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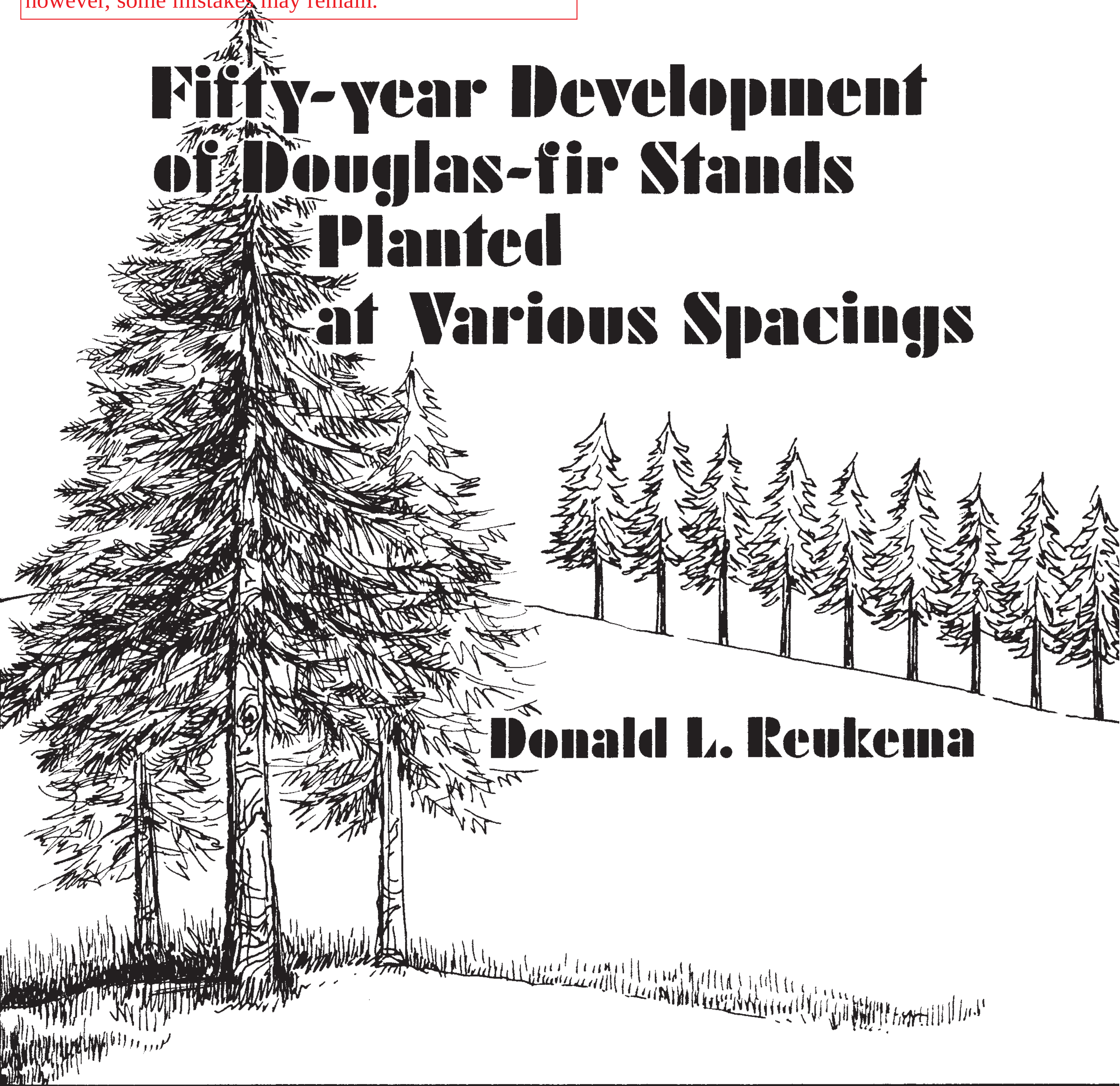
Fifty-year Development of Douglas-fir Stands Planted at Various Spacings



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PACIFIC NORTHWEST FOREST AND RANGE EXPERIMENT STATION
U.S. DEPARTMENT OF AGRICULTURE FOREST SERVICE

CONTENTS

METRIC CONVERSION FACTORS

1 inch . . . . . . .2.54 centimeters
1 foot . . . . . . .0.3048 meters
1 acre . . . . . . .0.4047 hectares
1 tree/acre . . . .2.471 trees/hectare
1 square foot/acre.0.2296 square meters/hectare
1 cubic foot/acre .0.06997 cubic meters/hectare

Fifty-Year Development of Douglas-fir Stands Planted at Various Spacings

Reference Abstract

Reukema, Donald L.
1979. Fifty-year development of Douglas-fir stands planted at various spacings. USDA For. Serv. Res. Pap. PNW-253, 21 p., illus. Pacific Northwest Forest and Range Experiment Station, Portland, Oregon.

A 51-yr record of observations in stands planted at six spacings, ranging from 4 to 12 ft, illustrates clearly the beneficial effects of wide initial spacing and the detrimental effects of carrying too many trees relative to the size to which they will be grown. Not only are trees larger, but yields per acre are greater at wide spacings.

KEYWORDS: Plantation spacing (-growth, stand density, stand development, *Douglas-fir, Pseudotsuga menziesii*.

Research Summary

Research Paper PNW-253

1979

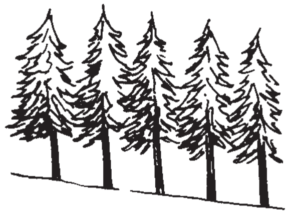
A 51-yr record of observations in Douglas-fir stands planted on site IV land at six different spacings-ranging from 4 to 12 ft (1.2 to 3.7 m)--illustrates very clearly the beneficial effects of wide initial spacing. It also illustrates the detrimental effects of carrying too many trees relative to the size to which they will be grown. Primarily as a result of initial spacing, average site index is currently 50 percent higher at the widest spacing than at the closest spacings. Differences between wide and close spacings by all measures of production are closely related to these differences in site index. Thus, not only are trees larger, but yield per acre is greater at wide spacings. Furthermore, most of this volume is contained in merchantable-size trees at wide spacings, whereas much of it is in submerchantable trees at closer spacings.

At age 53 (from seed), the 100 largest trees per acre (250/ha) are about 75 percent larger in d.b.h. and 60 percent taller at 12-ft than at 4-ft spacing. Corresponding diameters and heights are 13.6 vs. 7.8 inches (34.5 vs. 19.8 cm) and 95 vs. 60 ft (29 vs. 18 m). Gross volume production of the total stand to age 53 ranges from about 4,230 to 6,680 ft^3 per acre (296 to 467 3/ha), at 4- and 10-ft (1.2- and 3.0-m) spacings; corresponding volumes in live trees are 3,550 and 6,420 ft^3 per acre (248 and 449 m^3/ha). Volumes of the 100 largest trees per acre (250/ha) range from about 850 to 3,8840 ft^3 per acre (59 to 269 m^3/ha), at 4- and 12-ft spacings. *Total* yield is nearly as great at 12- as at 10-ft spacing; *merchantable* yield is greater at the 12-ft spacing.

Whereas current annual volume increment.(c.a.i.) of the total stand has declined with increasing age, c.a.i. of the 100 largest trees per acre has tended to remain nearly constant over the past 24 years. Mean annual increment (m.a.i.) is near culmination at close spacings, but is still far short of culmination at wide spacings.

The impact of mortality has been minor at wide spacings. At close spacings, however, much mortality was the result of snow and ice damage, which affected groups of trees and created openings in the crown canopy. This has reduced occupancy of the site and caused a further *indirect* loss in usable production.

These trends indicate that differences--in favor of wide spacings--will continue to increase.



INTRODUCTION

A Douglas-fir spacing trial established in 1925 at Wind River Experimental Forest, near Carson, Washington, has been observed periodically for over 50 years. These observations have provided an increasingly valuable record of long-term effects of initial spacing on subsequent stand development. Earlier results were reported by Isaac (1937), Munger (1946), Eversole (1955), Reukema (1959, 1970), and Curtis and Reukema (1970). This paper updates previously published information by 10 years. It also provides more information on stand components, growth trends, and relationships between the 100 largest trees per acre and the total stand.

THE STUDY

Study Area

Wind River Experimental Forest lies just north of the Columbia River Gorge, which bisects the Cascade Range. The climate of the area is wet, with average precipitation about 100 inches (250 cm) per year. The average annual snowfall is about 80 inches (200 cm). Most precipitation falls during 9 months of the year; summers are quite dry. The frost-free season averages about 120 days.

The spacing test plantations occupy a site IV alluvial flat at an elevation of about 1,300 feet (400 m). Felled old growth on the area was accidentally burned in 1920, after which all usable material was salvaged. A reburn in 1924 destroyed all reproduction and burned all duff and small debris down to mineral soil. Some spots were burned very heavily. Subsequent analyses showed that this heavy burning had reduced the moisture-holding capacity and released nitrogen from the soil.[1]

Soils are generally 5 to 10 feet (1.5 to 3.0 m) deep, well-drained and slightly acid. Surface soils are sandy loams; subsoils are loam, silt loam, or clay loam, with O to 30 percent small shot and gravel.[2] Soils are underlain by an olivine basalt flow. Despite the apparent uniformity of the site, there are local variations in site quality.

