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Thirty-Five-Year Growth of Ponderosa Pine Saplings in Response to Thinning and Understory Removal

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Abstract

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Diameter increments for individual trees increased curvilinearly and stand basal area increments decreased curvilinearly as spacing increased from 6.6 to 26.4 feet. Average height growth of all trees increased linearly, and stand cubic volume growth decreased linearly as spacing increased. Large differences in tree sizes developed over the 35 years of study with various spacing treatments. Plots without understory grew more during the first 20 years of study but soil quality decreased. During the last 15 years, growth rates on plots without understory were not superior to plots with understory when adjusted to common basal areas and volumes. Growth rates for the largest trees on the plots were decreased by competition from smaller trees. After 35 years, total cubic volume yield decreased linearly as spacing increased but Scribner board-foot yields increased curvilinearly as spacing increased, and spacings of 13.2, 18.7, and 26.4 feet produced about the same board-foot yield. Live crown ratios increased with increasing spacing, primarily because of increased height growth. Twenty years after thinning, crown width increased curvilinearly as spacing increased and was greater in the absence of understory. Crown cover appeared to be linearly related to stand density index. Mortality was so low that there was no practical difference in net and gross 35-year mean annual growth of cubic volume and basal area. Spacing for precommercial thinnings on similar sites should be at least 14 feet and much higher spacings could be warranted if managers wish to grow stands of large-diameter trees with low mortality from bark beetles.

Keywords: Thinning, understory vegetation, growth, ponderosa pine, *Pinus ponderosa*, saplings.

Summary

The development of suppressed ponderosa pine saplings was followed for 35 years after overstory removal and thinning to spacings of 6.6, 9.3, 13.2, 18.7, and 26.4 feet. Each spacing was replicated six times and understory vegetation was permanently removed from three of the six spacing replications. Diameter increments increased curvilinearly and stand basal area increments decreased curvilinearly as spacing increased from 6.6 to 26.4 feet. Average height growth for all trees increased linearly and stand cubic volume growth decreased linearly as spacing increased. Large differences in tree sizes with spacing developed over the 35 years of study. During the first 20 years of study, plots without understory grew more but soil quality apparently decreased. During the last 15 years, growth rates on plots without understory were not superior to plots with understory when adjusted to common basal areas and volumes. Growth rates for the largest trees on the plots were decreased by competition from smaller trees. After 35 years, total cubic volume yield decreased linearly as spacing increased but Scribner board-foot yields increased curvilinearly as spacing increased, and spacings of 13.2, 18.7, and 26.4 feet produced about the same board-foot yield. Plots without understory produced the highest volume yields after 35 years, but the difference in yields between the two understory treatments is expected to diminish in the future. Live crown ratios increased with increasing spacing, primarily because of increased height growth. Twenty years after thinning, crown width increased curvilinearly as spacing increased and was greater in the absence of understory. Crown cover appeared to be linearly related to stand density index. Mortality was so low that there was no practical difference in net and gross 35-year mean annual growth of cubic volume and basal area. Mortality due to snow bend would have been very high early in the study, but special steps were taken to save bent trees. Mortality due to pine beetles may be serious in the future as stand density and tree size increase. Managers usually desire ponderosa pine stands with large-diameter trees and a low probability of serious bark beetle problems. As a first step in developing these stands, spacing for precommercial thinnings on similar sites should be at least 14 feet, and much wider spacings could be warranted. Even the largest trees in dense stands of ponderosa pine saplings grow very slowly and thinning is necessary to speed stands toward mid-seral stages.

Introduction

Historically, most ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) forests experienced light, periodic ground fires, which controlled understory development and created open, shrub-depauperate conditions. A large-scale change in stand structure and understory vegetation composition began with the start of wildfire suppression shortly after the beginning of the 20th century. By the 1940s, millions of acres of ponderosa pine forests east of the Cascade Range in Oregon and Washington had a dense understory of suppressed trees and a well-developed shrub component consisting primarily of antelope bitterbrush (*Purshia tridentata* (Pursh) DC.), greenleaf manzanita (*Arctostaphylos patula* Green), and snowbrush (*Ceanothus velutinus* Dougl. ex Hook.). This understory was overtopped by mature and overmature trees that were becoming increasingly susceptible to attack by western pine beetle (*Dendroctonus brevicomis* Le Conte).

Many of these stands were selectively logged in the 1940s and 1950s to remove the trees judged susceptible to western pine beetle within 20 years. Still, many of the remaining overstory trees appeared to gradually decrease in vigor, thereby indicating the necessity of further removals to prevent serious losses from beetles. The understory trees, however, did not appear to be growing well enough to provide replacements for the portion of the overstory removed. By the late 1950s it became apparent that selective logging with no other treatments would not result in sustainable, productive, ponderosa pine stands, and other management options needed to be explored.

Consideration of even-aged management posed several questions in light of existing stand conditions: (1) Could the overstory be removed while leaving enough undamaged understory trees to form the next stand? (2) If enough undamaged trees could be left, would these long-suppressed saplings grow well when released? Or should a completely new stand be started? Work by Mowat (1953) suggested that these understory trees would respond. The possibility of selecting future crop trees from the large numbers of understory trees would perhaps be genetically advantageous. (3) If the long-suppressed saplings had the potential to develop into large trees, should they be thinned, and if so, what would be a reasonable leave-tree spacing? (4) How would competition from the other understory vegetation influence the development of thinned saplings? A long-term study was established in central Oregon at the Pringle Falls Experimental Forest in 1959 to answer these questions.

Several results have been published. Barrett (1960) demonstrated that it is possible, by careful overstory removal, to save large numbers of understory saplings. Barrett (1965) also found that even though the saplings were long suppressed, response in diameter growth to thinning was immediate. Height growth also responded to thinning although response took as long as 4 years after thinning to develop (Barrett 1970). Removal of competing understory grasses, forbs, and shrubs resulted in decreased water removal from the soil profile during the growing season and increased tree growth early in the study (Barrett 1965, 1970; Barrett and Youngberg 1965). Increased spacing resulted in increased tree growth and decreased stand growth (Barrett 1965, 1970, 1973, 1982). The 35-year absence of understory grasses, forbs, and shrubs produced changes in soil quality. A 25-percent greater carbon content in

Table 1—Adjusted means from analyses of covariance[a] for periodic annual increments (PAI) of basal area and volume for 8 consecutive growth periods between 1960 and 1994

Period	Basal area PAI		Cubic volume PAI	
	Understory absent	Understory present	Understory absent	Understory present
	-------- $Ft^2 \cdot acre^{-1} \cdot yr^{-1}$ --------		-------- $Ft^3 \cdot acre^{-1} \cdot yr^{-1}$ --------	
1 (1960-63)	2.5	1.8	14.3	11.9
2 (1964-67)	3.3	2.7	25.9	19.3
3 (1967-71)	4.0	3.3	41.3	31.4
4 (1972-75)	4.1	3.8	52.2	42.9
5 (1976-79)	3.7	3.8	59.0	54.9
6 (1980-84)	3.9	4.2	75.6	78.9
7 (1985-89)	3.4	3.7	78.2	82.6
8 (1990-94)	1.1	1.4	39.4	44.2

[a] Separate analyses of covariance were used with each period. Basal area (BA) at the start of the period and BA^2 were used as covariates in the analysis of basal area PAI. Volume (V) at the start of the period and V^2 were used as covariates in the analysis of volume PAI (Busse and others 1996).

the upper mineral soil, 189 pounds per acre more nitrogen in the combined O-horizon and upper 9.5 inches of mineral soil, and a higher microbial biomass for plots with understory than plots without understory were found in 1994 (Busse and others 1996). Basal area and volume growth for plots with continuously removed understory vegetation were clearly greater than for plots with understory vegetation during the first 20 years of study (1960-79). During the last 15 years (1980-94), these differences in stand growth rates between understory vegetation treatments disappeared (Busse and others 1966) when covariance analyses were used to adjust growth rates to common stand basal areas and volumes (table 1). Initial increases in tree growth in the absence of understory vegetation were attributed to greater soil water availability. Subsequent changes in soil nutrient content and availability counterbalanced differences in water availability and potentially contributed to similar rates of tree growth at comparable densities during the last 15 years of measurement (Busse and others 1996). Total understory vegetation cover for treatments with understory present averaged 35 percent (28 percent shrubs, 7 percent herbaceous plants) between 1959 and 1994. Cover was lowest in 1959, 1 year after logging and thinning operations were completed, and relatively low again in 1979 following severe winter kill in 1978-79 (Busse and others 1996). Differences in growth rates with time between the two understory conditions were not a result of suppression of understory cover as the trees became larger. A decline in understory vegetation cover between 1959 and 1994 was found only at the narrowest spacing (Busse and others 1996). During the last period of observation (1990-94), trees were partially defoliated twice by pandora moth (*Coloradia pandora* Blake), which severely reduced growth rates (Cochran 1998).

