Abstract

Cochran, P.H.; Barrett, James W. 1998. Thirty-five-year growth of thinned and unthinned ponderosa pine in the Methow Valley of northern Washington. Res. Pap. PNW-RP-502. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 24 p.

It is commonly expected that self-thinning will maintain small-diameter stands at near-normal densities and allow dominant trees to grow reasonably well. Such self-thinning did not occur in the unthinned plots in a thinning study in the Methow Valley of northern Washington, even though there was some suppression-caused mortality. A shift from suppression-caused mortality to insect-caused mortality took place when quadratic mean diameters (QMDs) reached 7 inches. Thinning to spacings wider than 9.3 feet reduced growth of both basal area and cubic volume per acre but greatly increased growth of board-foot volume per acre, and diameter and height growth. Periodic annual increments of cubic volume and QMD are curvilinearly related to stand density index. Growth of the largest 62 trees per acre was clearly reduced by the presence of smaller trees in the stand. Density management is necessary to produce reasonable growth rates of even the largest trees in the stand and to speed the development of mid-seral conditions.

Keywords: Growth, mortality, mountain pine beetle, *Dendroctonus ponderosae*, seral condition, forest health, thinning.

Summary

Four spacing treatments (9.3, 13.2, 18.7, and 26.4 feet) and control plots (average spacing 4.3 feet) were established in a 47-year-old pine stand with 2,300 stems per acre, averaging 3 inches in diameter and 27 feet in height. Plots were measured at 5-year intervals for either 35 years (thinned plots) or 30 years (control plots). It is commonly expected that self-thinning will maintain small-diameter stands at near-normal densities and allow dominant trees to grow reasonably well. Such self-thinning did not occur in the unthinned plots here, even though there was some suppression-caused mortality. A shift from suppression-caused mortality to insect-caused mortality took place when QMDs reached 7 inches. Thinning greatly increased both diameter and height growth, and these growth rates increased as spacing widened. Thinning to spacings wider than 9.3 feet reduced growth of both basal area and cubic volume per acre but greatly increased growth of board-foot volume per acre. Periodic annual increments (PAIs) of cubic volume and QMD are curvilinearly related to stand density index (SDI). For SDIs of 15, 30, 50, and 75 percent of full stocking (SDI = 365), corresponding gross volume PAIs are 46, 64, 80, and 92 percent of gross volume PAIs produced at full stocking. Growth of the largest 62 trees per acre clearly was reduced by the presence of smaller trees in the stand. Mean annual increments for both cubic- and board-foot volume were still increasing for all spacings at a stand age of 82 years. Density management is necessary to produce reasonable growth rates of even the largest trees in the stand and to speed the development of mid-seral conditions. A management strategy using precommercial thinning to produce 20-inch trees early with repeated commercial thinnings over long rotations to produce much larger trees seems reasonable. Some potential cubic-volume production will be lost by using this strategy, but the social and monetary values associated with large trees will be increased, and the probability of severe mortality to pine beetles (*Dendroctonus ponderosae* Hopkins) will be greatly reduced.

Introduction

Thinning ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) is expected to reduce cubic-volume yields but increase future tree sizes (Barrett 1981, 1982; Oliver 1979; Schubert 1971). Thinning could increase board-foot yields (Cochran and Barrett 1995, Oliver and Edminster 1988, Ronco and others 1985), probably delays culmination of mean annual increment (MAI) (Curtis 1994), and, at times, increases the quantity of understory vegetation (Clary 1975, 1988; McConnell and Smith 1970; Riegel and others 1992, 1995). Thinning can reduce the susceptibility of both lodgepole pine (*Pinus contorta* Dougl. ex Loud.) and ponderosa pine stands to mountain pine beetle (*Dendroctonus ponderosae* Hopkins) (Mitchell and Preisler 1991, 1993) and perhaps western pine beetle (*Dendroctonus brevicomis* LeConte) (Cochran and others 1994).

Three spacing studies (Barrett 1981, 1982; Cochran and Barrett 1993) and two replications of a westwide levels-of-growing-stock study (Barrett 1983, Cochran and Barrett 1995, Myers 1967) for ponderosa pine were established in the Pacific Northwest during the late 1950s and 1960s. The objective of these studies was to describe stand and tree growth rates in relation to spacing or stand density and, in one case, (Barrett 1982) presence or absence of understory vegetation.

The Methow spacing study, the subject of this paper, had an additional objective of comparing development of understory vegetation under the various treatments. Earlier reports for this study were made by Barrett (1981) on tree and stand growth, by McConnell and Smith (1965, 1970) on understory response to thinning, and by Sassaman and others (1973) on an economic analysis of timber and forage returns. This report examines tree and stand growth for the 35-year period. Similar soils, plant communities, and stand conditions are found over a large area in north-central Washington. Results of this study should be applicable elsewhere in the intermountain West where similar conditions occur.

Methods of Study

Study Area

This study is in the upper Methow River Valley near Winthrop, Washington, on state land, T. 35 N., R. 22 E., near the center of section 30. The plots are on a bench about 600 feet above the Methow River at an elevation of 2,350 feet. Annual precipitation averages 14.5 inches. The soil is a well-drained Katat sandy loam developing on glacial till and is classified as a Typic Xerochrept. Pinegrass (*Calamagrostis rubescens* Buckl.) is the predominant grass and balsamroot (*Balsamorhiza sagittata* (Pursh) Nutt.) the dominant forb. Antelope bitterbrush (*Purshia tridentata* (Pursh) DC.) is scattered throughout the understory.

The 30-acre stand containing the study plots originated about 1911 after logging and fire. Forty-seven years later, when the study was established, there were 2,300 stems per acre, averaging only 3 inches in diameter and 23 feet high. These trees grew only 0.6 inch in diameter and 3.5 feet in height in the decade before thinning. The trees were remarkably healthy, but branches and needles were short, and crowns of the dominants occupied only about 50 percent of tree height. Site index, estimated in a nearby stand where high stand densities had not substantially reduced height growth, is 62 feet (Meyer 1961) or 95.5 feet (Barrett 1978). No beetle activity was present when the study was initiated. The light mortality as evidenced by some dead stems throughout the stand was attributed to gradual suppression.

reatments and Design

The randomized block design consisted of a control (no thinning, average spacing 4.3 feet) and four spacing treatments:

9.3 by 9.3 feet (500 trees per acre)

13.2 by 13.2 feet (250 trees per acre)

18.7 by 18.7 feet (125 trees per acre)

26.4 by 26.4 feet (62.5 trees per acre)

The stand was divided into three blocks, and attempts were made to lay out five rectangular 0.192-acre plots, 79.2 by 105.6 feet, surrounded by a similarly treated 33-foot buffer strip in each block. Unfortunately, only four plots could be located on blocks one and two. The 9.3-foot spacing was limited to block three because observations of natural even-aged stands at that time indicated that wider spacings probably would be more practical in operational thinnings. Plots were thinned to spacings assigned randomly within blocks, leaving evenly distributed trees throughout each plot.

Measurements

Measurements were made in spring 1959, and then every 5 years over a 35-year period for the thinned plots. Control plots were not measured until fall 1963 but thereafter were measured with the thinned plots. At each measurement, diameters at breast height (d.b.h.) of all trees were determined to the nearest 0.1 inch. Heights (H) of every tree in the thinned plots were measured to the nearest 0.1 foot with height poles or optical dendrometers (accuracy with height poles is probably about 0.5 feet). Twelve trees in each thinned plot and 20 trees in each unthinned control plot were selected for volume determination, and volumes for these trees were determined each time the plots were measured. These trees represented the range of diameters and heights, but slightly more large than small trees were selected. These volume trees were climbed, and their diameters were measured at 5-foot intervals, or their diameters at various heights up the bole were determined with an optical dendrometer. Diameters at 1 foot and at 4.5 feet were measured with calipers. Bark thickness was determined at 4.5 feet. Cubic-foot stem volumes inside bark (V), including stump and tip, were calculated for each of these selected trees for each time of measurement by using equations from Grosenbaugh's (1964) STX program with a modification to describe bark thickness along the bole (Cochran 1976).

