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Growth of Lodgepole Pine Thinned to Various Densities on Two Sites With Differing Productivities in Central Oregon

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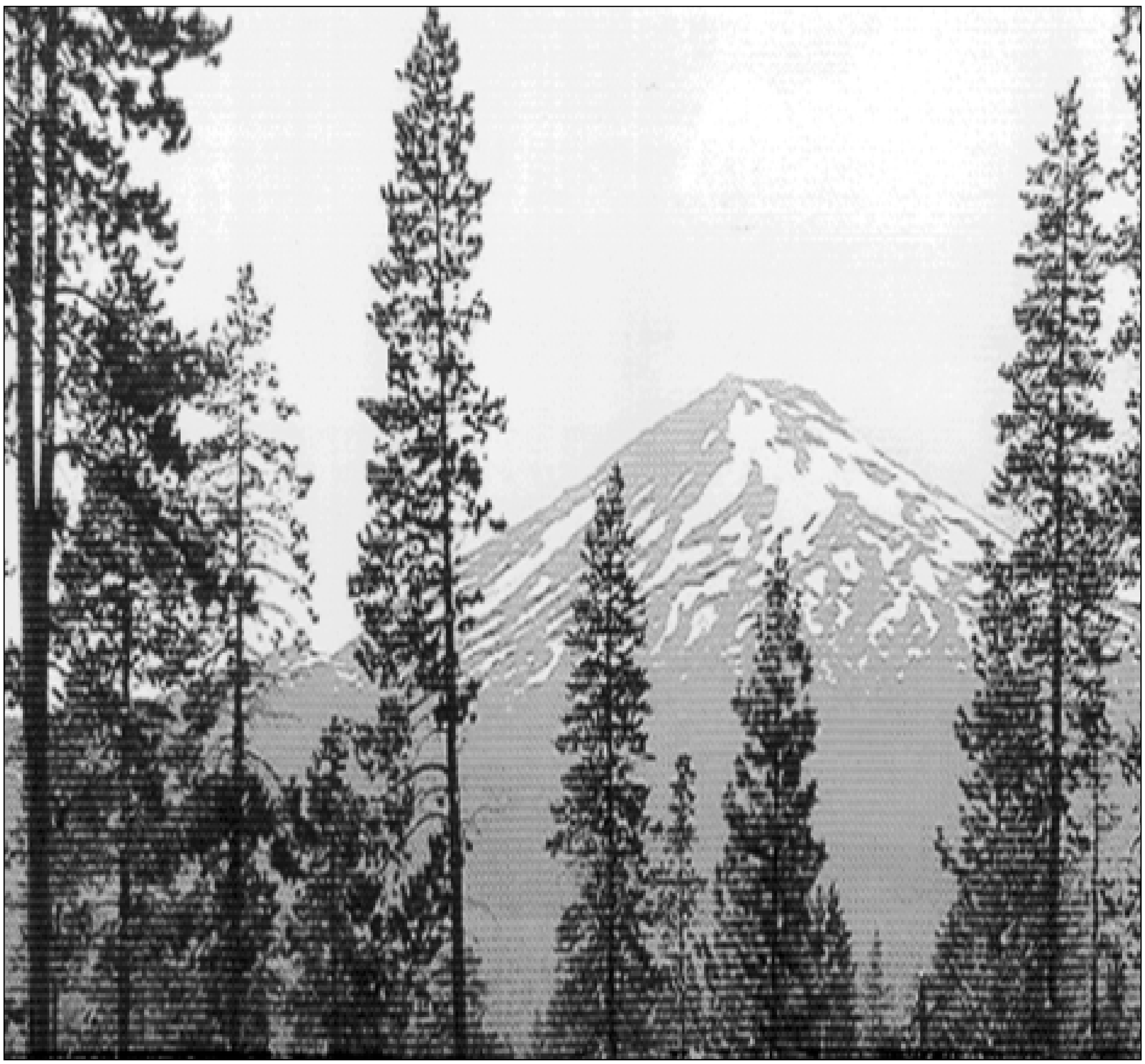