This paper summarizes mortality, tree growth, stand growth, and yield for the 1960-94 period and gives some information about crown ratios, crown width, and crown cover. Results are directly applicable only to the study area, but similar results can be expected of the large acreage of ponderosa pine lands in central and south-central Oregon having similar stand and site conditions.

Methods of Study

Study Area

The study area (43˚44′ N. lat., 121˚36′ W long.; 4,400 feet in elevation) is 35 miles southwest of Bend, Oregon, in the Pringle Falls Experimental Forest. Slopes range from 4 to 27 percent (average 10 percent), and the aspect is predominantly east facing (range 14 to 167 degrees). Mean annual precipitation of 24 inches falls mainly from October through April, with a 2-foot snowpack common between January and March. Maximum average temperature in July is 78 ˚F and frosts can occur in any month. The soil, a Xeric Vitricryand, is developing on 33 inches of dacite pumice from the eruption of Mount Mazama (Crater Lake). The pumice mantle overlies a sandy loam paleosol developed in older volcanic ash with cinders and basalt fragments.

Before the study was installed, the stand consisted of old-growth ponderosa pine with an average of 20 trees per acre, a mean tree diameter of 25.6 inches, and an understory of 40- to 70-year-old suppressed ponderosa pine saplings. Average diameter of the understory trees was 1.0 inch, average height was 8 feet, and average density was 6,998 stems/acre. Shrub and herbaceous vegetation consisted of antelope bitterbrush, snowbrush, and greenleaf manzanita, with scattered Ross sedge (*Carex rossi* Boott), western needle grass (*Stipa occidentalis* Trub. ex Wats.), and bottlebrush squirreltail (*Sitanion hystrix* (Nutt.) J.G. Smith). Site index for the area is 78 feet using Meyer’s (1961) system and 110 feet using Barrett’s (1978) method. Barrett’s site index is the height of the tallest tree on a 0.2-acre plot at a breast high age of 100 years. Meyer’s site index is the height attained by a tree with a diameter equivalent to the mean diameter of the dominant and codominant trees at a total stand age of 100 years.

Treatments and Design

There are thirty 0.192-acre plots distributed across 160 acres to provide a representative sample of the area. Each 79.2- by 105.6-foot plot is surrounded by a similarly treated 33-foot buffer strip. Six replications of five tree spacings were randomly assigned: 6.6 feet (1,000 trees per acre [TPA]), 9.3 feet (500 TPA), 13.2 feet (250 TPA), 18.7 (125 TPA), and 26.4 feet (62.5 TPA). Plot layout and treatment assignment were completed before overstory removal. Logging of all overstory and thinning of remaining saplings were completed in fall 1958. Saplings in the 160-acre area not in plots or buffer strips were thinned to about a 10-foot spacing. Each plot could conveniently be divided into 12 subplots, each containing 0.016 acre. This plot arrangement aided in selecting leave trees that were evenly distributed throughout the plot. Even distribution and tree quality were the primary guides in selecting leave trees. All logging and thinning slash was removed from the plots and burned. All understory vegetation was removed in spring 1959 and at successive 3- to 4-year intervals on three replications per tree spacing, randomly chosen in spring 1959, and allowed to develop naturally on the three remaining replications. Manual control and 2, 4, 5-T ([2, 4, 5-trichlorophenoxy] acetic acid) were used in the initial removal of understory vegetation; manual control and 2, 4,-D ([2, 4-dichlorophenoxy] acetic acid) were used in the following two removals; manual control alone has been used since. The design is a completely randomized, 5 by 2 factorial with three replications, and becomes a split plot in time for analysis of items measured during eight different growth periods.

Measurements and Calculations

Measurement of soil water use, understory cover and biomass, nutrient contents, microbial biomass, and defoliation (for 1990-94 period) are described in other publications (Barrett and Youngberg 1965, Busse and others 1996, Cochran 1998). Tree measurements also have been described earlier but are summarized here because this paper is concerned with tree and stand development.

Diameter and total height of all plot trees were measured in fall 1959, 1963, 1967, 1971, 1975, 1979, 1984, 1989, and 1994, thereby providing data for five 4-year and three 5-year periods. Diameters were measured with a steel tape and recorded to the nearest 0.1 inch. Heights were measured with height poles or optical dendrometers and recorded to the nearest 0.1 foot. Height to green crown was measured on each of the above dates, except 1994, and crown width was measured in fall 1979. Tree volumes (V, total cubic-foot inside bark including stump and tip) were calculated by using an equation for second-growth ponderosa pine developed by DeMars and Barrett (1987). Scribner board-foot volumes (V1) for trees 7 inches in diameter and larger to a 5-inch top, inside bark, were determined for 1994 by using,

$$\log_e V1=0.9608+1.4667(\log_e V)-0.1739(\log_e H)-0.1700[\log_e(\text{d.b.h.})] \ . \qquad (1)$$

This equation was developed from 100 ponderosa pine trees ranging from 8 to 27 inches in diameter at breast height (d.b.h.) that were destructively sampled across a wide range of sites in Oregon and Washington during other studies. Sixteen-foot log volumes were used.

Periodic annual increments (PAI, growth during each period divided by the number of growing seasons in the period) were calculated for gross and net cubic volume, survivor quadratic mean diameters (QMD), and survivor average heights. Gross and net mean annual cubic volume growth rates for the 1960-94 period were determined for all trees and for the largest 62.5, 125, 250, and 500 trees per acre where present.

Live crown ratios (length of green crown divided by total height) were calculated for the eight dates when the height to live crown was measured. Crown cover was calculated by assuming circular crown shapes. When crown widths were wider than spacing, crown cover was obtained by subtracting the area not covered by crown from the spacing squared.

Stand density index (SDI) was calculated for each plot at each measurement by using (Reineke 1933):

$$\text{SDI} = \text{TPA}(\text{QMD}/10)^b \ , \qquad (2)$$

where TPA is trees per acre, QMD is quadratic mean diameter, and b equals 1.77. A value of 1.77 instead of the traditional 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).

Analyses

Repeated measures analyses or standard analyses of variance (SAS Institute 1988) were used to test the following hypotheses: (1) The PAIs for QMD, average height, basal area, and cubic volume did not change with spacing, understory treatment, or period. (2) The 35-year mean annual cubic volume growth of the 62.5 largest diameter trees in 1994 did not differ with spacing or understory treatment. (3) Cubic volume yields and Scribner board-foot yields in 1994 did not differ with spacing or understory treatment. (4) Live crown ratios did not change with spacing, understory treatment, or time of measurement. (5) Crown widths and crown cover in 1979 did not change with spacing or understory treatment. (6) Height of the single tallest tree per plot and the average height of the eight tallest trees per plot in fall 1994 did not change with understory treatment. Linear, quadratic, and lack-of-fit effects for spacing were tested when appropriate by using orthogonal polynomial methods. Unequal intervals for spacing were taken into account in determining the coefficients used in these tests (Bliss 1970). Initial and final measurements only were used in the repeated measures analysis of crown ratios, because crown ratios for successive measurements probably depend in part on the crown ratios at the previous measurement. Two different tallest height components for 1994 were examined because Barrett's (1978) method for determining site index uses the single tallest tree on a 0.2-acre plot. Other methods for determining site index, however, often use a fixed number of tallest trees, often 40 trees per acre. With a plot size of 0.192 acre, eight trees is equivalent to 41.7 trees per acre, the closest available approximation of the height of the 40 tallest trees per acre.

Cubic volume PAI- and basal area PAI-SDI relations were examined by plotting gross PAIs versus mean period SDI (SDIm) for each period. The shape of this relation for plots without understory seemed to change by period more than the plots with understory. Regressions of the form,

$$\log_e PAI = a + b(SDIm) + c(\log_e[SDIm]) + d(\log_e[H]) \;, \qquad (3)$$

where H is the mean period average height, were used to describe the PAI-SDI relation for treatments with understory vegetation for the 1984-89 period. Only plots with understory vegetation were used because managers normally would not deal with stands permanently without understory, and the shape of the curves for plots with understory did not appear to change with period. Similar equations, without the height term, were used for Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) by Curtis and Marshall (1986), for ponderosa pine by Cochran and Barrett (1995, 1998), for western larch (*Larix occidentalis* Nutt.) by Cochran and Seidel (1999), and for lodgepole pine (*Pinus contorta* Dougl. ex Loud.) by Cochran and Dahms (1998). The height term was used here because of the large differences in heights among treatments by 1984. Coefficients for these regressions were determined with the general linear models procedure (SAS Institute 1988). By using the appropriate coefficients and a common average height, equation (3) can be solved for a range of SDIs. The PAIs for each SDI can be divided by the PAI at full stocking (SDI = 365) and plotted as a function of SDI/365. The resulting curve estimates the fraction of growth at full stocking produced at densities expressed as fractions of full stocking.

