cycling occurs primarily through the leaf litterfall of overstory and understory plants, both of which are at least temporarily enriched in N and P by fertilization (tables 4 and 6, figs. 5-8). Unfortunately, we have no measurements of tree litterfall on the study area, but from our data for the understory shrubs it is clear that they play only a minor role in nutrient cycling. The maximum total accumulated N and P in the shrubs of trial 1 in 1973 was in the NP plot and represented only 1 percent of the applied N and 0.3 percent of the applied P.

The sphagnum moss is a much larger nutrient sink, and the death of a large part of the sphagnum after fertilization released nutrients previously tied up in the living moss. This nutrient release may have contributed to the initial growth response (e.g., height growth, fig. 1) to fertilization with N or P individually. We estimate the accumulation of N and P in the sphagnum in the control plots at the time of fertilization to have been 132 and 18 kg/ha, respectively. The release of part of these nutrients (through sphagnum death) after fertilization would ensure that each fertilizer plot received both N and P, each of which appears necessary to increase growth.

SUMMARY AND CONCLUSIONS

Fertilization with N and P in combination dramatically increased the height and diameter growth of black spruce. The effects are long lasting, particularly for the heaviest fertilizer rate in which height growth was several times greater than the controls even after 16 years. Foliar nutrient concentrations responded rapidly to fertilization but by 9 to 10 years only foliar P was still significantly greater than on the controls. Shrub biomass was increased by fertilization and *Ledum* increased markedly at the expense of *Chamaedaphne*. Sphagnum was killed by the fertilizer treatments and its death may have contributed significant amounts of nutrients to the site. Within 10 years sphagnum coverage had returned to prefertilizer levels.

All the evidence points to fertilization as having improved the site. The average annual height growth for all plots fertilized with N and P has been about 17 cm/yr. This is excellent growth for 85-year-old black spruce. Based on limited data from this study it appears that a similar height growth response could be obtained with younger trees. Assuming that an average annual height growth of 17 cm could be obtained at age 40 by fertilization, this would correspond to a site index of 10 m at age 50 (Gevorkiantz 1957), which is about average for black spruce on organic soils. Thus, fertilization may have the potential to convert some marginally nonproductive muskeg sites into commercial forest stands.

Clearly much more work is needed to better define the kinds of sites that will respond to fertilization, to evaluate fertilizer movements off of the application site, and to determine the impacts of drainage in combination with fertilization.

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