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Abstract

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Plots in two natural lodgepole pine (*Pinus contorta* Dougl. ex Loud.) stands with differing productivities were repeatedly thinned to one of five growing-stock levels (GSLs). Bole area was used to define GSLs. A linear relation between stand density index (SDI) and bole area was found after each thinning on the highly productive site, but the slope of this relation decreased with successive thinnings as trees grew larger. On the site with intermediate productivity, the upper limit for bole area was higher and a curvilinear SDI-bole area relation occurred. A constant bole area level probably does not represent the same competition level across a range of tree sizes. Low incidence of mortality caused by mountain pine beetle (*Dendroctonus ponderosae* Hopkins) occurred at SDIs below 170 for both sites. Concave curvilinear decreases in diameter growth occurred with increasing GSLs. Significant decreases in height growth with increasing GSLs were not detected. A convex curvilinear increase in gross basal-area growth and cubic-volume growth took place with increasing GSLs. Gross total cubic-volume PAIs increased with increasing SDIs for both sites until stand densities reached 95 percent of the normal stand SDI. These cubic-volume PAI-SDI curves then flattened with increasing SDIs. Maximum cumulative net cubic-volume (total and merchantable) and board-foot yields were produced at the intermediate growing-stock level at the high site. Little apparent differences in these yields occurred among the four highest GSLs at the intermediate site. Net total cubic-volume yield was higher for the three highest GSLs than net yields for unmanaged stands from yield tables at comparable sites and ages. These studies have not continued long enough to determine the approximate age of culmination of net mean annual cubic- or board-foot volume increments. Ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) outgrew lodgepole pine for the range of stand ages on the highly productive site where the growth of both species was examined (33 to 58 years). Ponderosa pine should not be planted on lodgepole pine sites on flats and basins, however, because ponderosa pine is subject to radiation frost damage. Early spacing control coupled with later commercial thinnings to keep stand densities between SDI 114 and SDI 170 should reduce mortality considerably, allow most of the wood produced to be captured by merchantable trees, and greatly increase quadratic mean diameters and live crown ratios over unmanaged stands at the same age. These stands would be more pleasing visually, and their rotation ages may be longer.

Keywords: Growth, mortality, growing stock, thinning, lodgepole pine, stand density index, bole area.

Summary

Plots in highly productive and moderately productive natural lodgepole pine stands were repeatedly thinned to one of five growing-stock levels (GSLs) in two levels-of-growing-stock studies. Bole area was used to define GSLs. A linear relation between stand density index (SDI) and bole area was found after each thinning in the highly productive stand, but the slope for this relation decreased with successive thinnings as tree size increased. A curvilinear SDI-bole area relation occurred after thinning in the moderately productive stand where the upper limit of bole area was higher. A given level of bole area apparently does not represent a constant level of competition across a range of stand diameters. Incidences of mortality caused by mountain pine beetle were low at SDIs below 170. Managing lodgepole pine at densities not exceeding SDI 170 when 9-inch diameter trees are present apparently lowers the probability of serious mountain pine beetle outbreaks. A concave curvilinear decrease in diameter growth with increasing GSL occurred on both sites, and a linear decrease in live crown ratios with increasing GSL occurred on the high site. A significant decrease in height growth with increasing GSL was not detected on either site. A convex curvilinear increase in gross total cubic-volume growth occurred with increasing GSL. Maximum gross cubic volume PAIs for both sites occurred at SDIs equivalent to 95 percent of the normal stand density (SDI 277). Maximum cumulative net cubic-volume (total and merchantable) and board-foot yields were produced at an intermediate GSL on the high site. Little difference in the yields occurred with the four highest GSLs at the intermediate site. Net total cubic-volume yields for the three highest GSLs were greater than the net total cubic-volume yield for unmanaged lodgepole pine stands predicted from yield tables at comparable sites and ages. Net total cubic-volume mean annual increments (MAIs) culminate at 70 years for unmanaged lodgepole pine stands in south-central Oregon. Values of net cubic-volume MAIs for unmanaged stands range from 23.6 to 71 $ft^3 \bullet acre^{-1} \bullet yr^{-1}$. Higher net cubic-volume MAIs were found in this study for the three highest GSLs on the high site even though culmination perhaps has occurred only for the lowest GSL. Culmination of MAIs on the intermediate site has probably not occurred even at 77 years of age. This study has not continued long enough to determine the approximate age of culmination with certainty for either cubic or board-foot volumes. Ponderosa pine outgrew lodgepole pine for the range of stand ages where the growth of both species was examined (33 to 58 years). Ponderosa pine, however, should not be planted on lodgepole pine sites on flats and basins because ponderosa pine is more susceptible to damage by radiation frost. Keeping lodgepole pine stands between SDI 114 and 170 (41 and 61 percent of the normal SDI 277) once stands reach commercial size should result in capturing between 63 and 87 percent of the potential total cubic-volume production after the first commercial entry. Unmanaged lodgepole pine stands in south-central Oregon are relatively short lived, and their QMDs seldom exceed 10 inches. Early spacing control coupled with later commercial thinnings should reduce mortality considerably, allow most of the wood produced to be captured by merchantable trees, and greatly increase QMDs and live crown ratios over unmanaged stands at the same age. These stands would be more pleasing visually, certain species of wildlife may benefit, and stand rotation ages may be longer.