Results

After thinning to the assigned spacings treatment, average QMDs ranged from 1.7 to 2.5 inches, average heights ranged from 10.2 to 14.2 feet, SDIs ranged from 4 to 60, basal areas ranged from 1.6 to 22.4 square feet per acre, and cubic volumes ranged from 11.7 to 175.6 cubic feet per acre (table 2). Thirty-five years later, treatment average QMDs ranged from 5.8 to 14.2 inches, average heights ranged from 31.1 to 53.1 feet, SDIs ranged from 92 to 378, basal areas ranged from 52.9 to 183.1 square feet per acre, and cubic volumes ranged from 910 to 2,446 cubic feet per acre (table 2).

Table 2—Average stand statistics for the Pringle Falls spacing study over 35 years of observation, by spacing

Assigned spacing	Understory vegetation	Trees per acre	SDI	QMD	Average height	Basal area	Cubic volume
Feet				*Inches*	*Feet*	*Ft²/acre*	*Ft³/acre*
				Live trees after initial thinning—spring 1960			
6.6	present	1,000	60	2.0	12.6	22.4	175.6
6.6	absent	1,000	46	1.7	10.6	16.6	134.4
9.3	present	500	26	1.9	11.1	9.8	78.1
9.3	absent	500	24	1.8	10.2	8.4	68.7
13.2	present	250	15	2.0	11.4	5.8	45.2
13.2	absent	250	13	1.9	10.3	4.9	37.4
18.7	present	125	9	2.2	12.2	3.4	25.2
18.7	absent	125	11	2.5	14.2	4.1	30.8
26.4	present	62.5	4	2.1	11.5	1.6	11.7
26.4	absent	62.5	4	2.2	11.9	1.7	13.4
				Live trees—fall 1963–spring 1964			
6.6	present	1,000	95	2.6	13.3	32.0	278.0
6.6	absent	1,000	81	2.4	11.4	37.2	229.1
9.3	present	500	47	2.6	12.0	18.4	134.3
9.3	absent	500	52	2.8	11.4	20.9	145.4
13.2	present	250	31	3.0	12.5	12.4	87.6
13.2	absent	250	35	3.3	12.0	14.5	95.3

Table 2—Average stand statistics for the Pringle Falls spacing study over 35 years of observation, by spacing (continued)

Assigned spacing	Understory vegetation	Trees per acre	SDI	QMD	Average height	Basal area	Cubic volume
Feet				*Inches*	*Feet*	*Ft²/acre*	*Ft³/acre*
18.7	present	125	19	3.4	13.5	7.8	55.5
18.7	absent	125	26	4.1	15.9	11.4	84.1
26.4	present	62.5	9	3.3	12.9	3.8	25.9
26.4	absent	62.5	11	3.8	13.9	5.0	34.7
			Live trees—fall 1967–spring 1968				
6.6	present	988	132	3.2	14.5	54.1	407.2
6.6	absent	998	122	3.0	12.3	51.2	367.3
9.3	present	498	74	3.4	13.2	32.0	203.0
9.3	absent	498	85	3.7	13.4	37.2	261.4
13.2	present	248	49	4.0	14.3	21.3	153.8
13.2	absent	247	63	4.6	15.3	28.6	205.9
18.7	present	125	32	4.6	15.9	14.9	109.3
18.7	absent	125	46	5.7	19.3	22.4	182.3
26.4	present	62.5	17	4.7	15.6	7.7	56.0
26.4	absent	62.5	27	6.2	18.7	12.9	103.5
			Live trees—fall 1971–spring 1972				
6.6	present	985	170	3.7	16.4	74.0	587.4
6.6	absent	992	172	3.7	15.2	74.1	568.3
9.3	present	487	104	4.1	15.9	46.6	360.3
9.3	absent	498	123	4.5	17.0	55.7	437.5
13.2	present	247	70	4.9	17.6	32.8	262.2
13.2	absent	244	95	5.9	20.7	45.3	390.8
18.7	present	125	51	6.0	21.0	24.7	214.1
18.7	absent	125	72	7.3	25.1	36.6	359.0
26.4	present	62.5	28	6.3	21.0	13.6	116.8
26.4	absent	62.5	46	8.4	25.0	24.1	229.4
			Live trees—fall 1975–spring 1976				
6.6	present	977	214	4.2	18.4	96.0	825.7
6.6	absent	985	220	4.3	17.2	98.6	835.6

Table 2—Average stand statistics for the Pringle Falls spacing study over 35 years of observation, by spacing (continued)

Assigned spacing	Understory vegetation	Trees per acre	SDI	QMD	Average height	Basal area	Cubic volume
Feet				*Inches*	*Feet*	*Ft²/acre*	*Ft³/acre*
9.3	present	497	138	4.8	18.5	64.2	533.7
9.3	absent	498	161	5.3	20.1	75.3	657.7
13.2	present	247	94	5.8	21.0	45.8	409.7
13.2	absent	244	126	6.9	25.0	62.8	618.9
18.7	present	125	71	7.2	25.5	35.8	354.6
18.7	absent	125	96	8.6	30.1	50.5	578.3
26.4	present	62.5	40	7.8	25.7	20.7	205.1
26.4	absent	62.5	65	10.2	31.2	35.6	404.7
			Live trees—fall 1979–spring 1980				
6.6	present	976	251	4.6	21.2	115.5	1,097.7
6.6	absent	982	263	4.7	20.5	120.4	1,132.0
9.3	present	497	171	5.5	21.6	80.8	918.4
9.3	absent	498	195	5.9	23.5	93.8	657.7
13.2	present	247	121	6.7	25.2	60.1	613.1
13.2	absent	244	153	7.7	29.8	78.5	893.9
18.7	present	125	90	8.3	30.4	47.2	538.3
18.7	absent	125	116	9.6	35.5	62.6	821.6
26.4	present	62.5	53	9.1	31.2	28.5	329.9
26.4	absent	62.5	81	11.6	36.9	45.5	601.9
			Live trees—fall 1984–spring 1985				
6.6	present	972	293	5.2	25.7	141.0	1,592.8
6.6	absent	975	318	5.3	25.1	149.0	1,642.7
9.3	present	497	216	6.2	26.6	105.4	1,160.4
9.3	absent	498	240	6.6	29.1	118.9	1,388.4
13.2	present	247	155	7.7	30.9	79.8	972.0
13.2	absent	244	190	8.7	35.7	99.9	1,341.8
18.7	present	125	117	9.6	36.9	63.2	850.1
18.7	absent	125	143	10.8	41.7	79.5	1,212.5
26.4	present	62.5	72	10.8	38.1	40.0	546.9
26.4	absent	62.5	102	13.2	42.8	59.2	885.1

Table 2—Average stand statistics for the Pringle Falls spacing study over 35 years of observation, by spacing (continued)

Assigned spacing	Understory vegetation	Trees per acre	SDI	QMD	Average height	Basal area	Cubic volume
Feet				*Inches*	*Feet*	*Ft²/acre*	*Ft³/acre*
				Live trees—fall 1989–spring 1990			
6.6	present	951	343	5.6	29.7	163.4	2,044.2
6.6	absent	961	365	5.7	29.0	174.6	2,178.0
9.3	present	495	253	6.8	31.3	126.0	1,592.5
9.3	absent	498	277	7.2	33.9	139.2	1,842.4
13.2	present	247	186	8.5	35.7	97.7	1,356.6
13.2	absent	244	218	9.4	40.8	117.5	1,760.3
18.7	present	125	139	10.6	42.4	76.9	1,176.0
18.7	absent	125	166	11.7	47.2	94.0	1,590.4
26.4	present	62.5	87	12.1	44.9	49.6	782.4
26.4	absent	62.5	121	14.5	49.1	71.7	1,216.3
				Live trees–fall 1994			
6.6	present	948	362	5.8	31.5	172.8	2,341.0
6.6	absent	958	378	5.9	31.1	183.1	2,446.5
9.3	present	495	266	7.0	33.9	134.4	1,835.3
9.3	absent	498	291	7.4	35.8	147.7	2,086.1
13.2	present	247	198	8.8	39.1	104.2	1,556.9
13.2	absent	244	229	9.7	43.2	124.1	1,986.2
18.7	present	125	146	10.9	45.6	81.3	1,340.4
18.7	absent	125	171	11.9	50.4	96.8	1,771.3
26.4	present	62.5	92	12.4	48.4	52.9	909.9
26.4	absent	62.5	125	14.2	53.1	74.5	1,389.1

Mortality and 35-Year Mean Annual Growth

Immediately after logging and thinning, an outbreak of pine engraver (*Ips pini* (Say)) occurred in slash. This outbreak was more severe than any previous outbreak witnessed by local foresters, and the study appeared to be in danger. After emerging from the slash, the new population fortunately left, and only one or two trees were lost in the study area.

