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Growth of Ponderosa Pine Thinned to Different Stocking Levels in Central Oregon: 30-Year Results

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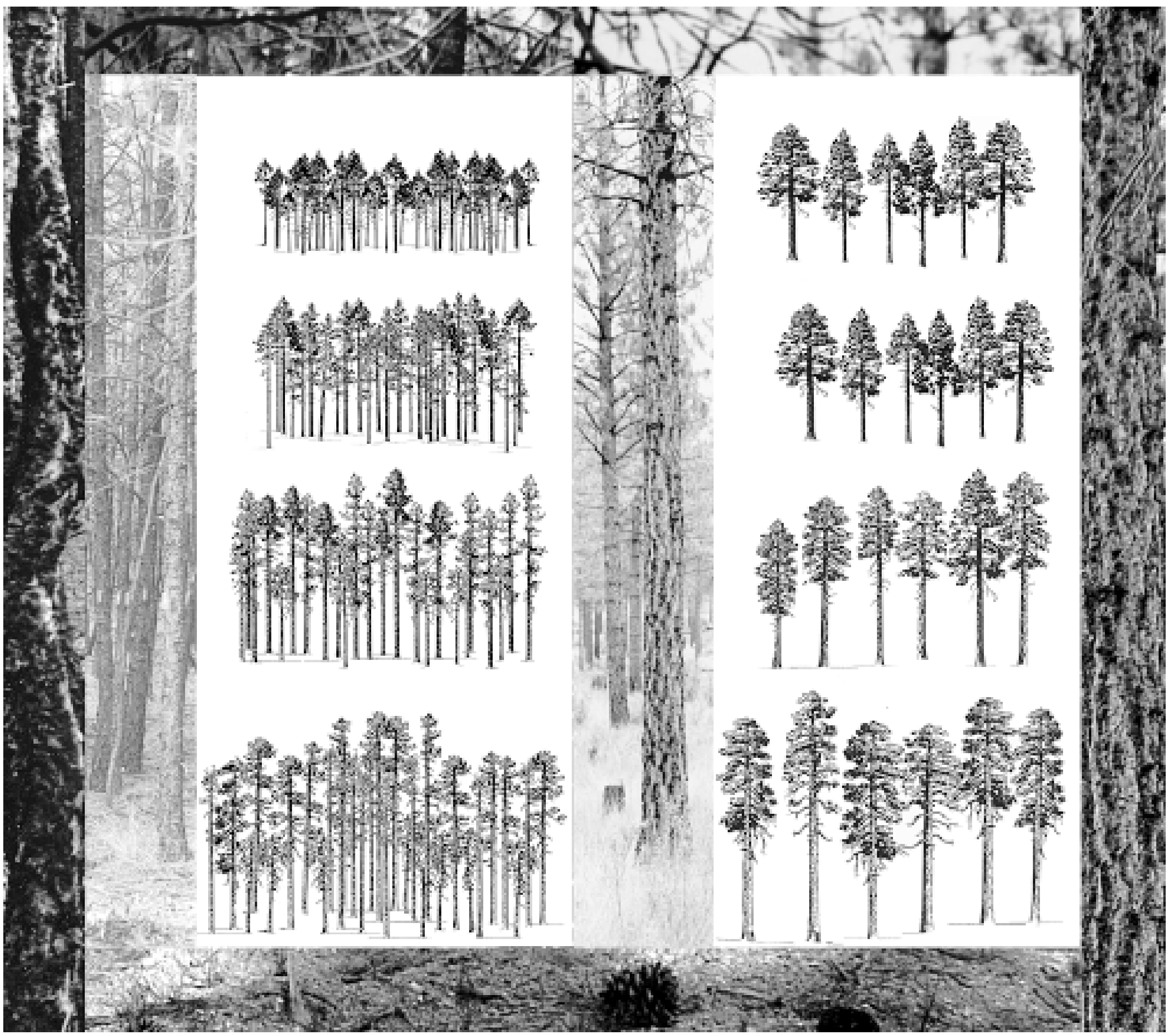

Authors

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Abstract

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No mortality occurred at the lowest growing stock level (GSL) during any of the six 5-year periods of study. After the first period, plot mortality never exceeded two trees per acre for any 5-year period where stand density index values were below 240 at the start of the period. All mortality was attributed to mountain pine beetles (*Dendroctonus ponderosae* Hopkins). Pandora moth (*Coloradia pandora* Blake) caused partial defoliation during 1992 and 1994, which reduced growth rates in the last period (1991-95). Periodic annual increments for survivor quadratic mean diameters decreased curvilinearly with increasing GSLs, and the survivor height PAI-GSL relation varied with period. Gross volume and basal area PAIs increased linearly with increasing GSLs. Gross basal area PAI and 30-year mean annual growth rates increased with increasing GSLs, but a significant curvilinear relation was not detected. Scribner board-foot yields at a stand age of 95 years increased linearly with increasing GSLs, while corresponding cubic-volume yields increased with increasing GSLs only if the initial thinnings were excluded. Mean annual increments (MAIs) for cubic volume increased with increasing stand age for all GSLs only if the initial thinning was excluded. Board-foot MAIs, with and without inclusion of initial thinning, increased with increasing stand age and with increasing GSLs. Mean annual growth of basal area and cubic volume for the 20 trees per acre with the largest diameters at the start of the study decreased curvilinearly with increasing GSLs. Increased periodic thinning levels greatly increased average tree size and reduced basal area and volume growth rates per acre.

Keywords: Growth, yield, mortality, thinning, ponderosa pine, pandora moth, mountain pine beetle.

Summary

Repeated thinnings every 10 years to six different growing stock levels (GSLs) were done for 30 years. Trees were measured every 5 years. No mortality occurred at the lowest GSL. Heaviest mortality occurred during the first 5-year period when trees had narrow crown ratios and were adjusting to new growing space. Later in the study, mortality greater than two trees per acre during 5-year periods did not occur on plots where stand density index values were below 240 at the start of the period. All mortality appeared to be caused by mountain pine beetle (*Dendroctonus ponderosae* Hopkins). Pandora moth (*Coloradia pandora* Blake) caused partial defoliation during 1992 and 1994, which reduced growth rates in the last period (1991-95). As expected, periodic annual increments (PAI) for survivor quadratic mean diameters decreased curvilinearly with increasing GSLs. The survivor height PAI-GSL curve shape varied with period. Height PAIs decreased with increasing GSLs to intermediate GSLs and then increased as GSLs increased further for some periods. In one period, height PAIs increased with increasing GSLs to intermediate GSLs and then decreased as GSLs increased further. For some other periods, height PAIs seemed to decrease linearly with increasing GSLs. Gross volume PAIs and 30-year mean annual growth rates increased linearly, not curvilinearly as expected, with increasing GSLs. Gross basal area PAI and 30-year mean annual growth rates increased with increasing GSLs, but an expected significant curvilinear PAI-GSL relation was not detected. Scribner board-foot yields at a stand age of 95 years increased linearly with increasing GSLs, while corresponding cubic-volume yields increased with increasing GSLs only if the initial thinnings were excluded. Mean annual increments (MAIs) for cubic volume increased with increasing stand age for all GSLs only if the initial thinning was excluded. Board-foot MAIs, with and without inclusion of initial thinning, increased with increasing stand age and with increasing GSLs. Mean annual growth of basal area and cubic volume for the 20 trees per acre having the largest diameters at the start of the study decreased curvilinearly with increasing GSLs. Increased periodic thinning levels greatly increased quadratic mean diameters and average heights as well as diameters of the largest 20 trees per acre in the stands while reducing cubic and board-foot volume growth. Board-foot yields have not culminated at stand age 95 years, and cubic-volume yields calculated by excluding the initial thinning also have not culminated. An early precommercial thinning to a spacing of at least 18 feet followed by commercial thinnings whenever the stand SDI exceeds 240 on this high site will produce large-diameter trees relatively soon and lower the probability of serious bark beetle outbreaks. These thinnings probably would lengthen the rotation age (the age of culmination of MAI) considerably.

Contents

Introduction

The levels-of-growing-stock (LOGS) study at Lookout Mountain in central Oregon is one of six studies established in even-aged, pole-sized ponderosa pine (*Pinus ponderosa* Dougl. ex. Laws) stands as part of a westwide investigation (Myers 1967, Oliver and Edminster 1988). Two of these studies are in the Black Hills of South Dakota, two are in Oregon (Barrett 1983, Cochran and Barrett 1995), one is in northern Arizona (Ronco and others 1985), and one is on the west slope of the Sierra Nevada in California (Oliver 1979). The objective is to compare cumulative wood production, tree size development, and growth-growing stock relations under several different thinning regimes.

The Lookout Mountain study is in a naturally regenerated, 1,000-acre stand in central Oregon, in the Pringle Falls Experimental Forest, Deschutes National Forest. These 30-year results include six measurement periods, each having five growing seasons. Results are directly applicable only to this stand, but they provide useful information about managing other ponderosa pine stands on similar sites.

Methods of Study

Study Area

Plots are on the south-facing slope of Lookout Mountain at an elevation of 5,000 feet (lat. 43º46' N.; long. 121º43' W.) east of the Cascade Range crest. Average annual precipitation is 40 inches, and a snowpack of 3 feet is common. Summers are dry with high temperatures ranging from 70 to 90 ºF. Nights are cool, and frost may occur at any time of year. The soil is a deep, well-drained, cindery over medial (loamy) Typic Cryorthent formed from dacite pumice originating from the eruption of Mount Mazama (Crater Lake). The pumice averages 3 feet deep and is underlain by sandy loam material developed in older volcanic ash containing some cinders and basalt fragments. The *Pinus ponderosa/Ceanothus velutinus* plant community in an *Abies concolor/Ceanothus velutinus* climax association (Franklin and Dyrness 1973) covers much of the mountainside.

Before initial thinning, the timber stand was dense, and only about 25 percent of total tree height consisted of live crown. A site index of 92 feet (Meyer 1961) was estimated from a few, very old ponderosa pine scattered throughout the study area. Site index (Meyer 1961) estimated from average heights of trees left after thinning was 80 feet. Excessive density has apparently suppressed height growth. Pretreatment stand characteristics compared to normal (Meyer 1961) were:

Characteristic	Pretreatment stand average	Normal site index 92, age 65
Trees per acre	1,133	462
Quadratic mean diameter (inches)	6.3	9.3
Basal area (square feet/acre)	240	216
Height (feet)	48	—
Volume (cubic feet/acre)	4,704	5,335

Treatments and Design

The six growing stock levels (GSLs) at Lookout Mountain, replicated three times in a completely randomized design, are 30, 60, 80, 100, 120, and 150. These GSLs are the basal area in square feet per acre that the stand has—or will have—after thinning, when the quadratic mean diameter (QMD) is 10 inches or more. Where QMDs were less than 10 inches, the prescribed basal area (PBA) for each GSL is tabulated in the study plan (Myers 1967). Where QMD is less than 10 inches (Cochran and Barrett 1995),

$$PBA = 0.05454(GSL)(QMD^2)Exp(-0.1696\ QMD)\ . \qquad (1)$$

Installation and Measurements

Treatments were assigned randomly to 18 one-half-acre plots with additional 33-foot buffer strips. Plots were scattered throughout a quarter section where site and stand density differences could be minimized. A pretreatment stand inventory was made by measuring the diameter of each tree on the 18 plots. Reserve trees were marked, and plots and buffer strips were thinned to the prescribed levels initially (fall 1965) and after the second (fall 1975) and fourth (fall 1985) periods (figs. 1 and 2).