Introduction

In many natural lodgepole pine (*Pinus contorta* Dougl. ex Loud.) stands, only a small portion of the wood produced is in merchantable trees. Natural stands tend to stagnate (Franklin and Dyrness 1973), and self-thinning cannot be expected to maintain stand densities at near-normal stocking levels while allowing reasonable growth rates for dominant and codominant trees (Cochran and Dahms 1998). The unmerchantable trees eventually die, often creating a fire hazard or are knocked down during logging to become a residue problem. Further, lodgepole pine stands in Oregon become susceptible to serious outbreaks of mountain pine beetle (*Dendroctonus ponderosae* Hopkins) when the stand density index (SDI) (Reineke 1933) exceeds 170 and 9-inch or larger diameter trees are present (Peterson and Hibbs 1989). Mortality in pine beetle outbreaks is not restricted to suppressed and intermediate classes; many of the largest trees in the stand are killed (Mitchell and others 1983, 1991, 1993). Thinning can nearly eliminate suppression mortality, reduce residue problems, lower the probability of serious mortality from pine beetles, and allow merchantable-sized trees to develop in a reasonable period.

Information on variation of productivity and mortality with thinning levels is necessary to properly manage lodgepole pine stands. This information comes from spacing and levels-of-growing-stock (LOGS) studies. Results from two LOGS studies, one on a highly productive site (for south-central Oregon) at Twin Lakes and another on a site with average productivity at Snow Creek, are presented here. The objective of these LOGS studies is to compare mortality, growth-growing-stock relations, tree size development, and cumulative wood production under various thinning regimes. These results are directly applicable only to the study areas. The plant communities exist over a wide area covered with Mazama pumice and ash, however, and similar results can be expected on other high and medium lodgepole pine sites in south-central Oregon.

Methods of Study

Study Areas

Twin Lakes area—The Twin Lakes study (lat. 43°43' N.; long. 121°45' W.) is located in the Deschutes National Forest near Twin Lakes about 45 miles southwest of Bend, Oregon, at an elevation of 4,300 feet. Topography is flat to gently sloping. Soils with a 2-inch A1 horizon and an 8- to 15-inch AC horizon are developing from 25 to 51 inches of dacite pumice originating from the eruption of Mount Mazama. The pumice overlays an older, sandy loam soil with a compacted layer starting 15 inches below the preeruption surface. This compacted layer limits rooting depth. Total rooting depth averaged 52 inches and ranged from 42 to 62 inches for single sample locations near each of the 10 study plots.

A fire occurred in 1934 (Dahms 1971), and the resulting 60-acre stand is composed mostly of lodgepole pine. Some ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) exists on the gently sloping areas. Predominant understory plants are bitter-brush (*Purshia tridentata* (Pursh) DC.), squaw currant (*Ribes cereum* Dougl.), strawberry (*Fragaria chiloensis* (L.) Duchesne), needlegrass (*Stipa occidentalis* Thurb. ex Wats.), and Ross's sedge (*Carex rossii* Boott). Whenever a slight slope is encountered, snowbrush (*Ceanothus velutinus* Dougl. ex Hook.) tends to become the dominant understory shrub. Plot site index values (total height of the tallest tree per 1/5-acre plot at a total age of 100 years, Dahms 1975) determined from heights measured in fall 1964 range from 103 to 118 feet and average 111 feet. Few central Oregon lodgepole pine stands have higher site index values.

Snow Creek area—The Snow Creek study (lat. 43°5' N.; long. 121°45' W.), also in the Deschutes National Forest, is about 50 miles southwest of Bend at an elevation of 4,500 feet on flat topography. The soil consists of 27 inches of well-mixed pumice over a sandy loam mixed with gravel and cobbles that appear to be glacial outwash. A high water table is present during spring snowmelt and through much of June. The pure, 40-acre lodgepole pine stand, 47 years old in fall 1962, has an understory dominated by antelope bitterbrush. Wax currant, western needlegrass, bottlebrush squirreltail (*Sitanion hystrix* (Nutt.) Smith), Ross's sedge, strawberry, and western yarrow (*Achillea lanulosa* Nutt. Piper) are also present (Dahms 1973). The study plots have site index values ranging from 80 to 93 feet with an average of 86 feet; 85 feet is the middle of the range of site index values for lodgepole pine in central Oregon (Dahms 1975).