Treatment

In the spring of 1925, 1+1 seedlings were planted in 2.8-acre (l.l-ha) blocks at square spacings of 4, 5, 6, 8, and 10 feet (1.2, 1.5, 1.8, 2.4, and 3.0 m). Surplus seedlings were planted in a 0.5-acre (0.2-ha) block at 12-ft (3.7-m) spacing. These seedlings were started in the Wind River Nursery. Source(s) of seed is unknown, but it appears to be compatible with the planting site.

Extra seedlings were held in the nursery for subsequent replacement of seedlings which died.

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[1] Progress Report No. 2, Spacing in Douglas-fir plantations. Leo Isaac and George Meagher, 1936. Unpubl. On file at Forestry Sciences Laboratory, Olympia, Washington.

[2] Soil survey Wind River Douglas-fir spacing study on Gifford Pinchot National Forest. LeRoy C. Meyer, 1971. Unpubl. Report on file at Forestry Sciences Laboratory, Olympia, Washington.

All seedlings which died were replaced annually for the first 5 years (table 1). The first year, 36 percent of the seedlings were replaced. Many seedlings subsequently planted were to replace initial replacements, as there were spots--on ashy or shallow soil--where mortality occurred repeatedly; unfortunately, we do not have a record of these locations. Likewise, all volunteer seedlings were removed annually during the first 5 years. The stand was cleaned again in 1945--at age 21.

Table 1--Replacements during the first 5 years to maintain spacing, Wind River spacing test[1]

Year	Percent	Number	Suspected principal cause of mortality
1926	36	7200	Drought
1927	17	3300	Drought
1928	5	1000	Drought
1929	4	730	Stock too large
1930	3	630	Shoestring fungus

[1]From progress report No. 2, Spacing in Douglas-fir Plantations. Leo Isaac and George Meagher. 1936. Unpubl.

Stands have not been thinned. At all six spacings tested, the stands have now passed the ages at which they would have been thinned if they had been managed intensively. They have been maintained without thinning, however, to provide information on the long-term consequences of carrying stands at higher densities than we believe to be desirable.

Sampling and Measurements

Different sampling systems were used as the study progressed, introducing some inconsistencies in reported results. At ages 7, 12, and 17 (years from seed germination), seedling heights were measured on selected rows of trees throughout each spacing, At age 23 (1945), three 1/4-acre (0.10-ha) plots were established in each spacing, except the 12-ft (3.7-m) spacing which contains a single 0.4-acre (0.16-ha) plot (fig. 1). In that year, diameters at breast height (d.b.h.) were measured on all trees on plots in the 8- through 12-ft (2.4- to 3.7-m) spacings, but on only a systematic sample of rows on plots in the 4- through 6-ft (1.2- to 1.8-m) spacings. In 1951 (age 29), plot 17 was added in the 8-ft spacing to substitute for plot 12, which was observed to be on poorer

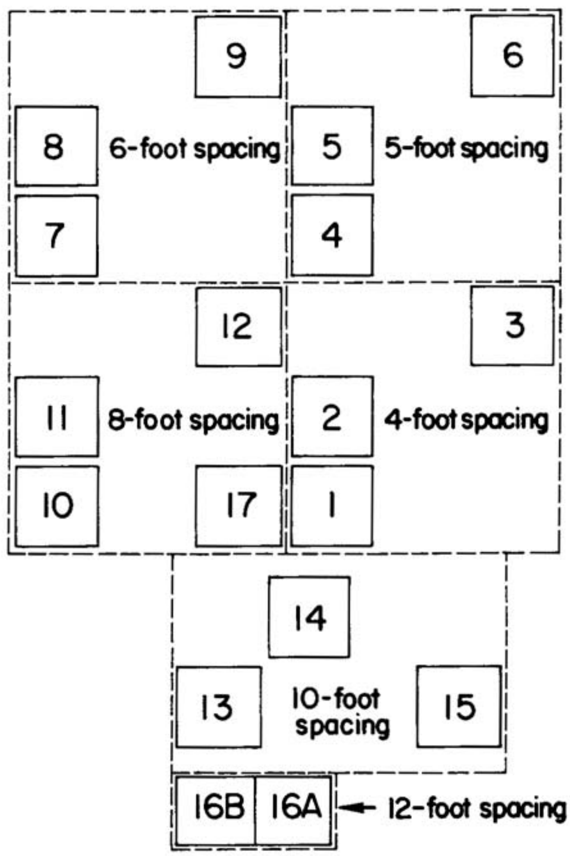

Figure 1.--Layout of Wind River Douglas-fir spacing trial (Plot 17 was added in 1951).

quality site. No measurements were made on plot 12 between 1951 and 1970; however, measurements were made again in 1970 and 1975.

Since age 29, diameters of all trees on plots (except plot 12) have been measured at approximately 5-year intervals.[3] Heights have been measured on varying numbers of trees distributed across the entire d.b.h. range; the minimum number of trees measured for height in any year has been 10 per plot. At ages 48 and 53, to assure a well-distributed sample, we gridded each plot into 16 squares and measured the height of the largest tree in each square. Measurements on all previous sample trees were also repeated to fill-out the distribution across the d.b.h. range.

All volumes for the period 1951-75 were recomputed by means of tarif equations (Brackett 1973). Cubic volumes (CVTS) of all trees measured for height were computed using the equation derived by Bruce and DeMars (1974), and tarifs were computed therefrom; these individual tree tarifs were averaged for each plot. Total and merchantable volumes of each tree were computed by d.b.h. and tarif, summed to give volumes per plot, and expanded to volumes per acre.

Because of the recomputed volumes and some adjustments to plot size (see appendix), per-acre values for ages 29 through 43 differ slightly from those reported previously.

[3]Plots were measured in 1951, 1956, 1960, 1965, 1970, and 1975. Number of growing seasons between measurements varied from 3.7 to 5.2.

RESULTS AND DISCUSSION

Our primary interest is in usable volume production. To place this in proper perspective, however, I first discuss the effects of spacing on the component parts of volume-namely, number of trees , height, diameter, and basal area. For each of these, I discuss development of selected stand components, as well as the total stand. Emphasis in this report is placed on tree size and yield as of 51 years after seedlings were planted (53 years from seed) and on changes which took place during the preceding 24-year period (ages 29 to 53). Earlier data, based on different sampling systems, are not directly comparable.

For each component discussed, figures illustrate both trends with spacing and individual plot data. I have split the 12-ft spacing plot into halves for this purpose. In figures where individual plots are represented by bars, these bars are always shown in the same order-decreasing top height within spacing-to facilitate comparisons. Trend curves illustrate what I believe to be reasonable approximations of effects of spacing, in the absence of other sources of variation. The fitting of these curves is discussed in the appendix.

Number of Trees

Number planted

Theoretical numbers of trees planted in 1925 ranged from 2,722 to 302 per acre (6,725 to 745/ha), at spacings of 4 through 12 ft (fig. 2). Stem maps reveal that actual numbers planted were very close to these theoretical numbers; the greatest disparity was on one 8-ft-spaced plot, where the number planted was 96 percent of the theoretical number.

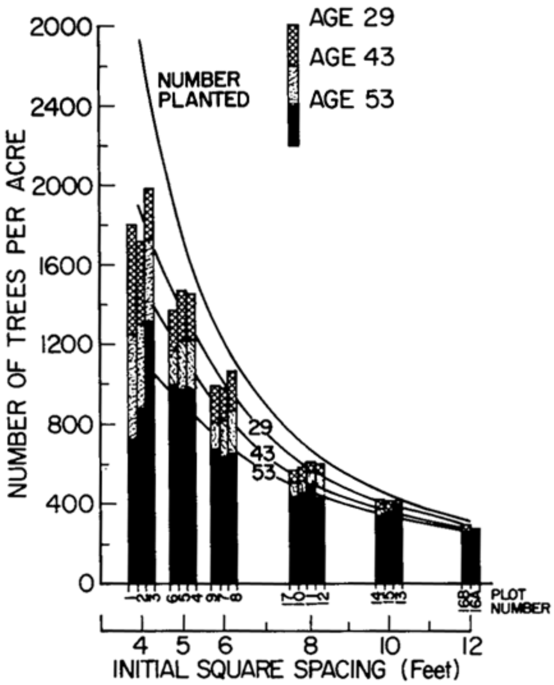

Figure 2.--Number of trees per acre, by age (clear space on bar for plot 12 indicates missing data).