Table 3—Actual trees per acre with the percentage of live trees at the start of the period that died during the period (mortality) given in parentheses

Spacing	Understory vegetation	Period							
		1960-63	1964-67	1968-71	1972-75	1976-79	1980-84	1985-89	1990-94
Feet		*Trees/acre(percent mortality)*							
6.6	present	0	12(1.2)	4(0.4)	9(0.9)	0	5(0.5)	19(2.0)	4(0.4)
6.6	absent	0	2(0.2)	7(0.7)	7(0.7)	4(0.4)	7(0.7)	4(0.4)	12(1.2)
9.3	present	0	2(0.3)	2(0.3)	0	0	0	2(0.4)	0
9.3	absent	0	2(0.3)	0	0	0	0	0	
13.2	present	0	2(0.7)	2(0.7)	0	0	0	0	0
13.2	absent	0	4(1.4)	4(1.4)	0	0	0	0	0
18.7	present	0	0	0	0	0	0	0	0
18.7	absent	0	0	0	0	0	0	0	0
26.4	present	0	0	0	0	0	0	0	0
26.4	absent	0	0	0	0	0	0	0	0

Observations of mortality consisted of trees lost on each of the 30 plots for each of the eight measurement periods for a total of 240 observations. Mortality was not subjected to analysis of variance because so little mortality occurred for the four highest spacings (table 3). No mortality occurred for the two widest spacings; mortality occurred in two of the eight periods for the intermediate spacing (13.2 feet), three of the eight periods for the 9.3-foot spacing, and in all periods for the 6.6-foot spacing.

Table 4—35-year mean annual growth rates, by spacing

Spacing	Basal area				Cubic volume			
	Understory absent		Understory present		Understory absent		Understory present	
	Gross	Net	Gross	Net	Gross	Net	Gross	Net
Feet	*Ft^2•$acre^{-1}$•yr^{-1}*				*Ft^3•$acre^{-1}$•yr^{-1}*			
6.6	4.8	4.8	4.4	4.3	66.4	66.1	61.6	61.1
9.3	4.0	4.0	3.6	3.6	57.6	57.6	50.2	50.2
13.2	3.4	3.4	2.8	2.8	55.8	55.7	43.2	43.2
18.7	2.6	2.6	2.2	2.2	49.7	49.7	37.6	37.6
26.4	2.1	2.1	1.5	1.5	39.3	39.3	25.7	25.7

A total of 67 plot trees were lost during the 35 years of observation out of the 2,290 plot trees present after thinning in spring 1960. Mortality was so low that 35-year gross and net mean annual growth rates for cubic volume and basal area are practically the same (table 4). The cause of tree deaths was unknown, although root rot (*Armillaria* sp.) was suspected. Mountain pine beetles (*Dendroctonus ponderosae* Hopkins) and western pine beetles did not appear to cause any mortality in the plots, although western pine beetles have caused the death of several old-growth trees near the study area.

Many saplings in the plots were severely bent in winter 1960-61; records concerning these snow-bent trees were lost in a fire at the Silviculture Laboratory in 1972. To preserve the study, small poles from previously dead lodgepole pine were attached to the bent saplings by using wire and padding cut from old fire hose. The saplings were then pulled upright with three or more guy wires fixed to the lodgepole poles. These guy wires were then fastened to stakes driven in the soil and the saplings were held in place for 2 years. The poles were then removed and the saplings remained upright. Diameter and height growth during this 2-year period did not seem to be affected by this procedure. Mortality from snow bend would have been high had these measures not been employed.

Periodic Annual Increments

Mortality was so low that gross and net basal area and volume PAIs were nearly identical, and PAIs for QMD and average height calculated for surviving trees were nearly the same as the PAIs calculated by using live trees at the beginning and end of the period. All PAIs differed ($p \leq 0.05$) with period and were highest ($p \leq 0.05$) in the absence of understory vegetation (table 5, figs. 1-4). The PAIs for survivor QMDs and average heights increased curvilinearly ($p \leq 0.05$) with increasing spacing, gross basal area PAI decreased curvilinearly ($p \leq 0.05$), and the gross cubic volume PAI decreased linearly ($p \leq 0.05$) as spacing increased. The increase in diameter growth as spacing increased was greater in the absence of understory vegetation as shown by the significance ($p \leq 0.05$) of the spacing-by-vegetation interaction term. The curvature of the QMD PAI-spacing relation and the basal area PAI-spacing relation differed with period as shown by the significance ($p \leq 0.05$) of the quadratic component of the period-by-spacing interaction term. A lack of consistency in the curve shape for the basal area PAI-spacing relation for all periods is indicated by the significance ($p \leq 0.05$) of the lack of fit component of the period-by-spacing interaction term. The slope of the volume PAI-spacing relation differed with period as shown by the significance ($p \leq 0.05$) of the linear component of the period-by-spacing interaction term. The differences in all PAIs in the presence and absence of understory vegetation varied with period as shown by the significance ($p \leq 0.05$) of the period-by-vegetation interaction terms. These differences changed with spacing for QMD and basal area PAIs as shown by the significance ($p \leq 0.05$) of the period-by-spacing-by-understory vegetation term (table 5).

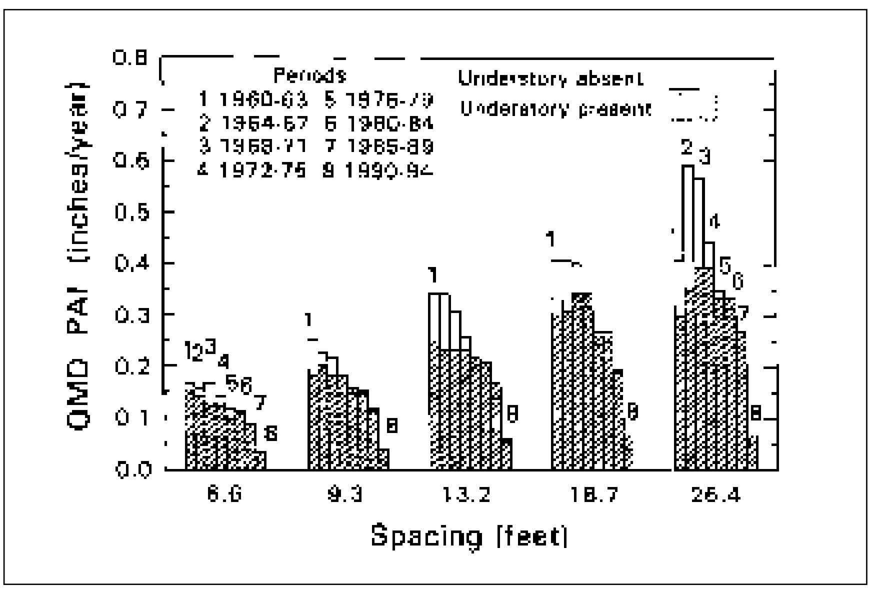

Figure 1—Survivor QMD PAIs (treatment means) for each spacing, understory treatment, and period. Numbers above the bars for each spacing indicate the period.