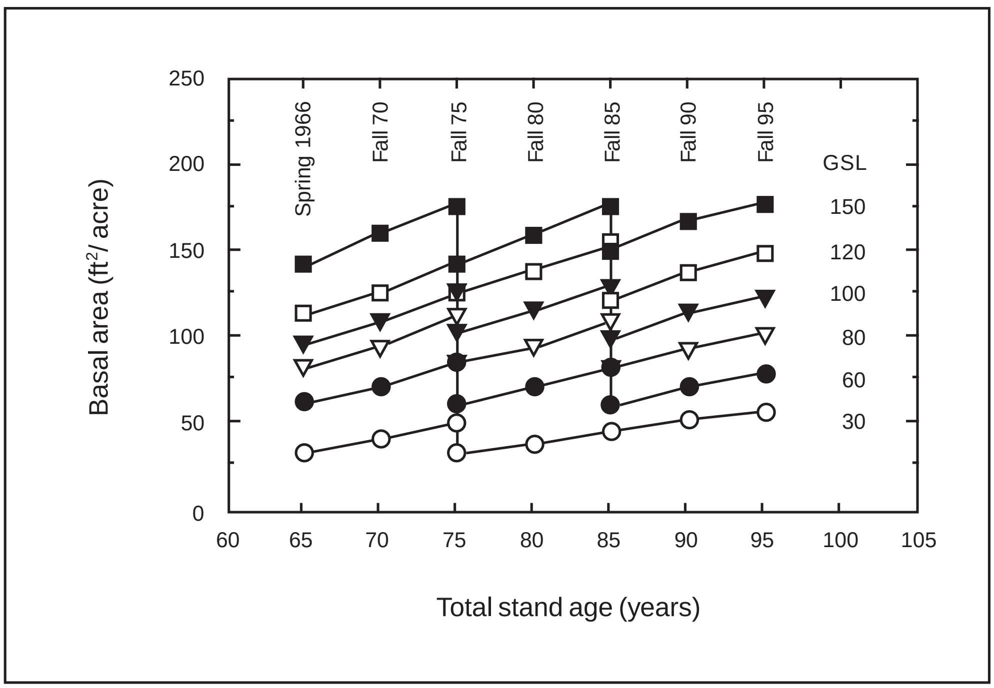

Figure 1—Live basal area (treatment means) in relation to total age and year of measurement for each GSL.

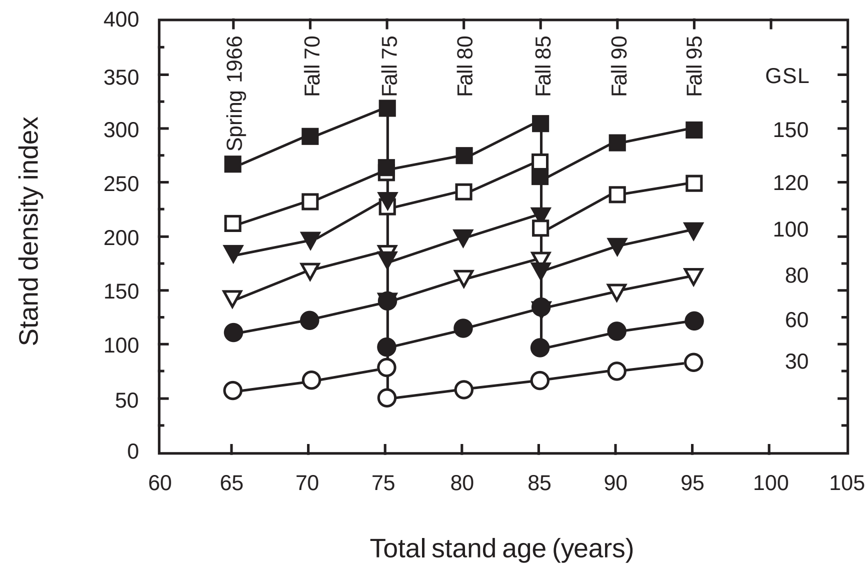

Figure 2—Stand density index of live trees (treatment means) in relation to total age and year of measurement for each GSL.

The lowest GSL plots were not thinned in fall 1985, because these plots had far fewer trees per acre than did old-growth stands on similar sites. Thinning slash was lopped and scattered. After the fourth remeasurement (fall 1985), GSLs were changed to stand density index (SDI) (Reineke 1933) values of 55, 110, 147, 183, 220, and 275. These values are equivalent to the original GSLs when the QMD is 10 inches. A wide range in QMDs had developed among treatments by the end of the fourth period. The change in defining densities was made because the GSLs defined by equation (1) have no relation to any biological limit and cannot be interpreted as a constant relative level of competition across a range of diameters. The SDI values were determined by using,

$$SDI = (N)(QMD/10)^{1.77} , \tag{2}$$

where N is the live trees per acre. An exponent of 1.77 instead of 1.605 was used because -1.7653 was the slope of a least squares fit of $\log_e N$ 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).

After the initial thinning, all trees were tagged and their diameters at breast height (d.b.h.) were measured to the nearest 0.1 inch. Fifteen trees on each thinned plot were selected for measuring with an optical dendrometer. Selection of these trees was made by constructing a diameter distribution series for each plot and then selecting trees at random from each diameter class so that the complete range of diameter classes was equally represented. Stem volume inside bark in cubic feet (V) and board feet (V1) were calculated by Grosenbaugh's (1964) STX program with a modification to describe bark thickness along the bole (Cochran 1976). Volumes and heights (H) for these trees were used to fit equations for each plot of the form (Husch and others1972, Schumacher and Hall 1933),

$$\log_e V = a_o + a_1[\log_e(d.b.h.)] , \tag{3}$$

$$\log_e V1 = b_o + b_1[\log_e(d.b.h.)] , \tag{4}$$

and (Curtis 1967),

$$\log_e H = c_o + c_1/(d.b.h.) + c_2/(d.b.h.)^2 . \tag{5}$$

These equations, with different coefficients for each plot at different times of measurement, were used to determine volumes and heights for each tree on each plot. If one of the trees initially selected for measurement with a dendrometer was cut in a subsequent thinning, another tree with the closest diameter at the time of cutting was picked as a replacement.

Periodic annual increments (PAI, growth during each period divided by the number of growing seasons in the period) were calculated for gross and net basal area, gross and net cubic volume, and gross and net board-foot volume. The PAIs of QMDs and average heights also were determined for surviving trees. Mean annual gross and net basal area and volume growth (growth during the study divided by the number of growing seasons in the study), taking into account the thinnings after the second and fourth periods, were calculated for the 30-year study. Mean annual basal area and cubic-volume growth for the 20 and 34 surviving trees with the largest diameters at the start of the study were determined. Volume yields (cumulative net yields), the live standing volume at a given time plus the live volume removed in previous thinnings were determined for each time of measurement. Net mean annual volume increments (MAI, cumulative net yields divided by age) also were calculated. Two sets of volume yields and MAIs were calculated; the initial thinning was included in one set and excluded in the other set. A lot of volume was removed in the initial thinning when the stand was 65 years old. Determination of yields and MAIs excluding the initial thinning was necessary, therefore, to examine thinning effects on later yields and MAIs. Yield, mean annual growth, and PAIs for board-foot volumes include ingrowth.

Analyses

Standard analyses of variance or repeated measures (split-plot in time) analyses (SAS Institute 1988) were used to test the following hypotheses:

1. There are no differences in PAIs with GSL or period (age).
2. There are no differences in 30-year mean annual growth with GSL.
3. There are no differences in cumulative net volume yield with GSL.
4. There are no differences in net mean annual volume increments with GSL.
5. Mean annual basal area and volume growth of the 20 largest diameter trees at the start of the study does not change with GSL.

Because there are six GSL levels, up to a fifth-degree polynomial can be used to describe the relation between response and GSL. Results from other LOGS studies (Cochran and Barrett 1995, Oliver and Edminster 1988, Ronco and others 1985) indicate that second-degree polynomials more logically describe this relation. Linear, quadratic, and lack-of-fit effects therefore were tested in both standard analyses and repeated measures analyses by using orthogonal polynomial methods. In the repeated measures analyses, linear, quadratic, and lack-of-fit terms also were tested for the time or period by GSL interactions. The unequal spacing between GSLs was taken into account in determining the coefficients used in these tests (Bliss 1970).

Results

Immediately after the initial thinning (spring 1966) treatment means for QMDs ranged from 8.8 to 12.3 inches, average heights ranged from 54.4 to 67 feet, and board-foot volumes ranged from 2,626 to 7,132 board feet. Thirty years later QMDs ranged from 14.1 to 21.2 inches, average heights ranged from 79.1 to 95.1 feet, and board-foot volumes ranged from 9,763 to 23,780 board feet (table 1).

Table 1—Average stand characteristics (per acre basis) of live trees at Lookout Mountain over the 30-year period of study

GSL	SDI	Basal area	Number of trees	Average spacing	Quadratic mean diameter	Average height	Volume[a]	
		Square feet		*Feet*	*Inches*	*Feet*	*Cubic feet*	*Board feet*
				After fall 1965 thinning (total age 65)				
30	55	31.4	38	33.9	12.3	67.0	775	2,626
60	111	60.7	97	21.2	10.8	62.8	1,441	4,180
80	148	81.1	140	17.6	10.3	62.2	1,809	4,790
100	185	98.6	215	14.2	9.2	58.1	2,071	3,992
120	213	113.1	272	12.7	8.8	54.4	2,357	4,425
150	268	144.1	308	11.9	9.4	58.9	3,235	7,132
				Fall 1970 (total age 70)				
30	66	38.7	38	33.9	13.7	70.7	998	3,929
60	122	69.2	93	21.6	11.8	65.8	1,735	5,860
80	169	94.1	140	17.6	11.1	64.6	2,259	7,065
100	201	109.0	211	14.4	9.8	60.3	2,326	5,526
120	226	121.9	261	12.9	9.4	58.8	2,761	6,328
150	295	159.9	303	12.0	10.0	62.9	3,794	9,809

Table 1—Average stand characteristics (per acre basis) of live trees at Lookout Mountain over the 30-year period of study (continued)