The LOGS Experiments

Both LOGS studies have a completely randomized design with two plots randomly assigned to each of five LOGS. Growing-stock levels (GSLs) were initially defined as levels of bole area. Bole area is a close estimate of the cambium area of the tree bole (Lexen 1943). Stand density index (SDI) is a more familiar and more widely used measure of stand density than bole area and is easier to determine. The relation between SDI and bole area is therefore examined, and figures use SDI as the measure of stand density. The equation,

$$SDI = TPA(QMD/10)^{b} , \tag{1}$$

where TPA is trees per acre and QMD is the quadratic mean diameter used to determine SDI. A value for b of 1.74 instead of the more common 1.605 was used because a least squares fit of $\log_e(TPA)$ versus $\log_e(QMD)$ for 90 normally stocked plots used by Dahms (1964, 1975) for development of gross yields of lodgepole pine in south-central Oregon produced a slope value of -1.74. A further indication that the exponent is greater than 1.6 is found in an early version of the stand prognosis model (Wykoff and others 1982), where an exponent of 1.76 was used with lodgepole pine diameters less than 10 inches for computing the contribution of each tree to the stand estimate of crown competition factor (CCF) (Krajicek and Brinkman 1961). Curtis (1970) demonstrates the proportionality of tree area-diameter curves for open-grown trees and for average trees in normal stands. When the contribution to stand CCF of each tree is expressed as a power function of diameter at breast height (d.b.h.), as is the case for lodgepole pine in the prognosis model, the exponent should be the same as the exponent used in equation (1) for calculating SDI.

Twin Lakes experiment—The Twin Lakes experiment was initiated in fall 1959 when the stand age was 22 years. The study plots are spread over the 60-acre stand. Areas with low densities were avoided when selecting plot locations. Growing-stock levels initially chosen for testing were 7,500, 12,500, 17,500, 22,500, and 27,500 square feet of bole area per acre. Density on plots selected for the two highest GSLs was not high enough to meet specifications in 1959. After remeasurement in 1964, new GSLs of 4,000, 8,000, 12,000, 16,000, and 20,000 square feet of bole area were selected. This change was made because results from the 1960-64 period indicated that 20,000 square feet of bole area would fully occupy the site and because 7,500 square feet of bole area was not low enough to clearly reduce cubic-volume increment.

Plots were measured at 5-year intervals and were thinned initially (1959) and again in 1964, 1969, and 1984 (table 1, fig. 1). Thinnings were mainly from below. Originally the plots were 0.1 acre in size with additional, similarly treated, 33-foot buffer strips, the largest reasonably homogeneous plot areas that could be found if the highest density treatment were to be applied. During the 1964 thinning, when it became apparent that not enough trees would be left on 0.1-acre plots at the lower densities, size of plots at the lowest density was increased to 0.4 acre and the next higher density to 0.2 acre. In 1969, the remaining plot areas were increased to 0.2 acre. All of these expansions incorporated the original 33-foot buffers and added another, similarly treated, 33-foot buffer. Small holes that seemed too large in 1959 were mostly occupied by the larger trees in 1969 and therefore acceptable for inclusion within the plot.

Snow Creek experiment—The Snow Creek experiment was initiated in fall 1962 when the stand was 47 years old. The study plots are spread over the 40-acre stand where site and stand density differences could be minimized. Plots are 0.2 acre surrounded by a 33-foot, similarly treated, buffer strip. The GSLs chosen for the first thinning were 5,000, 10,000, 15,000, 20,000, and 25,000 square feet of bole area per acre.

Plots were thinned initially in 1962 and measured at 5-year intervals. Plots were thinned again in 1967 and 1987 (table 2, fig. 2). In 1987, the plots were thinned back to the initially chosen GSLs, but in 1967, the plots were thinned back to 4,000, 8,000, 12,000, 16,000, and 20,000 square feet of bole area per acre. Thinnings were mainly from below.

Supplementary low-density lodgepole pine plots at Twin Lakes—Random assignment of treatments to plots after all plot locations had been chosen meant that all plots had to come from the denser portions of the original stand to be satisfactory for the highest density treatment. Consequently, there were no plots in the designed experiment that started at low densities. To obtain some idea of the effect of early low densities on stand development, two additional low-density plots were installed in 1963. Only two separate, small areas with naturally low densities and good individual tree development were available for plot establishment. These 0.2-acre plots with additional 33-foot buffer strips were thinned once in 1964 to a bole area of about 4,000 square feet (table 1) and never thinned again.

Supplementary ponderosa pine plots at Twin Lakes—Portions of the stand on slightly sloping topography near three of the LOGS plots had a high proportion of ponderosa pine. Three supplementary pure ponderosa pine plots next to three of the lodgepole pine LOGS plots were established in 1969 and thinned to bole areas close to the adjacent lodgepole pine plots. Two of these plots were located next to replications 1 and 2 for GSL 1; one of these plots was 0.2 acre and the other was 0.4 acre. The site index values (Barrett 1978) for these two plots were 112 and 127 feet, respectively. A third ponderosa pine plot was located next to replication 2 of GSL 3 and was 0.2 acre (table 1). This plot had a site index value of 112 feet. All three plots had similarly treated, 33-foot buffer strips. These ponderosa pine plots were thinned again in 1984 to bole areas prescribed for the matching lodgepole pine plots. Growth of ponderosa pine and lodgepole pine for the 1970-94 period was compared for these three sets of paired lodgepole and ponderosa pine plots.