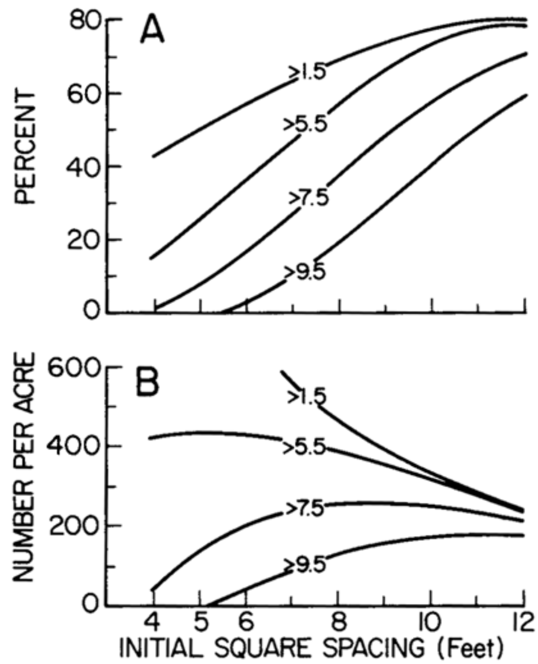

Figure 3.--Number of trees larger than specified d.b.h. at age 53: A, Percent of number planted; B, number per acre.

Number at age 53

Total stand

Fifty-one years after the trees were planted (53 years from seed), number of live trees ranged from about 1,080 to 240 per acre (2,670 to 595/ha)--or about 40 to 80 percent of the number planted (figs. 2 and 3). A very wide disparity has developed at the 4-ft (1.2-m) spacing, whereas at other spacings, numbers of trees are quite consistent among plots.

Merchantable trees.

Effect of spacing on number of merchantable trees depends, of course, on the merchantability standard. By all standards,however, the number of merchantable trees expressed as a percent of the number of trees planted increases with increased spacing (fig. 3A). At 4-foot (1.2-m) spacing, about 15 percent of the trees planted were larger than 5.5 inches (14cm) at age 53; less than 3 percent were larger than 7.5 inches (19 cm), and none were as large as 9.5 inches (24 cm). At 12-ft (3.7-m) spacing, corresponding percentages are about 78, 71, and 59.

Corresponding numbers of trees per acre are shown in figure 3B. Number of trees having a d.b.h. larger than 5.5 in (14 cm) is similar for spacings of 4 through 6 feet (1.2 to 1.8 m), averaging about 425 per acre (1,050/ha). At spacings wider than 6 feet, the number of trees larger than 5.5 inches declines with increased spacing--to about 240 per acre (595/ha) at 12-ft (3.7-m) spacing. Number of trees having a d.b.h. larger than 7.5 inches (19 cm) peaks at 8- to 10-ft (2.4- to 3.0-m) spacing--at about 260 trees per.acre (640/ha). The number having a d.b.h. larger than 9.5 in (24 cm) peaks at 10- to 12-ft (3.0- to 3.7-m) spacing--at about 180 trees per acre (445/ha).

Current guidelines for precommercial thinning (Reukema 1975) assume that all trees left at 10- and 12-ft spacings would attain a d.b.h. of at least 5.5 in (14 cm). That such was not the case in these plantations is a reflection of a combination of planting procedures, microsite, genotype, and damage. When desired spacing is attained through precommercial thinning, as opposed to planting, slow-growing and defective trees are removed and their better neighbors and trees bordering openings are favored.

Dominant and codominant trees

Although crown classification is very subjective, it provides additional indicators of trends and within-spacing variation. The latter are closely related to variations in yield.

There appears to be a linear relationship between initial spacing and the percent of all trees planted which were classed as dominant or codominant at age 53 (fig. 4A). This classification includes about 65 percent of all trees planted at 12-ft (3.7-m) spacing, whereas it includes only about 20 percent of those planted at 4-ft (1.2-m) spacing. Corresponding numbers of dominant and codominant trees per acre decreases curvilinearly with spacing (fig. 4B). This number ranges from about 570 trees per acre (1,410/ha) at 4-ft (1.2-m) spacing to 200 trees per acre (495/ha) at 12-ft (3.7-m) spacing.

Mortality

By age 29, stands had lost from about 30 to 850 trees per acre (75 to 2,100/ha) at spacings of 12 and 4 feet (3.7 and 1.2 m), respectively (fig. 2 table 2). At all but the closest spacing, fewer than 15 percent of the trees had died; this early mortality was very irregular, and due to factors not associated with spacing. Only at the 4-ft (1.2-m) spacing, had competition become a major factor contributing to mortality by age 29; at this spacing, more than 30 percent of the trees had died.

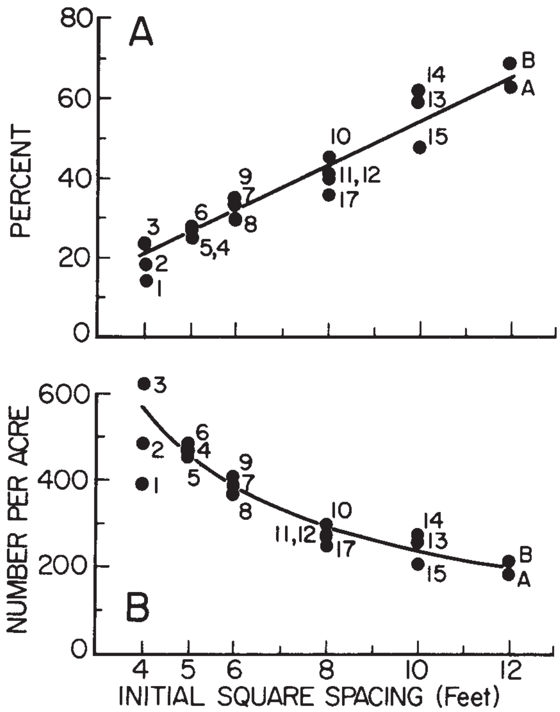

Figure 4.--Number of trees classed as dominant or codominant at age 53: A, Percent of number planted; B, number per acre.

During the 24-year period between ages 29 and 53, most mortality was related to level of competition; some was a carryover of earlier problems not related to spacing, including a little rootrot. At spacings of 4 through 6 feet (1.2 to 1.8 m), about 30 percent of the original number of trees died during this period (table 2). At spacings wider than 6 feet (1.8 m), the

Table 2--Distribution of mortality, by spacing[1] and age

Spacing (feet)	Age							Total
	7-29	29-34	34-38	38-43	43-48	48-53	29-53	
	Number of dead trees per acre							
4	850	142	55	217	286	167	867	1,717
5	256	96	44	125	142	86	493	749
6	176	31	18	134	113	61	357	533
8	85	16	7	44	47	8	122	207
10	31	4	7	30	10	7	58	89
12	31	2	3	14	9	0	28	59
	Percent of original number planted							
4	31.5	5.3	2.0	8.0	10.6	6.2	32.2	63.7
5	14.9	5.6	2.6	7.3	8.3	5.0	28.7	43.6
6	14.8	2.6	1.5	11.2	9.5	5.1	29.9	44.7
8	12.6	2.4	1.0	6.5	7.0	1.2	18.2	30.8
10	7.1	.9	1.6	6.9	2.3	1.6	13.3	20.4
12	10.3	.7	1.0	4.7	3.0	0	9.4	19.7

[1]Average of all plots within each spacing.

percent lost declined with increasing spacing--to less than 10 percent at 12-ft (3.7-m) spacing.

At close spacings, much of the density-related mortality was directly caused by snow and ice damage, which affected groups of trees and created openings in the crown canopy; at wider spacings, only scattered individual trees died (fig. 5). Among trees larger than 5.5 in (14 cm) in d.b.h., there has been relatively little mortality. On the average, only 18 such trees per acre (44/ha) have died; the distribution of these trees has been very erratic, with spacing having no clear effect. The impact of this mortality on growth and yield will be discussed later.

Height and Site Quality

Height at age 53

Average height of the 100 largest trees per acre (250/ha), as well as the averages for all trees in the stand and for other stand components, increases with increased spacing (fig. 6). Average heights of all components except the 40 tallest per acre (100/ha) were estimated by expressing height as a function of d.b.h., for each plot.

Total stand and merchantable trees

Average height of all trees in the stand ranged from less than 50 feet (15 m) at 4-ft (1.2-m) spacing to nearly 90 feet (27 m) at 12-ft (3.7-m) spacing. Average height of trees larger than 5.5 inches (14 cm) in d.b.h. ranged from about 55 to 90 ft (17 to 27 m).

The 100 largest trees per acre

The trend over spacing for the 100 largest (d.b.h.) trees per acre (250/ha) appears to nearly parallel the trend for all trees in the stand. Average height of these 100 largest trees per acre ranges from about 60 feet (18 m) at 4-ft spacing to 95 feet (29 m) at 12-ft spacing.

The 40 tallest trees per acre

To avoid the impact of errors in estimating height as a function of d.b.h., I computed the arithmetic averages of the 10 tallest

Figure 5.--Clumped damage was a common occurrence in the 4-foot (1.2-m) spacing (left), whereas there was little damage in the 10-foot (3.0-m) spacing (right). The stands pictured are both close to the boundary between the 4- and 10-foot spacings.

