PB99-165045

United States
Department of
Agriculture

Forest Service

Pacific Northwest
Research Station

Research Paper
PNW-RP-517
June 1999

Growth and Yield of Western Larch Under Controlled Levels of Stocking in the Blue Mountains of Oregon

P.H. Cochran and K.W. Seidel

Authors

P.H. COCHRAN is a consultant in forest resources, University of Idaho, Moscow, ID 83843. He was principal research soil scientist (retired); and K.W. SEIDEL was a research forester (retired), U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, Silviculture Laboratory (now closed), Bend, OR.

REPORT DOCUMENTATION PAGE

PB99-165045

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	June 1999	Research Paper

4. TITLE AND SUBTITLE

Growth and Yield of Western Larch Under Controlled Levels of Stocking in the Blue Mountains of Oregon

5. FUNDING NUMBERS

6. AUTHOR(S)

P. H. Cochran and K. W. Seidel

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Pacific Northwest Research Station
Communications Group
P. O. Box 3890
Portland, OR 97208-3890

8. PERFORMING ORGANIZATION REPORT NUMBER

FSRP-PNW-517

9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Same as number 7

10. SPONSORING /MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Release unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Repeated thinning to five growing-stock levels resulted in widely differing tree sizes and volumes per acre after 30 years. Largest trees butthe least cubin-volume yield per acre were produced in the heaviest thinning level, whereas highest board-foot yields were found in intermediate thinning levels. Partial defoliation by larch casebearer (Coleophora laricella Hubner), drought, and top damage from ice occurred, and site trees grew less in height than expected during the 30-year study. Curvilinear increases in periodic annual increments of both basal area and cubic volume generally occurred with increasing stand density, but increments dropped off at the highest stand densities for some periods. Anticipated patterns for these increments were found after fitting a model that included stand density index, height increments of site trees, and dummy variables for periods as independent variables. Heavy thinning did not increase the age of culmination of cubic-volume means annual increment as expected. Thinning stands of larch to densities as low as 50 percent of "normal" results in little loss of basal-area growth, a moderate loss in volume production, and a large increase in tree diameter. Thinning is necessary in many larch stands to maintain vigorous, rapidly growing trees.

14. SUBJECT TERMS

Stocking levels, bole area, stand density index, growth, yield, larch casebearer, ice damage, future stands

15. NUMBER OF PAGES 35

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

Abstract

Cochran, P.H.; Seidel, K.W. 1999. Growth and yield of western larch under controlled levels of stocking in the Blue Mountains of Oregon. Res. Pap. PNW-RP-517. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 35 p.

Repeated thinning to five growing-stock levels resulted in widely differing tree sizes and volumes per acre after 30 years. Largest trees but the least cubic-volume yield per acre were produced in the heaviest thinning level, whereas highest board-foot yields were found in intermediate thinning levels. Partial defoliation by larch casebearer (*Coleophora laricella* Hübner), drought, and top damage from ice occurred, and site trees grew less in height than expected during the 30-year study. Curvilinear increases in periodic annual increments of both basal area and cubic volume generally occurred with increasing stand density, but increments dropped off at the highest stand densities for some periods. Anticipated patterns for these increments were found after fitting a model that included stand density index, height increments of site trees, and dummy variables for periods as independent variables. Heavy thinning did not increase the age of culmination of cubic-volume mean annual increment as expected. Thinning stands of larch to densities as low as 50 percent of "normal" results in little loss of basal-area growth, a moderate loss in volume production, and a large increase in tree diameter. Thinning is necessary in many larch stands to maintain vigorous, rapidly growing trees. Thinning levels will greatly affect the appearance of future stands.

Keywords: Stocking levels, bole area, stand density index, growth, yield, larch casebearer, ice damage, future stands.

Summary

Repeated thinnings every 10 years to growing-stock levels (GSLs) of 5,000, 10,000, 15,000, 20,000, and 25,000 square feet of bole area per acre were done for 30 years. Trees were measured every 5 years. Stand density index (SDI) appeared to be curvilinearly related to bole area. Height growth of the site trees (the two tallest trees per plot) was less than predicted from height-growth curves due in part to partial defoliation by larch casebearer (*Coleophora laricella* Hübner), drought, and top damage from ice. Mortality was low; no mortality occurred at the lowest GSL level, and mortality appeared to increase curvilinearly with GSL for the higher GSLs. Largest trees but the least cubic-volume yield per acre were produced in the heaviest thinning level, whereas highest board-foot yields were found in intermediate thinning levels. Anticipated periodic annual increment (PAI) curves, which increase markedly at low densities as density increases then pass through an inflection point and approach a limit as normal stand density is neared were not found. Reasonable curve shapes for gross basal area and volume PAIs were found by fitting a model, which included SDI, height increments of site trees, and dummy variables for periods as independent variables. Heavy thinning did not increase the age of culmination of cubic-volume mean annual increment as expected. Growth of the 30 largest diameter trees per acre was reduced by the presence of smaller trees. Stands at 25, 50, and 70 percent of normal density produce 49, 70, and 87 percent, respectively, of the gross-volume PAI grown at normal stand densities. Thinning is necessary in many larch stands to maintain vigorous, rapidly growing trees. Thinning levels will greatly affect the appearance of future stands.

Introduction

Western larch (*Larix occidentalis* Nutt.) is a major seral species in the *Pseudotsuga menziesii* and *Abies grandis* zones in the Ochoco and Blue Mountains of northeastern Oregon and southeastern Washington, along the east side of the Washington Cascade Range, and in the Okanogan Highlands of Washington. Western larch is a minor but important species in these zones in the northern half of the Oregon Cascade Range and in the *Tsuga heterophylla* and *Abies lasiocarpa* zones on the east side of the Cascade Range in Washington (Franklin and Dyrness 1973).

Larch has rapid juvenile growth and desirable wood properties. Larch also enhances the appearance of landscapes, particularly in fall when the foliage becomes bright yellow. Larch, at times, experiences varying degrees of defoliation from various pests, including western spruce budworm (*Choristoneura occidentalis* Freeman), and its most serious pest, Larch casebearer (*Coleophora laricella* Hübner). Larch dwarf mistletoe (*Arceuthobium laricis* [Piper] St. John) is the most serious disease-causing parasite of western larch (Schmidt and others 1976). Even-aged stands, often heavily stocked, generally become established after fire or other disturbances. Larch is shade intolerant, and decreased vigor associated with reduced crown size usually occurs as stands develop so stocking level control often is necessary. Questions about stocking levels include (1) What spacings for precommercial thinnings allow leave trees to develop most rapidly into commercially sized stands with reasonable site occupancy? (2) What is the relation between levels of growing stock and growth and yield of stands of commercially sized trees? and (3) What is the relation between mortality and stand density?

Two levels-of-growing-stock (LOGS) studies have been established in the Blue Mountains of Oregon (Seidel 1986, 1987) to aid in answering the last two questions. These studies are also valuable because they provide field demonstrations of the influence of stocking levels on understory development, tree size, and volume yield.The studies additionally provide opportunities to study processes such as changes in soil quality that may be associated with stand and understory development (Busse and others 1996). Stand development influences all phases of forest management and greatly affects the ecology of forested or partly forested landscapes. This paper reports 30-year growth and yield results for one of these studies established in spring 1966. Results of the study aid in answering questions 2 and 3 but are directly applicable only to this study area. The soil and plant community have similar representatives over the range of western larch, however, thereby indicating corresponding results can be expected over a wide area.

Methods of Study

Study Area

This study is in sections 26 and 27 of T. 5 S., R. 41 E., Willamette Meridian, near Catherine Creek about 15 miles southeast of Union, Oregon, at an elevation of 4,000 feet. The soil is a Tolo silt loam (Typic Vitrandept) developing on 3 feet of ash originating from the eruption of Mount Mazama. The vegetation is a seral stage of the *Abies grandis/Calamagrosits* plant community (Johnson and Clausnitzer 1991). The 160-acre stand, established after a fire, was 35 years old (28 years old at breast height) in spring 1966 when the study was started. A site index of 70 feet (Schmidt and others 1976) or 90 feet (Cochran 1985) was determined from heights measured in spring 1966. The site index values of Schmidt and others are determined from average heights of dominants and codominants and their total age; site index values of Cochran are obtained from heights of the tallest five trees per acre and their age at breast height. The index age in both systems is 50 years.

Design and Installation

The experimental design is completely randomized with two replicates of five growing-stock levels (GSLs) installed on ten 0.4-acre square plots, each surrounded by a similarly treated 33-foot-wide buffer strip. These 10 treated areas (each 0.9 acre in size) were distributed over the untreated larch stand. Growing-stock levels of 5,000, 10,000, 15,000, 20,000, and 25,000 square feet of bole area per acre were assigned randomly to each plot. Bole area is an approximation of the surface area of the bole cambial surface (Lexen 1943). The randomly assigned treated areas containing each plot were then thinned from below to leave the required number of the largest and most vigorous trees as evenly spaced as possible.

All study plots were well stocked before the initial thinning; they contained about 1,270 trees per acre averaging 4.5 inches in diameter (table 1). The study was designed to be rethinned to the assigned levels of bole area at 10-year intervals and has been rethinned twice (figs. 1-3). Slash from all three thinnings was left on the plots. Two of the plots (one in the highest density level and the other in the next highest density level) had about 40 percent of their basal area in lodgepole pine (*Pinus contorta* Dougl. ex Loud.) after the initial thinning. Lodgepole pine was discriminated against in each thinning. The eight other plots were pure larch.

Values of stand density index (SDI) immediately after the first thinning for the five stocking levels were 52, 102, 149, 205, and 240 (table 1, fig. 3). These values are equivalent to 12.7, 24.8, 36.3, 50, and 58.5 percent of an SDI of 410, the SDI for "normal" or "fully stocked" stands of western larch (Cochran 1985). The SDI values for larch were determined from,

$$SDI = N(QMD/10)^{1.73}, \qquad (1)$$

where N is trees per acre and QMD is the quadratic mean diameter (Cochran 1985). An exponent of 1.73 instead of 1.605 as proposed by Reineke (1933) was used because -1.73 was the slope of a least squares fit of $\log_e N$ as a function of $\log_e QMD$ for 154 "normally" stocked plots sampled in Oregon and Washington.

Measurements

A pretreatment stand inventory was made by measuring the diameter at breast height (d.b.h.) of each tree. Heights (H) of all plot trees were measured after the initial thinning only. At the start and end of each 5-year measurement period, diameters (D) of all plot trees were measured to the nearest 0.1 inch. Fifteen trees in each plot, proportionally distributed over the range of diameters also were measured initially and at 5-year intervals with optical dendrometers to determine cubic-foot volume (V) and bole area or cambial surface area (CS) using Grosenbaugh's (1964) STX program. International board-foot volume (V1) to a 6-inch top inside bark also was calculated for each of these trees 10 inches in diameter or larger. These values were used to fit models describing individual tree volumes and bole areas at each time of measurement as functions of d.b.h. (Husch and others 1972):

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

$$\log_e V1 = a_1 + b_1[\log_e(\text{d.b.h.})] + c_1[\log_e(\text{d.b.h})]^2, \text{ and} \qquad (3)$$

$$\log_e CS = a_2 + b_2[\log_e(\text{d.b.h.})] + c_2[\log_e(\text{d.b.h.})]^2. \qquad (4)$$

Total heights (H) calculated from the dendrometer measurements were used to determine coefficients in the model (Curtis 1967),

$$\log_e H = a_3 + b_3/(\text{d.b.h.}) + c_3/(\text{d.b.h.})^2 . \quad (5)$$

New coefficients for equations (2) through (5) were determined by regression after each measurement and used to compute plot volumes, bole areas, and individual tree heights. Early in the study, pooled data from all plots were used in the regressions to determine the coefficients. Later, separate coefficients were determined for each plot. The second degree terms were used only when they were significant ($p \leq 0.10$). Heights of the two tallest trees per plot, the heights used in determining site index (Cochran 1985), were among the trees initially chosen for measurement with a dendrometer. These trees were remeasured with a dendrometer each time the plots were measured and used in determining coefficients for equations (2) through (5). Because the tallest trees were not always the trees with the largest diameters, estimates of volume and height for the plots may be slightly biased upward. These height measurements furnished the opportunity to compare actual height growth of the site trees during the 30-year period with height predicted from the height growth curves (Cochran 1985) using site index values and age determined in spring 1966.

Observations for mortality consist of losses for each plot during each 5-year period. Tree mortality (R_m) was calculated as a negative interest rate for each observation by using (Hamilton and Edwards 1976),

$$R_m = 1 - (N2/N1)^{(1/n)} , \quad (6)$$

where N1 and N2 are the number of live trees at the start and end of the 5-year period, respectively, and n is the number of years in the measurement period. Mean diameters at the beginning of each period for trees that died during that period were divided by mean diameters of all live trees at the start of the period for all plot-period combinations where mortality occurred. These ratios were used to examine the size of the trees that died in relation to the average tree size.

Heights to green crown were determined for all trees measured with optical dendrometers in spring 1966 and fall 1995. Live crown ratios were determined from these measurements.

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, gross and net board-foot volume, and site tree heights. The PAIs of QMDs and average heights were determined for surviving trees. Mean annual growth of gross and net basal area and volume (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. Volume yields (cumulative net yields), the live standing volume at a given time plus the live volume removed in any previous thinnings (including the initial thinning), were determined for each time of measurement. Mean annual volume increments (MAI, cumulative net yields divided by age) also were calculated. Yield, mean annual growth, MAIs and PAIs for board-foot volumes include ingrowth. Mean annual growth rates of volume and basal area for the 30-year study also were determined for the 30 surviving trees per acre that had the largest diameters at the start of the study. The lowest GSL had only 30 and 32.5 trees per acre for the two replications after the last thinning.