Text continues on page 12.

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

Growing-stock level	Bole area	Basal area	SDI[a]	Number of trees	Average spacing	Quadratic mean diameter	Average height	Total cubic volume[b]	Merchantable volume[c] ≥7 in d.b.h. to 5-in top	Merchantable volume[c] ≥4 in d.b.h. to 3-in top	Merchantable volume[c] Scribner
	Square feet				*Feet*	*Inches*	*Feet*	*Cubic feet*	*Cubic feet*	*Cubic feet*	*Board feet*
Fall 1959 before initial thinning (breast-height age 12 years)											
1	20,768	102.0	248	1,615	5.2	3.4	21.8	1,236	0	442	0
2	17,524	88.5	210	1,180	6.1	3.7	23.2	1,152	57	854	113
3	22,889	110.2	265	1,610	5.2	3.5	23.6	1,442	0	883	0
4	21,133	96.3	236	1,655	5.2	3.6	23.1	1,237	11	617	14
5	22,140	96.4	238	1,885	4.8	3.1	23.4	1,176	0	445	0
After fall 1959 thinning (breast-height age 12 years)											
1	7,330	41.7	97	405	10.4	4.4	25.8	534	0	442	0
2	12,454	70.0	155	610	8.5	4.6	28.2	981	57	854	113
3	16,538	85.3	195	925	6.9	4.1	27.2	1,159	0	883	0
4	19,305	92.4	224	1,345	5.7	3.6	24.6	1,197	11	617	14
5	20,484	93.6	232	1,705	5.1	3.2	22.8	1,137	0	445	0
Fall 1964 (breast-height age 17 years)											
1	10,496	62.0	134	405	10.4	5.3	32.5	1,016	93	926	174
2	16,343	88.6	193	610	8.5	5.2	34.3	1,461	711	1,332	408
3	21,822	107.4	241	920	6.9	4.9	33.0	1,806	67	1,535	120
4	24,700	113.6	258	1,315	5.8	4.0	30.3	1,765	23	1,277	49
5	25,078	115.4	276	1,645	5.1	3.6	27.9	1,725	19	1,020	37
Spring 1965 after thinning (breast-height age 17 years)											
1	4,264	26.8	55	114	19.6	6.6	37.3	420	149	436	312
2	8,050	45.3	96	260	12.9	5.6	35.8	705	107	746	243
3	12,352	63.8	137	400	10.4	5.4	36.5	993	93	1,020	73
4	16,131	78.4	176	675	8.1	4.6	33.5	1,126	22	1,062	46
5	20,255	95.0	220	1,065	6.5	4.1	30.4	1,217	18	969	36
Spacing[d]	3,982	29.6	57	85	22.7	7.9	41.7	554	402	519	1,045

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

Growing-stock level	Bole area	Basal area	SDI[a]	Number of trees	Average spacing	Quadratic mean diameter	Average height	Total cubic volume[b]	Merchantable volume[c] ≥7 in d.b.h. to 5-in top	Merchantable volume[c] ≥4 in d.b.h. to 3-in top	Merchantable volume[c] Scribner
	Square feet				*Feet*	*Inches*	*Feet*	*Cubic feet*	*Cubic feet*	*Cubic feet*	*Board feet*
Fall 1969 (breast-height age 22 years)											
1	6,375	37.8	74	114	19.6	7.8	43.7	740	494	693	1,252
2	11,342	58.6	120	260	13.0	6.4	41.8	1,146	374	1,068	941
3	16,336	78.3	164	400	10.4	6.0	42.2	1,553	242	1,446	519
4	20,932	93.4	204	670	8.1	5.0	38.8	1,774	123	1,568	275
5	26,124	108.5	264	1,045	6.5	4.4	35.4	1,921	184	1,469	81
Spacing[d]	6,434	38.8	73	85	22.7	9.2	46.5	788	685	739	1,972
Spring 1970 after thinning (breast-height age 22 years)											
1	3,640	25.1	49	70	25.0	8.1	45.1	502	354	455	928
2	7,972	43.4	88	170	16.1	6.9	43.6	873	359	820	908
3	12,162	60.2	124	265	12.8	6.4	43.9	1,227	339	1,119	770
4	16,041	73.0	159	485	9.5	5.2	39.7	1,406	101	1,325	234
5	19,825	86.4	195	782	7.6	4.5	36.2	1,571	85	1,240	211
Spacing[d]	6,434	38.8	56	85	22.7	9.2	46.5	788	658	739	1,972
Ponderosa[e]	4,334	33.0	62	79	23.5	8.9	41.8	520	394	488	1,145
Ponderosa[f]	12,252	77.9	157	310	11.8	6.8	33.5	1,034	466	982	1,027
Fall 1974 (breast-height age 27 years)											
1	5,282	34.5	64	70	25.0	9.5	51.0	801	670	731	2,104
2	10,726	57.8	113	170	16.0	7.9	49.4	1,392	939	1,297	2,613
3	15,672	77.6	154	265	12.8	7.4	50.1	1,959	1,143	1,818	2,963
4	20,976	88.3	186	475	9.6	5.8	46.6	2,063	390	1,933	986
5	26,116	101.1	221	732	7.9	5.1	41.6	2,292	322	1,943	806
Spacing[d]	7,431	48.8	89	85	22.7	10.2	52.1	1,222	1,073	1,155	3,651
Ponderosa[e]	5,678	46.6	84	79	23.5	10.6	48.2	899	772	852	2,698
Ponderosa[f]	14,268	103.4	201	305	17.5	7.9	39.9	1,707	1,143	1,602	3,062