In summarizing data collected over several years by different people, three different volume equations were used. Although this is unusual, no meaningful differences in results are expected. Volume equations of the form,

$$\log_e V = c + d[\log_e(\text{d.b.h})] ,$$

were fit separately for the three unthinned plots, using linear regression methods for each time of measurement. For the first four times of measurement, coefficients for the volume equation (Husch and others 1972),

$$V = a + b[(\text{d.b.h.})^2 H] ,$$

were fit with combined data from the thinned plots. A wide range in diameters and heights developed with time for the different treatments so the equation (Schumacher and Hall 1933),

$$\log_e V = a_1 + b_1[\log_e(\text{d.b.h.})] + c_1(\log_e H) ,$$

was fit to combined data from the thinned plots by using multiple linear regression techniques for the fifth and following measurements. These models with coefficients determined for each time of measurement were used with diameters and heights (thinned plots) or diameters (control plots) to determine corresponding plot volumes.

Heights were determined for trees in control plots by fitting the equation (Curtis 1967),

$$\log_e H = a_2 + c_2/(d.b.h) + d_2/(d.b.h.)^2 ,$$

to diameter and total height data for the 20 trees measured for volume in each unthinned plot. This fit was done for each time of measurement. This equation with separate coefficients for each plot and measurement time was then used to determine heights for each tree in the unthinned plots. The second-degree term was not used unless it was significant ($p \leq 0.05$).

Scribner board-foot volumes (V1) were calculated for trees 8 inches and larger in diameter with a 5-inch or greater top diameter inside bark at 17 feet by using,

$$\log_e V1 = 0.9608 + 1.4667(\log_e V) - 0.1737(\log_e H) - 0.17[\log_e(d.b.h)] .$$

This equation ($R^2 = 0.99$, standard error = 0.10) was developed from 100 ponderosa pine trees, ranging from 8 to 27 inches in diameter, destructively sampled over a wide range of sites in Oregon and Washington during other studies.

Stand density index (SDI) of each plot was determined for each time of measurement from,

$$SDI = TPA(QMD/10)^{1.77},$$

where TPA is live trees per acre and QMD is the quadratic mean diameter (DeMars and Barrett 1987). An exponent of 1.77 instead of 1.605 was used because -1.7653 was the slope of a least-squares fit of $\log_e$TPA as a function of $\log_e$QMD for Meyer's (1961) original data (DeMars and Barrett 1987). Oliver and Powers (1978) also found a slope of -1.77 for a least-squares fit of the same function for data collected in a survey of dense, natural, even-aged stands of ponderosa pine in northern California. The SDI for normally stocked stands in Meyer (1961) is 365 (DeMars and Barrett 1987).

Annual tree mortality (R_m) was calculated as a negative interest rate for each plot during each period from,

$$R_m = 1 - (N2/N1)^{(1/n)} ,$$

(Hamilton and Edwards 1976); where N1 and N2 are the number of live trees at the beginning and end, respectively, of each period, and n is the period length in years.

Gross and net periodic annual increments (PAI = growth during each period divided by the number of growing seasons in the period) were calculated for basal area, total cubic volume, and board-foot volume. The PAIs of QMDs and average heights also were determined for survivor trees. Mean annual gross and net growth (growth during the study divided by the number of growing seasons in the study) were determined for basal area, cubic volume, and board-foot volume. Mean annual cubic volume and basal-area growth for the largest diameter 31, 62, 125, and 500 trees per acre also were calculated when present for each treatment. Net mean annual cubic-volume and board-foot increments (MAI = live volume at each measurement divided by age) also were determined. Trees thinned at the start of this study were not included in the calculation of MAI for total cubic volume. The PAIs, mean annual growth rates over the period of this study, and MAIs for board-foot volumes included ingrowth. Thirty-five years (seven 5-year periods) of data exist for the thinned plots, and 30 years of data exist for the control plots. Only the last 30 years of data (six 5-year periods) were subjected to analyses of variance.

Mortality rates were not analyzed statistically because there were many plots with no mortality in each period. Standard analyses of variance or repeated measures analyses of variance (split-plots in time) were used to test the following hypotheses: (1) There are no differences in QMD, average height, basal area, cubic volume, or board-foot volume with spacing 35 years after treatment. (2) There are no differences in PAIs with spacing or period. (3) There are no differences in 30-year mean annual growth rates of all trees or a fixed number of largest trees with spacing. (4) There are no differences in MAIs with spacing or period.

Orthogonal polynomials cannot be used to examine response to all treatments because only one replication exists for the 9.3-foot spacing; hence, the sums of the orthogonal coefficients do not equal zero. Examination of the response surface was important, so data from the 9.3-foot spacing was not used in the analyses of variance. The unequal intervals between spacings were taken into account in determining the orthogonal polynomial coefficients used in these tests (Bliss 1970). Relations between PAIs and stand density were examined by plotting PAIs versus spacing and also mean period SDI. Regressions of the form,

$$\log_e PAI = a + a_1R_1 + a_2R_2 + b_1P_1 + \ldots + b_{i-1}\,P_{i-1} + c_1 SDIm_i + c_2 \log_e SDIm_i\ ,$$

were used to relate PAIs of gross volume to block or replication (R), period (P), and period mean SDIs (SDIm) for the thinned plots. Unthinned plots were excluded because their growth rates may be reduced by stagnation. Dummy variables were used for replications and periods. Coefficients for these regressions were determined with the general linear models procedure (SAS Institute 1988), with combined data from all thinned plots and periods (70 observations), assuming independence of all observations. The adjusted R^2 will tend to be overestimated because of lack of independence of all observations. A similar equation was used by Curtis and Marshall (1986) for Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), except their study was not blocked, so there were no terms for replication, and they used relative density instead of SDI. Estimates from the above equation were used to describe the fraction of gross volume PAI at full stocking (SDI = 365) produced at lower stocking levels.

Average QMDs for the thinned treatments ranged from 3.4 to 5.7 inches, and corresponding average heights ranged from 18.6 to 28.4 feet in 1959 (table 1). Thirty-five years later, all stand statistics for the thinned plots differed significantly with spacing ($p \leq 0.05$, statistics not shown); QMDs ranged from 7.2 to 13.6 inches, and average heights ranged from 41.3 to 63.1 feet. Control plots had the smallest QMDs and average heights, the least board-foot volume, but the greatest cubic-foot volume after 35 years.

Mortality was recorded by 5-year periods for each plot; 10 plots were observed for seven periods, and 3 plots were observed for six periods. Mortality occurred in only 24 of the 88 observation periods (fig. 1). Nineteen of these twenty-four observations had plot SDIs above 250 at the beginning of the period. Mortality occurred in every observation where plot SDIs were 250 or more at the start of a period. Mortality occurred in only 5 of the 69 observations where plots had SDIs lower than 250 at the beginning of the period.

The ratio (QMD of mortality during a period)/(QMD at the start of the period) was less than 0.7 in 17 of 18 instances when the initial QMD was less than 6 inches (fig. 2). This ratio ranged from 0.8 to 1.2 when the initial QMD was greater than 7 inches. Much of the mortality for plots with small QMDs was due to suppression, but mountain pine beetles were responsible for some mortality in intermediate and higher crown classes in later periods. Mountain pine beetles were responsible for much or all of the mortality for plots where QMDs were greater than 7 inches.