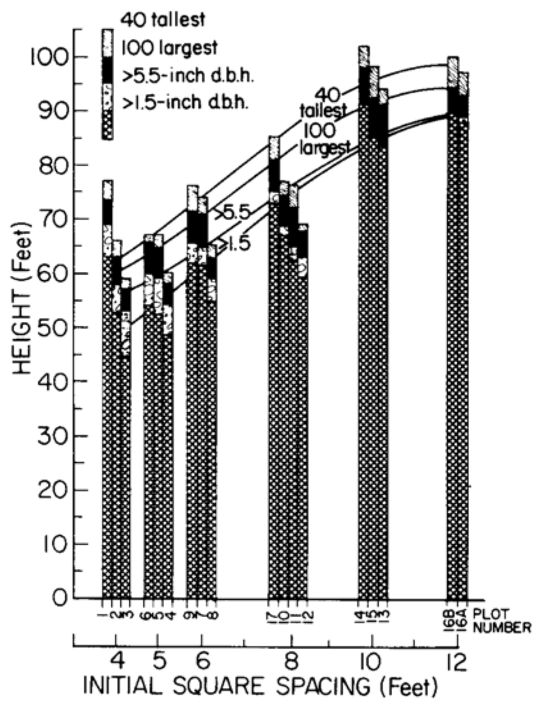

Figure 6--Average height at age 53, by stand component.

trees from among the 16 largest (by d.b.h.) well-distributed trees per plot. I consider these equivalent to the 40 tallest trees per acre (100/ha). There is a very clear trend of increasing height with increased spacing, with average height of these 40 tallest trees per acre (100/ha) ranging from about 62 ft (19 m) to 99 ft (30 m) at spacings of 4 and 12 ft (1.2 and 3.7 m).

Height growth

Most of the effect of spacing on height growth has occurred since about age 20. By age 29, the 100 largest trees per acre (250/ha) were about 8 feet, or 18 percent, taller at 12-ft than at 4-ft (3.2 vs. 1.2 m) spacing--51 vs. 43 feet (15.5 vs. 13.1 m) (fig. 7). During the 24-year period between ages 29 and 53, the 100 largest trees per acre grew an average of 43 feet (13.1 m) at 10- and 12-ft spacings, but only 17 feet (5.1 m) at 4-ft spacing.

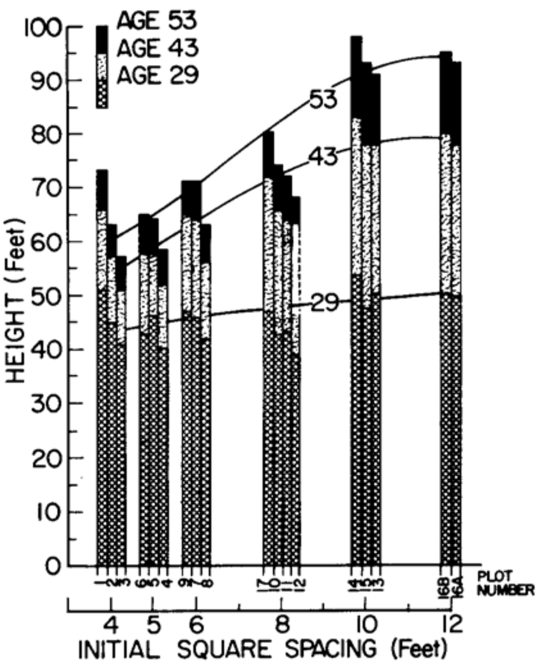

Figure 7.--Cumulated growth in height of the 100 largest trees per acre, by period (clear space on bar for plot 12 indicates missing data).

Effect of spacing vs. site quality

Current heights indicate (1) substantial within-spacing variation in site index and (2) a strong trend of increased site index with increased spacing. The question arises as to whether the latter is really an effect of spacing or of true differences in site quality. Several pieces of evidence bear on this question.

There is considerable evidence--dating back to early measurements--that the block planted at 8-ft spacing is generally on poorer quality site than blocks planted at other spacings. This is illustrated by the relative number of trees which had attained some specific minimum height; the 8-ft spacing had many fewer such trees than did other spacings (table 3). Even though current heights on plots at 8-ft spacing (except plot 17) fall out of line with the trend, height growth between ages 29 and 53 was greater on all four of these plots than on any plot at closer spacing.

The best plots at 4- and 10-ft spacing (plots 1 and 14) are in close proximity to each other (fig. 1). These plots are substantially superior in height and yield to other plots in their respective spacings, indicating that this portion of the area is better than the average quality site. Yet heights on this best plot at 4-ft spacing are much shorter than on any plot at 10-ft spacing. There is some evidence from soil characteristics that the 10- and 12-ft spacings may be on slightly better than the average site quality; however, there is nothing to suggest real site differences of anywhere near the magnitude indicated by current heights.

Table 3--Relationship between spacing and tree height (acre basis); trees taller than specified height at ages 12 and 17; Wind River spacing test

Spacing (feet)	Age 12, trees >9.5 feet tall		Age 17, trees >17.5 feet tall	
	Number of trees	Percent of total	Number of trees	Percent of total
4	463	17	426	16
5	364	21	317	18
6	256	21	235	19
8	46	7	65	10
10	111	25	168	39
12	85	28	139	46

It is also clearly evident from the exterior row of trees planted at close spacings that amount of available growing space does have an effect on height of even the tallest trees. The planted trees bordering the surrounding natural stand are substantially taller than trees in the interior of the closely spaced plantation.

Therefore, differences in site index among spacings are attributed primarily to effects of differing intensity of competition on height growth. Height growth in the wider spacings has improved relative to “normal” stands, whereas that in the closer spacings has diminished.

An accumulating body of evidence suggests that better height growth at wide spacings than at close spacings may be common on poor sites. On the other hand, spacing apparently has little effect on height growth on good sites, except at extremely dense spacings. Most of the literature pertaining to this subject has been reviewed by Sjolte-Jorgensen (1967) and Evert (1971, 1973). Some unpublished evidence[4] also supports the concept of better height growth at wide spacings on poor sites. It is reasonable that spacing should have more effect on poor sites because--for a given spacing--the poorer the site, the longer the time to crown closure (Reukema & Bruce 1977).

Diameter

Diameter at age 53

Average d.b.h.[5] of the total stand, of merchantable trees (larger than 5.5 inches (14 cm), and of the 100 largest trees per acre (250/ha) all increase with increased spacing (fig. 8).

Total stand

Virtually all live trees have a d.b.h. of at least 1.5 inches (4 cm). Average d.b.h. of these trees at age 53 ranged from about 5.1 inches (13 cm) at 4-ft (1.2-m) spacing to 11.3 inches (28.7 cm) at 12-ft (3.7-m) spacing. Distributions around these averages are tabulated in the appendix.

Merchantable trees

Average d.b.h. of trees larger than 5.5 inches (14 cm) ranged from about 6.5 inches (16.5 cm)

[4]On file at Forestry Sciences Laboratory, Olympia, Washington.

[5]Average d.b.h. refers to diameter at breast height of the tree of mean basal area.

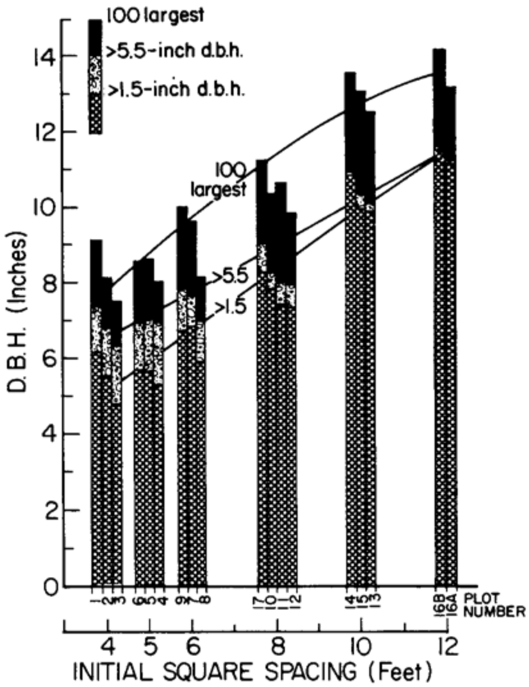

Figure 8.--Average d.b.h. at age 53, by stand component.

at 4-ft spacing to 11.4 inches (29 cm) at 12-ft spacing. At wide spacings, nearly all trees are larger than 5.5 inches. At 4- and 5-ft (1.2- and 1.5-m) spacings, fewer than half of all live trees are larger than 5.5 inches in d.b.h.

The 100 largest trees per acre

Average d.b.h. at age 53 of the 100 largest trees per acre (250/ha) ranged from about 7.8 inches (19.8 cm) at 4-ft (1.2-m) spacing to 13.6 inches (34.5 cm) at 12-ft (3.7-m) spacing. The trend over spacing for these largest trees nearly parallels that for all trees in the stand. The substantial variation among plots within spacing generally parallels variation in height.

Diameter Growth

The 100 largest trees per acre

During the 24-yr period between ages 29 and 53, diameter growth on the 100 largest trees per acre (250 per hectare) was about twice as much at 12-ft spacing as at 4-ft spacing (fig. 9); periodic annual increments (p.a.i) were 0.20 vs. 0.10 inch (0.50 vs. 0.24 cm). During the most recent 10 years of this period, corresponding rates of diameter growth were 0.15 vs. 0.08 inch (0.38 vs. 0.20 cm) per year.