Table 1—Average stand characteristics (per-acre basis) of live trees at Catherine Creek over the period of study

GSL[a]	Bole area	Basal area	SDI[b]	Number of trees	Average spacing	Quadratic mean diameter	Average height	Volume[c]	
	- Square feet -				*Feet*	*Inches*	*Feet*	*Cubic feet*	*Board feet*
				Fall 1965 before initial thinning (breast-height age 28)					
1	25,800	119	289	924	6.9	5.0	—	1,994	98
2	31,125	133	300	1,161	6.1	4.6	—	2,287	0
3	34,180	139	321	1,406	5.6	4.3	—	2,367	193
4	32,880	144	329	1,376	5.6	4.4	—	2,322	0
5	32,700	136	315	1,482	5.4	4.2	—	2,199	0
				After spring 1966 thinning (breast-height age 28)					
1	4,708	26	52	96	21.4	7.1	48.2	474	98
2	9,524	49	102	215	14.3	6.5	47.4	902	0
3	14,242	71	149	355	11.1	6.1	46.0	1,268	193
4	19,313	96	205	546	9.0	5.7	42.6	1,616	0
5	24,203	110	240	745	7.6	5.2	43.1	1,847	0
				Fall 1970 (breast-height age 33)					
1	6,347	40	76	96	21.4	8.8	55.1	749	948
2	12,068	68	134	215	14.2	7.7	52.8	1,333	294
3	17,797	93	189	354	11.1	7.0	52.2	1,780	532
4	23,792	120	249	539	9.0	6.4	49.4	2,250	345
5	29,120	134	286	740	7.7	5.8	48.8	2,510	102
				Before fall 1975 thinning (breast-height age 38)					
1	8,730	56	109	96	21.4	10.4	62.5	1,222	3,654
2	15,208	86	164	215	14.3	8.6	57.7	1,870	2,366
3	21,716	115	226	354	11.1	7.7	58.2	2,471	1,464
4	29,244	144	293	534	9.1	7.1	55.5	3,103	1,168
5	33,917	156	324	734	7.7	6.2	53.6	3,317	706
				After fall 1975 thinning (breast-height age 38)					
1	5,078	34	61	51	29.2	11.1	64.7	760	2,876
2	10,006	59	111	129	18.4	9.2	59.6	1,301	2,367
3	15,012	83	160	225	13.9	8.2	59.4	1,808	1,464
4	20,029	104	205	333	11.5	7.6	58.0	2,248	1,168
5	24,678	121	245	464	9.7	7.0	58.1	2,621	706

Table 1—Average stand characteristics (per-acre basis) of live trees at Catherine Creek over the period of study (continued)

GSL[a]	Bole area	Basal area	SDI[b]	Number of trees	Average spacing	Quadratic mean diameter	Average height	Volume[c]	
								Cubic feet	*Board feet*
	- Square feet -				*Feet*	*Inches*	*Feet*		
				Fall 1980 (breast-height age 43)					
1	6,592	45	77	51	29.2	12.7	70.7	1,146	5,110
2	12,505	73	133	129	18.4	10.2	65.8	1,862	4,949
3	18,736	99	187	225	13.9	9.0	63.5	2,412	3,583
4	24,433	121	234	329	11.5	8.2	63.4	2,986	2,797
5	29,960	138	273	462	9.7	7.4	62.7	3,398	1,357
				Before fall 1985 thinning (breast-height age 48)					
1	7,582	53	89	51	29.2	13.8	74.7	1,514	7,583
2	14,362	83	148	128	18.5	10.9	69.6	2,298	8,915
3	21,158	111	205	220	14.1	9.6	68.7	2,962	7,253
4	27,185	133	252	318	11.7	8.8	67.9	3,625	5,628
5	30,846	139	269	408	10.3	7.9	69.4	3,858	3,028
				After fall 1985 thinning (breast-height age 48)					
1	5,056	36	60	32	37.2	14.7	78.6	1,065	5,463
2	10,146	60	106	88	22.5	11.3	70.5	1,671	7,197
3	15,091	82	149	148	17.2	10.1	68.7	2,206	6,200
4	19,945	102	190	218	14.2	9.3	68.6	2,776	5,269
5	25,062	115	222	313	11.8	8.2	68.1	3,241	2,899
				Fall 1990 (breast-height age 53)					
1	5,885	44	76	32	37.2	16.1	83.0	1,345	7,434
2	11,397	69	121	88	22.4	12.1	74.0	1,991	9,845
3	16,909	92	166	48	17.2	10.7	72.0	2,633	9,351
4	22,987	116	212	216	14.3	10.0	72.3	3,384	7,862
5	28,868	127	241	310	11.9	8.7	71.6	3,702	5,042
				Fall 1995 (breast-height age 58)					
1	6,703	51	80	32	37.4	17.2	88.1	1,646	9,261
2	12,758	80	135	88	22.4	13.0	78.6	2,365	12,266
3	19,337	106	188	148	17.1	11.5	77.1	3,168	14,593
4	25,400	131	237	215	14.3	10.6	76.6	3,908	14,866
5	30,260	135	254	302	12.0	9.0	73.9	4,007	9,149

[a] GSL = growing-stock level.
[b] SDI = stand density index.
[c] Total cubic-foot volume of entire stem, inside bark, all trees; board-foot (international 1/4-inch rule) volume for all trees 10.0-inch diameter at breast height and larger to a 6-inch top diameter inside bark.

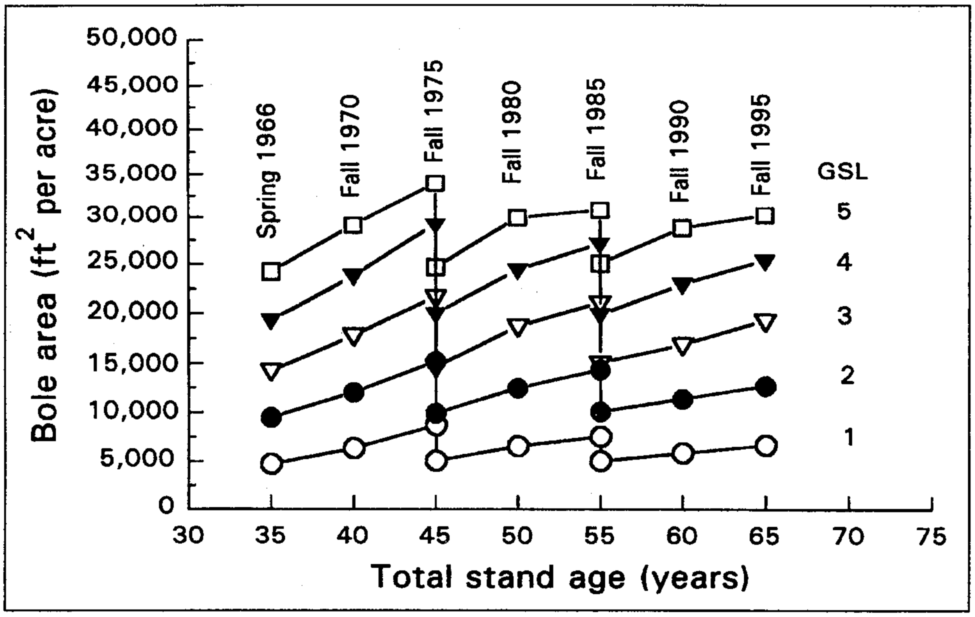

Figure 1—Live bole area (treatment means) in relation to total age and year for each GSL.

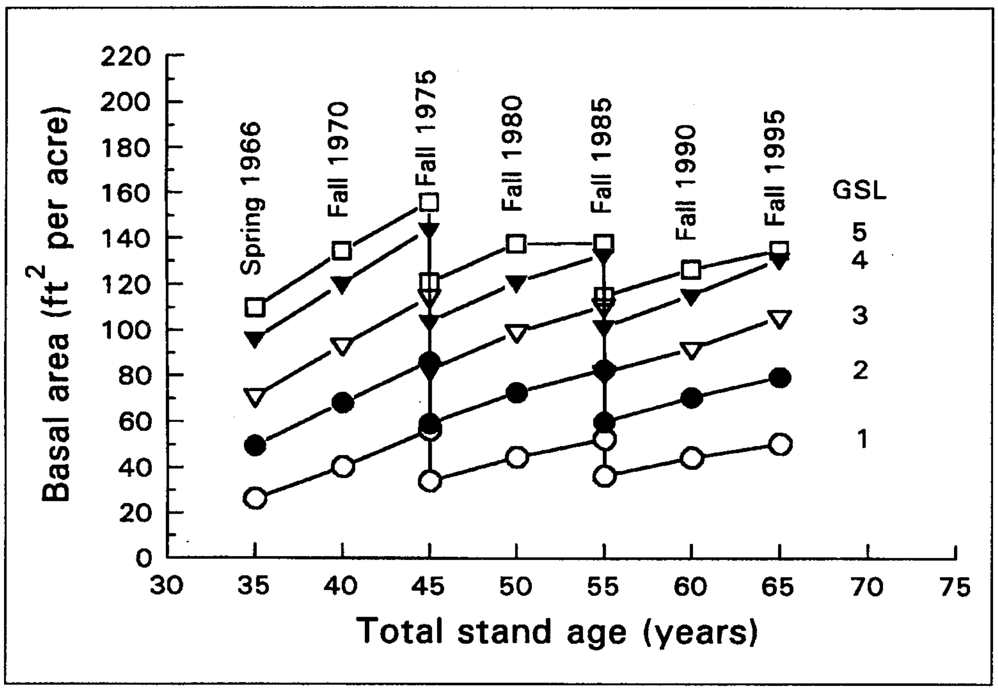

Figure 2—Live basal area (treatment means) in relation to total age and year for each GSL.

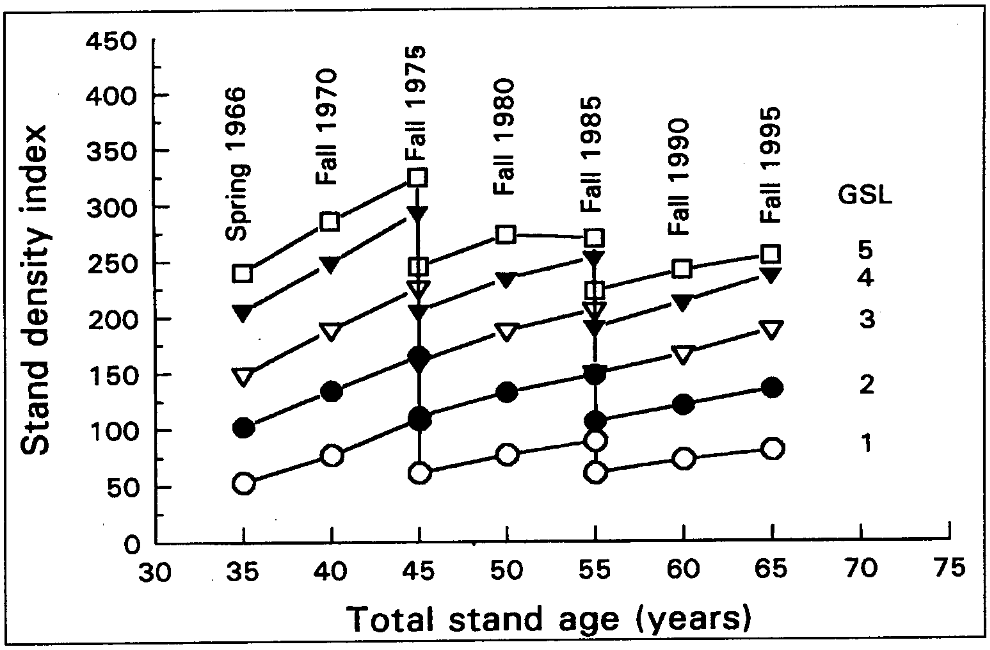

Figure 3—Stand density index of live trees (treatment means) in relation to total age and year for each GSL.

Analyses

The relation of SDI, a more familiar measure of stand density, to bole area (CS) was examined by plotting SDI as a function of bole area for each measurement. Ten sets of measurements exist; before the initial thinning, at the start of each period, at the end of periods 2 and 4 before rethinning, and at the end of period six. Repeated measures analysis of variance (SAS Institute 1988) was used to test the hypotheses that the SDI values immediately after the three thinnings were linearly related to GSL and that these SDI values did not vary with time of measurement (increasing tree size). This analysis assumes that plot SDIs are independent for these three separate times. Orthogonal polynomial methods with coefficients derived from the five equally spaced GSLs were used to test linear, quadratic, and lack-of-fit effects. Only SDI values immediately after the three thinnings were used in this analysis because values for other measurements are in part dependent on the SDI values 5 years earlier. A given SDI value is commonly interpreted as a constant relative level of competition across a range of stand diameters. If the relation between SDI and bole area is linear and the slope and intercept values are the same for each measurement, a given value for bole area also would indicate a constant relative level of competition across a range of stand diameters.

Standard or repeated measures (split-plot-in-time) analyses of variance (SAS Institute 1988) were used to test the following hypotheses: (1) Differences in projected and actual heights of the site trees did not vary with period or GSL. (2) There are no differences in PAIs with GSL or period (age). (3) There are no differences in mean annual growth of basal area or volume during the 30-year study with GSL. (4) There are no differences in mean annual volume increments with GSL or period (age). (5) There are no differences in cumulative net volume yields with GSL. (6) Crown ratios did not differ with GSL or vary between spring 1966 and fall 1995. Repeated measures analyses of MAIs and differences between actual and projected heights may produce levels of significance that are too high because these variables are cumulative. These analyses, however, seemed the most reasonable way to examine the relation of these variables to GSL. Because there are five GSLs, up to a fourth-degree polynomial can be used to describe the relation between response and stocking level. Results from other LOGS studies in ponderosa pine (Barrett 1983, Cochran and Barrett 1995, Oliver and Edminster 1988, Ronco and others 1985) and in Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) (Curtis and Marshall 1986, Marshall and others 1992) indicate second-degree polynomials would sufficiently describe this relation. Linear, quadratic, and lack-of-fit effects were therefore tested in both the standard and repeated measures analyses (except for the analysis of crown ratios) by using orthogonal polynomial methods. Coefficients used in these tests were determined from the five equally spaced levels of bole area used to define the GSLs.