Response in diameter growth to thinning was immediate (fig. 3). Survivor PAIs for QMD increased linearly ($p \leq 0.05$) as spacing widened (table 2) and generally decreased significantly ($p \leq 0.05$) with succeeding periods (increasing age). The slope of the relation of diameter growth to spacing decreased with succeeding periods as shown by the significance ($p \leq 0.05$) of the linear term in the period-by-spacing interaction (table 2). Thinning also produced an immediate response in height growth, and height increment increased curvilinearly ($p \leq 0.05$) with increased spacing (table 2) for all periods. The greatest height increment was not produced, however, until the third or later periods (fig. 4). Average gross and net basal-area PAI and average PAIs for gross and net volume decreased linearly ($p \leq 0.05$) as spacing widened (figs. 5 and 6, table 2). These PAIs differed ($p \leq 0.05$) with period, and gross volume PAIs reached the maximum in the sixth period for all but the control treatments. The slope of the relation of PAI to spacing for both gross cubic volume and net basal area differed with period as shown by the significance ($p \leq 0.05$) of the linear component of the period-by-spacing interaction. The relation of gross basal-area PAI and net cubic-volume PAI to spacing was curvilinear for some periods, as shown by the significance ($p \leq 0.05$) of the quadratic component of the period-by-spacing interaction. The PAIs for gross and net Scribner board-foot PAIs varied curvilinearly ($p \leq 0.05$) with spacing ($p \leq 0.05$), and differed ($p \leq 0.05$) with period. The relative board-foot volume produced by each spacing differed with period as shown by the significance ($p \leq 0.05$) of the quadratic term in the period-by-spacing interaction (fig. 7, table 2). In the first period, the greatest board-foot PAI occurred at the 26.3-foot spacing, primarily because this spacing had the most trees larger than 8 inches. The maximum board-foot PAI shifted to narrower spacings with later periods, but the control plots always produced the least board feet in the later periods.

Table 1—Average stand statistics over the 35-year study

Assigned spacing	Initial SDI[a]	Trees per acre	QMD[b]	Average height	Basal area	Cubic volume	Scribner volume
Feet			*Inches*	*Feet*	*Ft^2/acre*	*Ft^3/acre*	*Bd. ft/acre*
Live trees after initial thinning—spring 1959							
26.3	24	62.5	5.7	28.4	11.4	124	17
18.7[c]	46	128	5.0	25.5	17.8	183	88
13.2	59	250	4.4	23.4	26.8	250	0
9.3	76	500	3.4	18.6	32.4	258	0
Control[d]	—	—	—	—	—	—	—
Live trees—fall 1963 and spring 1964							
26.3	36	62.5	7.3	32.6	18.8	226	309
18.7	55	128	6.2	29.3	27.1	312	203
13.2	79	250	5.2	26.6	36.8	381	104
9.3	115	500	4.4	20.8	51.9	438	74
Control[e]	294	2,387	3.2	24.5	122.2	1,107	124
Live trees—fall 1968 and spring 1969							
26.3	50	62.5	8.8	37.1	26.5	371	644
18.7	76	128	7.4	33.8	38.7	505	625
13.2	108	250	6.2	29.7	53.0	607	156
9.3	145	500	5.0	23.9	68.1	666	109
Control	318	2,362	3.3	25.3	133.9	1,346	220
Live trees—fall 1973 and spring 1974							
26.3	61	61	10.0	44.2	33.0	550	1,379
18.7	92	128	8.3	39.5	48.3	744	1,272
13.2	129	248	6.9	34.4	64.8	862	737
9.3	178	500	5.6	27.4	84.7	938	212
Control	351	2,320	3.6	26.2	149.7	1,647	337
Live trees—fall 1978 and spring 1979							
26.3	72	61	11.0	48.7	40.2	752	2,028
18.7	110	128	9.1	43.7	58.7	973	2,254
13.2	153	248	7.6	38.0	78.5	1,119	1,554
9.3	207	500	6.1	30.6	100.7	1,239	434
Control	380	2,272	3.8	27.7	164.5	1,402	543

Table 1—Average stand statistics over the 35-year study (continued)

Assigned spacing	Initial SDI[a]	Trees per acre	QMD[b]	Average height	Basal area	Cubic volume	Scribner volume
Feet			*Inches*	*Feet*	*Ft ^{2}/acre*	*Ft ^{3}/acre*	*Bd. ft/acre*
			Live trees—fall 1983 and spring 1984				
26.3	83	61	11.9	54.1	47.4	903	2,665
18.7	126	128	9.9	48.4	68.7	1,175	2,900
13.2	173	248	8.2	42.7	90.1	1,379	2,432
9.3	236	500	6.5	35.1	116.9	1,538	1,212
Control	400	2,177	4.0	27.4	175.2	2,272	914
			Live trees—fall 1988 and spring 1994				
26.3	93	61	12.8	59.6	54.0	1,197	3,886
18.7	141	128	10.5	53.6	77.6	1,540	4,287
13.2	191	247	8.7	46.8	101.0	1,749	3,586
9.3	260	500	6.9	38.9	130.2	1,935	1,913
Control	412	1,973	4.3	29.8	183.9	2,506	1,186
			Live trees—fall 1993				
26.3	104	61	13.6	63.1	61.1	1,436	4,869
18.7	155	128	11.1	56.6	86.6	1,800	5,513
13.2	199	236	9.1	49.0	106.3	1,943	4,540
9.3	273	484	7.2	41.3	138.2	2,212	2,871
Control	420	1,811	4.6	31.7	190.2	2,789	1,579

[a] SDI = stand density index.

[b] QMD = quadratic mean diameter.

[c] An 18.7-foot spacing should have 125 trees per acre, but two extra trees were left in one of the replications.

[d] Control plots were not measured in 1959.

[e] Spacings for each of the 3 control plots averaged 4.3, 5.3, and 3.3 feet.

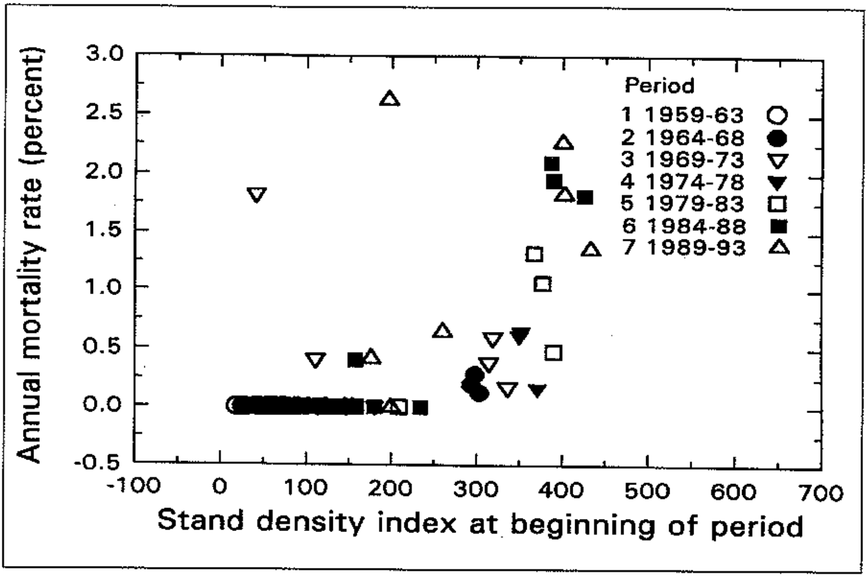

Figure 1—Relation of annual mortality rates to SDI at the start of the period for the 88 plot-period combinations.