GSL	SDI	Basal area	Number of trees	Average spacing	Quadratic mean diameter	Average height	Volume[a]	
		Square feet		*Feet*	*Inches*	*Feet*	*Cubic feet*	*Board feet*
				Before fall 1975 thinning (total age 75)				
30	80	49.1	38	33.9	15.2	74.6	1,323	5,562
60	144	83.3	93	21.6	12.9	69.2	2,201	8,297
80	193	110.7	139	17.7	12.1	68.0	2,861	10,122
100	227	125.1	210	14.4	10.5	63.0	2,869	8,055
120	261	142.5	260	12.9	10.1	60.2	3,137	9,216
150	317	174.7	295	12.2	10.5	66.2	4,558	13,565
				After fall 1975 thinning (total age 75)				
30	52	29.9	22	44.5	15.8	75.8	827	3,539
60	99	58.2	57	27.6	13.8	72.0	1,624	6,473
80	141	100.8	89	22.1	13.0	71.2	2,126	8,025
100	178	99.9	146	17.3	11.3	66.3	2,340	7,491
120	224	122.3	207	14.5	10.6	62.8	3,000	8,616
150	264	148.5	223	14.0	11.2	68.7	3,975	12,894
				Fall 1980 (total age 80)				
30	58	36.3	22	44.5	17.4	82.1	1,024	4,580
60	116	69.4	57	27.6	15.1	75.9	1,990	8,175
80	158	93.6	87	22.3	14.0	73.8	2,527	10,128
100	202	113.9	146	17.3	12.1	69.3	2,760	9,533
120	245	137.8	205	14.6	11.3	65.7	3,365	10,972
150	276	156.8	211	14.4	11.9	71.9	4,298	14,879
				Before fall 1985 thinning (total age 85)				
30	67	42.8	22	44.5	18.9	86.9	1,397	7,119
60	132	81.2	56	27.9	16.4	80.7	2,603	12,089
80	180	108.7	87	22.3	15.1	77.3	3,135	13,114
100	223	128.2	146	17.3	12.8	71.8	3,521	13,006
120	269	154.3	201	14.7	12.0	68.8	4,178	14,936
150	304	174.8	208	14.5	12.7	75.2	5,194	20,062

Table 1—Average stand characteristics (per acre basis) of live trees at Lookout Mountain over the 30-year period of study (continued)

GSL	SDI	Basal area	Number of trees	Average spacing	Quadratic mean diameter	Average height	Volume[a]	
		Square feet		*Feet*	*Inches*	*Feet*	*Cubic feet*	*Board feet*
				After fall 1985 thinning (total age 85)				
30	67	42.8	22	44.5	18.9	86.9	1,397	7,119
60	96	59.6	38	33.8	17.0	81.8	1,945	9,274
80	135	82.0	62	26.5	15.5	78.4	2,380	10,065
100	171	99.6	105	20.3	13.2	73.7	2,779	10,506
120	210	121.2	141	17.6	12.7	71.0	3,367	12,508
150	257	149.7	164	16.3	13.1	76.2	4,531	18,135
				Fall 1990 (total age 90)				
30	77	47.9	22	44.5	20.4	90.0	1,668	9,133
60	111	69.9	38	33.8	18.4	87.3	2,279	11,517
80	151	92.9	61	26.7	16.7	83.3	2,812	12,707
100	193	114.1	105	20.4	14.1	78.2	3,248	12,938
120	235	137.3	140	17.6	13.5	75.6	3,947	15,582
150	286	168.0	164	16.3	13.9	80.9	5,185	21,530
				Fall 1995 (total age 95)				
30	83	53.9	22	44.5	21.2	95.1	1,876	9,763
60	121	77.2	38	33.8	19.3	91.4	2,605	13,204
80	163	102.1	61	26.7	17.4	86.8	3,134	15,199
100	204	121.7	105	20.4	14.6	81.5	3,561	15,495
120	251	148.1	140	17.6	14.1	79.1	4,328	18,029
150	300	177.7	164	16.3	14.3	83.4	5,494	23,780

[a] Total cubic-foot volume for entire stem, inside bark, all trees; Scribner board-foot volume for all trees 10.0 inches in diameter at breast height and larger to a 6-inch top diameter inside bark.

Mortality

Observations for mortality consisted of losses for each plot during each 5-year period. Each treatment had three replicates so there were 18 observations for mortality for each treatment for the 30-year study, or a total of 108 observations. Mortality occurred on only 35 of these 108 observations. No statistical analyses of mortality were performed because numerous observations with no mortality occurred throughout subsets of the design matrix. No mortality occurred on the lowest stocking level (GSL 30) during the 30-year period. Mortality occurred for 5 observations for GSL 60, 4 observations for GSL 80, 5 observations for GSL 100, 10 observations for GSL 120, and 11 observations for GSL 150. Total losses by GSL over 30 years ranged up to 82 trees per acre, 44.8 square feet of basal area, and 1,164 cubic feet of volume; average size of the trees that died was slightly smaller than the trees that survived (table 2). Mortality appeared to differ with period (table 3); little mortality was observed for the last two periods. The relation of mortality and stand density seemed to differ with period (fig. 3). Losses at lower stand densities seemed to occur during period 1. For the other periods, mortality greater than 2 trees per acre did not occur below an SDI of 240 (fig. 3).

Table 2—Average periodic mortality rates, mortality (trees per acre, basal area, and cubic volume per acre), and average ratios of QMD for mortality during each 5-year period divided by QMD of all live trees at the start of that period for each GSL for the 30-year study

GSL	Mortality rates	Trees per rates	Basal area per acre	Cubic volume per acre	R[a]
	Percent		*Square feet*	*Cubic feet*	
30	0	0	0	0	--
60	.31	18	13.1	306	0.86
80	.10	8	4.9	109	.81
100	.09	16	5.8	134	.77
120	.26	56	22.0	476	.91
150	.41	82	44.8	1,164	.89

[a] Average of (quadratic mean diameter of mortality/quadratic mean diameter of live trees at start of period) for each 5-year period.

Table 3—Average periodic mortality rates, all mortality (trees per acre, basal area, and cubic volume per acre), and average ratios of QMD for mortality divided by QMD of all live trees for each 5-year period for the 30-year study

Period	Mortality rates	Trees per acre	Basal area per acre	Cubic volume per acre	R[a]
			Square feet	*Cubic feet*	
1	0.46	74	24.4	493	0.80
2	.13	30	13.0	288	.73
3	.31	48	37.8	847	.98
4	.14	20	22.8	355	.90
5	.05	4	2.4	41	.96
6	.08	4	5.3	163	1.00

[a] Average of (quadratic mean diameter of mortality/quadratic mean diameter of live trees at start of period) for each 5-year period.

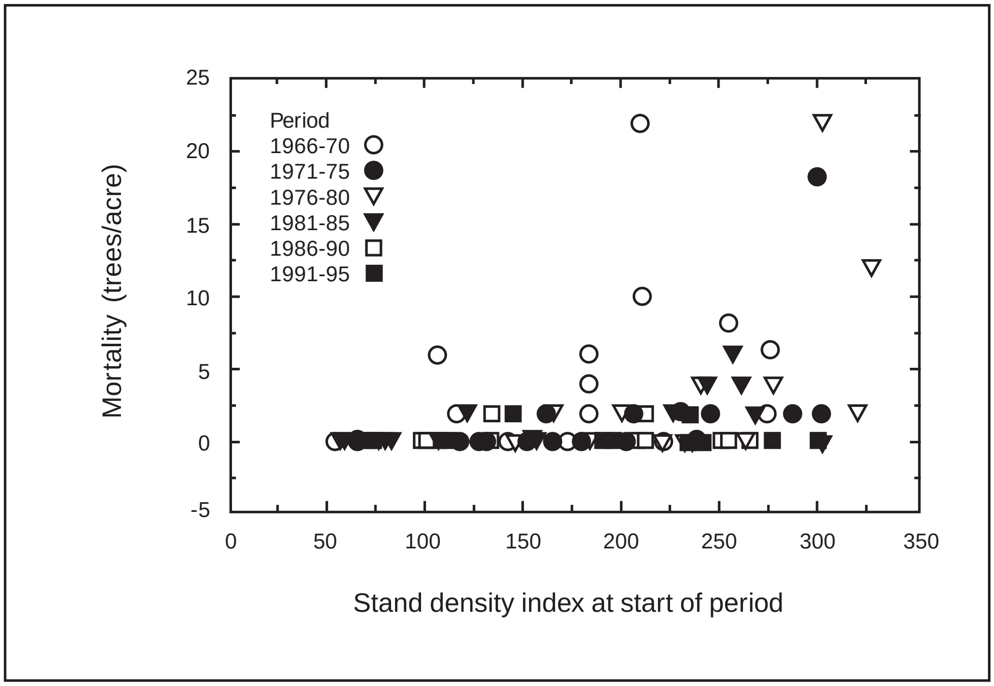

Figure 3—Trees per acre that died on each plot during each 5-year period as a function of SDI of live trees at start of the period.

Periodic Annual Increments

Periodic annual increments for survivor QMDs decreased curvilinearly ($p \leq 0.10$) with increasing stand density (table 4, fig. 4). These PAIs differed with period ($p \leq 0.10$); periods 1 and 6 had the lowest QMD PAIs and period 5 generally had higher PAIs. Curvature differed with period as shown by the significance ($p \leq 0.10$) of the quadratic component of the period by GSL interaction. The PAIs for survivor heights varied curvilinearly ($p \leq 0.10$) with stand density and they differed ($p \leq 0.10$) with period (table 4, fig. 5). These PAI curves also were shaped differently for different periods, resulting in significance ($p \leq 0.10$) of the quadratic component of the period by GSL interaction. For periods 1 through 4, height PAIs seemed to decrease with increasing GSLs to intermediate GSLs and then increase with increasing stand density. For period 5, the decrease in height PAI with increasing stand density seemed nearly linear, but for period 6, height PAI seemed to increase curvilinearly with increasing stand density to GSL 80 and then decrease curvilinearly as stand density increased to GSL 150.

The PAIs for gross basal area and gross cubic volume increased linearly ($p \le 0.10$) with increasing stand density (table 4, figs. 6 and 7). These PAIs differed ($p \le 0.10$) with period and the slopes of the PAI-GSL relation differed with period as shown, by the significance ($p \le 0.10$) of the linear component of the period by GSL interaction. The PAIs for net basal area increased curvilinearly (p W 0.10) with increasing stand density, and this curvature differed with period, thereby resulting in significance ($p \le 0.10$) of the quadratic component of the period by GSL interaction (table 4). The PAIs for net cubic volume overall varied linearly ($p \le 0.10$) with GSL (table 4). Plots of net cubic-volume PAI versus period mean SDI (not shown) indicated a curvilinear relation for some periods. This curvature differed among periods as indicated by the significance ($p \le 0.10$) of the quadratic component of period by GSL interaction. Overall, the gross and net PAIs for board-foot volume increased linearly ($p \le 0.10$) with increasing GSL (table 4). Some curvature in these PAI-GSL relations occurred for some periods (fig. 8); However, this curvature differed among periods as indicated by the significance ($p \le 0.10$) of the quadratic component of the period by GSL interaction terms for both net and gross board-foot PAIs.

Table 4—Probability of higher F-values for the repeated measures analyses of variance of periodic annual increments (PAIs)

				Probability of higher F-values					
				PAI[b]					
				Basal area		Cubic volume		Scribner board feet	
Source	Df[a]	Mean[c] d.b.h	Average height	Gross	Net	Gross	Net	Gross	Net
GSL:									
Linear	1	0.0001	0.0151	0.0001	0.0089	0.0001	0.0003	0.0006	0.0012
Quadratic	1	.0042	.0993	.1018	.0664	.6275	.3462	.7051	.5320
Lack of fit	3	.4874	.7773	.6250	.9268	.5898	.7851	.5115	.6075
Error	12								
Period (P):	5	.0001	.0001	.0001	.0001	.0001	.0001	.0001	.0001
P x GSL									
Linear	5	.0001	.0383	.0004	.0036	.0001	.0001	.3542	.3536
Quadratic	5	.0001	.0133	.1403	.0030	.2290	.0775	.0114	.0211
Lack of fit	15	.1578	.9637	.6044	.4204	.1062	.2841	.2725	.4093
Error	60								
Error MS:[d]									
Whole plot		.00291	.07995	.63710	.3355	1333.4	1576.8	57,779	56,895
Subplot		.000403	.01193	.09264	.2187	207.1	294.6	11,018	12,453

[a] Df = degrees of freedom.
[b] PAI = periodic annual increment.
[c] Mean d.b.h. = quadratic mean diameter or QMD.
[d] Error MS = error mean square.