Regression analyses were employed to relate PAIs of gross cubic volume and gross basal area to height PAI of site trees (the two tallest trees per plot (SHPAI)), period mean SDI (SDIm), and period (P) using,

$$\log_e PAI = a_0 + a_1 \log_e(SHPAI) + a_2 \log_e(SDIm) + a_3(SDIm) + b_1 P_1 + \ldots + b_{i-1} P_{i-1}, \qquad (7)$$

with combined data from all periods (50 observations) assuming independence of each observation. Dummy variables were used for each period. Observations are not independent, and equation (7) probably underestimates the error term. Therefore, R^2 values for individual coefficients were calculated to determine their contribution to the R^2 for the complete model instead of conducting probability tests. An equation similar to equation (7) was used by Curtis and Marshall (1986) for Douglas-fir except they did not include height increments. If significant differences in SHPAI with density do not occur and there are correlations of gross basal area and volume PAI with SHPAI, then equation (7) can be used with actual SDIs and period mean SHPAIS to smooth the gross basal area and volume PAI curves. Further, fractions of gross volume PAI at full stocking (SDI = 410) produced at lower stocking levels can be estimated by using equation (7) with some assumptions. These assumptions are (1) differences in SHPAI do not occur with density as density increases to SDI 410 and (2) coefficients found in the regression analysis describe gross volume PAIs to SDI 410. If the assumptions are correct, the fraction (PAI at any density lower than SDI 410)/(PAI at SDI 410) can be determined and plotted versus the fraction (SDI/410).

Results and Discussion

Quadratic mean diameters ranged from 5.2 to 7.1 inches, and corresponding average heights ranged from 43.1 to 48.2 feet after initial thinning in spring 1966 (table 1). Three of the treatments had no board-foot volume because there were no trees 10 inches or larger in diameter. Thirty years later, QMDs ranged from 9.0 to 17.2 inches, average heights ranged from 73.9 to 88.1 feet, and GSLs 3 and 4 had almost 15,000 board feet per acre.

Relation of SDI to Bole Area

The SDI-GSL relation immediately after thinning is curvilinear ($p \leq 0.10$) and varies ($p \leq 0.10$) with time of measurement or tree size (table 2). Plots of SDI versus bole area for each measurement also appear to be curvilinear and appear to show that plots with a given amount of bole area have lower SDI values as the trees become larger (fig. 4). A given bole area cannot, therefore, be interpreted as a constant relative level of competition across a wide range of stand diameters.

Table 2—Probability of higher *F*-values for the repeated measures analyses of SDI values after each of the three thinnings[a]

Source	Degrees of freedom	Probability of higher *F*-values: Stand density index
GSL:		
Linear	1	0.0001
Quadratic	1	.0627
Lack of fit	2	.4681
Error	5	
Time or measurement (M)	2	.0004
M x GSL:		
Linear	2	.0005
Quadratic	2	.8141
Lack of fit	4	.4646
Error	10	
MSE:[a]		
Whole plot		45.26
Subplot		15.1977

[a] MSE = mean square error form the analysis of variance.

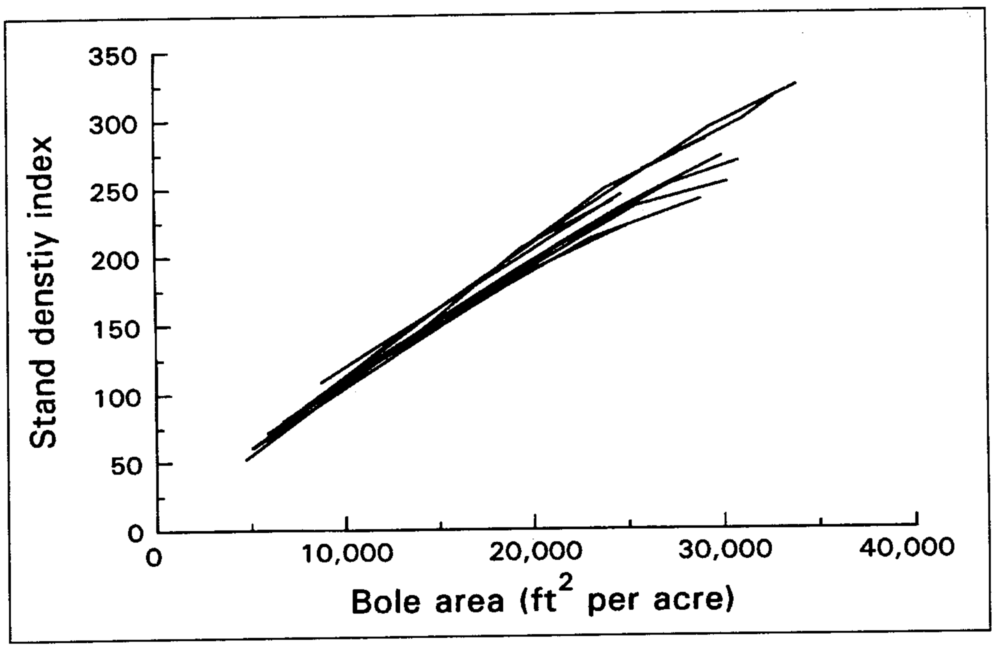

Figure 4—Relation of stand density index to bole area for the 10 different times the plots were measured; before and after initial thinning, after each of the six 5-year growth periods, and after the second and third thinnings. The upper curve is the relation before thinning (lowest QMDs); the lowest curve is the relation after the sixth period (highest QMDs).

Bole areas were used to define GSLs for this study so the analyses of variance tested for responses to different levels of bole area. Stand density index, however, is easier for managers to determine and is a more familiar measure of stand density than bole area. Further, a given SDI indicates the same relative level of competition across a range of stand diameters. Some figures in this paper, therefore, show mortality rates, growth responses, and crown ratios plotted as a function of SDI and not bole area.

Mortality

A total of 60 observations of mortality are available from the 10 plots observed over six 5-year periods. Mortality occurred for only 20 of these 60 observations so no formal statistical tests were performed. Out of 1,567 study trees initially, 915 were thinned, and 87 died during the 30-year study. Mortality appeared to differ with GSL and period (table 3). No mortality occurred for the lowest GSL and 1, 5, 21, and 60 trees (2.5, 12.5, 52.5, and 150 trees per acre) died during the study on the four succeeding higher GSL treatments, respectively. Mortality ranged from 2.5 to 145 trees per acre for the six study periods (table 3). The average mortality rate (from equation (6)) for all plots and all periods was 0.15 percent. Mortality did not appear to be serious unless plot SDIs were greater than 225 at the start of the period (fig. 5). Mortality rates were high during period four (1981-85) because an ice storm in 1984 broke 58 tree boles below the live crown and caused mortality rates averaging 1.15 percent for the highest density level. For other observations, average mortality rates did not exceed 0.64 percent. Mean diameters of trees that died on any plot during any period averaged 83 percent (range, 39 to 109 percent) of the mean diameter of all trees on the plot. No relation between this percentage and stocking level was evident.

Actual and Predicted Tallest Tree Heights

The actual average heights of the two tallest trees per plot fell short of the heights predicted from the height-growth equations for these trees as the study progressed (fig. 6). Stem analysis data from site index and height-growth studies for ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) (Barrett 1978), Douglas-fir (Cochran 1979a), and white fir (*Abies concolor* (Gord. & Glend.) Lindl. ex Hildebr.) (Cochran 1979b) showed that the particular trees that were tallest on 0.2-acre plots changed with time. Similar data from a larch study (Cochran 1985), however, did not show a change in height ranking as time progressed. Further, the two trees that were the tallest at the start of this study were also the tallest of the trees measured at the end of the study. Overall differences between actual and projected heights with GSL were not detected ($p \leq 0.10$) (table 4). Differences between actual and projected heights increased ($p \leq 0.10$) with time (table 4), and these differences varied erratically with GSL during different periods as shown by the significance ($p \leq 0.10$) of the lack of fit term for the period by GSL interaction.

Height PAIs for the site trees (SHPAIs) varied erratically with GSL for most periods (fig. 7) resulting in significance ($p \leq 0.10$) for the lack of fit term for GSL (table 4). These SHPAIs differed ($p \leq 0.10$) with period (table 4), and their relation to GSL changed with period as indicated by the significance ($p \leq 0.10$) of the linear component of the period by GSL interaction. Larch crop trees in thinned plots in one thinning study in Montana exceeded expected height growth described by site index curves of Schmidt and others (1976) (Schmidt and Seidel 1988). Further, the height growth of the crop trees in thinned stands in this Montana study was far superior to height growth of crop trees in unthinned stands, and crop tree-height growth increased with decreasing numbers of trees per acre. In another Montana thinning study, height growth of larch crop trees was greater in the thinned treatments than the controls, but there was no difference in these growth rates between thinning levels (Roe and Schmidt 1965).

Table 3—Total mortality for each growing-stock level (GSL) and period[a]

GSL	Period						
	1966-70	1971-75	1776-80	1981-85	1986-90	1991-95	Total
	Trees per acre[b]						
1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	0	0	0	2.5	0	0	2.5
3	2.5	0	0	10	0	0	12.5
4	17.5	7.5	5	22.5	0	0	52.5
5	10	10	2.5	110	2.5	15	150
Total	30	17.5	7.5	145	2.5	15	217.5

[a] Each GSL has 2 replications so average mortality for each GSL would be the total mortality divided by 2.
[b] Plot size is 0.4 acre, therefore, 1 tree per plot equals 2.5 trees per acre.

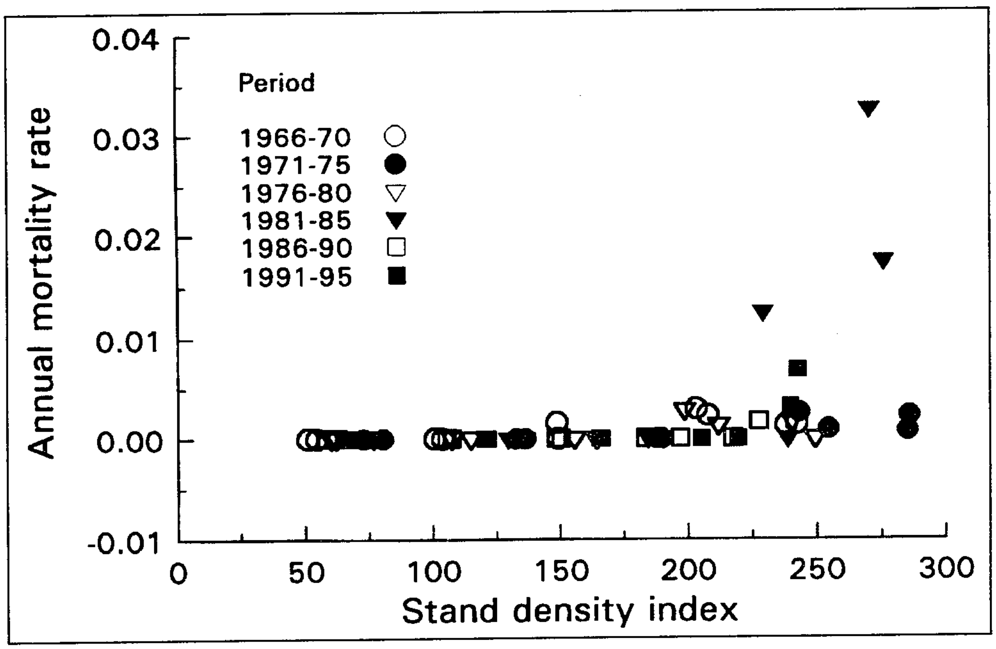

Figure 5—Relation of annual mortality rates calculated using equation (6) to SDI at the start of the period for the 60 observations. The high values for the 1981-85 period are due to a 1984 ice storm.

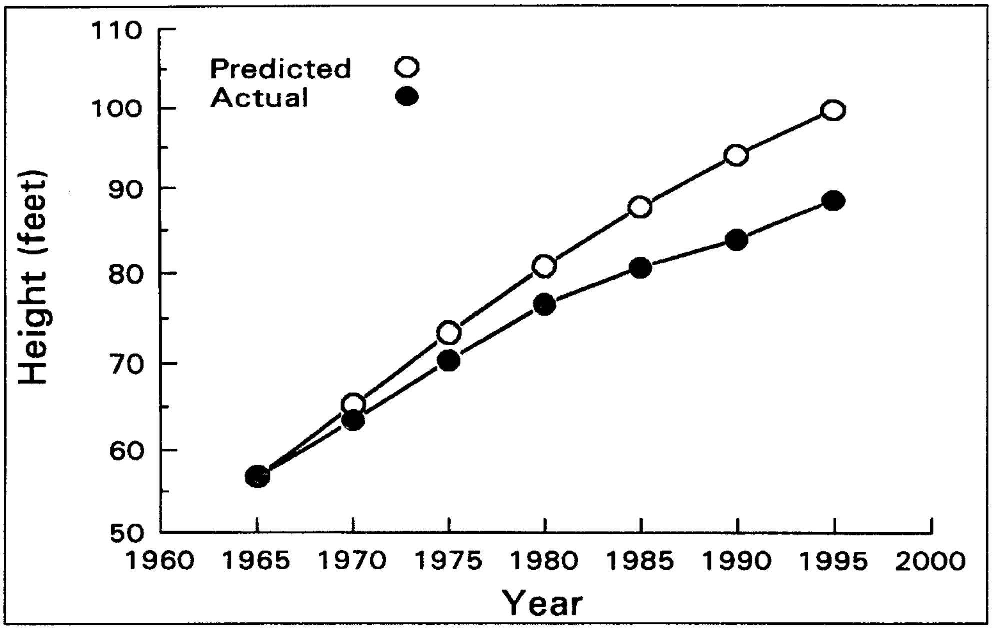

Figure 6—Predicted and actual heights for the site trees (the two tallest trees per plot) from fall 1965 to fall 1995. Plotted points are averages for all GSLs.