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

									Merchantable volume[c]		
Growing-stock level	Bole area	Basal area	SDI[a]	Number of trees	Average spacing	Quadratic mean diameter	Average height	Total cubic volume[b]	≥7 in d.b.h. to 5-in top	≥4 in d.b.h. to 3-in top	Scribner
	Square feet				*Feet*	*Inches*	*Feet*	-----------	*Cubic feet*	------------	*Board feet*
Fall 1979 (breast-height age 32 years)											
1	6,045	43.4	78	69	25.0	10.8	56.8	1,036	930	985	3,368
2	12,272	71.4	135	170	16.0	8.8	55.1	1,759	1,717	1,653	4,573
3	18,285	92.1	179	265	12.8	8.0	54.5	2,419	1,845	2,266	5,349
4	23,533	102.6	211	470	9.6	6.3	50.3	2,478	840	2,293	2,242
5	28,315	114.7	246	715	7.9	5.5	46.1	2,657	570	2,386	1,553
Spacing[d]	7,860	57.5	102	85	22.7	11.1	56.6	1,410	1,275	1,343	4,772
Ponderosa[e]	7,379	62.2	109	79	23.5	12.2	54.6	1,332	1,217	1,277	4,855
Ponderosa[f]	18,237	131.1	248	305	17.5	8.9	46.3	2,430	1,905	2,284	5,967
Before fall 1984 thinning (breast-height age 37 years)											
1	7,258	51.5	91	69	25.2	11.7	61.8	1,289	1,186	1,235	4,548
2	14,384	80.2	150	170	16.0	9.3	59.7	2,064	1,802	1,952	6,186
3	20,995	107.4	200	260	13.0	8.6	58.9	2,829	2,346	2,657	7,406
4	26,534	113.7	231	458	9.8	6.8	54.3	2,818	1,283	2,640	3,702
5	31,549	127.2	268	693	8.0	5.9	49.6	2,968	773	2,734	2,267
Spacing[d]	9,125	65.0	114	85	22.7	11.8	61.0	1,637	1,507	1,572	6,035
Ponderosa[e]	8,882	79.2	134	79	23.5	13.8	61.3	1,738	1,629	1,683	7,173
Ponderosa[f]	21,627	156.3	289	305	17.5	9.7	51.7	3,087	2,594	2,922	9,062
After fall 1984 thinning (breast-height age 37 years)											
1	3,970	29.2	51	35	35.4	12.4	62.2	735	681	707	2,799
2	7,374	42.0	77	80	23.4	9.8	62.8	1,107	988	1,051	3,551
3	12,339	63.6	119	140	17.6	9.1	61.2	1,751	1,525	1,650	5,016
4	15,904	70.6	140	235	13.6	7.4	57.8	1,819	1,110	1,701	3,178
5	20,156	85.2	174	378	10.9	6.5	53.0	2,053	686	1,867	2,014
Spacing[d]	9,125	61.0	110	85	22.7	11.8	61.0	1,637	1,507	1,572	6,035
Ponderosa[e]	4,183	37.3	63	41	32.6	14.6	65.1	852	828	852	3,764
Ponderosa[f]	12,373	55.9	171	140	17.6	11.2	55.9	1,985	1,792	1,892	6,719