Table 5—Probability of higher F-values in repeated measures analyses of PAIs for quadratic mean diameter(QMD), average height, basal area, and total cubic volume

Source	Degrees of freedom	Probability of higher F-value for PAIs			
		QMD	Height	Basal area	Volume
		Whole plot			
Spacing (space):					
Linear	1	0.0001	0.0001	0.0001	0.0001
Quadratic	1	.0004	.0002	.0001	.3298
Lack of fit	2	.4795	.6787	.2871	.2128
Understory (veg)	1	.0001	.0001	.0001	.0001
Space × veg	4	.0015	.4487	.8982	.5586
Error	20				
		Split plot			
Period (P)	7	.0001	.0001	.0001	.0001
P × space:					
Linear	7	.0001	.0001	.0001	.0001
Quadratic	7	.0001	.0605	.0382	.7613
lack of fit	14	.9387	.8907	.0015	.6383
P × veg	7	.0001	.0001	.0001	.0001
P × space × veg	28	.0001	.0726	.0348	.6464
Error	140				
Error mean square:					
Whole plot		.0011	.0285	.4645	288.6262
Split plot		.0004	.0154	.0621	27.0976

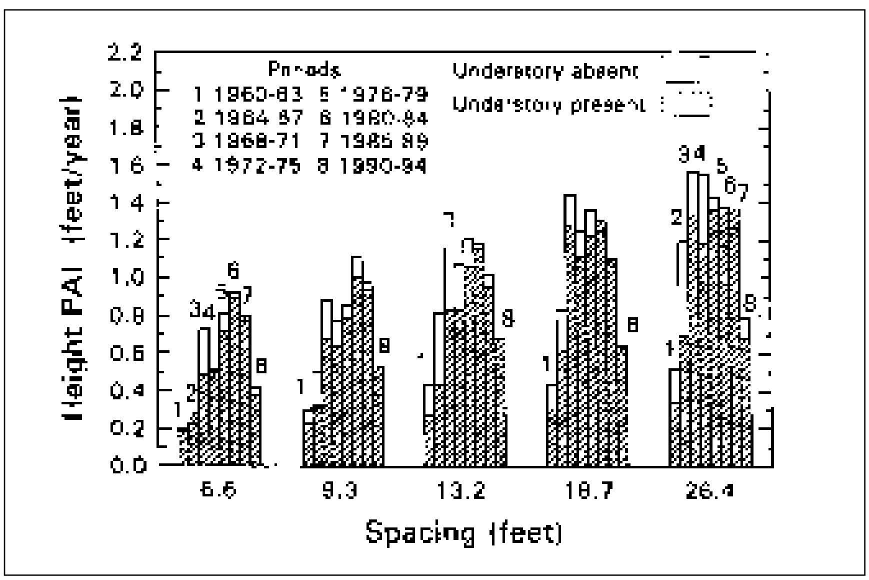

Figure 2—Survivor height PAIs (treatment means) for each spacing, understory treatment, and period. Numbers above the bars for each spacing indicate the period.

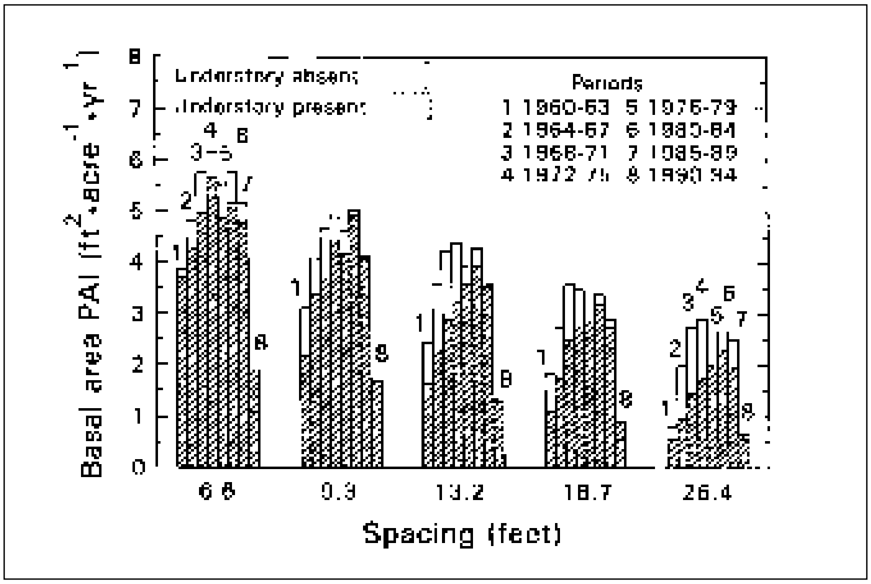

Figure 3—Gross basal area PAIs (treatment means) for each spacing, understory treatment, and period. Numbers above the bars for each spacing indicate the period.

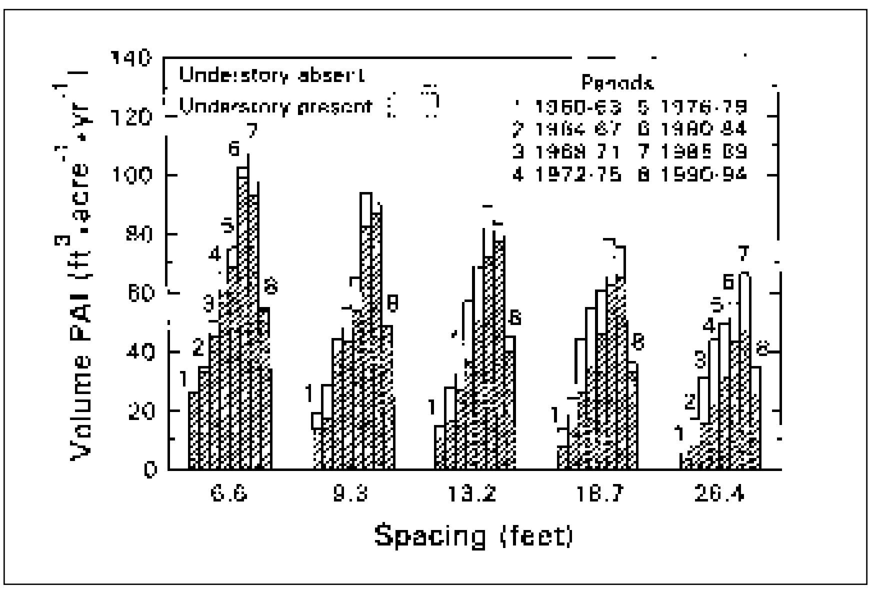

Figure 4—Gross cubic-volume PAIs (treatment means) for each spacing, understory treatment, and period. Numbers above the bars for each spacing indicate the period.

35-Year Mean Annual Growth for the Largest Diameter Trees per Acre

The 35-year mean annual volume growth for the 62.5 trees with largest diameters in 1994 increased curvilinearly ($p \leq 0.05$) with increased spacing, was greater ($p \leq 0.05$) in the absence of understory vegetation, and increased more in the absence of understory vegetation as spacing increased. This is shown by the significance ($p \leq 0.05$) of the spacing-by-vegetation interaction term (table 6, fig. 5).

Table 6—Probability of higher F-values in the analyses of variance of mean annual growth for the 62.5 largest trees per acre

Source	Degrees of freedom	Probability of higher F-value
Spacing (space):		
Linear	1	0.0001
Quadratic	1	.0372
Lack of fit	2	.8200
Vegetation (veg)	1	.0001
Space × veg	4	.0093
Error	20	
MSE[a]		9.1555
C.V.%[b]		13.58

[a] MSE = mean square for error from the analyses of covariance.
[b] C.V.% = coefficient of variation.

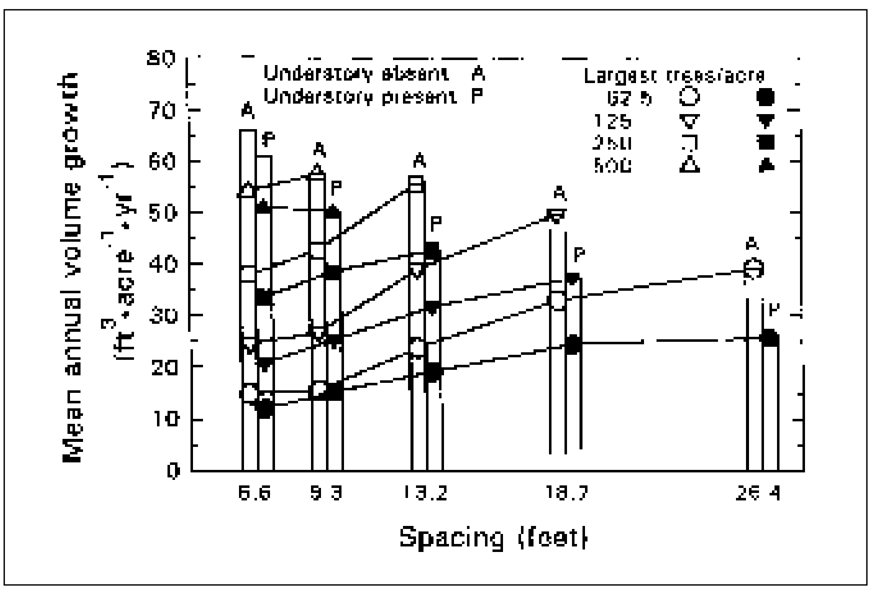

Figure 5—Thirty-five-year net mean annual cubic volume growth (bars) for all trees (treatment means) at various spacings and mean annual cubic volume growth of the largest diameter 62.5, 125, 250, and 500 trees per acre (treatment means).