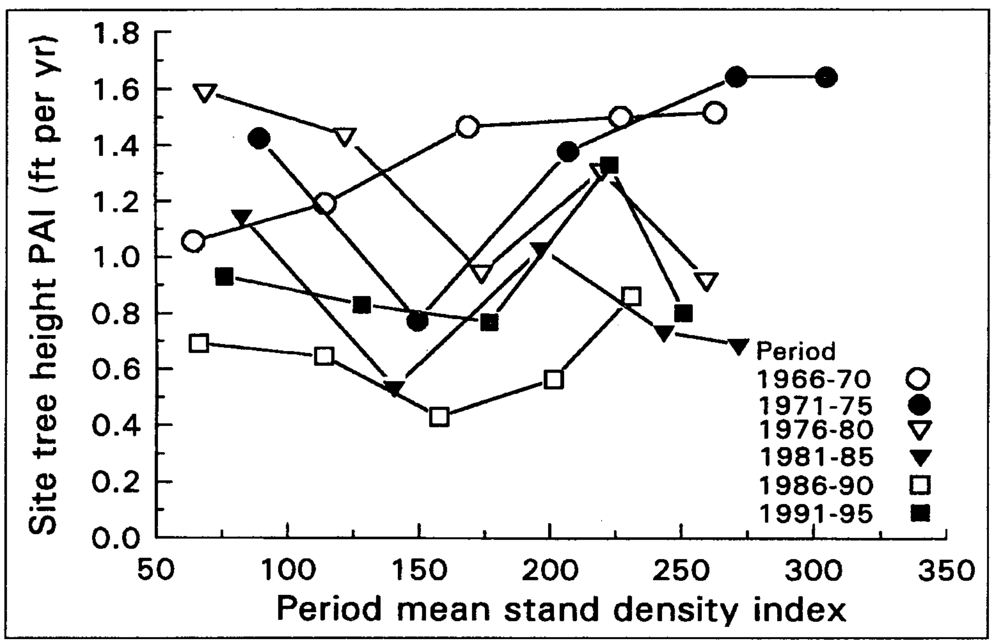

Figure 7—Relation of PAIs for site trees (the two tallest trees per plot) to period mean SDI for the 6 periods of study. Plotted points are averages for GSLs 1 to 5.

Table 4—Probability of higher *F*-values for the repeated measures analyses of variance of differences in predicted and actual site tree heights, and periodic annual increments (PAIs) of site trees

Source	Degrees of freedom	Probability higher *F*-values: Differences in predicted and actual site tree heights	Probability higher *F*-values: Site tree height PAIs
GSL:			
Linear	1	0.2467	0.5004
Quadratic	1	.8421	.2252
Lack of fit	2	.2153	.0702
Error	5		
Time or period (P)	5	.0001	.0001
P x GSL:			
Linear	5	.5710	.0653
Quadratic	5	.5940	.7398
Lack of fit	10	.0832	.3377
Error	25		
MSE:[a]			
Whole plot	46.9176	.0495	
Subplot	2.7408	.0982	

[a] MSE = mean square error from the analysis of variance.

Larch casebearer was first noticed in the study area in 1972 (Ryan 1990), and the resulting defoliation probably reduced height growth. Although no reports exist confirming height-growth reduction in larch from defoliation by casebearer, radial growth has been severely decreased by casebearer invasion (Denton 1979). Reduction in height growth by western spruce budworm damage has been reported for larch (Schmidt and Fellin 1973), and budworm may have been present in the study, but budworm damage was not observed. Casebearer populations continued high in the study area until 1986 (Ryan 1990). The ice storm in 1984 may have broken out small portions of the fine tips of these trees, further reducing height and then height growth as lateral branches formed new terminals in succeeding years. Annual precipitation was low in the Blue Mountains during many of the years of study, and the radial growth of nondefoliated ponderosa pine was very low in 1974 and 1979 (Wickman 1986). This general drought must have further reduced height growth of the site trees. The combination of casebearer, drought, and the ice storm are probably responsible for reducing the height development of the site trees below expected levels. Reduced height growth probably indicates reduction in other growth rates as well. Variation in SHPAI-GSL relations with period are probably due to differences in growing conditions between periods and to differences in defoliation between GSLs in the same period.

Periodic Annual Increments

All PAIs differed ($p \leq 0.10$) with period or age (table 5). Survivor PAIs for QMD (fig. 8), average height (fig. 9), and gross basal area PAIs (fig. 10) generally decreased with increasing age or period until the last period when these PAIs increased for some GSLs. The PAIs for cubic volume (fig. 11) generally increased from period one to period two or three, and were then lower for the remaining periods. Board-foot PAIs (fig. 12), which include ingrowth, generally increased with increasing periods or age.

Survivor PAIs for QMD decreased ($p \leq 0.10$) curvilinearly with increasing stand density. The gradual decline in QMD PAI with increasing GSL did not occur for all GSLs in the last two periods (fig. 8) resulting in significance ($p \leq 0.10$) of the lack of fit term for the period by GSL interaction (table 5). Survivor PAIs for height appeared to decrease linearly with increasing GSL for some periods but varied erratically with GSL for other periods resulting in significance ($p \leq 0.10$) of the lack of fit term for GSL (table 5, fig. 9).

The gross and net PAIs for basal area generally increased ($p \leq 0.10$) curvilinearly with increasing stand density (table 5, fig. 10). The shape of the basal area PAI curves varied with period resulting in significance ($p \leq 0.10$) of the quadratic component of the period by GSL interaction. Gross and net cubic volume PAIs generally increased with increasing stand density, but this pattern was erratic, thereby resulting in significance ($p \leq 0.10$) of the lack-of-fit term for GSL (table 5, fig. 11). The board-foot PAIs varied curvilinearly with density, but the curve shape varied with period as shown by the significance ($p \leq 0.10$) of the quadratic component of the period by GSL interaction (table 5). Maximum board-foot PAIs were produced at low stand densities initially then at intermediate stand densities later (fig. 12) as trees grew into the 10-inch class. By fall 1995, all trees in the lowest GSL were above 10 inches in diameter. There were 2, 22, 89, and 219 trees per acre less than 10 inches in diameter for GSLs 2 through 5, respectively, at this time. Maximum board-foot annual increment can be expected to shift to the highest GSL in this study in the future.

No good explanation can be offered for the significance ($p \leq 0.10$) of the quadratic component of the period by GSL interaction found for the QMD, basal area and board-foot PAI-GSL curves. Curves for gross PAIs of basal area and cubic volume are expected to increase rapidly with increasing stand density at low stand densities, go through an inflection point as stand densities increase further, and then approach an upper limit as normal density is neared. The decline in gross PAIs for both basal area and cubic volume between GSLs 4 and 5 during several periods is particularly puzzling. These declines seem to be matched by a decline in site tree and survivor height PAIs (figs. 7 and 9) for some periods.

Table 5—Probability of higher *F*-values for the repeated measures analyses of variance of periodic annual increments (PAIs)

		Probability of higher *F*-values						
		PAI						
				Basal area		Cubic volume		Bd. ft[c]
Source	Df[a]	QMD[b]	Height	Gross	Net	Gross	Net	Gross[d]
GSL:								
Linear	1	0.0001	0.0008	0.0020	0.0052	0.0001	0.0001	0.5707
Quadratic	1	.0036	.1812	.0262	.0086	.0063	.0003	.0931
Lack of fit	2	.0424	.0098	.3818	.2933	.0319	.0035	.7657
Error	5							
Period (P)	5	.0001	.0001	.0001	.0001	.0001	.0001	.0001
P x GSL:								
Linear	5	.0001	.6128	.0001	.0006	.0222	.0784	.0008
Quadratic	5	.0001	.4086	.0033	.0514	.4537	.5592	.0668
Lack of fit	10	.0095	.5325	.4759	.8878	.7755	.9575	.3441
Error	25							
MSE:[e]								
Whole plot		.00078	.00748	.41061	.33556	123.56	56.315	67,622.2
Subplot		.000069	.03779	.03095	.11388	223.05	441.11	31,901.1

[a] Df = degrees of freedom.
[b] QMD = quadratic mean diameter.
[c] International board-boot volume to a 6-inch top inside bark.
[d] Gross and net values for board-foot PAIs were equal.
[e] MSE = mean square error from analyses of variance.

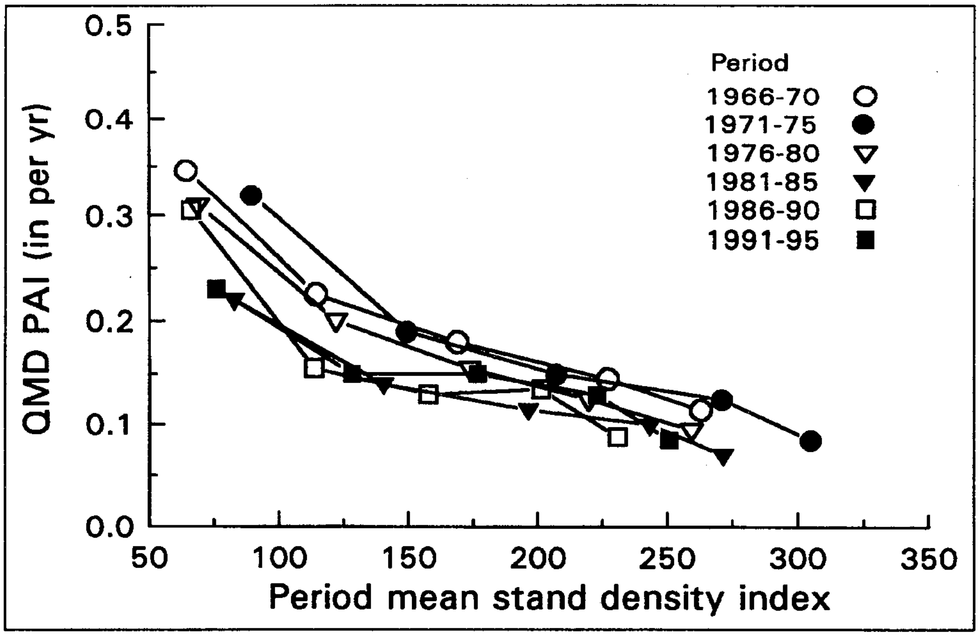

Figure 8—Relation of survivor PAIs for quadratic mean diameter to period mean SDI for the 6 periods of study. Plotted points are averages for GSLs 1 to 5.

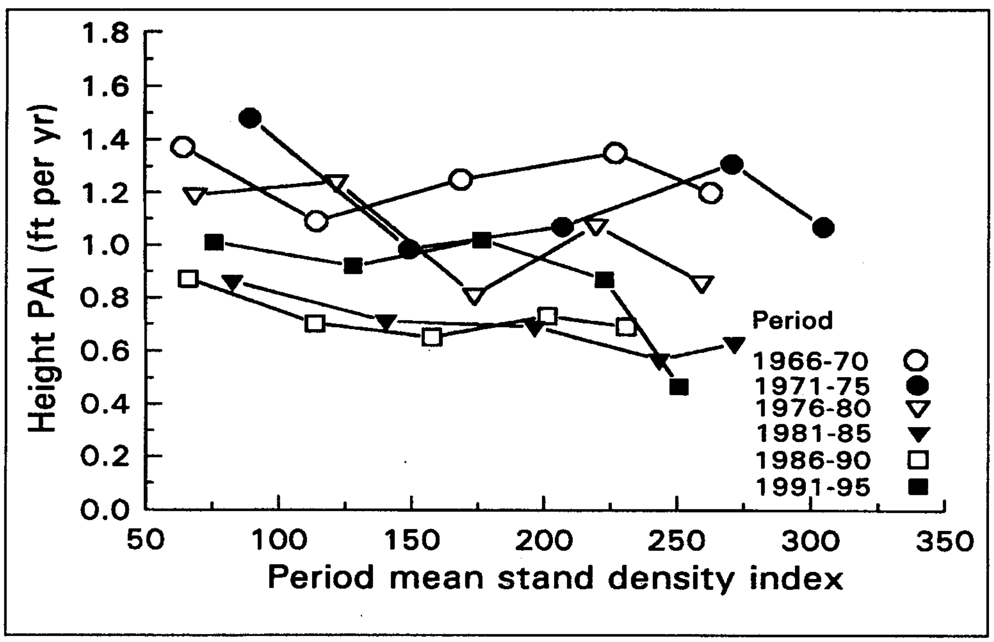

Figure 9—Relation of survivor PAIs for average height to period mean SDI for the 6 periods of study. Plotted points are averages for GSLs 1 to 5.