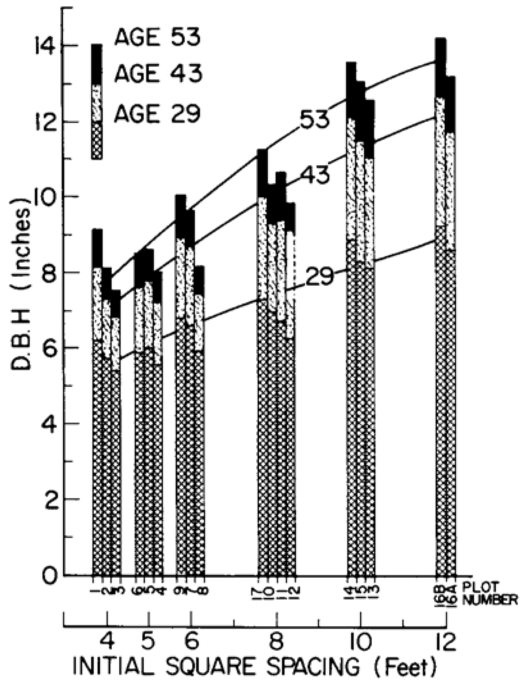

Figure 9.--Cumulated growth in d.b.h. of the 100 largest trees per acre, by age (clear space on bar for plot 12 indicates missing data).

Other trees

Growth as a function of tree diameter also has varied by spacing in recent years, contrary to previous trends (Reukema 1970). For trees of a given d.b.h. at the start of the period, those at close spacings have grown more during the past 10 years than those at wide spacings. Trees of a given size are in a more favorable crown position at successively closer spacings; i.e, we are comparing dominants at close spacing with intermediates at wide spacings.

Very few additional trees reached the minimum merchantable d.b.h. of 5.6 inches (14 cm) during the most recent 5-yr period. A few more will, but most submerchantable trees are growing very slowly, if at all. At the closest spacings, a few of these submerchantable trees are codominants and will grow to merchantable size; even a few intermediates may. At 8-ft (2.4-m) and wider spacings, the few submerchantable trees which remain in the stands are mostly in the suppressed crown class; they have essentially ceased growing.

Basal Area

Basal area at age 53

Basal area of live trees (i.e., net basal area) and gross basal area produced (including basal area of trees which have died) are both quite variable and only loosely associated with spacing. Basal area of merchantable trees and, especially, the 100 largest trees per acre are much more closely related to spacing (fig. 10). Variation, among plots *within spacing*, in the basal area of the 100 largest trees per acre (250/ha) closely parallels variation in height; it undoubtedly reflects variation in site quality. The much greater variation in basal area of the total stand reflects, in addition, differences in fullness and uniformity of stocking.

Total stand

Gross basal area production to age 53 still tends to decrease with increased spacing from about 210 ft^2 per acre (48 m^2/ha) at 4-ft (1.2-m) spacing to 190 ft^2 per acre (44 m^2/ha) at 10-ft (3.0-m) spacing, and 175 ft^2 per acre (40 m^2/ha) at 12-ft (3.7-m) spacing. Basal area of live trees

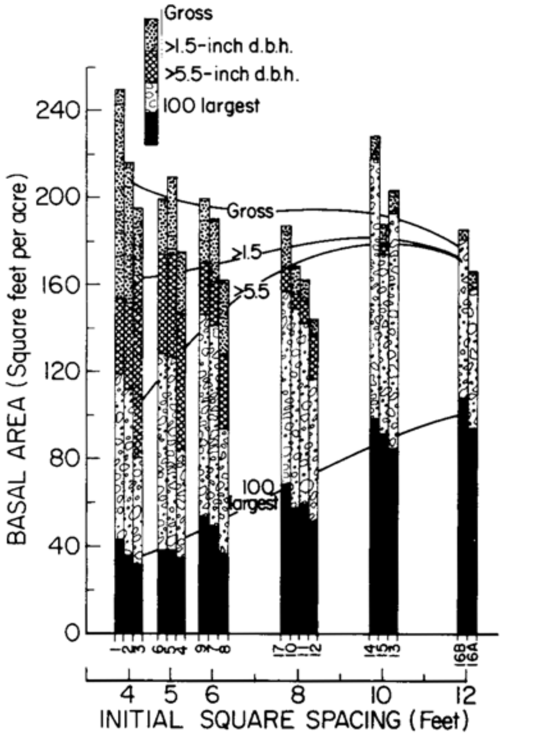

Figure 10.--Basal area per acre at age 53, by stand component.

tends to increase as spacing increases; from about 160 ft^2 per acre (37 m^2/ha) at 4-ft spacing to 180 ft^2 per acre (42 m^2/ha) at 10-ft spacing.

Gross basal area production at close spacings would be greater than indicated *if* sizeable areas had not been lost to production because of the clumpwise distribution of damage and mortality. Smith[6] has shown much greater growth in *fully stocked* portions of stands planted at close spacings.

[6] J. Harry G. Smith. Maximal annual basal area growth at various spacings estimated by tree ring analyses. Paper presented at Pacific Division, AAAS 59th Annual Meeting (Seattle, Wash.), June 1978.

Merchantable trees

Basal area of trees larger than 5.5 inches (14 cm) clearly increases with increased spacing--up to 10-ft (3.0-m) spacing; via the trend curve, it ranges, from about 95 ft^2 per acre (22 m^2/ha) at 4-ft (l.2-m spacing to l80 ft^2 per acre (41 m^2/ha) at 10-ft (3.0-m) spacing. Basal area of these merchantable trees appears to be a little less at 12-ft (3.7-m) than at 10-ft spacing, although the basal area in such trees is greater on the best 12-ft-spacing plot than on the poorest l0-ft-spacing plot. Trees larger than 5.5 inches (14 cm) in d.b.h. account for less than 75 percent of the total-stand basal area at close spacings, whereas they account for nearly all of the total-stand basal area at wide spacings.

The 100 Largest trees per acre

Basal area of the 100 largest trees per acre (250/ha) obviously increases with increased spacing--from about 35 to 100 ft^2 per acre (8 to 23 m^2/ha) at spacings of 4 and 12 ft (1.2 and 3.7 m), respectively. The trend appears to be only slightly curvilinear; basal area of these 100 largest trees per acre is nearly proportional to spacing.

Basal area mortality

The difference between gross basal area production and basal area of the total live stand is mortality. This is quite closely related to spacing. During the period between ages 29 and 53 about 50 ft2 per acre (11.5 m^2/ha) was lost at the 4-ft (1.2-m) spacing, whereas less than 5 ft^2 per acre (1 m2/ha) was lost at the 12-ft (3.7-m) spacing. Corresponding percentages of total production lost to mortality are about 22 and 3 percent, at 4- and 12-ft (1.2- and 3.7-m) spacings.

Basal area growth

To provide a more complete picture of effect of spacing on growth, I have examined not only total-stand growth but also the contribution of the 100 largest trees per acre (250/ha) to this total.

Total stand

Gross basal area growth during the period between ages 29 and 53 averaged 27 percent greater at the two widest spacings than at the two closest. Thus, the effect of spacing on cumulated gross basal area production--i.e., reduced production with increased spacing--has diminished with increasing age (fig. 11). Basal

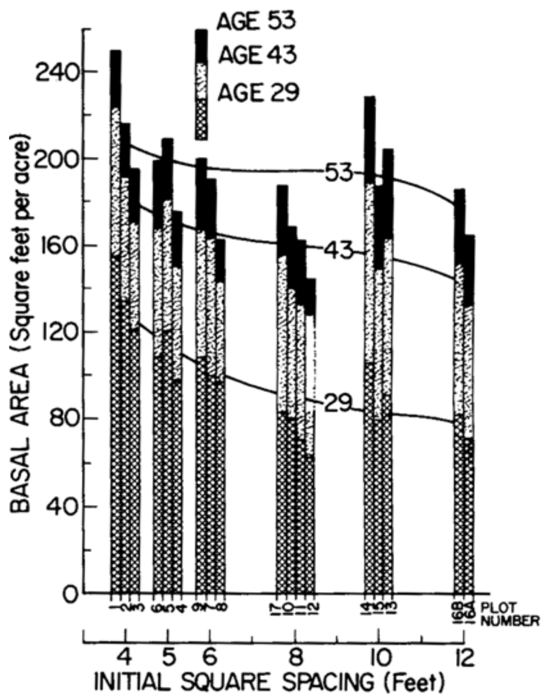

Figure 11.--Cumulated growth in basal area per acre, by period (clear space on bar for plot 12 indicates missing data).

area growth for the total stand has clearly been greatest at 10-ft (3.2-m) spacing (fig. 12A); it has been greater even on the poorest of the l0-ft-spacing plots than on any plot at either closer or wider spacing.