Cubic Volume and Scribner Board-Foot Yields in 1994

Cubic volume yield decreased linearly ($p \leq 0.05$) as spacing increased, and Scribner board-foot yields varied curvilinearly ($p \leq 0.05$) with spacing. These yields were lower ($p \leq 0.05$) when understory vegetation was present (table 7, figs. 6 and 7).

Table 7—Probability of higher F-values in the analyses of variance of net cubic- and Scribner board-foot yields, fall 1994

Source	Degrees of freedom	Probability of higher F-values: Cubic-foot yield	Probability of higher F-values: Board-foot yield
Spacing (space):			
Linear	1	0.0001	0.0009
Quadratic	1	.1263	.0003
Lack of fit	2	.1244	.7501
Vegetation (veg)	1	.0001	.0001
Space × veg	4	.5259	.1570
Error	20		
MSE[a]		39,444.741	366,887.37
C.V.%[b]		11.26	16.31

[a] MSE = mean square for error from the analyses of covariance.
[b] C.V.% = coefficient of variation.

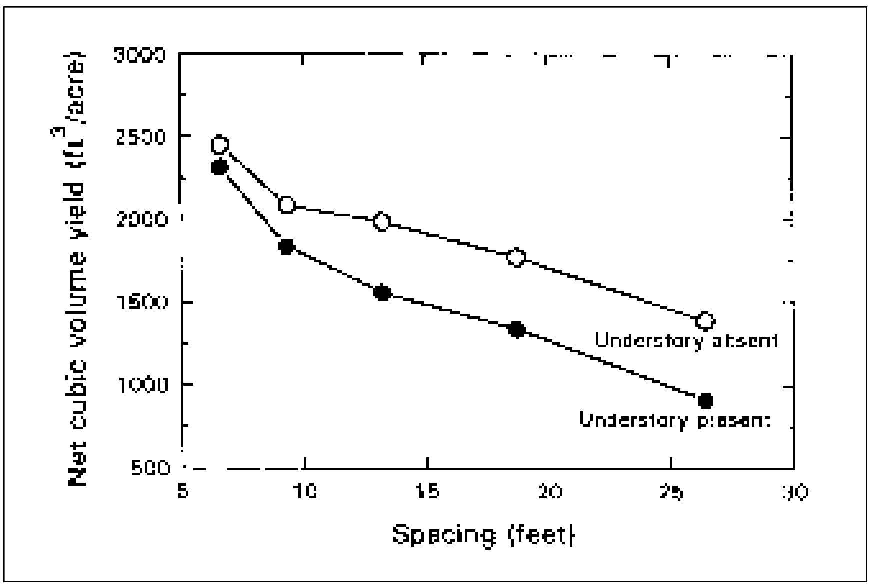

Figure 6—Net cubic volume yields in 1994 (treatment means) as a function of spacing. Plotted points from left to right represent spacings of 6.6, 9.3, 13.2, 18.7, and 26.4 feet, respectively.

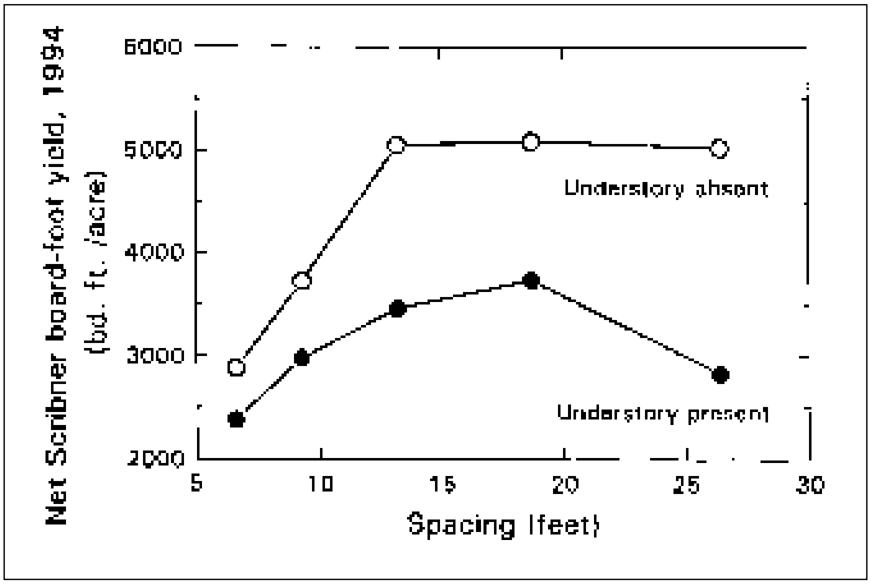

Figure 7—Net Scribner board-foot yields in 1994 (treatment means) as a function of spacing. Plotted points from left to right represent spacings of 6.6, 9.3, 13.2, 18.7, and 26.4 feet, respectively.

Crown Ratios, Crown Widths, and Crown Cover

Live crown ratios changed ($p \leq 0.05$) with time and varied curvilinearly ($p \leq 0.05$) with spacing. This curvature changed with time as shown by the significance of the quadratic component of the time-by-spacing interaction term (table 8). Live crown ratios were greater ($p \leq 0.05$) in the absence of understory vegetation, and the difference in these ratios for the two understory conditions changed with time, which produced a significant ($p \leq 0.05$) time-by-vegetation interaction (table 8, fig. 8).

Crown widths in fall 1979 increased curvilinearly ($p \leq 0.05$) as spacing increased. Crown widths were greater ($p \leq 0.05$) in the absence of understory and the difference in crown widths with and without understory vegetation increased as spacing increased, which produced a significant ($p \leq 0.05$) spacing-by-understory vegetation interaction (table 9, fig. 9). Crown cover in fall 1979 increased ($p \leq 0.05$) as spacing decreased. The surface of the crown cover-spacing relation is not well defined, as indicated by the significance ($p \leq 0.05$) of the lack of fit component of the spacing term. Crown cover was less ($p \leq 0.05$) at a given spacing in the absence of understory (table 9). Differences in crown cover between the two understory conditions

Table 8—Probability of higher F-values in the repeated measures analyses of live crown ratios

Source	Degrees of freedom	Probability of higher F-value
	Whole plot	
Spacing (space):		
Linear	1	0.0001
Quadratic	1	.0033
Lack of fit	2	.3306
Vegetation (veg)	1	.0117
Space × veg	4	.8249
Error	20	
	Split plot	
Time	7	.0001
Time × space:		
Linear	7	.0001
Quadratic	7	.0001
Lack of fit	14	.4373
Time × veg	7	.0001
Time × spac x veg	28	.8465
Error	140	
Error mean square:		
Whole plot		64.7542
Split plot		5.5589

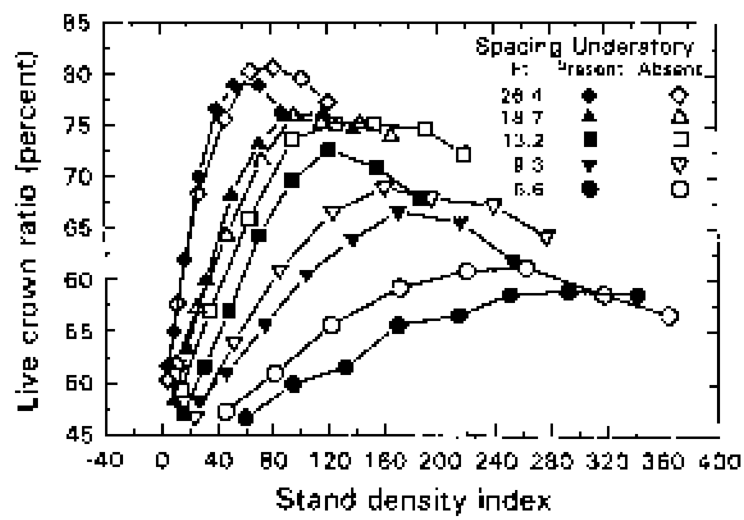

Figure 8—Live crown ratios as a function of SDI for each spacing-understory treatment combination. Plotted points are treatment means for periods 1 through 8, respectively.