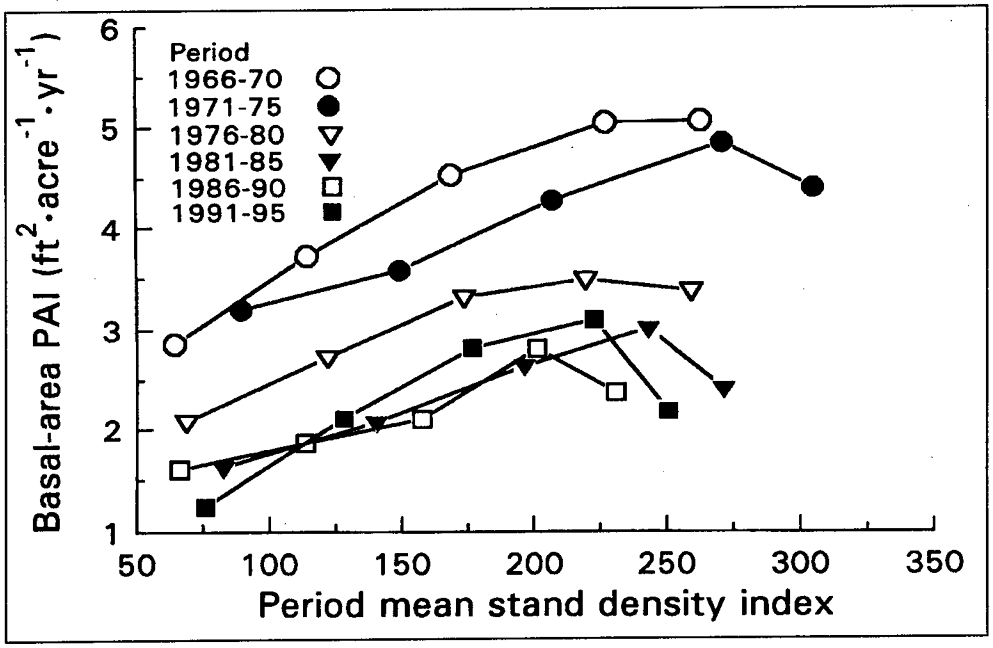

Figure 10—Relation of PAIs for gross basal area to period mean SDI for the 6 periods of study. Plotted points are averages for GSLs 1 to 5.

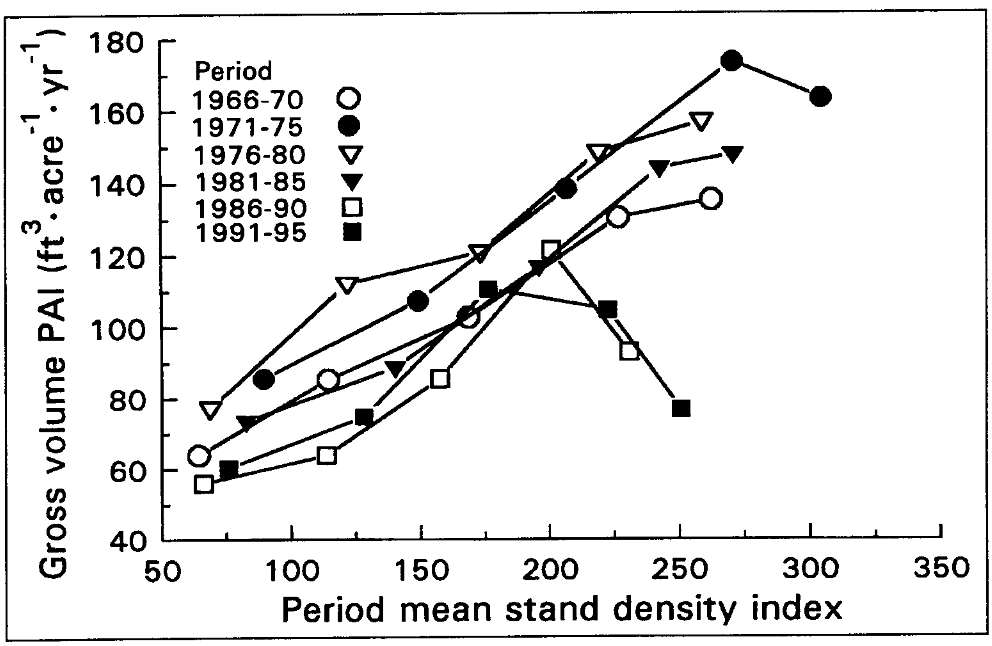

Figure 11—Relation of PAIs for gross cubic volume to period mean SDI for the 6 periods of study. Plotted points are averages for GSLs 1 to 5.

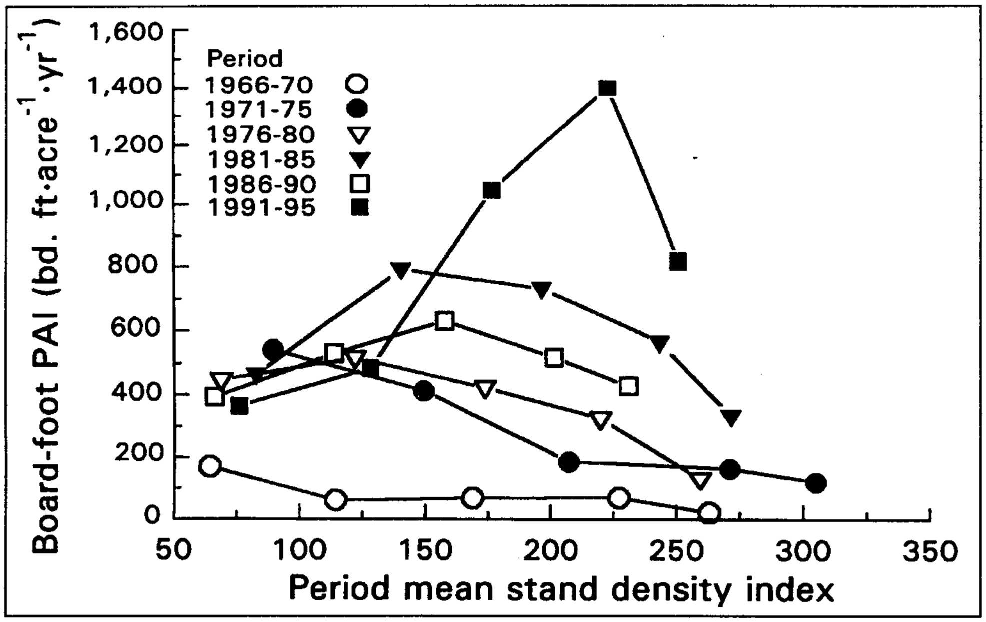

Figure 12—Relation of PAIs for gross board-foot volume to period mean SDI for the 6 periods of study. Plotted points are averages for GSLs 1 to 5.

Mean Annual Growth for 30 Years

Results of analyses of variance of mean annual growth rates are the same as the whole-plot results of the repeated measures analyses for the corresponding PAIs (table 5). Mean annual growth of gross and net basal area increased curvilinearly ($p \leq 0.10$) with increasing GSL (table 5, fig. 13). Curves for mean annual growth of gross and net volume seem to have two inflection points (one at GSL 2, another at GSL 4), resulting in significance ($p \leq 0.10$) for the lack-of-fit term for GSL (table 5, fig. 14). All of these mean annual growth rates appear to increase nearly linearly as stand densities increase from GSL 1 to GSL 4 and then decrease for the highest GSL. Board-foot mean annual growth varied curvilinearly ($p \leq 0.10$), increasing from GSL 1 to GSL 3, decreasing slightly to GSL 4, and then decreasing sharply to GSL 5 (table 5, fig. 15). As with PAIs, maximum board-foot annual growth can be expected to shift to the highest GSL in the future as ingrowth occurs.

The curve shapes for mean annual growth of basal area and cubic volume do not conform to the anticipated convex second degree curve, which approaches an upper limit at higher densities. Because there are only two replications for each GSL, the estimates for each GSL are not as precise. The decrease in mean annual growth of basal area and cubic volume from GSL 4 to GSL 5 is not readily explainable. The shape of the mean annual board-foot growth curve seems reasonable when tree size and ingrowth are considered. Board-foot mean annual growth is lowest at the highest GSL because so many trees are less than 10 inches in size and, therefore, are producing no board feet. Board-foot production has been comparatively high at the lowest GSL level because the trees reached 10 inches in diameter early and the board-foot/cubic-foot ratios become larger as trees increase in size. A combination of tree size and ingrowth has resulted in fairly similar board-foot growth for the intermediate GSLs during the 30-year period.

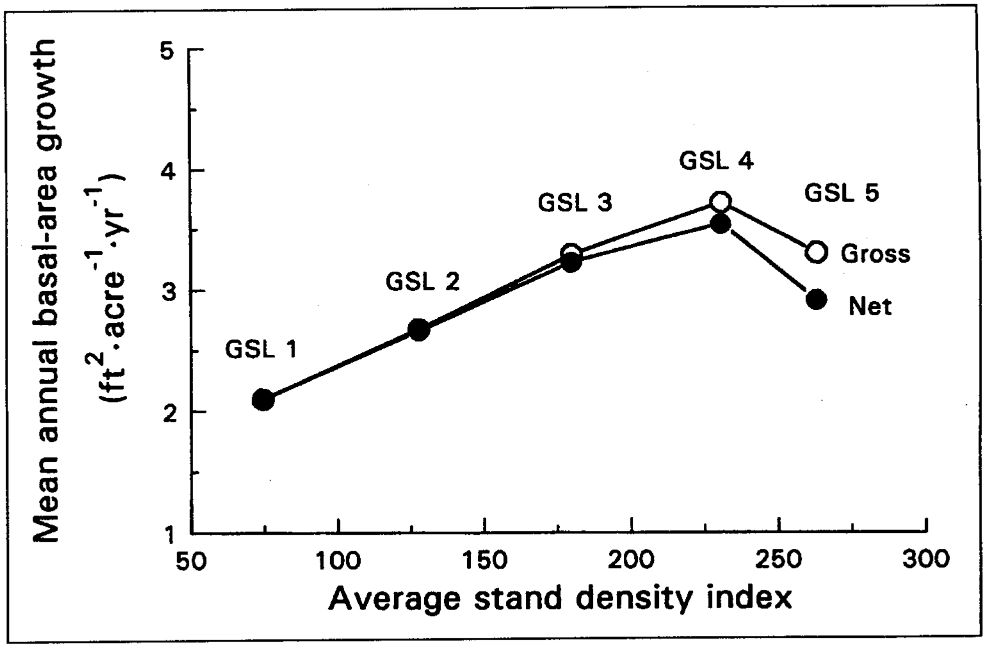

Figure 13—Mean annual basal-area growth for the 30-year period (GSL averages) as a function of the average period mean SDIs for the 5 periods for each GSL.

Yields

Cubic-volume yield at a total stand age of 65 years (fall 1995) increased ($p \leq 0.10$) curvilinearly with increasing GSL (table 6), increasing from GSL 1 to GSL 4, and then decreasing to GSL 5 (fig. 16). International board-foot volume yield also varied curvilinearly ($p \leq 0.10$), increasing from GSL 1 to GSL 3, declining slightly to GSL 4, and then declining sharply to GSL 5 (table 6, fig. 17). Future ingrowth is expected to increase board-foot volume yields more at the higher GSLs.

Decline in cubic-volume yields between GSLs 4 and 5 is partly due to the higher level of mortality for GSL 5 than lower GSLs but is also due to the unexplained drop in cubic-volume growth rates for this level. The variation in board-foot yield with GSL is related to the number of trees 10 inches or greater in size, board-foot/cubic-foot ratios which increase with tree size, as well as differences in cubic-volume growth rates with GSL.

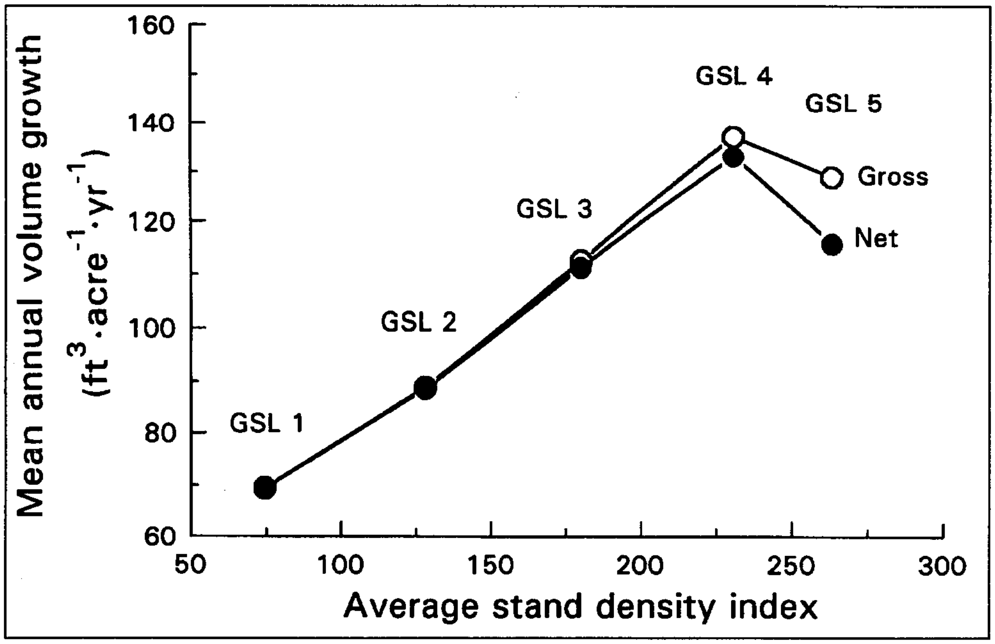

Figure 14—Mean annual cubic-volume growth for the 30-year period (GSL averages) as a function of the average period mean SDIs for the 5 periods for each GSL