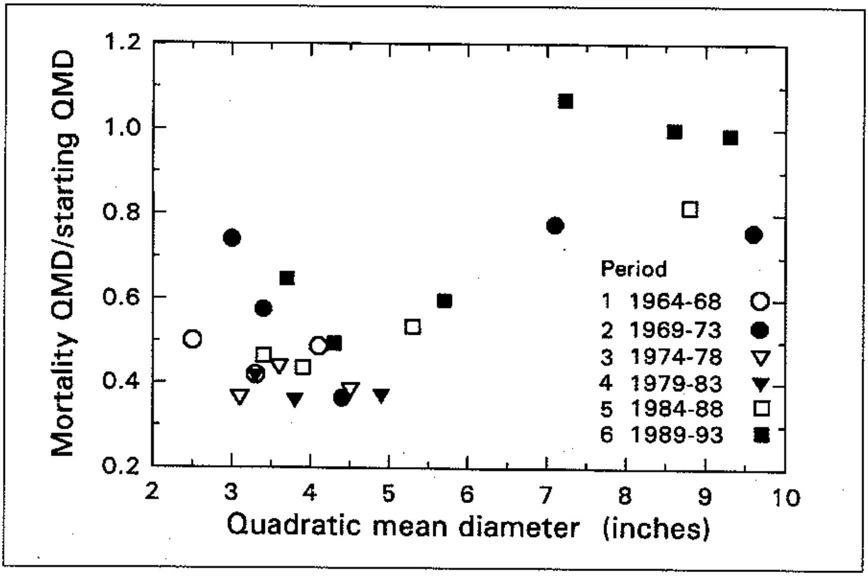

Figure 2—The relation of the ratio (QMD of periodic mortality)/(QMD at the start of that period) to QMD at the start of that period.

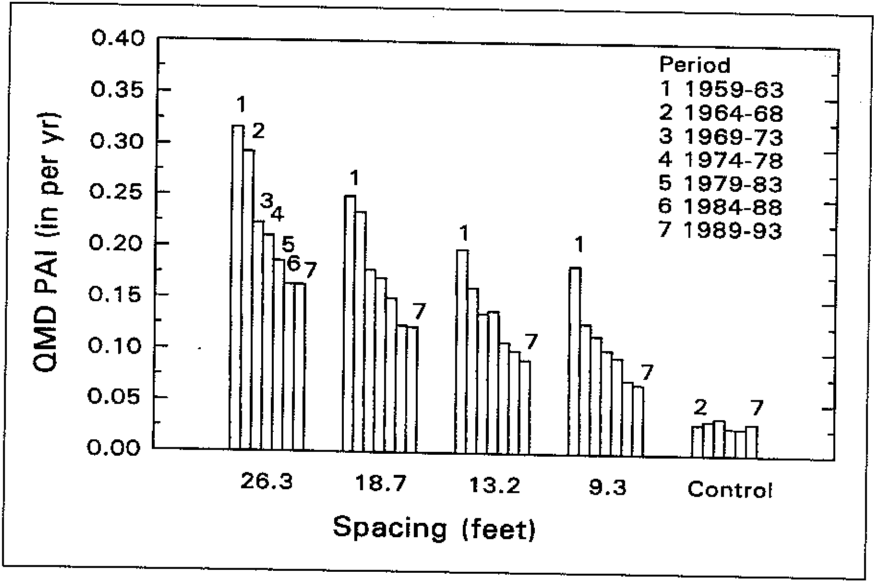

Figure 3—Survivor QMD PAIs for each spacing and period. Numbers above the bars for each spacing indicate the period.

Table 2—Probability of higher *F*-values for the repeated measures analyses of variance of periodic annual increments (PAIs)

		Probability of higher *F*-values							
		PAI[a]							
				Basal area		Cubic volume		Scribner bd. ft	
Source	Degrees of freedom	QMD[b]	Average height	Gross	Net	Gross	Net	Gross	Net
Block	2	0.6753	0.3337	0.8122	0.9666	0.0691	0.1413	0.0150	0.0255
Spacing:									
Linear	1	.0001	.0001	.0005	.0052	.0015	.0112	.0005	.0008
Quadratic	1	.0533	.0001	.2882	.1073	.8306	.4437	.0016	.0031
Cubic	1	.8326	.3546	.6947	.9628	.7559	.5860	.9937	.7911
Error	6								
Period	5	.0001	.0001	.0001	.0001	.0001	.0001	.0001	.0001
P x S:[c]									
Linear	5	.0001	.0066	.0001	.0001	.0035	.0004	.0005	.0012
Quadratic	5	.1280	.3841	.0403	.1360	.8728	.0136	.0007	.0038
Cubic	5	.6985	.3240	.5913	.0292	.8158	.1664	.0554	.0698
Error	40								
MSE:[d]									
Whole plot		.0011	.0025	.3224	.3638	147.61	162.97	2,389	2,850
Subplot		.0001	.0164	.0436	.0693	269.73	58.63	828	953

[a] PAI = periodic annual increment.

[b] QMD = quadratic mean diameter.

[c] P x S = period-by-spacing interaction.

[d] MSE = error mean square from the analyses of variance.

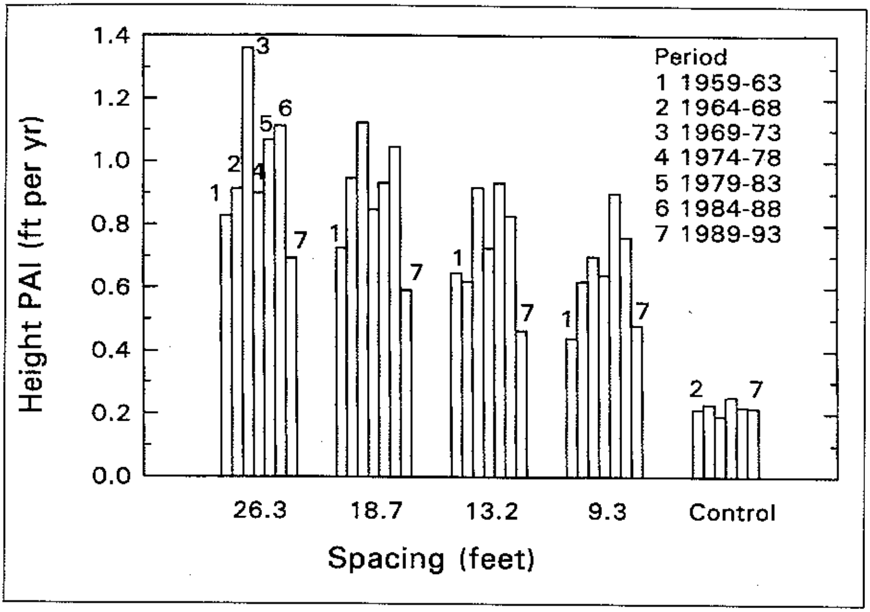

Figure 4—Survivor height PAIs for each spacing and period. Numbers above the bars indicate the period.