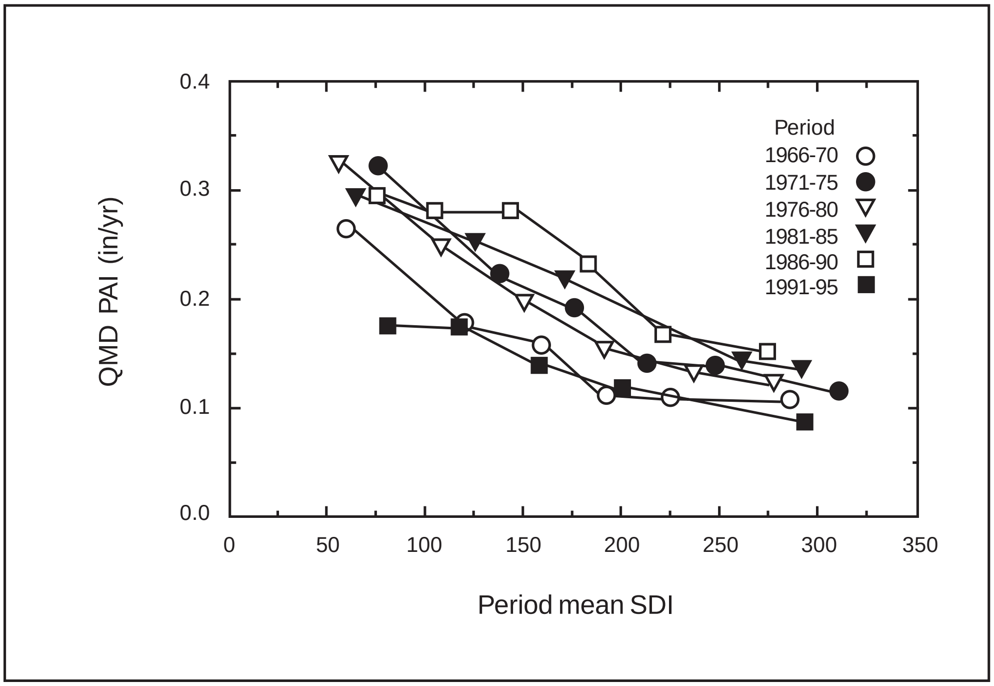

Figure 4—Relation of survivor PAIs for quadratic mean diameter to period mean SDI for the six periods of study. Plotted points are treatment means for each GSL.

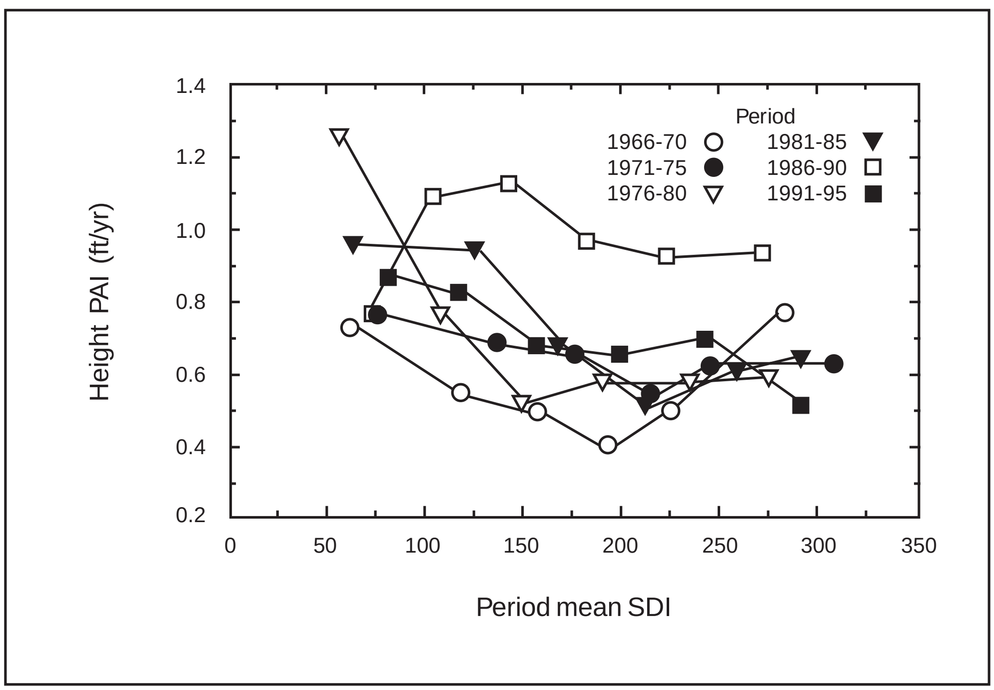

Figure 5—Relation of survivor PAIs for average height to period mean SDI for the six periods of study. Plotted points are treatment means for each GSL.

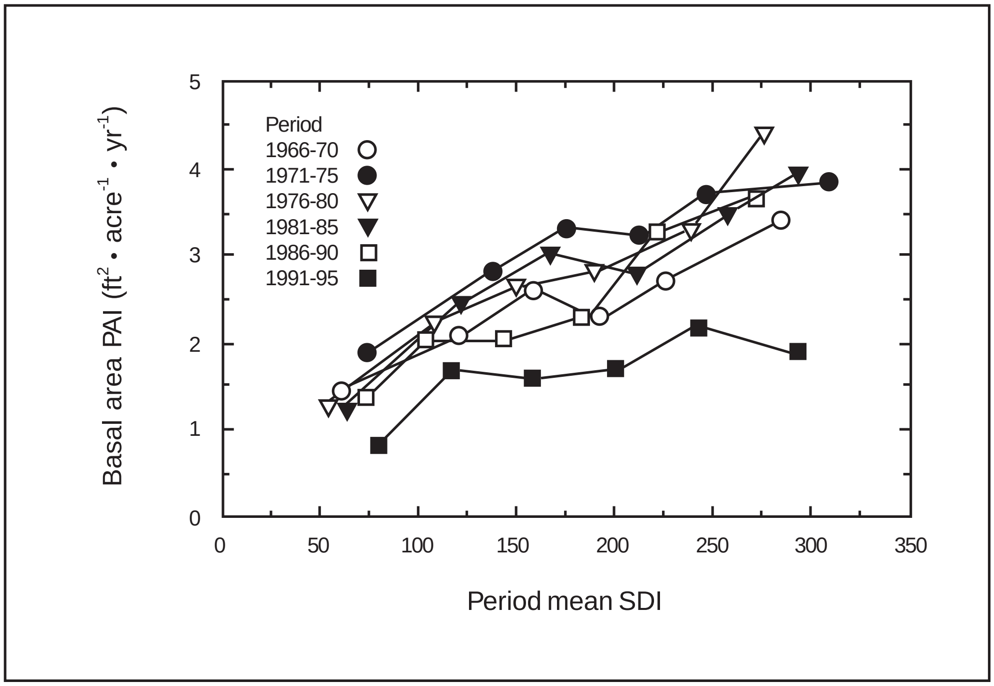

Figure 6—Relation of gross basal area PAI to period mean SDI for the six periods of study. Plotted points are treatment means for each GSL.

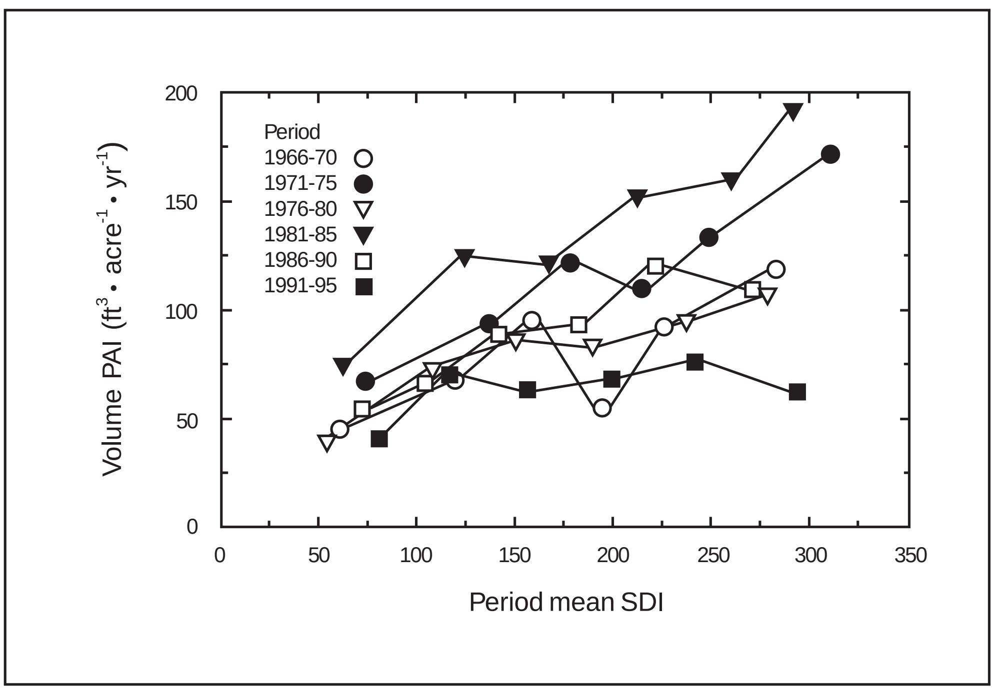

Figure 7—Relation of gross cubic-volume PAI to period mean SDI for the six periods of study. Plotted points are treatment means for each GSL.

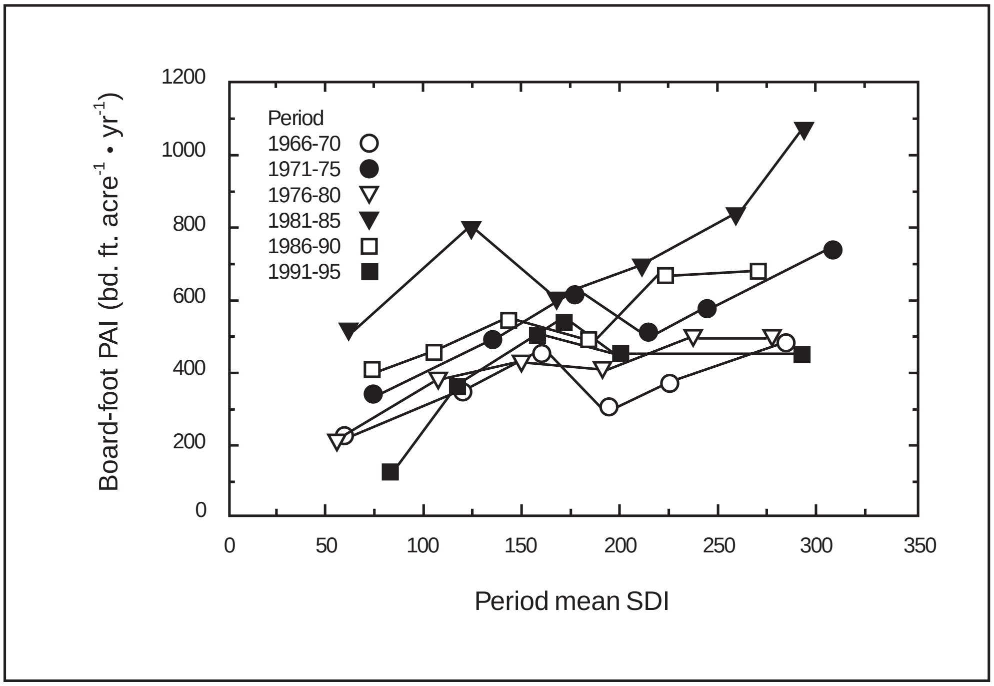

Figure 8—Relation of gross Scribner board-foot PAI to period mean SDI for the six periods of study. Plotted points are treatment means for each GSL.