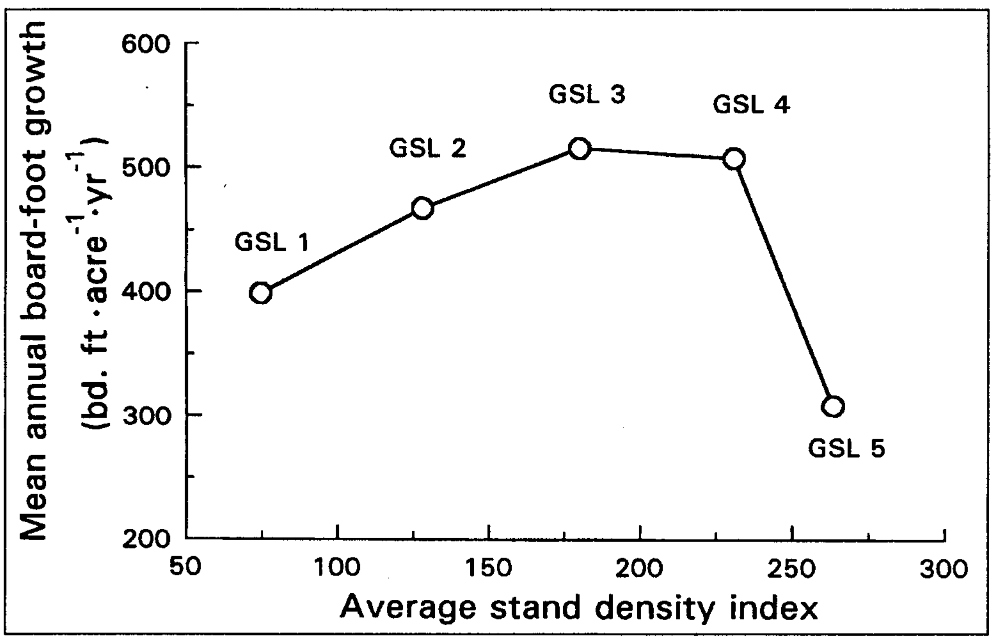

Figure 15—Mean annual board-foot growth for the 30-year period (GSL averages) as a function of the average period mean SDIs for the 5 periods for each GSL. Gross and net board-foot growth were the same.

Table 6—Probability of higher *F*-values for the analyses of variance of net volume yields in fall 1995 (total stand age equals 65 years)

Source	Degrees of freedom	Probability of higher *F*-values — Yield: Cubic volume	International bd.ft
GSL:			
Linear	1	0.0010	0.5861
Quadratic	1	.0100	.0887
Lack of fit	2	.2369	.7771
Error	5		
MSE[a]		90,159.0	10,255,173.3
C.V.%[b]		5.6	24.2

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

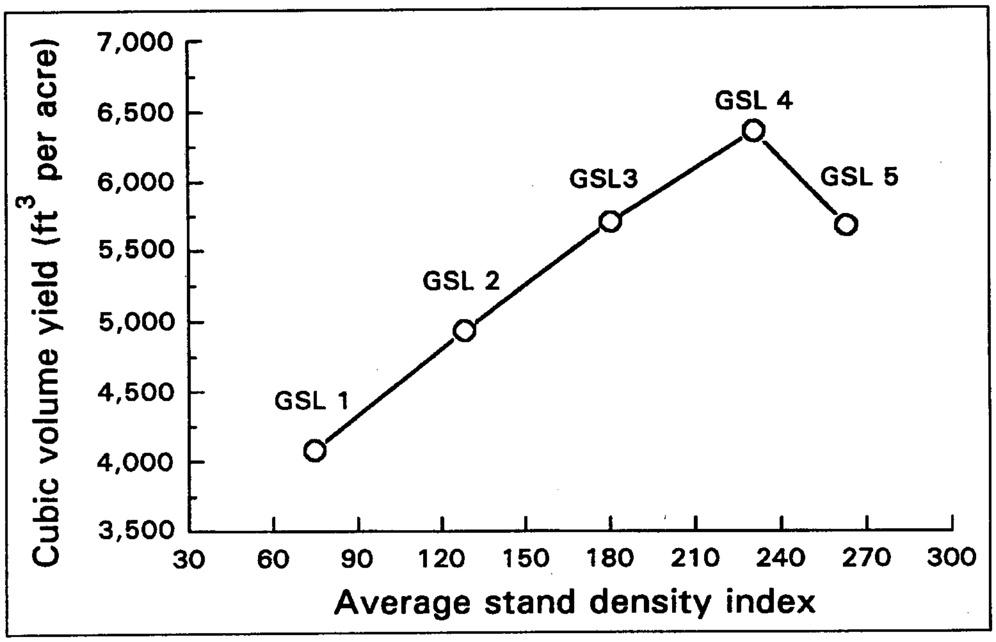

Figure 16—Cubic-volume yield (GSL averages) as a function of the average period mean SDIs for the 6 periods of study.

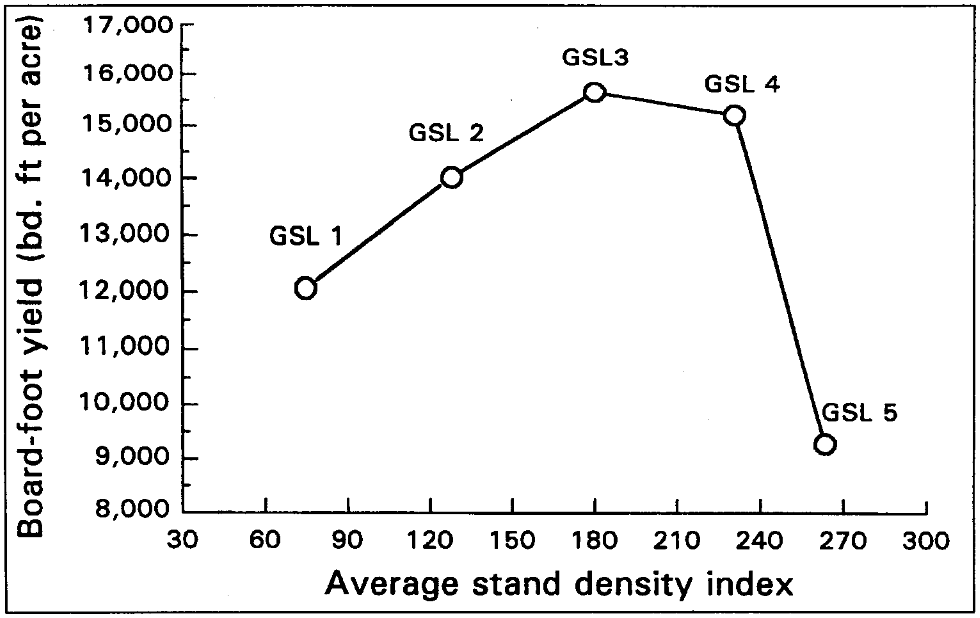

Figure 17—Board-foot yield (GSL averages) as a function of the average period mean SDIs for the 6 periods of study.

Mean Annual Increments

Mean annual cubic-volume increments varied curvilinearly ($p \leq 0.10$) with GSL, (table 7, fig.18) generally increasing from GSLs 1 to 4 and decreasing to GSL 5. Expected differences ($p \leq 0.10$) in MAIs occurred with age, but differences in the cubic volume-GSL curve shape with age were not detected ($p \leq 0.10$). The board-foot MAI-GSL relation changed with age (table 7, fig. 19), resulting in significance ($p \leq 0.10$) of the quadratic component of the age by GSL interaction. For stand ages 45 and 50, board-foot MAIs increase with decreasing GSL, but intermediate GSLs have the highest board-foot MAIs at age 65. Cubic-volume MAI seems to level off or decline at stand ages greater than 55 years for all but GSLs 3 and 4 (fig. 18). Board-foot MAI (which includes ingrowth) appears to be sharply increasing with stand ages beyond 55 years for the three highest GSLs but seem to be leveling off somewhat for the two lowest GSLs (fig. 19). This increase for the highest GSLs can be expected to continue for some time as ingrowth occurs.

Changes in cubic-volume MAIs with age found in this study do not match anticipated results. Curtis (1994) examined MAIs predicted by four widely used simulators for westside Douglas-fir. He found that three of the four simulators predicted delayed culmination with thinnings. One of the thinnings simulated by Curtis was a precommercial thinning at an earlier age than the initial thinning in this study. In this study, total cubic-volume MAI appears to culminate at a total stand age of 55 years for the two heaviest thinning levels (GSLs 1 and 2) and at age 60 for the lightest thinning level (GSL 5), whereas culmination has not occurred for the intermediate and next to lightest thinning levels (fig. 18). Schmidt and Seidel (1988) report that culmination of cubic-volume MAI and international board-foot volume MAI occurs at about 70 and more than 140 years, respectively, for normal larch stands. Larch can attain ages of 700 years (Schmidt and others 1976), and older ages for culmination of these MAIs would be expected for thinned stands if larch responds like simulated Douglas-fir. Cubic-volume MAI did not appear to culminate at a stand age of 85 years for a LOGS study in ponderosa pine (Cochran and Barrett 1995), another long-lived species that responds to new growing space even at old ages.

Table 7—Probability of higher *F*-values for the repeated measures analyses of variance of mean annual increments (MAI) for cubic- and board-foot volumes

Source	Degrees of freedom	Probability of higher *F*-values	
		Cubic-volume MAI	International bd.-ft MAI
GSL:			
Linear	1	0.0057	0.0974
Quadratic	1	.0560	.4169
Lack of fit	2	.6659	.9852
Error	5		
Age	6	.0001	.0001
Age x GSL:			
Linear	6	.0001	.0341
Quadratic	6	.3476	.0407
Lack of fit	12	.4063	.9506
Error	30		
MSE:[a]			
Whole plot		202.427	6,589.136
Subplot		6.439	555.405

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

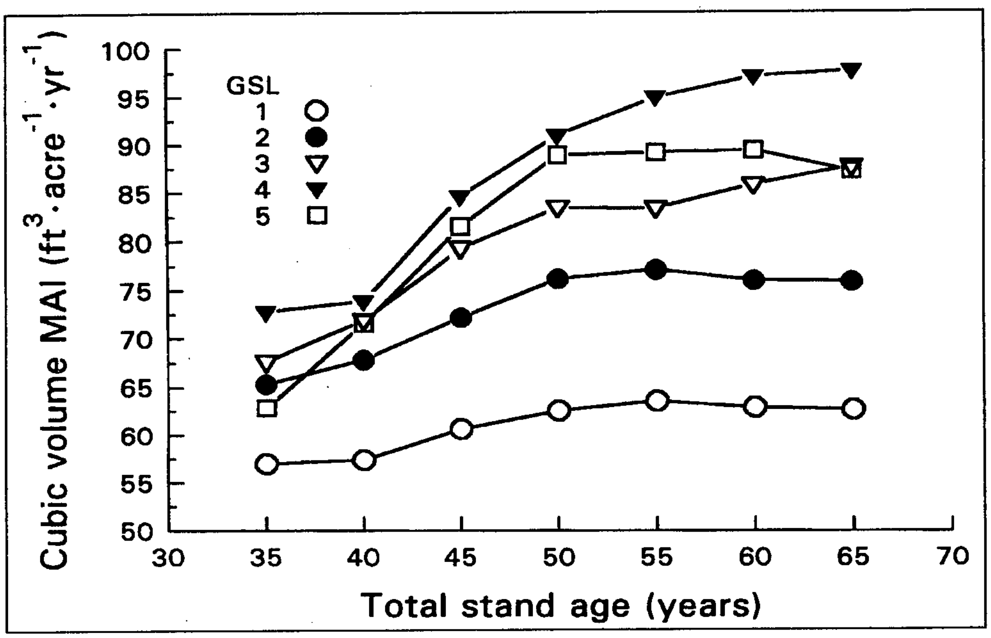

Figure 18—Average cubic-volume MAIs for each GSL as a function of total stand age.

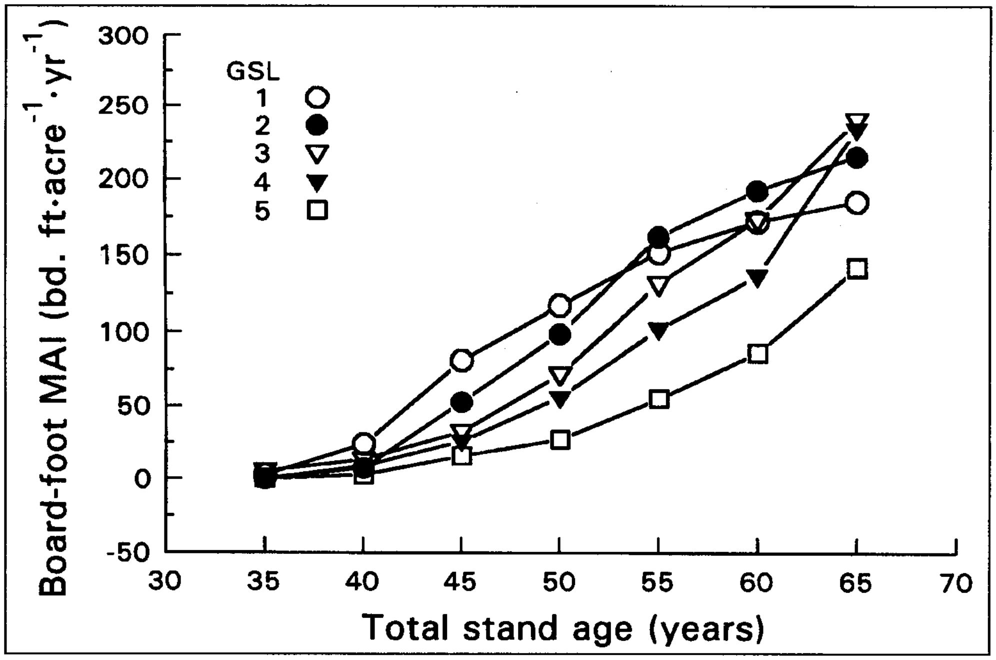

Figure 19—Average board-foot MAIs for each GSL as a function of total stand age.