The 100 largest trees per acre

Growth per tree increases with increased spacing, as indicated by growth of the 100 largest trees per acre (fig. 12B). The

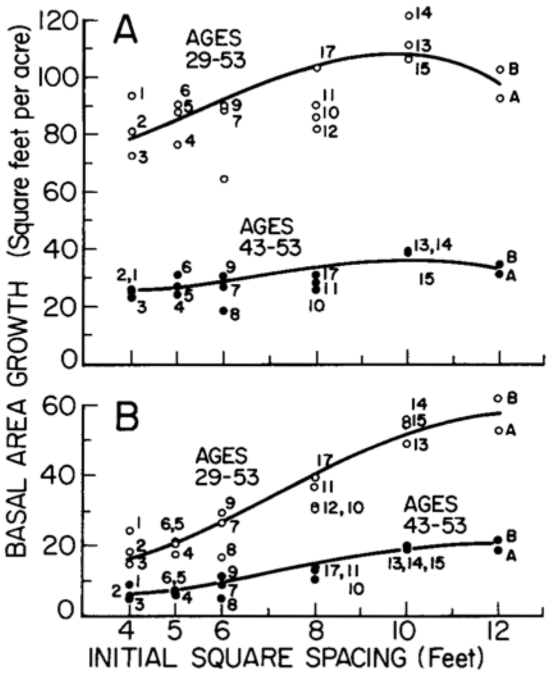

Figure 12.--Basal area growth per acre between ages 29-53 and 43-53: A, Total stand; B, The 100 largest trees.

relationship appears to be essentially linear for spacings of 4- through 10-ft (1.2- to 3.0-m); however, it appears curvilinear when the 12-ft (3.7-m) spacing is included. The ratio of growth of these 100 largest trees to growth of the total stand is essentially linearly related to spacing (fig. 13). Variations

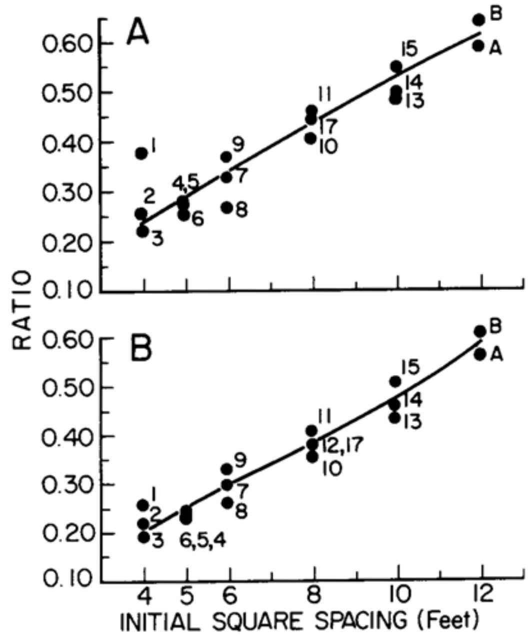

Figure 13.--Basal area growth of the 100 largest trees relative to growth of the total stand: A, Ages 43-53; B, Ages 29-53.

around this trend indicate, primarily, variations in stocking; the greater the ratio for a given spacing, the less complete the stocking. The 100 largest trees per acre (250/ha) accounted for less than 25 percent of the total-stand growth at the closest spacing and for about 60 percent of it at the widest spacing. Their contribution to growth is essentially the same as their contribution to growing stock.

Cubic Volume

Total cubic volume at age 53

I first examined effect of spacing on total-stem volume of both (1) all trees in the stand and (2) selected components of the stand. I then examined effect of spacing on the merchantable (or usable) portion of this volume.

Contrary to trends of basal area with spacing, volume of live trees and gross volume produced are both greater at wide spacings than at close spacings. This is due mostly to the fact that trees are taller at wider spacings. Trends for trees larger than 5.5-inches (14-cm) d.b.h. and for the 100 largest trees per acre (250/ha) are very similar to those for basal area. Likewise, variation among plots within spacing is quite similar to that for basal area (fig. 14).

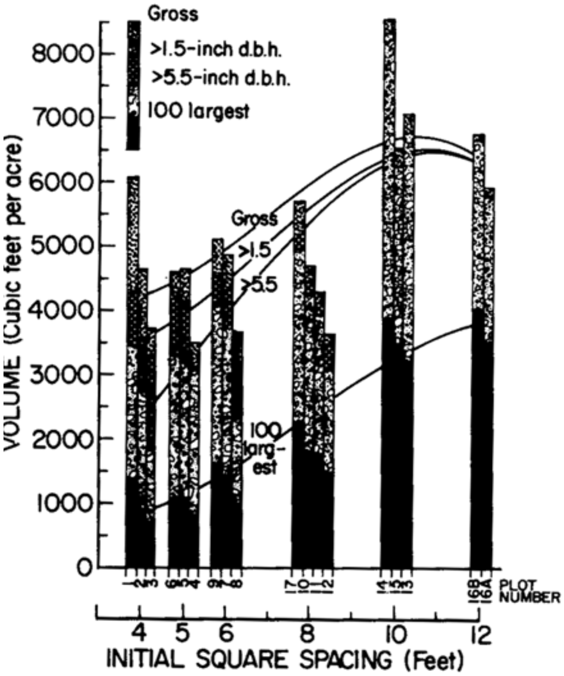

Figure 14.--Cubic volume per acre at age 53, by stand component.

Total stand

Cubic volume produced is clearly greater at 10- and 12-ft (3.0- and 3.7-m) spacings than at closer spacings. Gross volumes via the trend curve range from about 4,235 to 6.685 ft^3 per acre (296 to 468 m^3/ha) at 4- and 10-ft (1.2- and 3.0-m) spacings, respectively. Corresponding net volume volumes (live trees) range from about 3,545 to 6,425 ft^3 per acre (248 to 450 m^3/ha).

Merchantable trees

Cubic volume of trees larger than 5.5-inches (14-cm) d.h.h. ranges from about 2,340 ft^3 per acre (164 m^3/ha) at 4-ft (1.2-m) spacing to 6,360 ft^3 per acre (445 m^3/ha) at 10-ft (3.0-m) spacing. Volume in trees larger than 5.5 inches accounts for nearly all of the total stand volume at 10- and 12-ft (3.0- and 3.7-m) spacings; at the 4-ft (1.2-m) spacing, volume in trees larger than 5.5 inches accounts for only about two-thirds of the total volume.

The 100 largest trees per acre

Cubic volume of the 100 largest trees per acre (250/ha) ranges from about 850 ft^3 per acre (59 3/ha) at 4-ft (1.2-m) spacing to 3,840 ft^3 per acre (269 m^3/ha) at 12-foot spacing. The trend is only slightly curvilinear. These trees account for about 25 percent of total volume at 4-ft (1.2-m) spacing and for about 60 percent of it at 12-ft (3.7-m) spacing.

Cubic volume mortality

Mortality--the difference between gross volume production and volume of the total live stand--has been less at wide spacing than at close spacings, but varies widely within spacing (fig. 14). As defined by the trend curve, the volume lost to mortality during the 24-year period between ages 29 and 53 ranged from about 690 ft^3 per acre (48 3/ha) at 4-ft (1.2-m) spacing to 90 ft^3 per acre (6 m^3/ha) at 12-ft (3.7-m) spacing.

At the 4- and 8-ft (1.2- and 2.4-m) spacings, the volume lost to mortality appears to be related to stocking level; the greater the stocking level, the greater the mortality. At other spacings, however, no such relationship between stocking level and mortality was evident.

Cubic volume growth

Gross cubic volume growth during the period between ages 29 and 53 averaged twice as much at the two widest spacings as at the two closest spacings. Therefore, the effect of spacing on gross volume production has increased with increasing stand age (fig. 15).

During both the total 24-year period and the most recent 10 years, growth was clearly greater at 10- and 12-ft (3.0- and 3.7-m) spacings than at closer spacings (fig. 16A). Growth was apparently a little less at the 12-ft than at the 10-ft (3.7-m vs. 3.0-m) spacing; however, growth on the best 12-ft-spaced plot was virtually identical to growth on the two poorer l0-ft-spaced plots. Via trend curves, growth between ages 29 and 53 ranged from about 2,370 to 5.130 ft^3 per acre (166 to 359 m^3/ha) at spacings of 4 and 10 ft (1.2 and 3.0 m), respectively. Thus, annual growth during the 24-yr period averaged 99 to 214 ft^3 per acre (6.9 to 15.0 m^3/ha).

The 100 largest trees per acre

The trend of growth of the 100 largest trees per acre (250/ha) relative to spacing is S-shaped (fig. 16B). The rate of growth increases rapidly as spacing is increased from 4 to 10 ft (1.2 to 3.0 m). The rate of increase then levels-off somewhat with yet wider spacing--as it must, eventually.

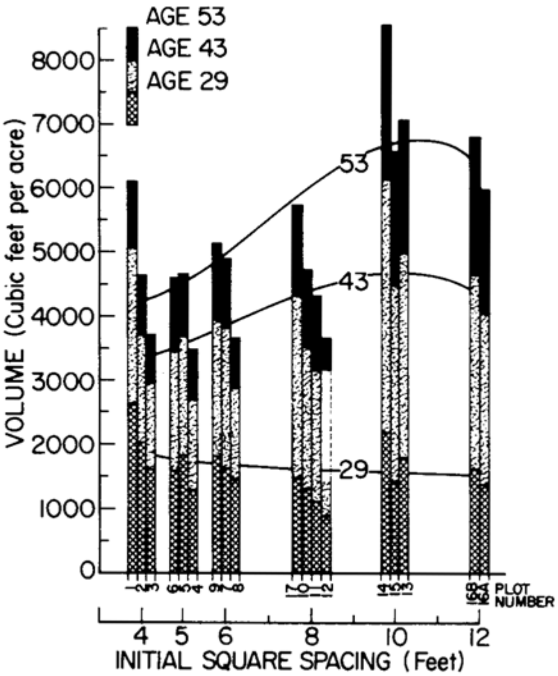

Figure 15.--Cumulated growth in cubic volume per acre, by period (clear space on bar for plot 12 indicates missing data).