Mean Annual Growth for 30 Years

Results of the analyses of variance for gross and net mean annual growth of basal area, cubic-volume, and board-foot volume matched the whole-plot analyses (the analyses of the effect of GSL) for the corresponding periodic annual increments (table 4). Gross mean annual basal area growth increased linearly ($p \leq 0.10$) with increasing GSL, while net mean annual basal area growth increased curvilinearly ($p \leq 0.10$) with increasing GSL (fig. 9). Both gross and net cubic and board-foot volume growth increased linearly ($p \leq 0.10$) with increasing GSL (figs. 10 and 11).

Yields

Cubic-volume yields at stand age 95 years, which included the initial thinning did not vary ($p \leq 0.10$) with GSL, but cubic-volume yields that excluded the initial thinning increased linearly ($p \leq 0.10$) with increasing GSL (table 5, fig.12). Board-foot yields with and without initial thinning increased linearly ($p \leq 0.10$) with increasing GSL (table 5, fig.12).

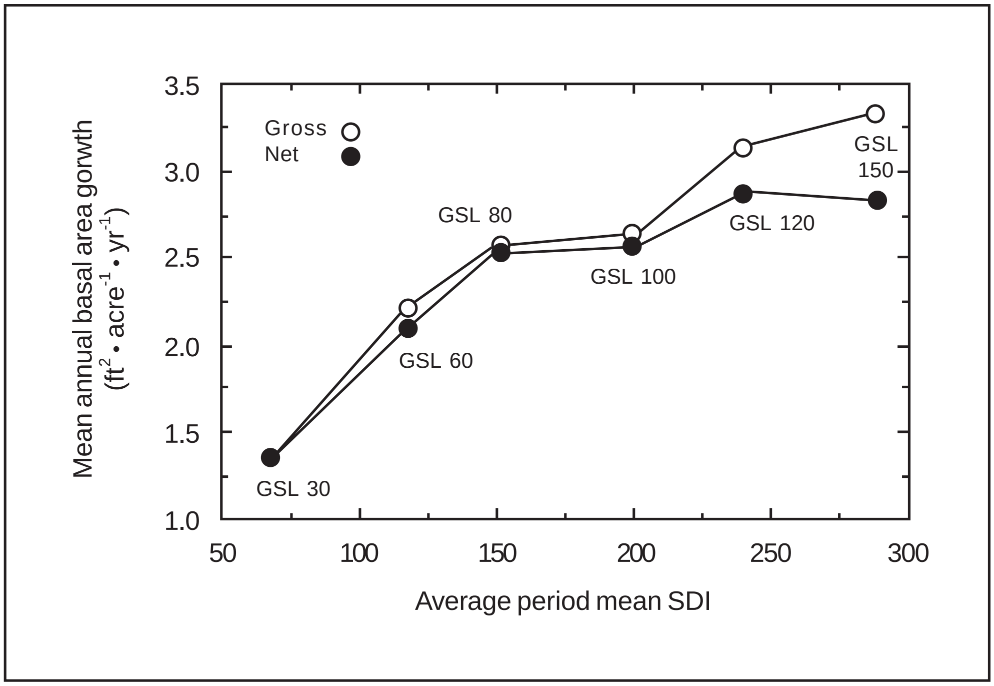

Figure 9—Mean annual basal area growth for the 30-year period (treatment means) as a function of the average period mean SDIs for the six periods for each GSL.

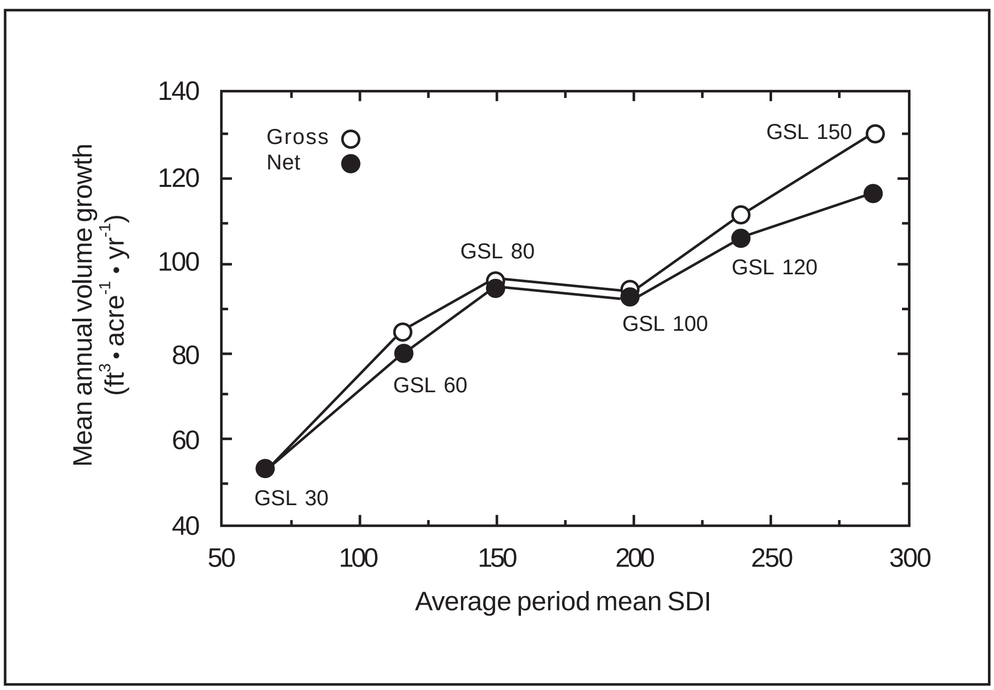

Figure 10—Mean annual cubic-volume growth for the 30-year period (treatment means) as a function of the average period mean SDIs for the six periods for each GSL.

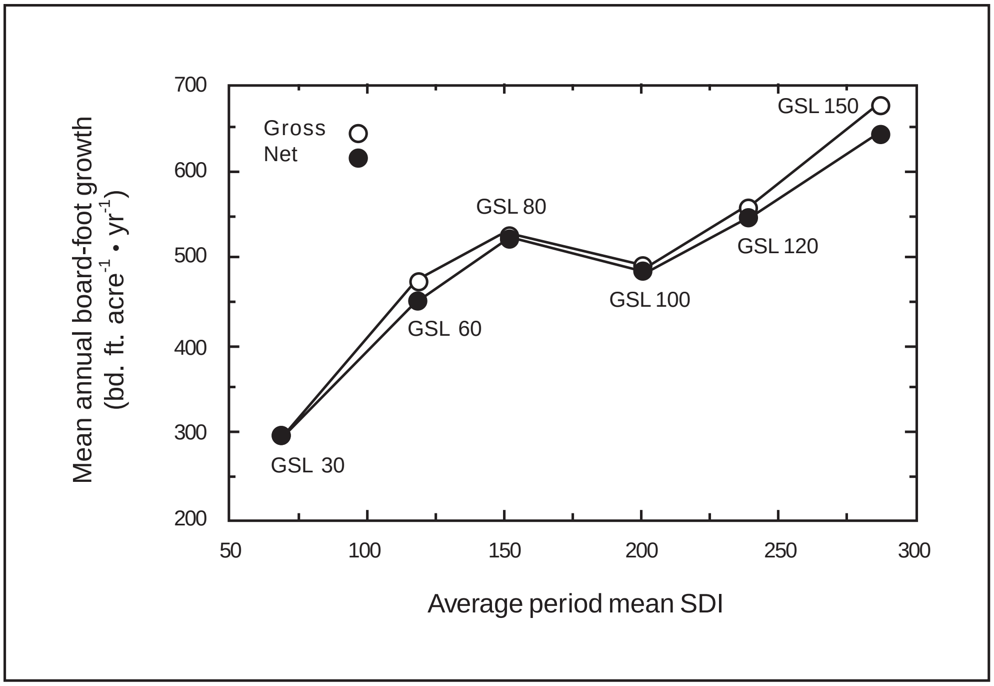

Figure 11—Mean annual Scribner board-foot growth for the 30-year period (treatment means) as a function of the average period mean SDIs for the six periods for each GSL.

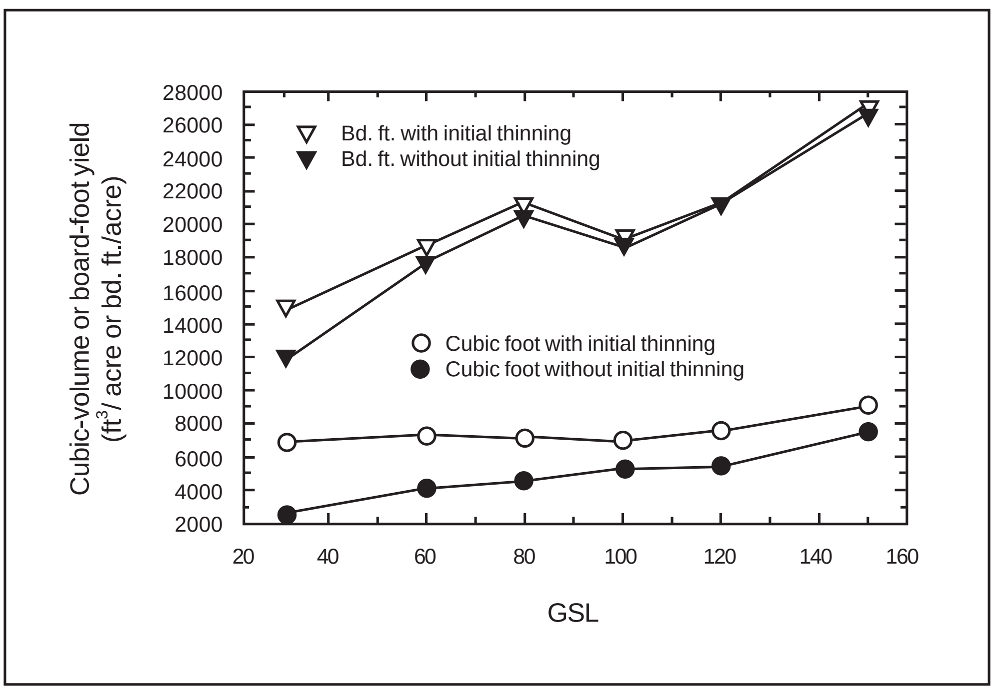

Figure 12—Cumulative net cubic-volume and Scribner board-foot yields (treatment means) at stand age 95 years.