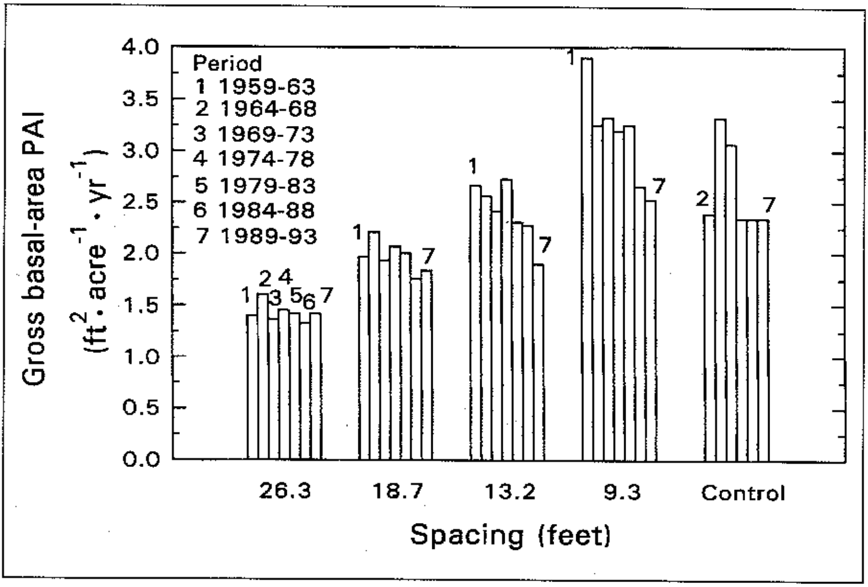

Figure 5—Gross basal-area PAIs for each spacing and period. Numbers above the bars indicate the period.

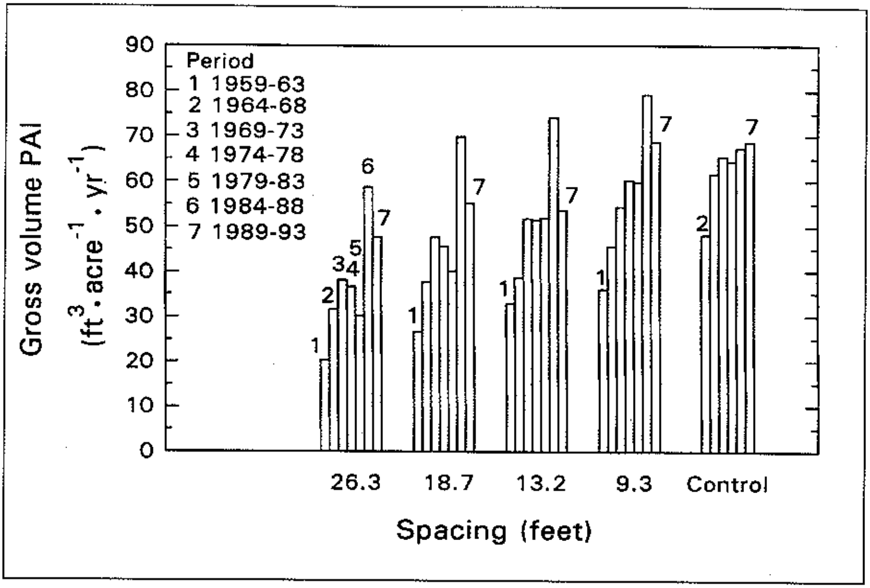

Figure 6—Gross cubic-volume PAIs for each spacing and period. Numbers above the bars indicate the period.

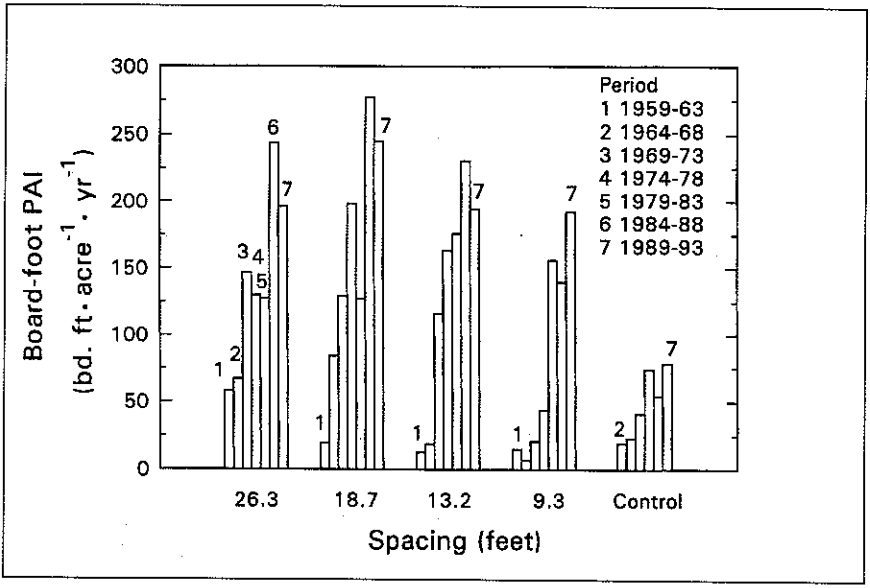

Figure 7—Gross board-foot PAIs for each spacing and period. Numbers above the bars indicate the period.

Plots of PAIs over mean period SDIs demonstrate a curvilinear response to SDI for survivor QMD PAI (fig. 8) and gross volume PAI (fig. 9). Similar plots for gross basal-area PAI (fig. 10), and survivor height PAI (fig. 11) demonstrate a curvilinear response for some periods.

Gross volume increments at varying densities were predicted from the regression equation derived by using all thinned plot data (table 3). These growth rates, when expressed as a fraction of gross cubic-volume PAI at full stocking, are curvilinearly related to stocking level expressed as a fraction of full stocking (SDI/365) (fig. 12). For SDIs of 15, 30, 50, and 75 percent of full stocking, corresponding gross volume PAIs are 46, 64, 80, and 92 percent, respectively, of gross volume PAIs produced at full stocking.

Results from analyses of variance of mean annual growth rates for all trees are the same as the whole-plot or block and spacing results of the repeated measures analyses for the corresponding PAIs (table 2). Mean annual growth rates of basal area and cubic volume increased linearly ($p \leq 0.05$) as spacing decreased (table 2, figs. 13 and 14). Spacings of 26.3, 18.7, 13.2, and 9.3 feet produced 67, 82, 89, and 102 percent, respectively, of the 30-year gross mean annual cubic-volume growth of the unthinned stand. Corresponding values for net mean annual growth are 70, 88, 91, and 105 percent of the unthinned stand for the 26.3-, 18.7-, 13.2-, and 9.3-foot spacings, respectively, (fig. 14). Mean annual growth rates for board feet varied curvilinearly ($p \leq 0.05$) with spacing (table 2). Net board-foot mean annual growth rates were 49, 93, 149, 177, and 149 board feet • acre^{-1} • year^{-1} for the narrowest to widest spacings, respectively. Corresponding gross mean annual growth rates were 49, 96, 154, 177, and 152 board feet • acre^{-1} • year $^{-1}$. Mean annual growth of a fixed number of largest trees was reduced by the presence of smaller trees (figs. 13 and 14). Mean annual basal-area growth for the 62 trees with the largest diameters in fall 1994 decreased linearly ($p \leq 0.05$) with decreasing spacing (table 4). Mean annual volume growth for these 62 trees decreased curvilinearly ($p \leq 0.05$) with increasing spacing (table 4). Mean annual volume growth for the 62-trees-per-acre treatment (26.4-foot spacing) was 70 percent of the net mean annual growth for the control treatment for the 30-year period. Mean annual volume growth for the largest 62 trees in the control treatments was only 23 percent of the net mean annual volume growth for the 26.4-foot spacing.