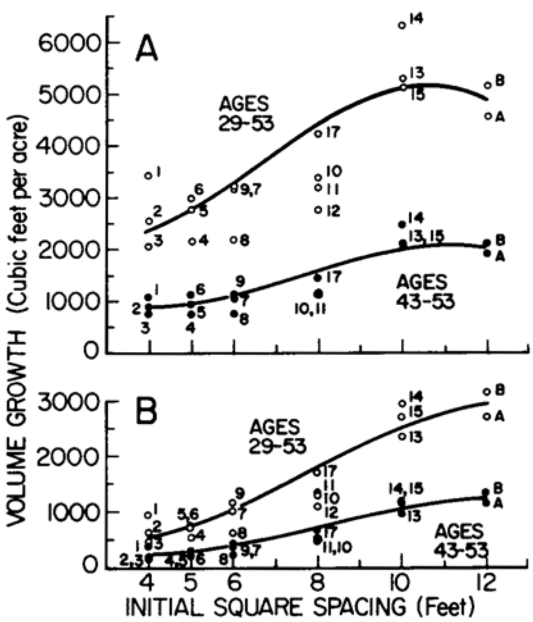

Figure 16.--Cubic volume growth per acre between ages 29-53 and 43-53: A, Total stand; B, The 100 largest trees.

The ratio of growth of these 100 largest trees to growth of the total stand appears to be linearly related to spacing, as for basal area growth. Growth of these 100 largest trees per acre (250/ha) accounted for about 25 percent of the total-stand growth at 4- and 5-ft (1.2- and 1.5-m) spacings to 60 percent of total-stand growth at the 12-ft (3.7-m) spacing. Thus, as for basal area, the contribution of these 100 largest trees per acre (250/ha) to growth has been nearly proportional to their current contribution to growing stock.

Growth relative to growing space

Plotting growth relative to growing space (S^2), rather than to spacing (S), perhaps gives a little clearer picture of relationships (fig. 17). This shows that volume growth--between ages 29 and 53-of the 100 largest trees per acre (250/ha) was nearly proportional to growing space (S^2) for spacings of 4 through 10 ft (1.2 to 3.0 m). The slope of this curve declines sharply, however, as spacing is increased from 10 to 12 ft (3.0 to 3.7 m).

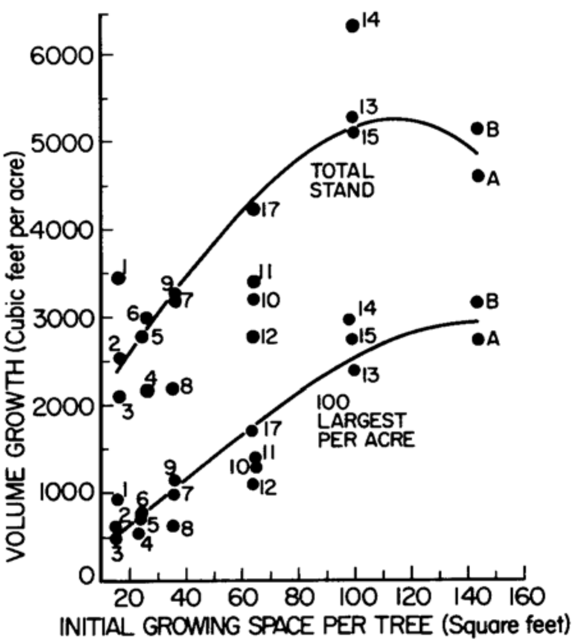

Figure 17.--Cubic volume growth per acre of the total stand and the 100 largest trees, ages 29-53.

Corresponding growth of the total stand is nearly linearly related to growing space (S^2) through about 8-ft spacing. The rate of increase declines as spacing increases from 8 to 10 ft. The sharp decline in growth rate thereafter is associated with the growth trend for the 100 largest trees per acre; with spacing greater than about 10 ft, growth of individual trees has not been enough greater to offset the impact on total growth of having fewer trees than at 10-ft spacing.

Trends and culmination of growth

Periodic annual growth (p.a.i.) of both total stands and the 100 largest trees per acre (250/ha) has been very erratic (fig. 18).[7] As expected, p.a.i. of the total stand tended to decrease as age increased. P.a.i. of the 100 largest trees per acre generally tended to remain nearly constant as age increased from 29 to 53; trends for 6- and 8-ft (1.8- and 2.4-m) spacings appear to deviate from this generality.

At close spacings, gross mean annual increment (m.a.i.) of the total stand apparently culminated at about age 50, or is currently very close to culmination; at wide spacings, m.a.i. is still far short of culmination (fig. 19). Likewise, at close spacings, m.a.i. of the 100 largest trees per acre (250/ha) is near to culmination, whereas at wide spacings m.a.i. is still increasing substantially with increasing age.

[7] Length of periods varied from 3.7 to 5.2 growing seasons.

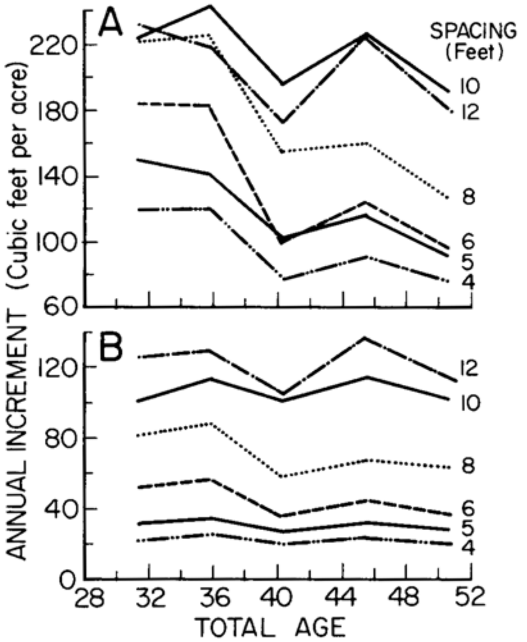

Figure 18.--Gross periodic annual increment (p.a.i.) in cubic volume per acre, by periods from ages 29 to 53: A, Total stand; B, The 100 largest trees.

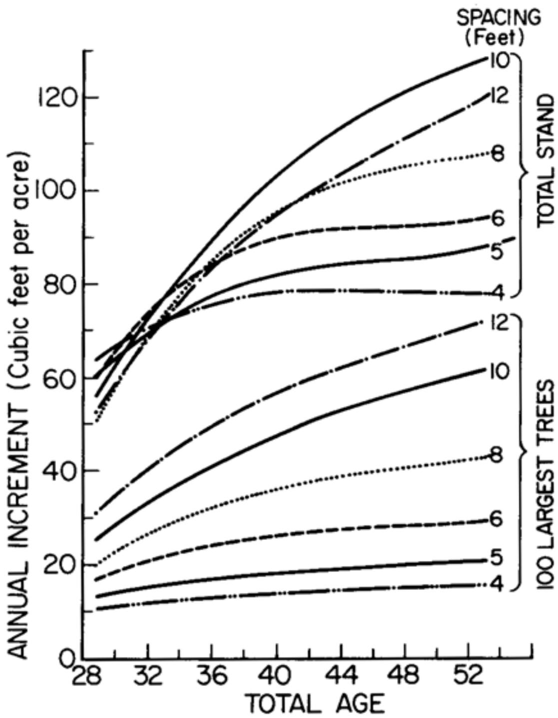

Figure 19.--Gross mean annual increment (m.a.i.) in cubic volume per acre from ages 29 to 53: Total stand and the 100 largest trees

Differences in current growth rates, and age at which m.a.i. culminates, are associated with differences in crown dimensions and vigor. At age 45, average crown length of the 100 largest trees per acre at 4-ft spacing was only about 20 ft (6 m); that a 12-ft spacing was about 40 ft (12 m) (Curtis and Reukema 1970). Corresponding crown widths were about 12 ft (3.7 m) and 18 ft (5.5 m).

Impact of mortality on growth and yield

Since most trees which have died have been of submerchantable size, there has been very little *direct* effect on usable production. Some of these submerchantable trees, however, would have otherwise reached merchantable size, especially those at close spacings which were dominant or codominant trees when damaged. Therefore, the clumpwise mortality pattern at close spacings has been responsible for an *indirect* loss in usable production. The close spacings have more dominant and codominant trees, but these trees occupy the area much less efficiently than at wider spacings. Furthermore, in the close spacings, trees surrounding the openings have less vigorous crowns than those in wide spacings, so have been less able to respond to release received from these natural openings.