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

									Merchantable volume[c]		
Growing-stock level	Bole area	Basal area	SDI[a]	Number of trees	Average spacing	Quadratic mean diameter	Average height	Total cubic volume[b]	≥7 in d.b.h. to 5-in top	≥4 in d.b.h. to 3-in top	Scribner
	Square feet				*Feet*	*Inches*	*Feet*	------------	*Cubic feet*	------------	*Board feet*
					Fall 1989 (breast-height age 42 years)						
1	4,845	34.0	58	35	35.4	13.4	68.4	984	926	953	4,070
2	9,122	52.8	94	80	23.4	11.0	66.4	1,554	1,425	1,488	5,606
3	14,868	77.0	139	140	17.6	10.0	65.7	2,326	2,089	2,210	7,576
4	19,814	83.4	163	235	13.6	8.1	62.2	2,558	1,937	2,400	6,045
5	24,308	97.6	196	373	10.9	7.0	57.3	2,700	1,374	2,542	4,152
Spacing[d]	10,691	72.6	126	85	22.7	12.5	66.1	2,049	1,912	1,977	8,120
Ponderosa[e]	5,600	47.2	77	34	35.8	16.4	74.0	1,308	1,254	1,278	6,170
Ponderosa[f]	15,907	116.8	205	140	17.6	12.4	63.2	2,850	2,645	2,747	11,009
					Fall 1994 (breast-height age 47 years)						
1	4,949	35.5	59	31	37.4	14.4	72.3	1,081	1,024	1,049	4,773
2	10,592	62.1	109	80	23.4	12.0	71.2	1,946	1,824	1,878	7,664
3	15,192	78.8	142	128	18.5	10.6	68.7	2,534	2,326	2,420	8,937
4	21,622	93.0	177	230	13.8	8.6	65.4	2,948	2,488	2,779	8,213
5	27,218	111.7	221	373	10.9	7.5	60.5	3,200	1,998	2,998	6,313
Spacing[d]	9,228	62.4	107	68	25.5	13.0	67.5	1,864	1,750	1,804	7,645
Ponderosa[e]	6,506	57.5	92	34	35.8	18.1	79.5	1,645	1,586	1,605	8,157
Ponderosa[f]	18,190	133.7	229	140	17.6	13.2	67.6	3,483	3,275	3,375	14,484

[a] SDI = stand density index.
[b] Total cubic-foot volume of entire stem, inside bark, all trees.
[c] Merchantable cubic-foot volume for all trees 7 inches d.b.h. and larger to a 5-inch top diameter inside bark; merchantable cubic-foot volume for all trees 4 inches d.b.h. and larger to a 3-inch top diameter inside bark; and Scribner board-foot volume for all trees 7 inches d.b.h. and larger to a 5-inch top diameter inside bark.
[d] Average values for two plots added in 1963 in relatively open portions of the stand.
[e] Average values for two ponderosa pine plots paired with the two GSL 1 lodgepole plots. One plot was 0.4 acre and the other was 0.2 acre when installed. The 0.2-acre plot was enlarged to 0.4 acre in 1984.
[f] Values are for one ponderosa pine plot paired with the lodgepole pine plot replication 2 of GSL 3.

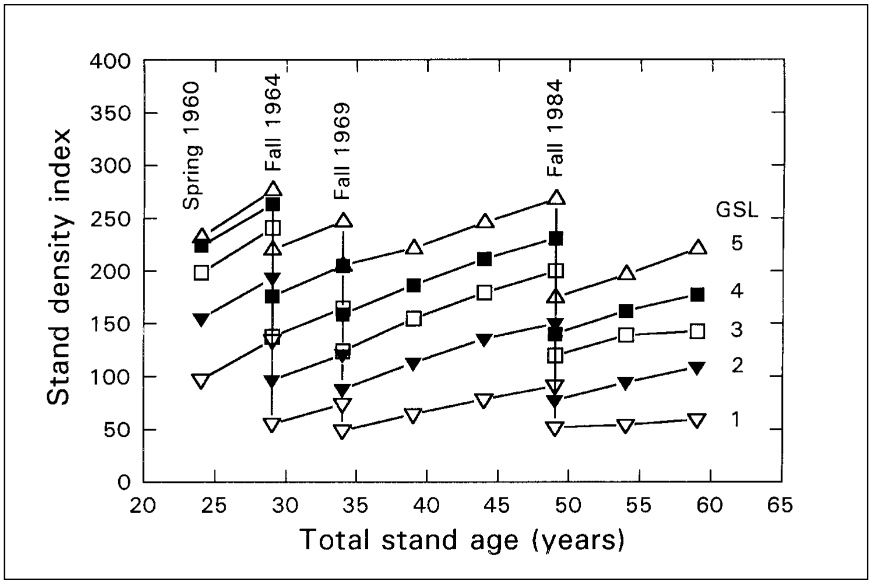

Figure 1—Stand density index of the Twin Lakes LOGS study (treatment means) in relation to total age for each GSL.