Growth of Largest Diameter Trees

Growth of the largest trees in the plots was reduced by competition from smaller trees. Mean annual growth of basal area and volume for the 30 trees per acre (12 trees per plot) with the largest diameters at the start of the study decreased ($p \leq 0.10$) curvilinearly with increasing GSLs (table 8). There was a large decrease in these growth rates between GSLs 1 and 2 and then a continuing moderate decrease in mean annual growth as stand density increased (figs. 20 and 21). The significance ($p \leq 0.10$) of the lack-of-fit term indicates that the second degree model does not adequately describe the variation in mean annual growth with GSL, thereby suggesting that the decrease in growth rates between GSLs 4 and 5 is greater than between GSLs 2 and 4 for this study, which used only two replications. The reduction of growth of large trees from competition by smaller trees in the stand is expected and also has been found for ponderosa (Barrett 1963; Cochran and Barrett 1993, 1995, in press) and lodgepole pine (Cochran and Dahms, in press).

Table 8—Probability of higher *F*-values for the analyses of variance of 30-year mean annual growth for the surviving 30 largest diameter trees at the start of the study

Source	Degrees of freedom	Probability of higher *F*-values	
		Basal area	Cubic volume
GSL:			
Linear	1	0.0001	0.0005
Quadratic	1	.0048	.0102
Lack of fit	2	.0383	.0654
Error	5		
MSE[a]		.0063	13.1082
C.V.%[b]		10.45	13.90

[a] MSE = mean square error from the analyses of variance.
[b] C.V.% = Coefficient of variation.

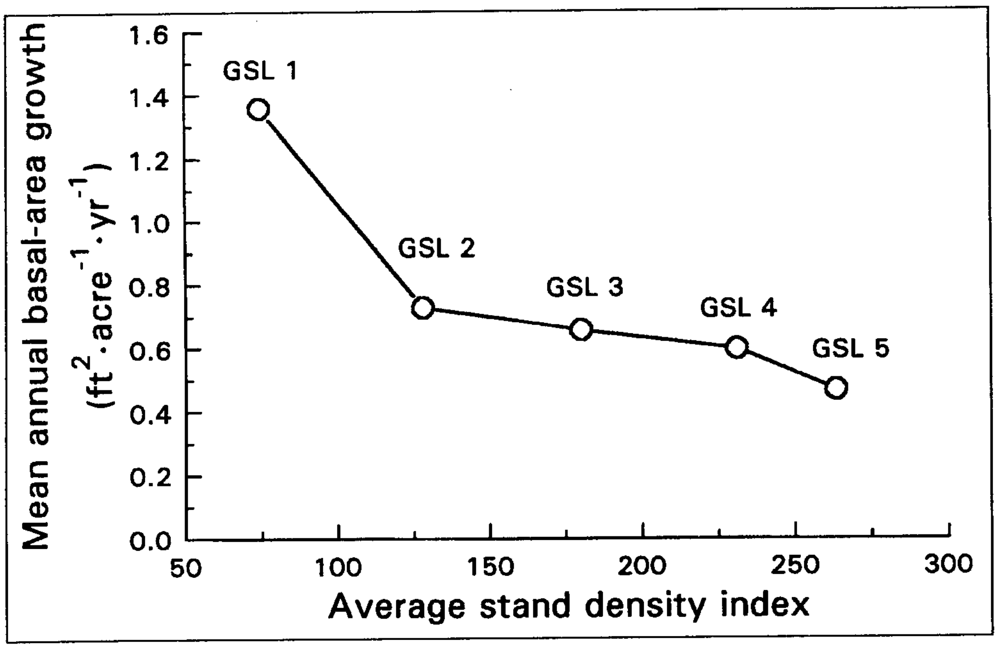

Figure 20—Relation of mean annual basal-area growth of the 30 trees per acre for each GSL with the largest diameters at the start of the study to the average period mean SDI for each of the 6 periods.

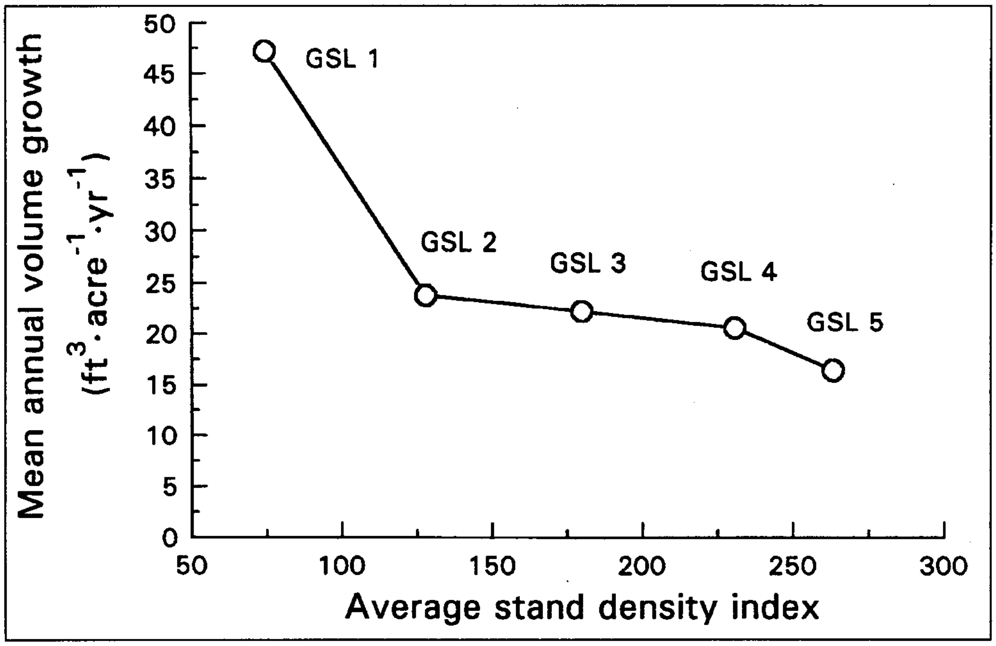

Figure 21—Relation of mean annual cubic-volume growth of the 30 trees per acre for each GSL with the largest diameters at the start of the study to the average period mean SDI for each of the 6 periods.

Growth Patterns

Fitting equation (7) smooths gross PAI-stand density relations for basal area and volume (table 9). Height growth has a strong influence on volume growth (Curtis and Marshall 1986). Although differences in site index among treatments were not significant ($p \leq 0.10$, table 10), other factors probably influenced height growth on the plots. Use of site tree height PAIs as an independent variable reduces differences in gross PAIs of basal area and volume that are due to differences in growing conditions among periods, and to differences in growing conditions among plots during the same period. Differences in growing conditions among plots in the same period may have occurred in this study due to differing degrees of defoliation or wind and ice damage to tops. Patterns of change in gross PAIs with density and age (or period) differ for basal area (fig. 22) and volume (fig. 23). Increases in gross basal-area PAI with increasing stand density are fairly small for SDIs greater than 150. Although increases in gross volume PAI do decrease with increasing stand density, the curves do not approach a plateau toward normal density (SDI = 410). Gross volume-growth curves for Douglas-fir also do not show a clear plateau (Curtis 1992, Marshall and others 1992). The differing relations of PAIs of basal area and volume with stand density is a consequence of continuing rapid height growth (Curtis 1992).

Examining how gross-volume PAIs change with increasing stand density (figs. 23 and 24) shows the practical effects of thinning, assuming that the coefficients in table 8 reasonably describe growth rates to 100 percent of normal density. Stands at 25, 50, and 70 percent of normal density produce 49, 70, and 87 percent, respectively, of the gross-volume PAI grown by a "normal" or fully stocked stand. These estimates indicate that stands can be heavily thinned from below with only a moderate sacrifice in cubic-volume production, which translates into a large increase in individual tree size.

Crown ratios immediately after thinning in 1966 are somewhat irregular probably because of varying densities of the plots before treatment. Because of this irregularity, the linear, quadratic, and lack-of-fit components of the period by GSL interaction were not examined.

Table 9—Coefficients from regression analysis for equation (7), R^2 values for these individual coefficients, and R^2 values for the complete model[a]

	Volume		Basal area	
Coefficient	Estimate	R^2	Estimate	R^2
a_0	1.6175	–	-3.4163	–
a_1	.0503	0.0582	.0511	0.1104
a_2	.5667	.6455	.9471	.2986
a_3	-.00019	3.0019	-.003611	.0014
b_1	.1660	.0003	.6882	.2122
b_2	.3033	.0250	.5757	.1845
b_3	.3363	.0769	.3334	.0785
b_4	.2173	.0458	.06224	.0013
b_5	.001065	.0000	.04048	.0009
Model R^2		.8537		.8878

[a] $\log_e PAI = a_0 + a_1 \log_e(SHPAI) + a_2 \log_e(SDIm) + a_3(sdim) + \quad + b_1P_1 + \ldots .b_{i-1}P_{i-1}$.

Table 10—Probability of higher *F*-values for the analyses of variance of site index values (Cochran 1985) in spring 1966[a]

	Degrees of freedom	Probability of higher *F*-values
Source		Site index
GSL:		
Linear	1	0.3852
Quadratic	1	.4474
Lack of fit	2	.4715
Error	5	
MSE[b]		31.5672
C.V.%[c]		6.22

[a] These site index values averaged 94.4, 89.6, 92, 84.7, and 90.9 feet for GSLs 1 through 5, respectively.
[b] MSE = degrees of freedom.
[c] C.V.% = coefficient of variation.

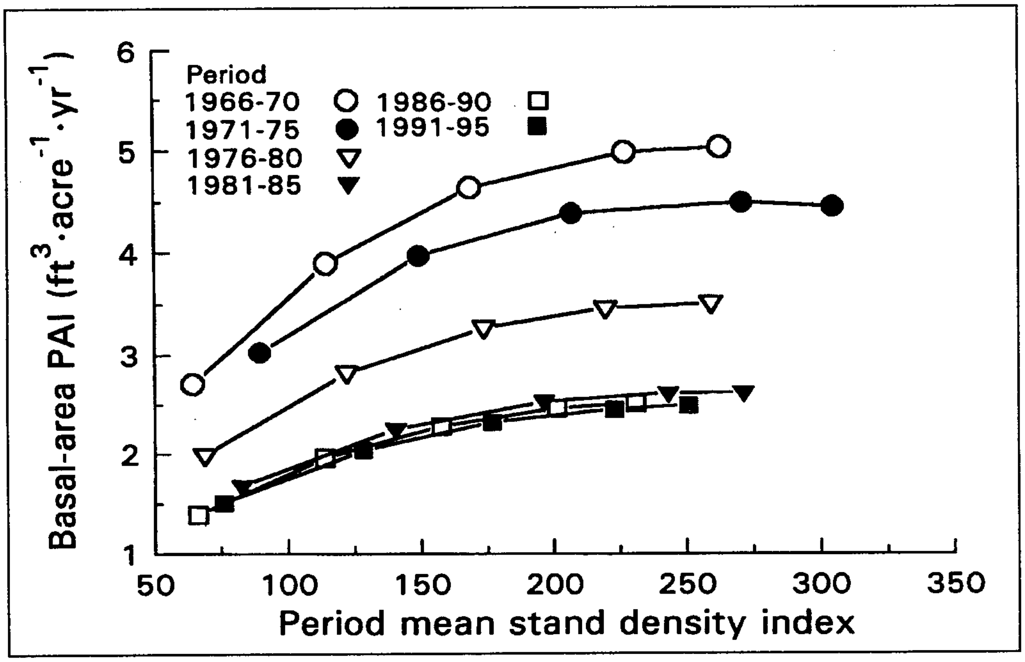

Figure 22—Gross basal-area PAI as a function of SDI using the coefficients in table 9 with a period average site tree height PAI.

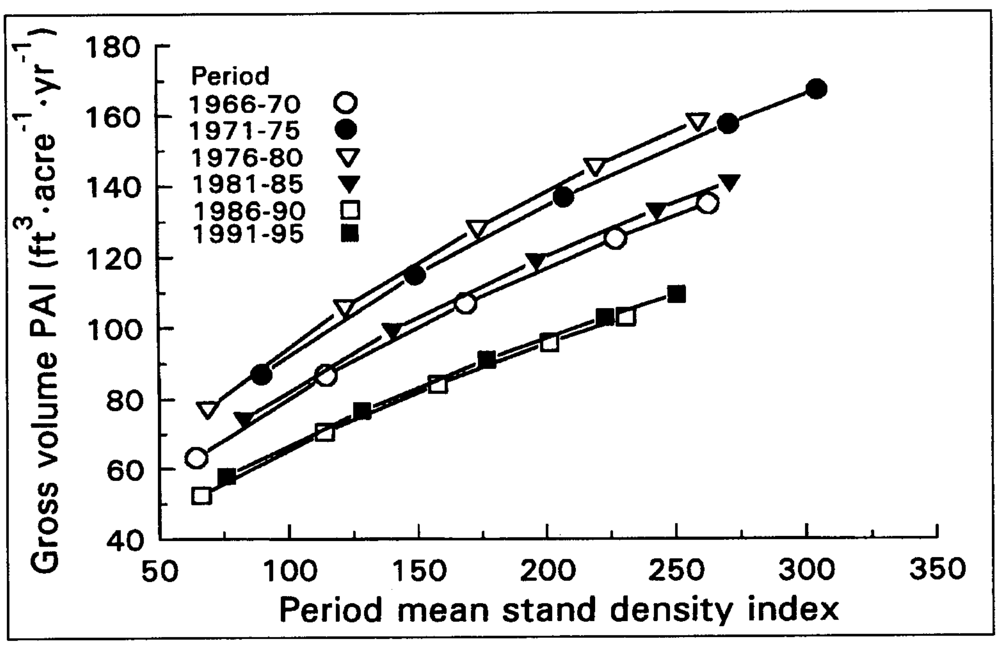

Figure 23—Gross cubic-volume PAI as a function of SDI using the coefficients in table 9 with a period average site tree height PAI.