Table 5—Probability of higher F-values for the analyses of variance of cubic and board foot-volume yields

		Probability of higher F-values			
		Cubic volume yield		Scribner board foot yield	
Source	Df[a]	With initial thinning	Without initial thinning	With initial thinning	Without initial thinning
GSL:					
Linear	1	0.1382	0.0001	0.0056	0.0009
Quadratic	1	.6144	.6064	.6300	.8691
Lack of fit	3	.8617	.6544	.5841	.4516
Error	12				
Error mean square		969,030.54	351,146.89	16,274,070.90	1,545,0131.90
C.V.%[b]		13.3	12.7	19.9	20.3

[a] Df = degrees of freedom.
[b] C.V.% = coefficient of variation.

Mean Annual Increments

Results from the repeated measures analyses of MAIs were interpreted as though each MAI was not correlated with past MAIs for a particular GSL. A much better fit of the analysis of variance model is expected than if each MAI was independent. Use of repeated measures analysis still seemed, however, the most straightforward way of examining variations in MAIs.

Net cubic-volume MAIs that included the initial thinning differed ($p \leq 0.10$) with stand age, and the MAI-GSL relation varied with age as shown by the significance ($p \leq 0.10$) of the quadratic component for the age by GSL interaction (table 6). These cubic-volume MAIs for GSL 30 seemed to decrease linearly with age, while MAIs for higher GSLs seemed to increase curvilinearly with age at least to stand age 95 years (fig. 13). Net cubic-volume MAIs that excluded the initial thinning differed ($p \leq 0.10$) with GSL and stand age (table 6, fig.14). Overall these MAI-GSL relations were linear; curvature occurred, however, for some of the stand ages, and this curvature differed with stand age giving rise to significance ($p \leq 0.10$) for quadratic component of the period by GSL interaction term. Net board-foot MAIs with and without the initial thinning increased linearly ($p \leq 0.10$) with GSL and increased ($p \leq 0.10$) with stand age for all GSLs. Slopes for the board-foot MAI-GSL relation differed with stand age, resulting in significance ($p \leq 0.10$) of the linear term for the age by GSL interaction (table 6, figs. 15 and 16).

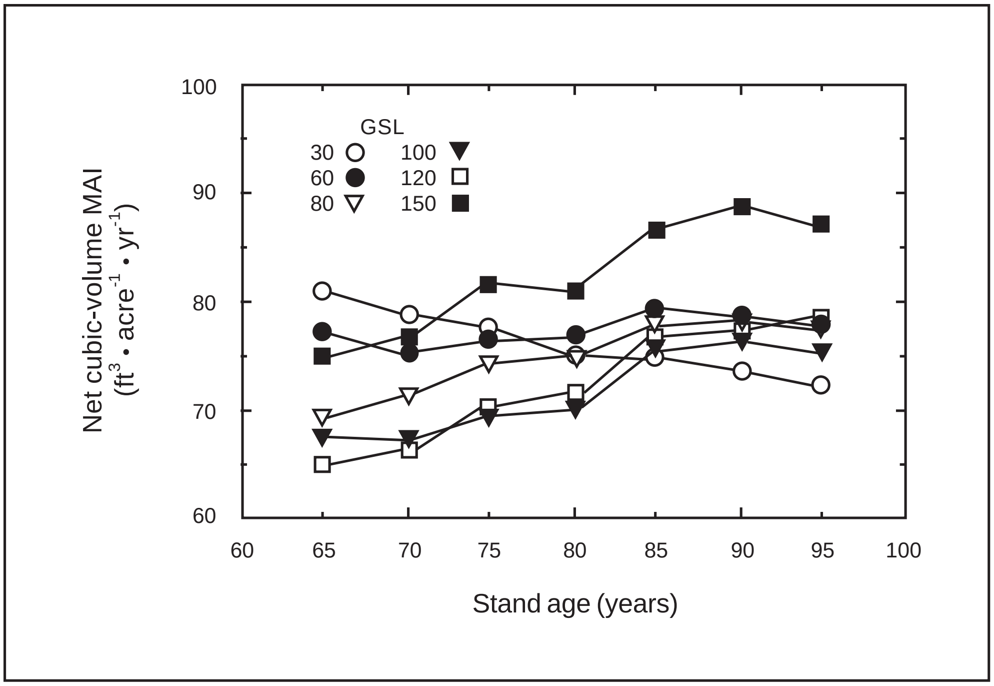

Figure 13—Net cubic-volume MAIs (treatment means) for each GSL in relation to stand age. These MAIs include the live thinning volume at the start of the study.

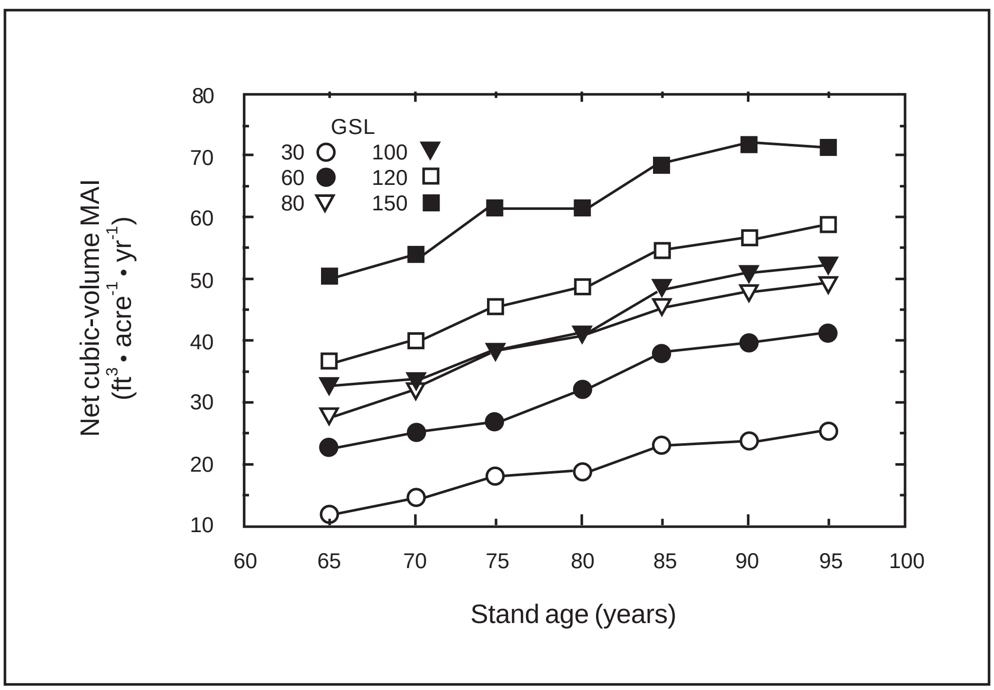

Figure 14—Net cubic-volume MAIs (treatment means) for each GSL in relation to stand age. These MAIs do not include the live thinning volume at the start of the study.

Table 6—Probability of higher F-values for the repeated measures analyses of variance of mean annual increments for cubic and board-foot volumes

		Probability of higher F-values			
		Cubic volume MAI		Scribner board feet MAI	
Source	Df[a]	With initial thinning	Without initial thinning	With initial thinning	Without initial thinning
GSL:					
Linear	1	0.7264	0.0001	0.0171	0.0005
Quadratic	1	.2887	.9800	.1724	.7386
Lack of fit	3	.7929	.2325	.4428	.2232
Error	12				
Age (A):	6	.0001	.0001	.0001	.0001
A x GSL					
Linear	6	.0001	.0004	.0001	.0001
Quadratic	6	.0001	.0951	.1942	.6532
Lack of fit	18	.9380	.8028	.8857	.9006
Error	72				
Error mean square:					
Whole plot		637.09	98.42	6,423.12	5,510.82
Subplot		3.21	4.37	122.44	115.48

[a] Df = degrees of freedom.

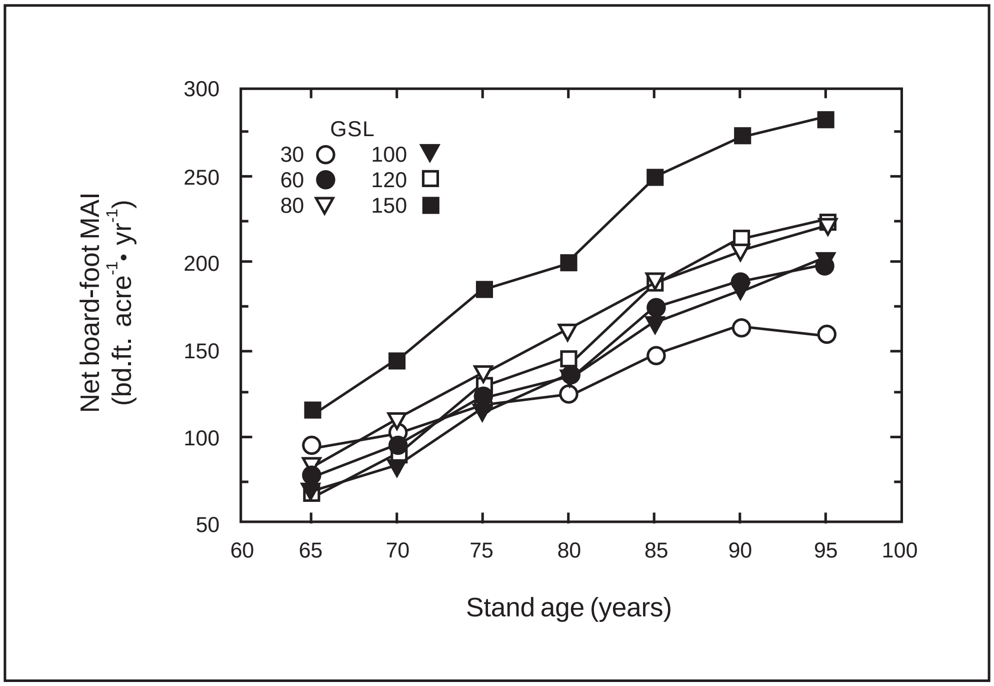

Figure 15—Net Scribner board-foot MAIs (treatment means) for each GSL in relation to stand age. These MAIs include the live thinning volume at the start of the study.

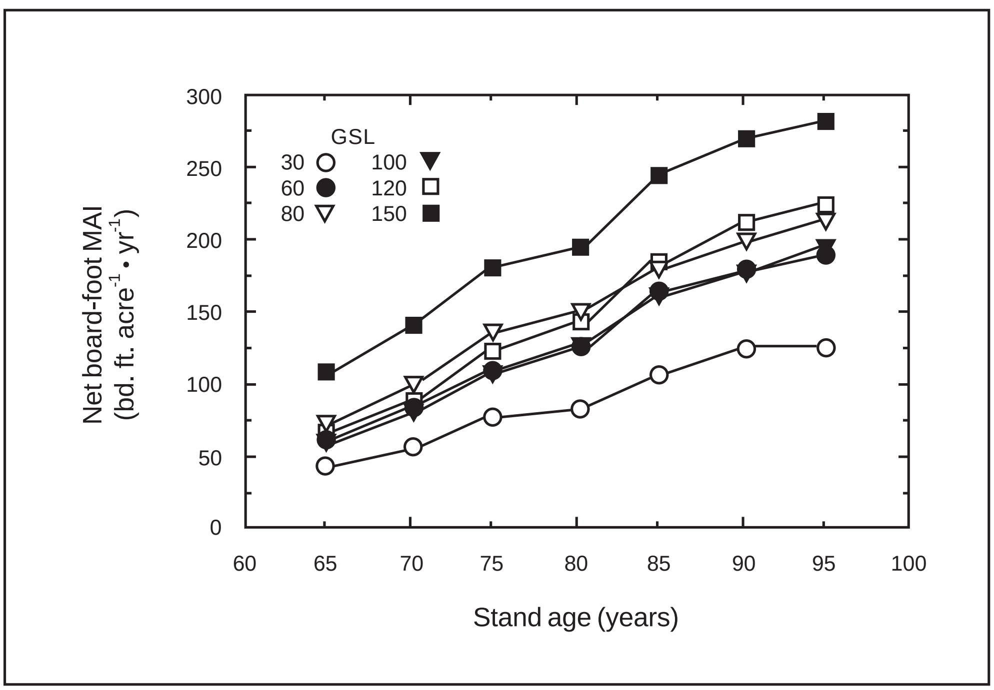

Figure 16—Net Scribner board-foot MAIs (treatment means) for each GSL in relation to stand age. These MAIs do not include the live thinning volume at the start of the study.