Cubic-volume MAIs increased linearly ($p \leq 0.05$) with decreasing spacing (table 5, fig. 15), but Scribner board-foot MAIs varied curvilinearly ($p \leq 0.05$) with spacing (table 5, fig. 16). Both cubic- and board-foot volume MAIs increased ($p \leq 0.05$) with period or age (table 5). The relation of both cubic-volume and board-foot MAIs to spacing changes with time as shown by the significance ($p \leq 0.05$) of the linear (cubic-volume MAI) and quadratic (board-foot MAI) components of the period-by-spacing interaction.

(Text continues on p. 20)

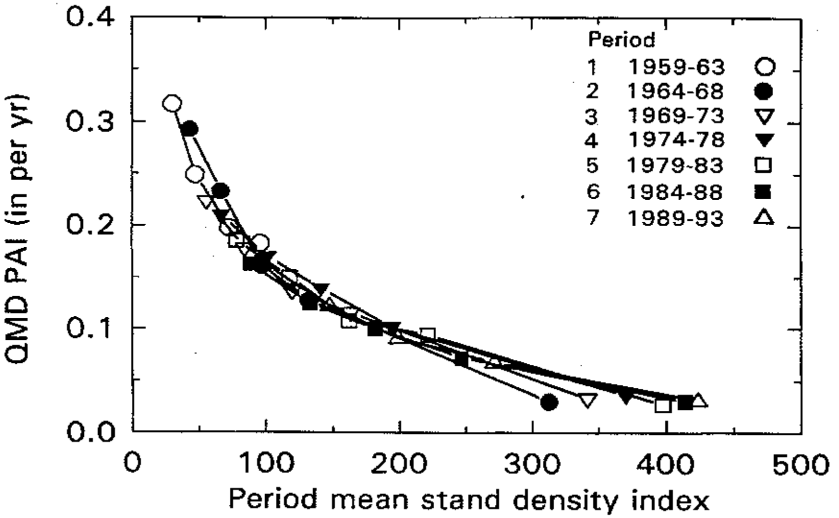

Figure 8—Relation of survivor QMD PAIs to period mean SDI for each period.

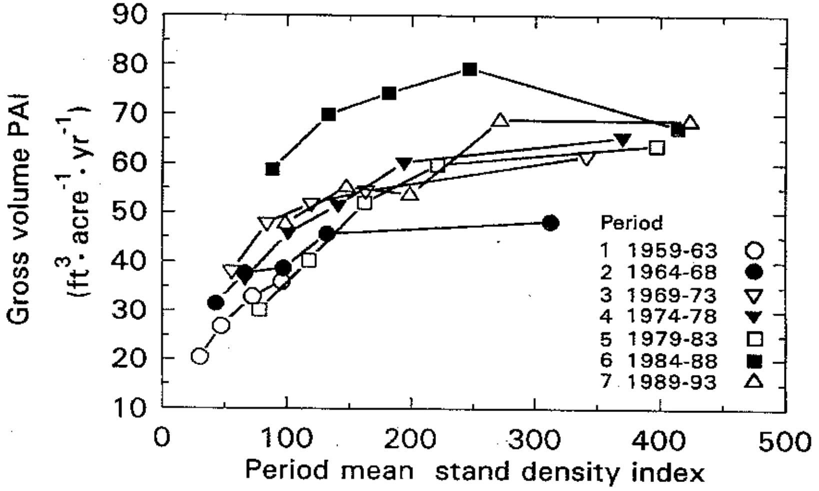

Figure 9—Relation of gross volume PAIs to period mean SDI for each period.

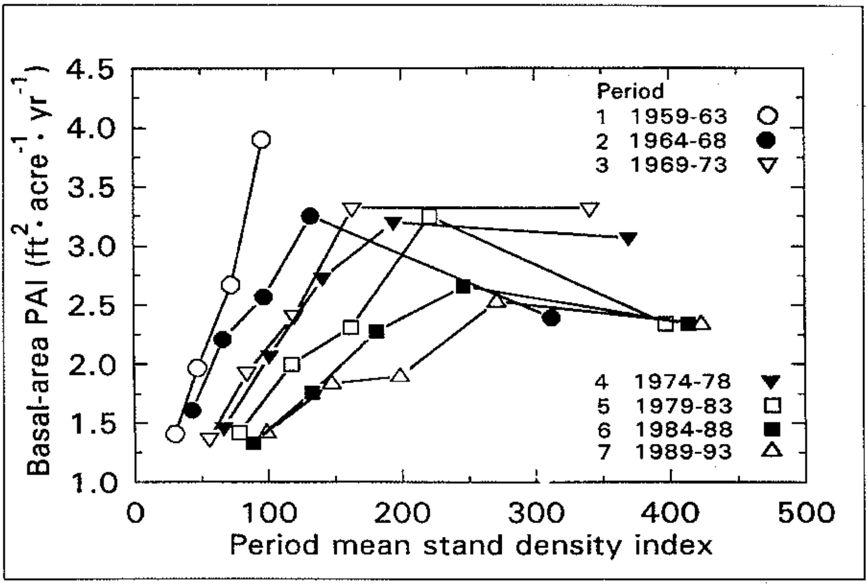

Figure 10—Relation of gross basal-area PAIs to period mean SDI for each period.

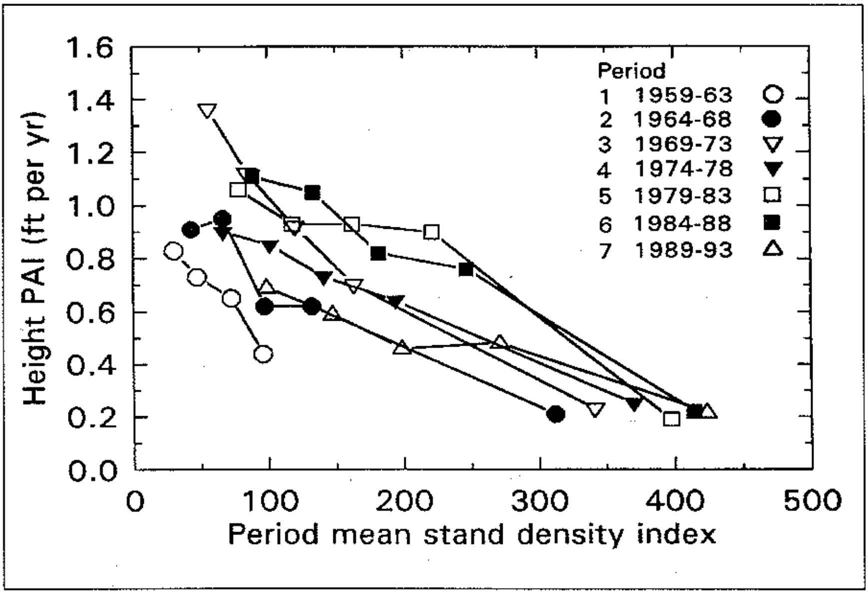

Figure 11—Relation of survivor height PAIs to mean period SDI for each period.

Table 3—Parameter estimates for the regression analysis[a] of gross periodic annual volume increments from the thinned plots as a function of replication, period, and mean period stand density index (SDIm) assuming independence of all values

Coefficient	Parameter estimate	P > T
a	1.2010	0.0009
a_1	.1538	.0001
a_2	.1029	.0023
b_1	-.1664	.0097
b_2	-.0179	.7503
b_3	.1052	.0528
b_4	.0058	.9102
b_5	-.1549	.0030
b_6	.2933	.0001
c_1	-.000919	.2949
c_2	.5660	.0001
Adjusted R^2	.90	

[a] $\log_e PAI = a + a_1R_1 + a_2R_2 + b_1P_1 + ... + b_{i-1}P_{i-1} + c_1SDIm_i + c_2\log_e SDIm_i$.