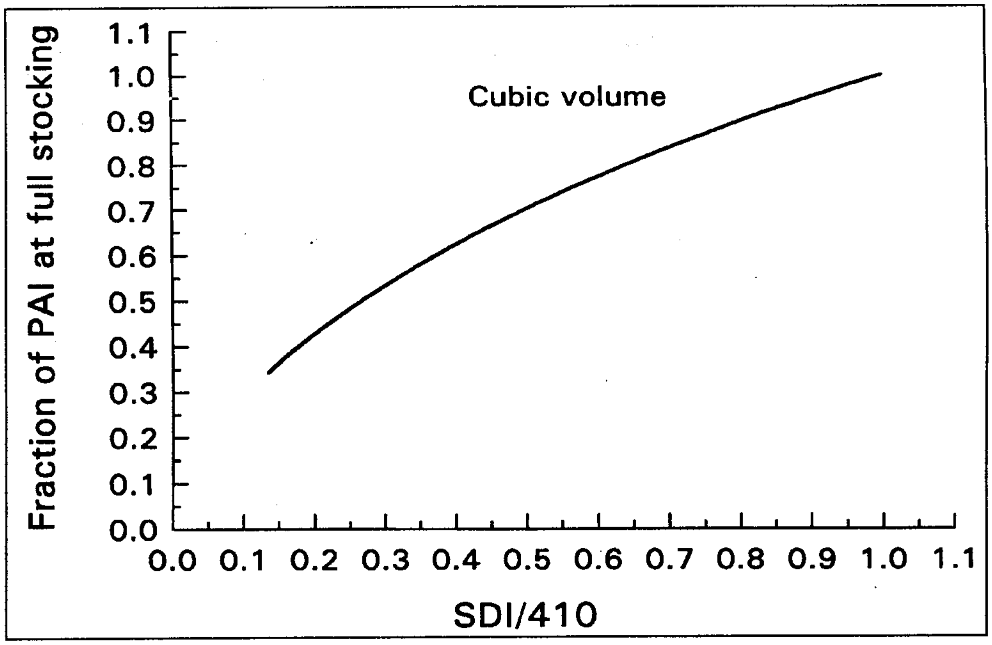

Figure 24—Estimates of the fraction of gross periodic annual cubic-volume increment at full stocking produced at various fractions of normal stand density. The curve was calculated assuming that the coefficients in table 9 adequately describe gross PAIs of cubic volume up to full stocking (SDI = 410).

Crown Ratios

Crown ratios decreased ($p \leq 0.10$) with increasing GSLs, and this decrease was greater in fall 1995 than in spring 1966, as shown by the significance ($p \leq 0.10$) of the period by GSL interaction (table 11, fig. 25). Crown ratios increased at the lower GSLs and decreased at the higher GSLs during the course of the study, ranging from 60 to 49 percent in spring 1966 and from 70 to 39 percent in fall 1995. Larch is extremely shade intolerant so reduction in crown ratio with increasing stand density is expected and has occurred in other studies (Schmidt and Seidel 1988).

Table 11—Probability of higher *F*-values for the repeated measures analyses of variance of crown ratios in spring 1966 and fall 1995

Source	Degrees of freedom	Probability of higher *F*-values
		Crown ratios
GSL	4	0.0017
Error	5	
Time (T)	1	.0843
T x GSL	4	.0062
Error	5	
MSE:[a]		
Whole plot		.0011
Subplot		.0015

[a] MSE = mean square error from the analysis of variance.

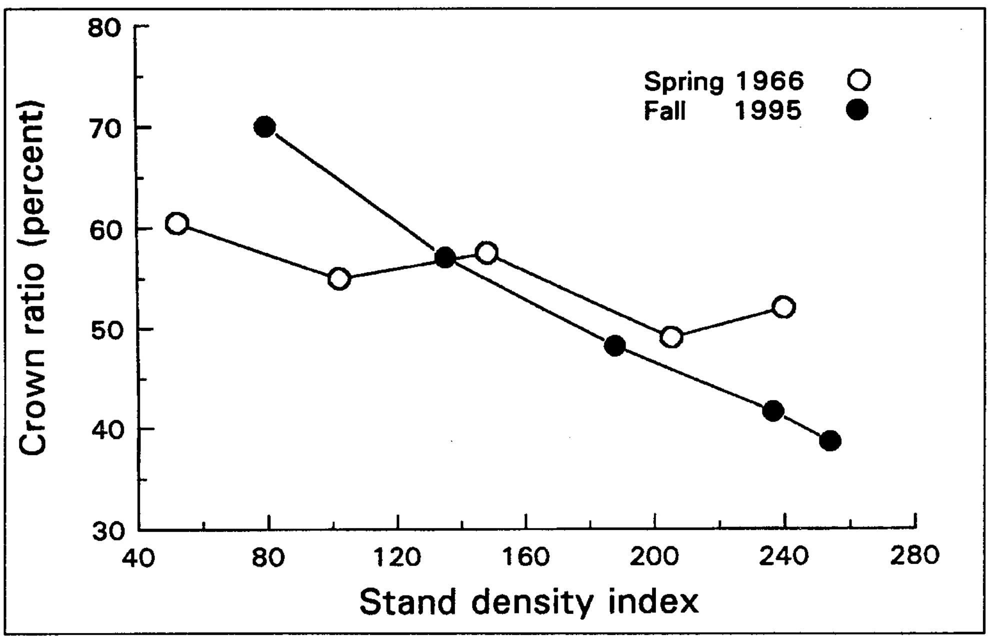

Figure 25—Crown ratios for trees measured with an optical dendrometer in spring 1966 and fall 1995 as a function of plot SDI at the time of determination.

Conclusions

Partial defoliation by larch casebearer must have reduced growth. Defoliation was not estimated, and no plots escaped the infestation of casebearer in the general area so this growth loss cannot be estimated.

Obvious, but unmeasured, differences in shrubs, forbs, and grasses exist among GSLs. These differences should be evaluated. Possible variation in soil quality among GSLs due to the divergent understory that developed since the initial thinning should be investigated (Busse and others 1996).

The nonparabolic response to GSL for gross PAIs of basal area, gross mean annual growth of basal area and volume, and mean annual growth of 30 largest diameter trees per acre points out the desirability of using more than two replications in future studies. These results demonstrate that thinning is necessary if large-diameter trees are to be grown in a reasonable period. There is a tendency to leave too many trees after thinning for future stands to have vigorous, fast-growing trees. Regulation of density in merchantable stands can be accomplished by applying the stocking-level curves of Cochran and others (1994). Thinning to levels lower than those shown by the curves is reasonable where the object is to produce large-diameter trees in a short time. Thinning should be from below. Thinning young western larch stands can greatly affect future tree diameters (and hence the appearance of the stand) without causing a severe change in wood production. Managers have the opportunity to create a wide range of stand conditions. Mosaics of even-aged stands of dense, small-diameter trees and stands of large-diameter trees with an open, parklike appearance maintained by underburning are possible within the same landscape.

The shade intolerance of larch, the reduction of growth of large larch trees by the presence of smaller trees in the stand, and the seriousness of dwarf mistletoe (Filip and others 1989) rule out consideration of uneven-age management for larch stands. These factors also would make it nearly impossible to maintain a significant larch component over a long time in mixed-species stands managed in ways to maintain several size classes on each acre.

Decisions about the desired future condition and appearance of landscapes containing western larch stands and the silvicultural practices necessary to create and maintain these landscapes need to be made, probably with public input. The public needs to know what is biologically possible and silviculturally reasonable, and at the same time managers need to obtain the public's concepts of the appearance of future forests. In this communication process, it might be possible to settle on management goals and methods to achieve these goals that would be supported by most people interested in future forests.

Metric Equivalents

1 inch = 2.54 centimeters
1 foot = 0.3048 meter
1 mile = 1.609 kilometers
1 square foot = 0.09290 square meter
1 acre = 0.4047 hectare
1 square foot per acre = 0.2296 square meter per hectare
1 cubic foot per acre = 0.06997 cubic meter per hectare
1 tree per acre = 2.471 trees per hectare

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. 1978. Height growth and site index curves for managed even-aged stands of ponderosa pine in the Pacific Northwest. Res. Pap. PNW-232. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 14 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.

Busse, M.D.; Cochran, P.H.; Barrett, J.W. 1996. Changes in ponderosa pine site productivity following removal of under-story vegetation. Soil Science Society of America Journal. 60: 1614-1621.

Cochran, P.H. 1979a. Site index and height growth curves for managed even-aged stands of Douglas-fir east of the Cascades in Oregon and Washington. Res. Pap. PNW-251. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 16 p.

Cochran, P.H. 1979b. Site index and height growth curves for managed even-aged stands of white or grand fir east of the Cascades in Oregon and Washington. Res. Pap. PNW-252. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 13 p.

Cochran, P.H. 1985. Site index, height growth, normal yields, and stocking levels for larch in Oregon and Washington. Res. Note PNW-424. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 24 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.; Dahms, Walter G. 1998. Lodgepole pine development after early spacing in the Blue Mountains of Oregon. Res. Pap. PNW-RP-503. 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 southeastern 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. 1992. Levels-of-growing-stock cooperative study in Douglas-fir: report no. 11—Stampede Creek: a 20-year progress report. Res. Pap. PNW-RP-442. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 47 p.

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 Research Station. 27 p.

Curtis, Robert O.; Marshall, David D. 1986. Levels-of-growing-stock cooperative study in Douglas-fir: report no. 8—the LOGS study: twenty-year results. Res. Pap. PNW-356. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station. 113 p.

Denton, Robert E. 1979. Larch casebearer in western larch forests. Gen. Tech. Rep. INT-55. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 62 p.

Filip, Gregory M.; Cobert, J.J.; Parks, Catherine A. 1989. Effects of thinning on volume growth of western larch infected with dwarf mistletoe. Western Journal of Applied Forestry. 4(4): 143-145.

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. 417 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.

Hamilton, David A., Jr.; Edwards, Bruce M. 1976. Modeling the probability of individual tree mortality. Res. Pap. INT-185. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 22 p.

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

Johnson, Charles Grier, Jr.; Clausnitzer, Rodrick R. 1991. Plant associations of the Blue and Ochoco Mountains. R6-ERW-TP-036-92. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region. 203 p.

Lexen, Bert. 1943. Bole area as an expression of growing stock. Journal of Forestry. 41(12): 883-885.

Marshall, David D.; Bell, John F.; Tappeiner, John C. 1992. Levels-of-growing-stock cooperative study in Douglas-fir: report no. 10—the Hoskins study, 1963-83. Res. Pap. PNW-RP-448. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 65 p.

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.

Reineke, L.H. 1933. Perfecting a stand-density index for even-aged forests. Journal of Agricultural Research. 46(7): 627-638.

Roe, Author L.; Schmidt, Wyman C. 1965. Thinning western larch. Res. Pap. INT-16. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station. 10 p.

Ronco, Frank, Jr.; Edminster, Carleton B.; Trojillo, David P. 1985. Growth of ponderosa pine 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.

Ryan, Roger B. 1990. Evaluation of biological control: introduced parasites of larch casebearer (Lepidoptera: Coleophoridae) in Oregon. Environmental Entomology. 19(6): 1873-1881.

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

Schmidt, Wyman C.; Fellin, David G. 1973. Western spruce budworm damage affects form and height growth of western larch. Canadian Journal of Forest Research. 3: 17-26.

Schmidt, Wyman C.; Seidel, Kenneth W. 1988. Western larch and space: thinning to optimize growth. 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.

Schmidt, Wyman C.; Shearer, Raymond C.; Roe, Arthur L. 1976. Ecology and silviculture of western larch forests. Tech. Bull. 1520. Washington, DC: U.S. Department of Agriculture. 96 p.

Seidel, K.W. 1986. Growth and yield of western larch in response to several density levels and thinning methods: 15-year results. Res. Note PNW-RN-455. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 18 p.

Seidel, K.W. 1987. Results after 20 years from a western larch levels-of-growing-stock study. Res. Pap. PNW-RP-387. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 18 p.

Wickman, Boyd E. 1986. Radial growth of grand fir and Douglas-fir 10 years after defoliation by the Douglas-fir tussock moth in the Blue Mountains outbreak. Res. Pap. PNW-367. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 11 p.

Cochran, P.H.; Seidel, K.W. 1999. Growth and yield of western larch under controlled levels of stocking in the Blue Mountains of Oregon. Res. Pap. PNW-RP-517. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station. 35 p.

After 30 years, largest trees but lowest cubic-volume yield were produced in the lightest thinning level, while highest board-foot yields were found in intermediate thinning levels. Partial defoliation by larch casebearer occurred. Ice damage caused the most mortality. Mortality caused by other agents was low. The stand density index bole area relation appears to be curvilinear.

Keywords: Stocking levels, bole area, stand density index, growth, yield, larch casebearer, ice damage, future stands.

Pacific Northwest Research Station
333 S.W. First Avenue
P.O. Box 3890
Portland, Oregon 97208-3890

U.S. Department of Agriculture
Pacific Northwest Research Station
333 S.W. First Avenue
P.O. Box 3890
Portland, Oregon 97208-3890

do NOT detach label