Table 9—Probability of higher F-values in the analyses of variance of crown width and crown cover, fall 1979

Source	Degrees of freedom	Probability of higher F-value	
		Width	Cover
Spacing (space):			
Linear	1	0.0001	0.0001
Quadratic	1	.0001	.0001
Lack of fit	2	.0736	.0001
Vegetation (veg)	1	.0001	.0001
Space × veg	4	.0001	.0456
Error	20		
MSE[a]		0.0949	6.78
C.V.%[b]		2.99	5.43

[a] MSE = mean square for error from the analyses of covariance.
[b] C.V.% = coefficient of variation.

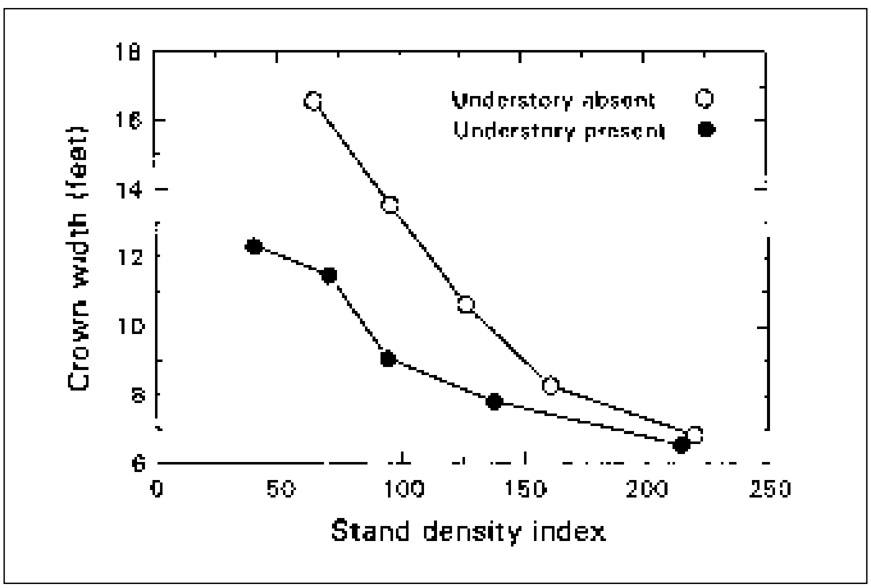

Figure 9—Crown width in 1979 (treatment means) as a function of SDI. Plotted points from left to right represent spacings of 26.4, 18.7, 13.2, 9.3, and 6.6 feet, respectively.

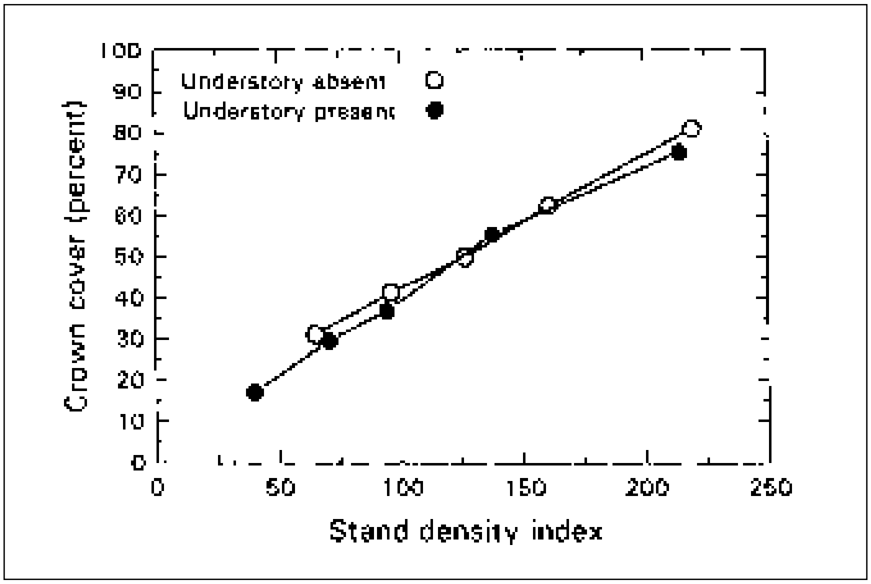

Figure 10—Percentage of crown cover in 1979 (treatment means) as a function of SDI. Plotted points from left to right represent spacings of 26.4, 18.7, 13.2, 9.3, and 6.6 feet, respectively.

Table 10—Probability of higher F-values in the analyses of variance of the single tallest tree per plot and the 8 tallest trees per plot, fall 1994

		Probability of higher F-value	
Source	Degrees of freedom	Single tallest tree per plot	8 tallest trees per plot
Spacing (space):			
Linear	1	0.0001	0.0001
Quadratic	1	.1875	.0268
Lack of fit	2	.1370	.3319
Vegetation (veg)	1	.1084	.0034
Space × veg	4	.3152	.3346
Error	20		
MSE[a]		6.3639	6.6692
C.V.%[b]		6.36	5.04

[a] MSE = mean square for error from the analyses of covariance.
[b] C.V.% = coefficient of variation.

decreased as spacing decreased, which produced a significant ($p \leq 0.05$) understory vegetation-by-spacing interaction. Plots of crown cover versus SDI indicate a linear crown cover-SDI relation (fig. 10). These plots also show that the effect of understory vegetation on crown closure is not direct but an indirect effect of the differences in the development of stand density for the two understory treatments from spring 1959 to fall 1979.

Heights of Tallest Trees in Fall 1984

The height of the single tallest tree per plot increased linearly ($p \leq 0.05$) as spacing increased and did not differ significantly ($p \leq 0.05$) with understory condition (table 10, fig. 11). The average height of the eight tallest trees per plot increased curvilinearly ($p \leq 0.05$) as spacing increased and was highest ($p \leq 0.05$) in the absence of understory (table 10, fig. 11).

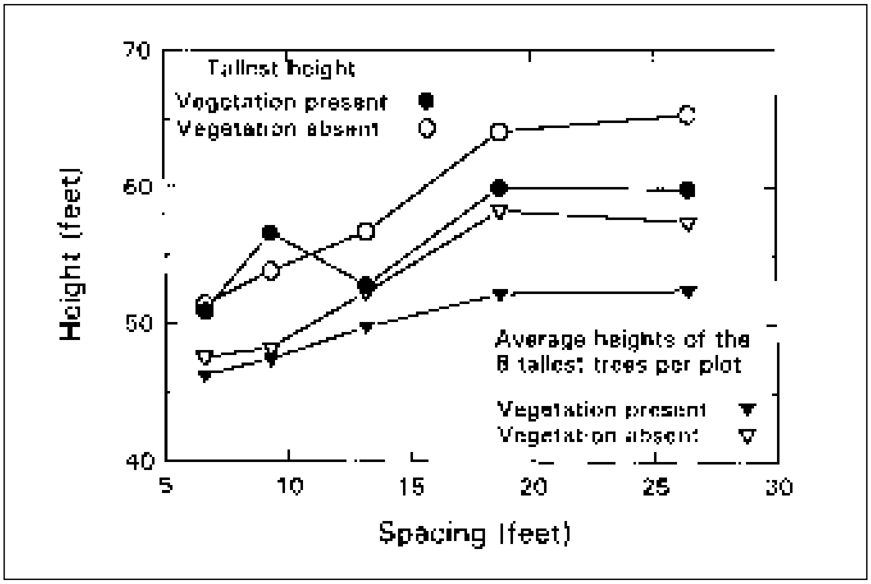

Figure 11—Heights in fall 1994 for the single tallest tree per plot (treatment means) and the height equivalent to the average height of the 40 tallest trees per acre (treatment means) as a function of spacing. Plotted points from left to right represent spacings of 6.6, 9.3, 13.2, 18.7, and 26.4 feet, respectively.

Table 11—Parameter estimates for the regression analyses of gross periodic annual increments (PAIs) of cubic volume and basal area, 1984-89, as a function of period mean stand density index (SDIm) and period mean average height(H)[a]

	Parameter estimate	
Coefficient	Cubic volume PAI	Basal area PAI
a	-1.9603	-2.3878
b	-0.0016	-0.0021
c	.9435	.9334
d	.4847	-0.2328
	Adjusted R^2 = 0.9140	Adjusted R^2 = 0.9451

[a] $\log_e PAI = a + b(SDIm) + c(\log_e[SDIm]) + d(\log_e[H])$.