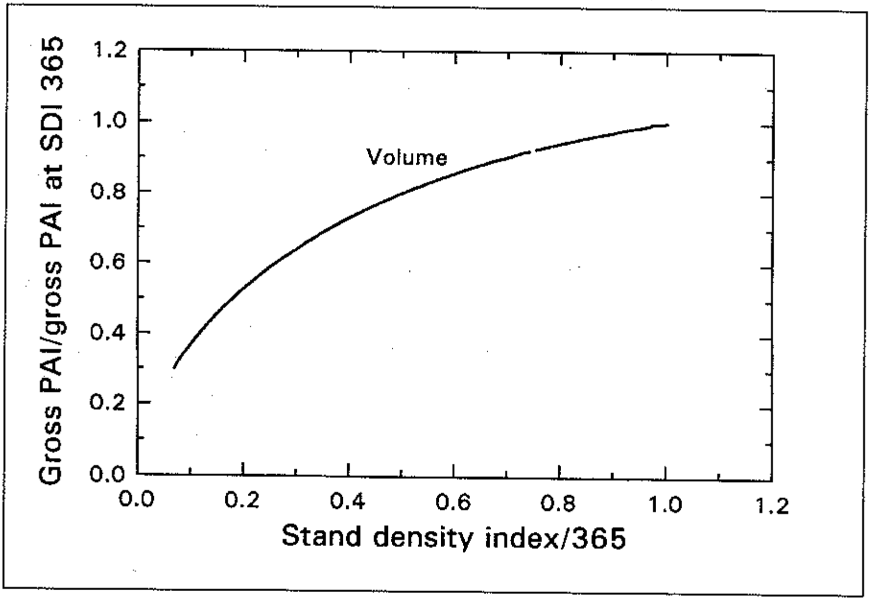

Figure 12—Cubic-volume growth expressed as a fraction of the gross volume PAI at full stocking as a function of stocking level expressed as a fraction of full stocking (SDI at full stocking is 365).

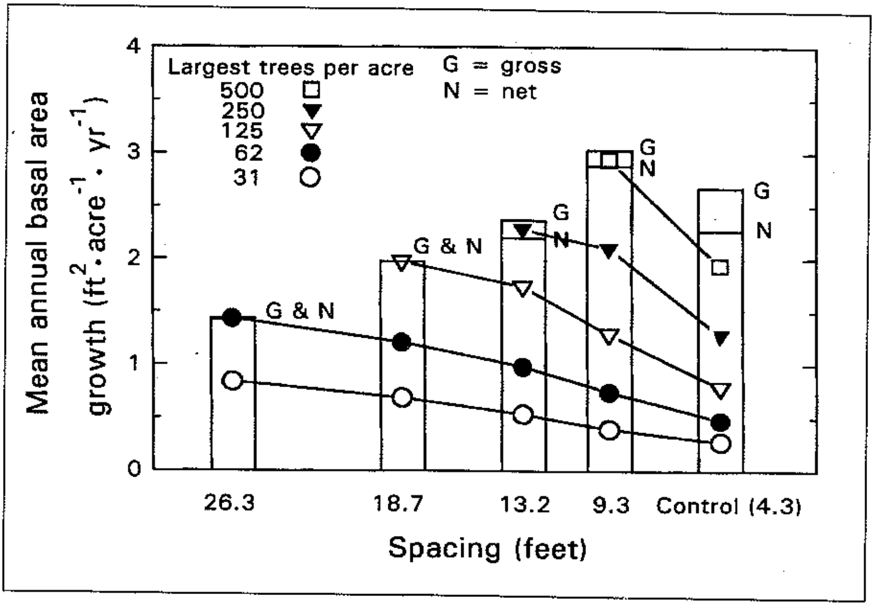

Figure 13—Thirty-year net and gross mean annual basal-area growth for all trees at various spacings and the mean annual basal-area growth of the largest diameter 500, 250, 125, 62, and 31 trees per acre for different spacings. Mean period SDIs for the last six periods were 72, 100, 150, 205, and 377 for the 26.3-, 18.7-, 13.2-, 9.3-, and 4.3-foot spacings, respectively.

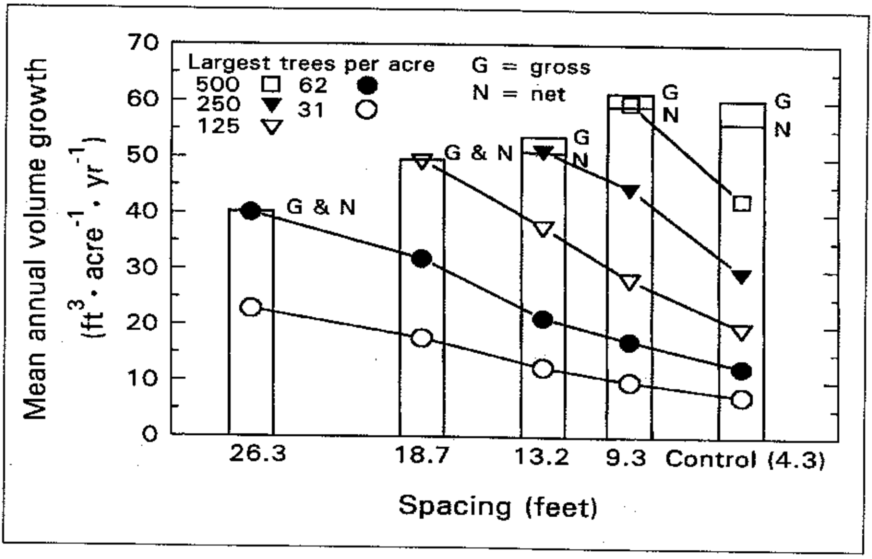

Figure 14—Thirty-year net and gross mean annual cubic-volume growth for all trees at various spacings and the mean annual cubic-volume growth of the largest diameter 500, 250, 125, 62, and 31 trees per acre at different spacings. Mean period SDIs for the last six periods were 72, 100, 150, 205, and 377 for the 26.3-, 18.7-, 13.2-, 9.3-, and 4.3-foot spacings, respectively.

Table 4—Probability of higher *F*-values for analyses of variance for mean annual growth of basal area and volume for the largest 62 trees per acre during the last 30 years of the 35-year study

Source	Degrees of freedom	Probability of higher *F*-values	
		Mean annual basal-area growth	Mean annual cubic-volume growth
Block	2	0.6678	0.0246
Spacing:			
Linear	1	.0001	.0001
Quadratic	1	.1305	.6900
Cubic	1	.9776	.0477
Error	6		
MSE[a]		.0131	4.0142
CV%[b]		11.12	7.73

[a] MSE = mean square error from the analysis of variance.
[b] CV% = coefficient of variation.

Table 5—Probability of higher *F*-values for repeated measures analyses of variance of mean annual increments for cubic and Scribner board-foot volumes

Source	Degrees of freedom	Probability of higher *F*-values for mean annual increments	
		Cubic volume	Scribner bd.-ft volume
Block	2	0.0011	0.0078
Spacing (S):			
Linear	1	.0004	.0005
Quadratic	1	.6048	.0157
Cubic	1	.5947	.3721
Error	6		
Period (P)	6	.0001	.0001
P x S:[a]			
Linear	6	.0001	.0003
Quadratic	6	.0772	.0009
Cubic	6	.8394	.7442
Error	48		
MSE:[b]			
Whole plot		10.9550	125.6542
Subplot		.5410	21.2121

[a] P x S = period-by-spacing interaction.
[b] MSE = mean square error from analyses of variance.