Growth of the 20 Largest Trees Per Acre

For the 30-year study, mean annual basal area and volume growth for the 20 surviving trees with the largest diameters in spring 1966 decreased ($p \leq 0.10$) curvilinearly with increasing GSL (table 7, figs. 17 and 18).

Table 7—Probability of higher F-values for the analyses of variance of 30-year mean annual growth for the surviving 20 trees having the largest diameters at the start of the study

	Probability of higher F-values		
Source	Df[a]	Basal area	Cubic volume
GSL:			
Linear	1	0.0001	0.0003
Quadratic	1	.0295	.0221
Lack of fit	3	.3548	.5761
Error	12		
Error mean square		.0135	31.4217
C.V.%[b]		16.3	18.7

[a] Df = degrees of freedom.
[b] C.V.% = Coefficient of variation.

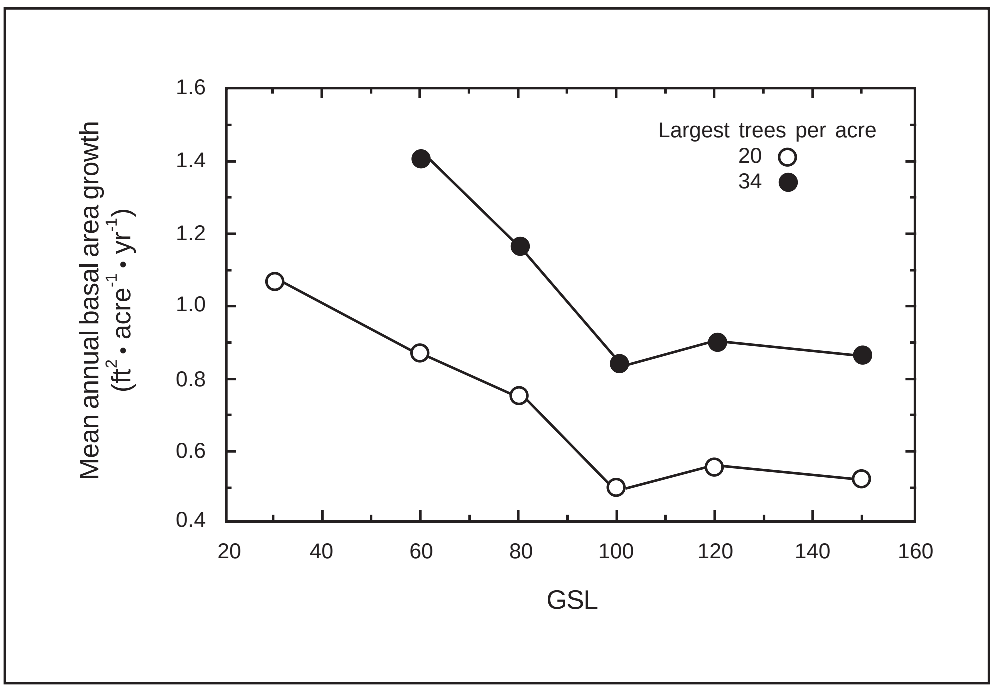

Figure 17—Thirty-year mean annual basal area growth (treatment means) for the 20 and 34 surviving trees having the largest diameters at the start of the study for each GSL.

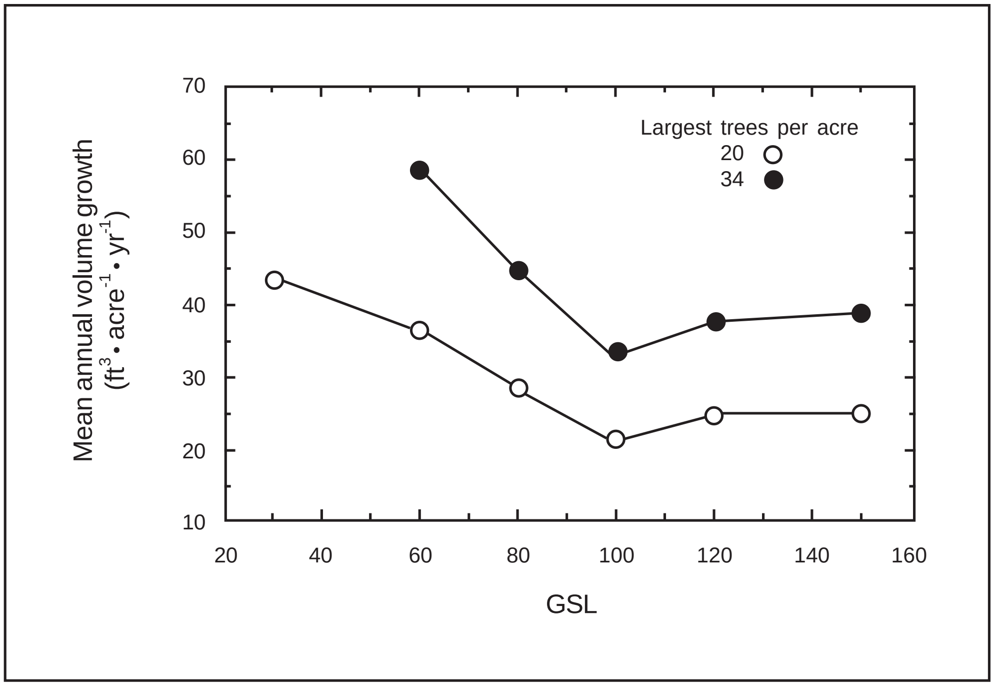

Figure 18—Thirty-year mean annual cubic-volume growth (treatment means) for the 20 and 34 surviving trees having the largest diameters at the start of the study for each GSL.

Understory Development

Because of the large amount of slash created in the initial thinnings, little understory development was expected, and thus, the understory has not been monitored. Only GSL 30 has understory trees, shrubs, forbs, and grasses for all three replications. Most of the other plots appear to have little or no understory.

Discussion

Almost all the mortality in this study is attributed to mountain pine beetles (*Dendroctonus ponderosae* Hopkins). This mortality seems to be related to density and period. Overall mortality rates were greatest in the first period when crown ratios were low (table 3, fig. 3). In later periods, as the trees adjusted to the available growing space and became more vigorous, mortality rates of two or more trees per acre for a 5-year period were confined to densities of SDI 240 or greater at the start of the period. Trees that died were only slightly smaller than surviving trees.

The relation of mortality caused by mountain pine beetle and stand and tree characteristics is unclear. For lodgepole pine (*Pinus contorta* Dougl. ex Loud.), tree size, spacing, tree vigor, and other factors seem to be involved (Mitchell and Preisler 1991). Attacks by mountain pine beetles in lodgepole pine occur mostly on the largest trees in both thinned and unthinned plots, but more of the attacked trees survive on thinned plots (Mitchell and Preisler 1993). Small trees are not likely to be attacked unless they are close to large trees under attack. Beetle attacks on both thinned and unthinned stands are clustered and associated with the largest trees. This pattern of mortality has been found in ponderosa pine studies as well (Cochran and Barrett 1993, 1995, 1998; Oliver 1995). 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. This threshold density is SDI 170 for lodgepole pine stands if 9-inch d.b.h. or larger trees are present. For ponderosa pine, this threshold density increases with increasing site index (Cochran and others 1994) and is estimated to range from SDI 238 to SDI 270 for this study site.

A recent pandora moth (*Coloradia pandora* Blake) outbreak was first detected in parts of central Oregon in 1988 (Wickman and others 1996). Partial defoliation by pandora moth occurred in this study in 1992 and 1994. The degree of defoliation was not estimated for each plot, but it appeared to be moderate to severe and resulted in reduced PAIs for the last period of study (1991-95). Previous pandora moth outbreaks occurred only once in central Oregon in the 20th century (Wickman and others 1996). No mortality was attributed to pandora moth in this study. Patterson (1929), however, reported serious outbreaks of mountain pine beetle and western pine beetle (*D. monti-colae* Hopkins) in defoliated stands in south-central Oregon in 1923, 5 years after the beginning of a pandora moth outbreak.

The curvilinear decrease in QMD PAIs with increasing stand density was expected and has been found in other ponderosa pine studies (Cochran and Barrett 1993, 1995, 1998). Survivor height PAIs also have decreased curvilinearly with increasing stand density in some ponderosa pine spacing studies (Barrett 1982, Cochran and Barrett 1993). The varying response of height PAI to changes in stand density found in this LOGS study, however, was also found for the ponderosa pine LOGS study in the Blue Mountains (Cochran and Barrett 1995). No reasonable explanation for this varying response in survivor height PAI with stand density is evident.

Periodic annual increments and mean annual growth rates for gross basal area and cubic volume were found to vary curvilinearly with stand density in other ponderosa spacing and LOGS studies (Cochran and Barrett 1995, 1998; Edminster 1988; Oliver and Edminster 1988). The lack of significance ($p \leq 0.10$) for the quadratic terms in the analyses of variance for these PAIs and mean annual growth rates in this study was not expected. One possible factor contributing to this lack of significance may be the low productivity of two of the three replications for GSL 100 (figs. 9 and 10). The 30-year mean annual gross volume growth for replications 1, 2, and 3 for GSL 80 is 87.8, 106.5, and 92.6 $ft^3 \cdot acre^{-1} \cdot yr^{-1}$. Corresponding values for GSL 100 are 91.0, 103.1, and 86.4 $ft^3 \cdot acre^{-1} \cdot yr^{-1}$. Using analyses of covariance with site index or height growth of the tallest trees as a covariate might have produced a curvilinear response for gross PAIs and mean annual growth of basal area and volume. This information is not available, however. Height of every tree was not measured, and trees with the tallest heights may have been thinned during the study. The curvilinear response ($p \leq 0.10$) for net mean annual basal area growth, net basal area PAI, and net volume PAI during some periods was due to the increased mortality at higher stocking levels.