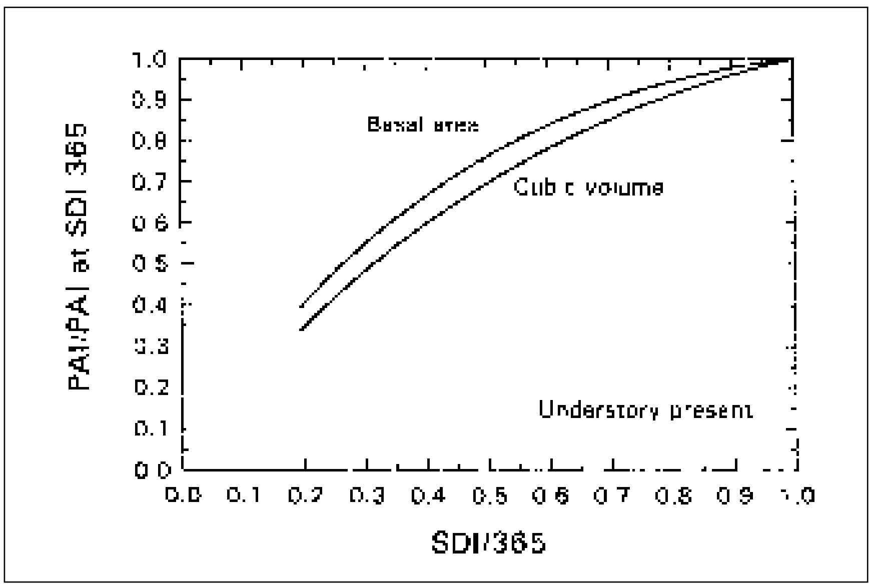

Figure 12—Predicted values of cubic volume and basal area PAIs with understory present (assuming the same average height for all densities) expressed as a fraction of the gross PAIs at full stocking as a function of stocking level expressed as a fraction of full stocking (SDI at full stocking is 365).

Growth-SDI Relations in 1985-89 With Understory Present

Models for $\log_e$PAIs for both basal area and cubic volume (equation (3)) were significant ($p \leq 0.05$) (table 11), and various PAI-SDI plots indicated a concave curvilinear PAI-SDI relation when heights were held constant (fig. 12). At 50 percent of normal stand density (SDI = 182.5), 77 percent of basal area and 70 percent of the volume growth of a fully stocked stand are produced. At 74 percent of normal stocking (SDI = 270), 92 percent of the basal area growth and 88 percent of the volume growth of a fully stocked stand are produced (fig. 12).

Discussion and Conclusions

Growth rates for the first 20 years of the study were greater in the absence of understory vegetation. The decrease in soil quality in the absence of understory and the relative increases in growth rates in the presence of understory in the last 15 years, however, indicates that long-term elimination of understory would have long-term implications on soil productivity and growth. Increasing numbers of ponderosa pine seedlings and saplings have developed in the study plots with understory (Barrett 1982) and would eventually decrease the growth rates of the larger trees if not controlled. These understory trees were cut in 1994. Operationally, prescribed burning would be a reasonable way to reduce the numbers of unwanted seedlings and saplings in thinned stands. Prescribed burning has been shown in other studies to reduce growth rates of surviving trees (Landsberg 1992). This reduction in growth does not appear to be permanent, and prescribed burning is recognized as a useful management tool to reduce fuel loading and improve forage quality.

Growth responses to varying density levels in this study are not unusual. Results from several ponderosa pine spacing and levels-of-growing-stock (LOGS) studies indicate that diameter growth decreases curvilinearly with increasing stand density, while stand basal area growth usually increases curvilinearly with increasing stand density (Cochran and Barrett, 1993, 1995, 1998, 1999; Oliver 1979, 1997; Oliver and Edminster 1988; Ronco and others 1985). Stand cubic volume growth increases curvilinearly with increasing stand density in most studies (Cochran and Barrett 1998, 1995; Oliver 1997, 1979; Oliver and Edminster 1988) but linearly with increasing stand density in some studies (Cochran and Barrett 1999). Height growth decreases with increasing density in some studies (Cochran and Barrett 1998, 1995; Oliver 1979; Oliver and Edminster 1988) and appears unaffected by stand density in other studies (Cochran and Barrett 1993, Oliver 1997, Oliver and Edminster 1988). Increases in height for the single tallest tree per plot and the tallest eight trees per plot as spacing widened indicated that site index values can be influenced by stand density. The increase in cubic volume yield with increasing density combined with the decreased tree size and reduced board foot-cubic foot ratios for smaller trees often produces a curvilinear board-foot yield-density relation that flattens at relatively low density levels. Many studies also demonstrate that growth rates of even the largest trees in the stand decrease curvilinearly with increasing stand density (Barrett 1963; Cochran and Barrett 1993, 1995, 1998, 1999).

Although mortality in this study has been low, future losses could be high. Stand density levels in combination with individual tree size greatly affect pine beetle-related mortality in some ponderosa pine and lodgepole pine studies (Cochran and Barrett 1993, 1995, 1998, 1999; Cochran and Dahms 1998; Mitchell and Preisler 1991, 1993). Often the relation between mortality and stand density is not linear. Usually plots of mortality versus SDI indicate a threshold density level above which the probability of serious pine beetle-caused mortality exists if largest trees are 9 inches d.b.h. or larger. For lodgepole pine, this threshold stand density seems to be SDI 170 (Cochran and Dahms 1998, Peterson and Hibbs 1989). The threshold stand density for ponderosa pine seems to be related to site index and would be SDI 270 for this study site (Cochran and others 1994). In a nearby ponderosa pine LOGS study on a more productive site, mortality from mountain pine beetle became serious at SDI 240 (Cochran and Barrett 1999). The study plots and their buffer strips in this LOGS study, however, are surrounded by an unthinned, very dense stand, while the stand surrounding the spacing study was thinned in 1958. The combination of SDI

270 and the presence of 9-inch diameter or larger trees occurred for only 3 of the 30 plots by 1984, 8 plots by 1989, and 10 plots by 1994. No mortality due to mountain pine beetles was detected, however, in any of these plots. Because the general study area outside the plot boundaries was thinned to only a 10- to 12-foot spacing, the general area may now be susceptible to mountain pine beetle.

If managers wish to retain trees with large diameters, stands need to be managed so that they do not become susceptible to serious pine beetle outbreaks, and the trade-off between yields and tree size needs to be considered in prescribing thinning levels. Seven-inch diameter ponderosa pine trees with a 5-inch diameter inside bark at the top of an 8-foot log are currently merchantable. The QMD is about 1.5 times the smallest tree diameter on the plots at intermediate spacings. To attain an SDI of 270 and have the smallest salable trees, a QMD of 10.5 inches must be attained. Rearranging equation (2) and solving for TPA at an SDI of 270 and a QMD of 10.5 inches produces 248 TPA (spacing 13.3 feet). The 13.3-foot spacing is regarded as the minimal spacing for precommercial thinning on this site. Narrower spacings have a high probability of being successfully attacked by mountain pine beetles before a commercial entry could be made. Increasing the spacings will reduce cubic volume yields, promote larger tree sizes, but may not reduce the Scribner board-foot yield at the first commercial entry. More than 60 percent of the potential cubic volume growth can be captured at stand densities as low as 0.4 of normal (fig. 11).

The reduction of growth rates of even the largest trees with increasing stand densities indicates that unmanaged stands that escape thinning through fire or other disturbance will progress very slowly toward mid- or late-seral conditions. Late-seral condition has 10 to 30 TPA that are 21 inches or greater in diameter (depending on the site), with three 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).

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 in 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. Some wildlife species may prefer the resulting forests (Hayes and others 1997).

Metric Equivalents

1 inch = 2.54 centimeters
1 foot = 0.3048 meter
1 mile = 1.609 kilometers
1 acre = 0.405 hectare
1 square foot = 0.09290 square meter
1 cubic foot = 0.02832 cubic meter
1 square foot/acre (ft^2/acre)= 0.2293 square meter/hectare
1 cubic foot/acre (ft^3/acre) = 0.06997 cubic meter/hectare
1 tree/acre = 2.471 trees/hectare
(˚F-32)/1.8 = ˚C

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Long-suppressed ponderosa pine saplings responded to overstory removal, thinning, and competing vegetation. Trees on plots without competing vegetation had greater growth for 20 years but soil quality decreased. Height and diameter growth of individual trees increased as spacing increased. Cubic volume growth decreased as spacing increased but Scribner board-foot yields 35 years after treatment increased curvilinearly as spacing increased.

Keywords: Thinning, understory vegetation, growth, ponderosa pine, *Pinus ponderosa*, saplings.

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