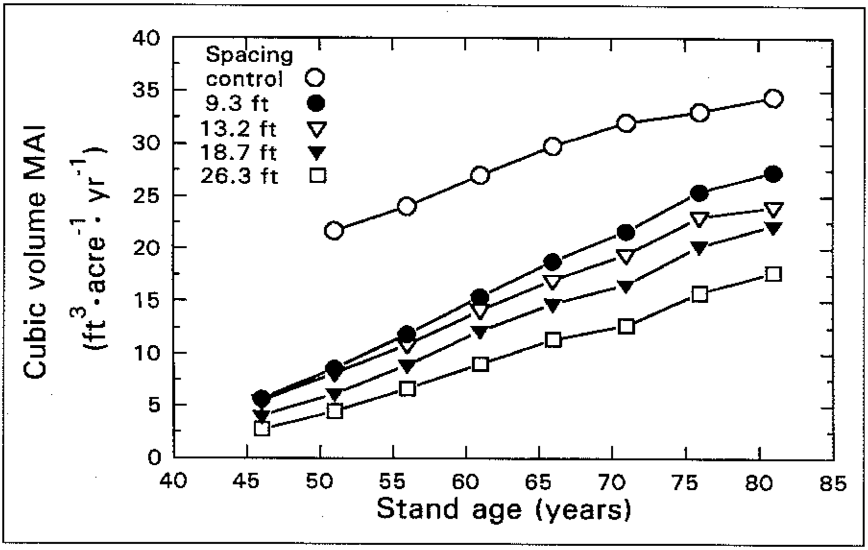

Figure 15—Cubic-volume MAI for the various spacings as a function of total stand age. This MAI does not include the volume removed in the thinning at the start of the study.

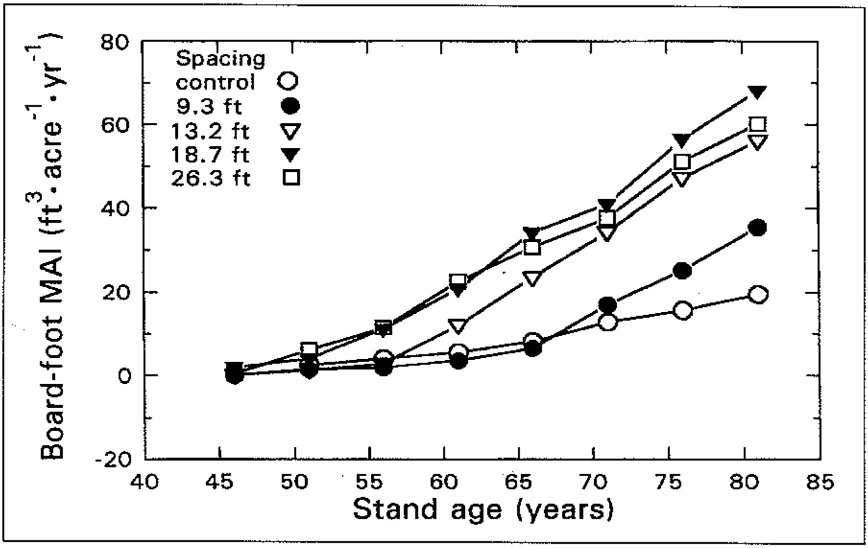

Figure 16—Scribner board-foot MAIs for the various spacings as a function of total stand age.

Diameter and height growth of individual trees were greatly reduced at high stocking levels, but net cubic-volume growth rates continued to increase at SDIs greater than 365. It is commonly expected that self-thinning will maintain small-diameter stands at near-normal densities and allow dominant trees to maintain reasonable growth rates. Such self-thinning did not take place in the unthinned plots although suppression-caused mortality occurred. Growth rates of even the largest trees were much reduced at high stand densities, thereby indicating that unmanaged stands that escape thinning through fire or other disturbance cannot be expected to produce large trees or progress toward mid- and late-seral conditions in reasonable time.

Attacks by mountain pine beetles in lodgepole pine occur mostly on the largest trees, regardless of whether they are in thinned or unthinned plots, but more of the attacked trees survive on thinned plots (Mitchell and Presler 1993). Small trees are apparently not preferred by beetles and are not likely to be attacked unless they are close to larger trees under attack. Beetle attacks on both thinned and unthinned stands are clustered and associated with the largest trees. This pattern of mortality occurred in this study and in other ponderosa pine studies as well (Cochran and Barrett 1993, 1995; Oliver 1995).

These results indicate that even the largest trees in dense stands can be expected to grow slowly with time as the stand incurs light, mostly suppression-related mortality. A shift from suppression- to beetle-caused mortality can be expected when some of the largest trees reach 6 to 9 inches in size, resulting in an increase in relative size of trees that die (fig. 2). Preventing or reducing beetle-caused mortality is an important benefit from thinning, but thinning must be heavy enough to keep stand density below a certain critical threshold.

Mountain pine beetle can be expected to cause serious mortality at SDIs above 170 in lodgepole pine stands if trees 9 inches or larger are present. The density at which mountain pine beetle may cause serious mortality in ponderosa pine stands increases with increasing site index. For medium and lower sites, this threshold density is considerably below normal and is equivalent to an SDI of 217 for this study site (Cochran and others 1994). A light thinning in dense sapling stands merely hastens the development of 6- to 9-inch trees without keeping densities below a beetle susceptibility threshold, thereby establishing a situation where a high probability of serious mortality exists. Setting the upper management zone at an SDI of 217 (59 percent of 365) should avoid high mortality rates associated with pine beetles. A reasonable lower management zone would be an SDI of 143 (39 percent of 365). Management within these limits would capture between 72 and 85 percent of the gross cubic-volume growth at full stocking (fig. 12).

Reduction in diameter and height growth with increasing density also has been found for ponderosa pine in other studies (Barrett 1963, 1982; Cochran and Barrett 1993, 1995). Reduction of basal area and volume growth of a fixed number of largest trees in a stand because of competition from smaller trees also occurred in these studies. These growth reductions indicated that intertree competition exists even at spacings that would be considered too wide for many species in other areas. Much potential growth, however, can be captured at low densities (fig. 12). Low densities produce larger trees with higher volumes per tree and, at times, higher stand board-foot volumes.

Only 3 to 5 percent of unclassified Forest Service land historically occupied by ponderosa pine east of the Cascade Range in Oregon and Washington is currently in late-seral condition.[1] Late-seral condition has 10 to 30 TPA 21 inches or greater in diameter (depending on the site) with 3 snags greater than 14 inches in diameter or 10 percent of the stand with dead tops and three to six 8-foot pieces of down woody debris 12 inches or larger (Hopkins and others 1992). Two or three TPA with diameters greater than 30 inches should occur in the very late-seral condition. The slow growth rates of unmanaged, dense, second-growth ponderosa pine stands indicate that density management is necessary to speed development of mid- and late-seral size and density conditions. Ponderosa pine is a long-lived species, and mean annual increments may keep increasing to old ages under certain management schemes. A management strategy using precommercial thinning to produce 20-inch trees early with repeated commercial thinnings over long rotations to produce much larger trees seems reasonable. Some potential cubic-volume production will be lost from using this strategy, but the social and monetary values associated with large trees will be increased, and the probability of severe mortality to pine beetles will be greatly reduced.

1 inch = 2.54 centimeters

1 foot = 0.3048 meter

1 acre = 0.4047 hectare

1 tree per acre = 2.47 trees per hectare

1 square foot = 0.09290 square meter

1 square foot per acre = 0.2296 square meter per hectare

1 cubic foot per acre = 0.06997 cubic meter per hectare

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