Merchantable volume at age 53

Up to now, I have considered only the effect of spacing on cubic volume of the *total.* stem (CVTS). I have shown how much of this total is included in selected components of the stand. The effect of spacing on the usable part of this volume depends on merchantability standards; the larger the desired diameter, the greater the advantage of wide spacing (fig. 20).

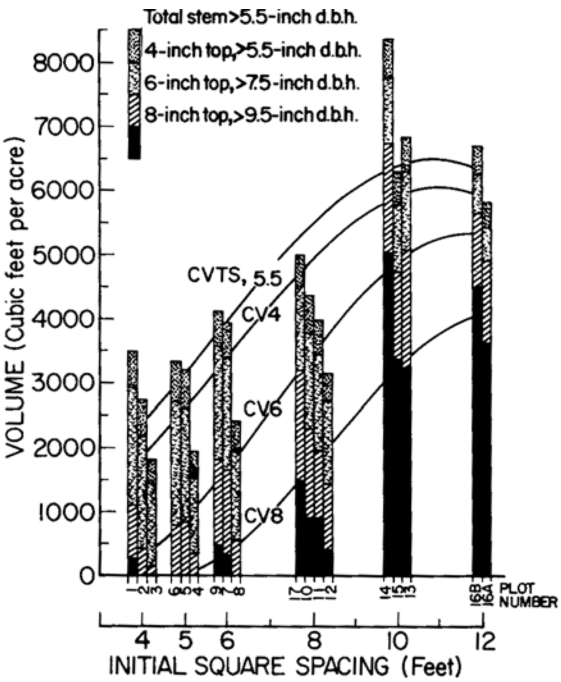

Figure 20.--Merchantable cubic volume per acre at age 53, by merchantability standard.

For the following discussion, merchantable volume-in trees larger than a specified d.b.h.--is the total volume of the portion of the stem included between the stump and the specified minimum top diameter. In all cases, the stump height is 1 percent of total tree height or 1 ft (30 cm), whichever is less.

If minimum top diameter is 4 inches (10 cm), merchantable volume (CV4) in trees larger than 5.5-inch (14-cm) d.b.h. ranges from less than 2,000 ft^3 per acre (140 m^3 /ha) at 4-ft (1.2-m) spacing to about 6,000 ft per acre (420 m^3/ha) at 10- and 12-foot (3.0- and 3.7-m) spacings. Thus, on the average it is about 500 ft^3 per acre (35 m^3/ha) less than the total stem volume of those same trees.

If stems can be utilized only to a minimum top diameter of 6 in (15 cm), merchantable volume (CV6) in trees larger than 7.5-inch (19-cm) d.b.h. ranges from less than 300 ft^3 per acre (20 m^3/ha) at 4-ft spacing to about 5,300 ft^3 per acre (370 m^3/ha) at 12-ft spacing. If minimum top diameter is 8 inches (20 cm), then merchantable volume (CV8) in trees larger than 9.5-inch (24-cm) d.b.h. ranges from zero at 4-ft spacing to over 4,000 ft^3 per acre (280 m^3/ha) at 12-ft spacing.

Advantages of 12-ft spacing relative to 10-ft spacing are obvious. Production of usable volume has been as great or *greater* at the 12-ft as at the 10-ft spacing, depending upon merchantability standards. Furthermore, there need be little concern about excessive size of branches at the wide spacings. Branch size at the 12-foot spacing is currently quite acceptable. Crowns closed many years ago and have lifted well.

CONCLUSIONS AND MANAGEMENT IMPLICATIONS

Trees planted at wide spacings have attained a much larger diameter and height and have produced much more merchantable volume than have those planted at close spacings. Differences, in favor of wider spacings, have continued to increase during the past 10 years.

Height and diameter growth of even the largest trees has been strongly affected by spacing. The 100 largest trees per acre are currently (age 53) nearly 60 percent taller and 75 percent larger in diameter at 12-ft than at 4-ft spacing. At 12-ft spacing, these trees now average 94 ft (28.6 m) tall and 13.6 inches (34.5 cm) in d.b.h.

Total volume production has been greatest at the 10-ft spacing. Growth rate of individual trees is greater at 12-ft than at 10-ft spacing, but not enough greater to offset the effect on total growth of fewer trees being present. Production of *usable* volume, however, has been as great or *greater* at the 12- as at the 10-ft spacing, depending on merchantability standards.

Current mean annual increment (m.a.i.) of the 100 largest trees per acre at the 12-ft spacing is almost as much as m.a.i. of *all* trees at the 4-ft spacing. Furthermore, m.a.i. has culminated at close spacings, whereas it is still far short of culmination at wide spacings. In terms of live trees, the 12-ft spacing currently has more volume in the 100 largest trees than the 4-ft spacing has in more than 1,000 trees.

Where trees have been planted at close spacings, only a small fraction of the trees reached a merchantable size; and a substantial part of the total volume produced was in submerchantable trees. Furthermore, these very uniform stands did not self-thin effectively. This caused growth of even the best trees in the stand to be severely retarded, and it made the stands more susceptible to snow and ice damage which created openings within the stand.

The apparent effects of spacing illustrated by this study are greater than those indicated in most published results of studies elsewhere (Sjolte-Jorgensen 1967; Evert 1971, 1973). It appears common, however, for maximum production on low-site-quality land to be attained through much wider than normal spacing of trees. Results of this study are believed to be typical of what can be expected on comparable sites. On better sites, spacing apparently has little effect on height growth; thus, effects of spacing on tree size and yields are somewhat less than observed in this study.

One should use caution in drawing implications from a single study, such as this. Therefore, information derived from several studies--including this one--has been formulated into a model of stand structure and development (Reukema & Bruce 1977). Management implications may be drawn from this model.

This spacing trial clearly illustrates the potential benefits from planting trees at wider spacing, or making an early precommercial thinning to such spacing, on lands of poorer than average site quality. Proper spacing of trees depends on the tree size desired at the first commercial entry. If one plans to commercially thin when trees average about 8-inch (20-cm) d.b.h., trees should be spaced about 10 feet (3 m) apart. If one wishes to have a larger average d.b.h. at the time of the first commercial entry, trees should be spaced more widely.

The detrimental consequences of carrying too many trees is clearly illustrated by the close spacings. Conversely to the above spacing guide, stands should be thinned when trees reach the size commensurate with their spacing. Thus, if stands in this spacing trial were being managed intensively, the stand planted at 12-ft (3.7 m) spacing should have been thinned at about age 45-when trees averaged about l0-inch (25-cm) d.b.h. and 80 ft (24 m) tall. Stands planted at closer spacings should have been thinned at progressively younger ages--with smaller trees being cut. Failure to thin at the appropriate time can offset the potential benefit from early control of spacing.

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APPENDIX

Fitted Curves

Trend curves illustrate what I believe to be reasonable approximations of effects of *spacing*, in the absence of other sources of variation. Equations were fitted to selected plots to facilitate automation in plotting graphs. Most of these relationships are represented by third-degree curves, which closely approximate former freehand curves.

For this purpose, 7 of the 18 plots were excluded from influencing the shape of these curves, because inclusion of all plots would result in unrealistic curve shapes. Three of these plots sample the 8-foot spacing, which is apparently on generally poorer-quality site than the average; only the best plot in this spacing (plot 17) falls in line with general trends. Others excluded were the best of the plots at 4- and l0-foot spacings (plots 1 and 14), which are apparently on better-quality site than any other plots, and the poorest of the plots at 5- and 6-foot spacings (plots 4 and 8), which are much poorer than other plots at these spacings.

Adjustments for Plot Size

Because dimensions of plots--e.g., 104.36 feet for a square quarter-acre plot-are not exact multiples of spacing distances, some plots have either more or fewer planting spots than would theoretically be found on that fraction of an acre. Therefore, the expansion factor to an acre basis has always been derived from an adjusted plot size (the theoretical area initially occupied by trees), rather than from the nominal size of the plot.

Adjusted size of plots which are nominally O.25-acre varies from 0.2296 to 0.2661 acre. Adjusted size of each half of the plot at 12-foot spacing is 0.2116 acre.

Examination of stem maps revealed some errors in the previous determination of this adjusted plot size. Therefore, some per acre values in this report have been changed, relative to those reported previously. The greatest impact is on the 12-foot spacing, where the plot is 6.7 percent larger than previously believed; thus, all per acre values for this spacing are less than previously reported.

D.b.h. Distribution

D.b.h. distributions at age 53, by spacing, are tabulated in Table 4. These are based on only the plots to which trend curves were fitted.

Table 4--D.b.h. frequency distribution 1975 (age 53)

D.b.h. class	Spacing feet					
	4	5	6	8	10	12
	- - Number of trees per acre - -					
2	67	49	24	8		
3	191	129	40	8	2	
4	244	154	68	28	8	2
5	217	162	88	45	9	3
6	237	213	98	40	24	9
7	110	131	130	60	55	14
8	23	85	94	65	26	5
9	16	39	70	72	45	31
10	4	8	22	49	61	33
11			10	40	42	33
12			4	12	47	43
13			4	12	7	25
14				4	9	29
15					9	4
16					0	6
17					4	4
Total	1,109	970	652	443	348	241

GPO 988-388

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