Differences in cubic-volume yields and MAIs with and without initial thinning were due to the large amount of cubic volume present on each plot when the plots were first thinned at stand age 65 years. When initial thinnings were included in the MAI calculations of cubic volume, culmination occurred at stand age 65 years or earlier (fig.13) for GSL 30, the most heavily thinned treatment. Curtis (1994) examined MAIs predicted by four widely used simulators for west-side Douglas-fir. He found that three of the four simulators predicted delayed culmination with thinnings. The first of the thinnings in the Douglas-fir simulations was a precommercial thinning at a much younger stand age than the initial thinning in this study. Plots of cubic-volume MAIs without initial thinnings show that culmination has not occurred for any of the GSLs except perhaps GSL 150. Board-foot MAIs with and without initial thinnings do not differ as much as cubic-volume MAIs. Board-foot MAIs seem to have culminated only for GSL 30.

Reduction of basal area and volume growth of a fixed number of largest trees in a stand due to competition from smaller trees has been found for ponderosa pine in several other studies (Barrett 1963, 1982; Cochran and Barrett 1993, 1995). The possible reduction in height growth of the 20 largest trees per acre could not be determined with certainty in this study because the height of every tree was not measured.

Conclusions

Results suggested that very large trees could be grown on this site by managing stand density because (1) there were large differences in average tree sizes among different GSLs 30 years after the initial thinning; (2) growth rates of the 20 largest diameter trees per acre were reduced by competition from smaller trees; and (3) net cubic-volume MAIs, which do not include the initial thinnings, have not culminated. The National Forest Management Act (U.S. Laws, Statutes 1976) specifies the approximate age of culmination as the rotation age. Meyer (1961: tables 21 and 25) shows culmination of MAIs for cubic and Scribner board-foot volumes for the site index of this study to be about 40 and 60 years, respectively. The MAIs estimated by the different Douglas-fir simulators resulting in an increased rotation age (age of culmination of MAI) included precommercial and commercial thinnings. Combinations of precommercial and commercial thinnings probably would increase rotation age for ponderosa pine. With longer rotations and increased individual tree growth in thinned stands, much larger trees would be produced than in unthinned stands. When bark beetle mortality reduces stand density in unthinned stands, some of the best trees are lost, and the mortality often occurs in clumps, resulting in uneven distribution of growing space among remaining trees. Stand and individual tree growth after bark beetle mortality therefore would be less than if the stand was mechanically thinned to the same density.

Only a very small percentage of unclassified Forest Service land historically occupied by ponderosa pine east of the Cascade Range in Oregon and Washington is currently in the late seral condition. Late seral condition has 10 to 30 trees per acre, 21 inches or greater in diameter (depending on the site), with three snags per acre 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 debris12 inches in diameter or larger (Hopkins and others 1992). Two or three trees per acre with diameters greater than 30 inches should occur in the very late seral condition. The very slow growth rates of trees in unmanaged, dense, second-growth ponderosa pine stands indicates that density management is necessary to speed development of mid and late seral size and density conditions.

For this high site, a precommercial thinning to a spacing of at least 18 feet followed by commercial thinnings whenever the stand SDI exceeds 240 will produce very large trees. This suggested upper management zone for this high site, SDI 240, should lower the probability of serious mortality from mountain and perhaps western pine beetles. Because ponderosa pine is a long-lived species that responds well to increased growing space even at advance ages, MAIs under the suggested thinning regime may not culminate until stands are very old.

Some potential volume production would be lost in using the above scheme, but product and aesthetic values associated with large trees plus reduction of the probability of serious mortality due to mountain and western pine beetles are compelling reasons for density management.

Metric Equivalents

1 inch = 2.54 centimeters
1 foot = 0.3048 meter
1 acre = 0.405 hectare
1 square foot = 0.09290 square meter
1 cubic foot = 0.02832 cubic meter
1 square foot/acre = 0.2293 square meter/hectare
1 cubic foot/acre = 0.06997 cubic meter/hectare
1 tree/acre = 2.471 trees/hectare
(ºF-32)/1.8 = ºC

Literature Cited

Barrett, James W. 1963. Dominant ponderosa pine do respond to thinning. Res. Note PNW-9. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 8 p.

Barrett, James W. 1982. Twenty-year growth of ponderosa pine saplings thinned to five spacings in central Oregon. Res. Pap. PNW-301. Portland, OR: U.S. Department of Agriculture, Forest Service. Pacific Northwest Forest and Range Experiment Station.18 p.

Barrett, James W. 1983. Growth of ponderosa pine poles thinned to different stocking levels in central Oregon. Res. Pap. PNW-311. Portland, OR: U.S. Department of Agriculture, Forest Service. Pacific Northwest Forest and Range Experiment Station. 9 p.

Bliss, C.I. 1970. Statistics in biology. New York: McGraw-Hill Book Company. 639 p. Vol. 2.

Cochran P.H. 1976. Predicting wood volumes for ponderosa pine from outside bark measurements. Res. Note PNW-238. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 8 p.

Cochran, P.H.; Barrett, James W. 1993. Long-term response of planted ponderosa pine to thinning in Oregon's Blue Mountains. Western Journal of Applied Forestry. 8(4): 126-132.

Cochran, P.H.; Barrett, James W. 1995. Growth and mortality of ponderosa pine poles thinned to various densities in the Blue Mountains of Oregon. Res. Pap. PNW-RP-483. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 27 p.

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.

Cochran, P.H.; Geist, J.M.; Clemens, D.L. [and others]. 1994.Suggested stocking levels for forest stands in northeastern Oregon and southwestern Washington. Res. Note PNW-RN-513. Portland, OR: U.S. Department of Agriculture, Forest Service. Pacific Northwest Research Station. 21 p.

Curtis, Robert O. 1967. Height-diameter and height-diameter-age equations for second-growth Douglas-fir. Forest Science.13(4): 365-367.

Curtis Robert O. 1994. Some simulation estimates of mean annual increment of Douglas-fir: results, limitations, and implications for management. Res. Pap. PNW-RP-471. Portland, OR: U.S. Department of Agriculture, Forest Service. Pacific Northwest Forest and Range Experiment Station. 27 p.

DeMars, Donald J.; Barrett, James W. 1987. Ponderosa pine managed-yield simulator: PPSIM users guide. Gen. Tech. Rep. PNW-GTR-203. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 36 p.

Edminster, Carleton B. 1988. Stand density and stocking in even-aged ponderosa pine stands. In: Baumgartner, David M.; Lotan, James E., comps. Ponderosa pine the species and its management: Proceedings of a symposium; 1987 September 29-October 1; Spokane, WA. Pullman, WA: Washington State University: 253-260.

Franklin, Jerry F.; Dyrness, C.T. 1973. Natural vegetation of Oregon and Washington. Gen. Tech. Rep. PNW-8. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 49 p.

Grosenbaugh, L.R. 1964. Program estimates of tree populations from 3P sample-tree-measurements. Res. Pap. PSW-13. Berkeley, CA: U.S. Department of Agriculture, Forest Service. Pacific Southwest Forest and Range Experiment Station. 49 p.

Hopkins, Bill; Simone, Steve; Schafer, Mike; Lillybridge, Terry. 1992. Region 6 interim old growth definition for ponderosa pine series. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region. 109 p. [+app.].

Husch, Betram; Miller, Charles I.; Beers, Thomas W. 1972. Forest mensuration. 2d ed. New York: The Ronald Press Company. 410 p.

Meyer, Walter H. 1961. Yield of even-aged stands of ponderosa pine. Revised. Tech. Bull. 630. Washington, DC: U.S. Department of Agriculture. 59 p.

Mitchell, Russel G.; Preisler, Haiganoush K. 1991. Analysis of spacial patterns of lodgepole pine attacked by outbreak populations of mountain pine beetle. Forest Science. 37(5): 1390-1408.

Mitchell, Russel G.; Preisler, Haiganoush K. 1993. Colonization patterns of the pine beetle in thinned and unthinned lodgepole pine stands. Forest Science. 39(3): 528-545.

Myers, Clifford A. 1967. Growing stock levels in even-aged ponderosa pine. Res. Pap. RM-33. Fort Collins, CO: U.S. Department of Agriculture, Forest Service. Rocky Mountain Forest and Range Experiment Station. 8 p.

Oliver, William W. 1979. Growth of planted ponderosa pine thinned to different stocking levels in northern California. Res. Pap. PSW-47. Berkeley, CA: U.S. Department of Agriculture, Forest Service. Pacific Southwest Forest and Range Experiment Station.11 p.

Oliver, William W. 1995. Is self-thinning of ponderosa pine ruled by *Dendroctonus* bark beetles? In: Eskew, Lane G., comp. Forest health through silviculture: Proceedings of a national silviculture workshop: 1995 May 8-11; Mescalero, NM. Gen. Tech. Rep. RM-GTR-267. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station: 213-218.

Oliver, William W.; Edminster, Carleton B. 1988. Growth of ponderosa pine thinned to different stocking levels in the Western United States. In: Schmidt, Wyman C., comp. Proceedings—future forests of the mountain west: a stand culture symposium; 1986 September 29-October 3; Missoula, MT. Gen. Tech. Rep. INT-243. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station: 87-92.

Oliver, William W.; Powers, Robert F. 1978. Growth models for ponderosa pine: I—Yield of unthinned plantations in northern California. Res. Pap. PSW-133. Berkeley, CA: U.S. Department of Agriculture, Forest Service. Pacific Southwest Forest and Range Experiment Station. 21 p.

Patterson, J.E. 1929. The pandora moth, a periodic pest of western pine forests. Tech. Bull.137. [Place of pubication unknown]: U.S. Department of Agriculture. 19 p.

Reineke, L.H. 1933. Perfecting a stand-density index for even-aged forests. Journal of Agricultural Research. 46: 627-638.

Ronco, Frank, Jr.; Edminster, Carleton B.; Trojillo, David P. 1985. Growth of ponderosa pine forests thinned to different stocking levels in northern Arizona. Res. Pap. RM-62. Fort Collins, CO: U.S. Department of Agriculture, Forest Service. Rocky Mountain Forest and Range Experiment Station. 15 p.

SAS Institute. 1988. SAS/STAT users guide, release 6.03 ed. Cary, NC: SAS Institute.1028 p.

Schumacher, Francis X.; Hall, Francisco dos Santos. 1933. Logarithmic expression of timber-tree volume. Journal of Agricultural Research. 47(9):719-734.

U.S. Laws, Statues, etc.; Public Law 94-558. National Forest Management Act of 1976. Act of Oct. 22, 1976. 16 U.S.C.1600 (1976).

Wickman, B.E.; Mason, R.R.; Paul H.G. 1996. Ponderosa pine response to fertilization with nitrogen while being defoliated by pandora moth, *Coloradia pandora* Blake. In: Mattson, William J.; Niemela, Pekka; Rousi, Matti, eds. Proceedings: Dynamics of forest herbivory: quest for pattern and principle: IUFRO symposium S.2.05-06; 1994 February 2-6; Maui, HA. Gen. Tech. Rep. NC-183. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Research Station: 118-126.

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Cochran, P.H.; Barrett, James W. 1999. Growth of ponderosa pine thinned to different stocking levels in central Oregon: 30-year results. Res. Pap. PNW-RP-508. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 27 p.

Periodic annual increments (PAI) for survivor diameters decreased curvilinearly with increasing stand density. Gross volume and basal area PAIs increased linearly with increasing stand density. Growth of basal area and volume for the 20 largest trees per acre were reduced curvilinearly with increasing stand density. Bark beetles were the primary cause of mortality. No mortality occurred at the lowest density.

Keywords: Growth, yield, mortality, thinning, ponderosa pine, pandora moth, mountain pine beetle.

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