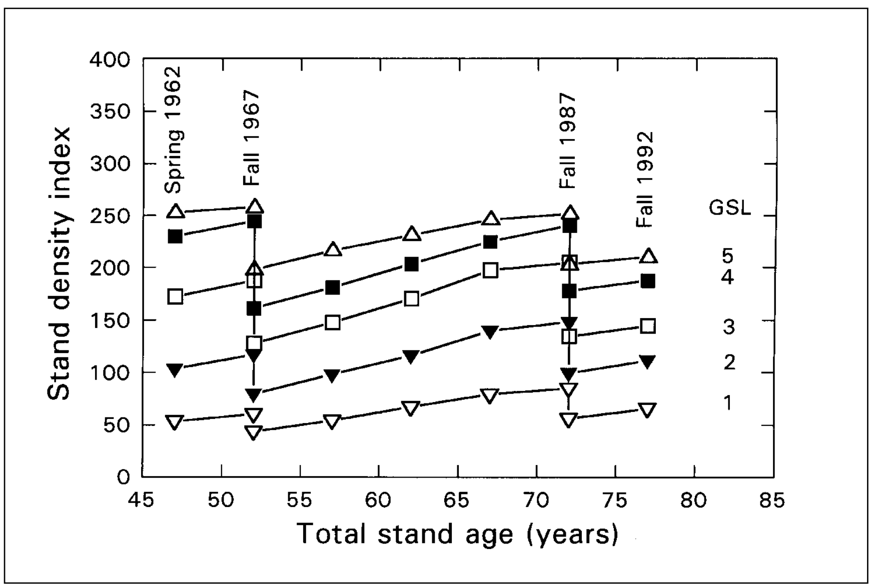

Figure 2—Stand density index of the Snow Creek LOGS study (treatment means) in relation to total age for each GSL.

Table 2—Average stand characteristics (per-acre basis) of live trees at Snow Creek over the period of study

Growing-stock level	Bole area	Basal area	SDI[a]	Number of trees	Average spacing	Quadratic mean diameter	Average height	Total cubic volume[b]	Merchantable volume[c] ≥7 in d.b.h. to 5-in top	Merchantable volume[c] ≥4 in d.b.h. to 3-in top	Merchantable volume[c] Scribner
	Square feet				*Feet*	*Inches*	*Feet*	------------	*Cubic feet*	------------	*Board feet*
Fall 1962 before initial thinning (breast-height age 37 years)											
1	29,153	130.2	268	1,587	5.2	3.9	26.9	1,236	167	1,602	369
2	25,768	125.2	292	1,048	6.4	4.8	34.2	1,152	487	1,898	1,200
3	25,184	123.6	317	1,384	5.6	4.3	28.8	1,442	392	1,632	941
4	27,756	127.2	287	1,415	5.5	4.0	28.4	1,237	391	1,716	901
5	24,519	121.1	281	1,085	6.3	4.6	32.4	1,176	426	1,882	1,056
After fall 1962 thinning (breast-height age 37 years)											
1	4,970	25.5	53	128	18.5	6.1	41.0	488	119	464	251
2	10,019	48.3	104	298	12.1	5.5	38.7	926	211	803	487
3	15,940	80.5	172	502	9.3	5.6	37.0	1,508	392	1,359	941
4	22,078	105.1	230	750	7.6	5.0	35.5	1,967	391	1,723	901
5	24,601	115.4	253	830	7.2	5.0	35.8	2,206	426	1,882	1,056
Fall 1967 (breast-height age 42 years)											
1	5,739	29.4	60	124	18.7	6.6	43.6	606	232	569	539
2	11,919	55.7	117	245	8.5	5.9	41.2	1,160	372	1,073	891
3	18,062	88.9	188	502	6.9	5.9	40.2	1,305	556	1,544	1,427
4	25,124	113.1	244	732	5.8	5.3	38.9	2,285	506	1,961	1,267
5	26,426	119.1	258	788	5.1	5.3	38.9	2,387	589	2,035	1,523

Table 2—Average stand characteristics (per-acre basis) of live trees at Snow Creek over the period of study (continued)

									Merchantable volume[c]		
Growing-stock level	Bole area	Basal area	SDI[a]	Number of trees	Average spacing	Quadratic mean diameter	Average height	Total cubic volume[b]	≥7 in d.b.h. to 5-in top	≥4 in d.b.h. to 3-in top	Scribner
	Square feet				*Feet*	*Inches*	*Feet*	-----------	*Cubic feet*	----------	*Board feet*
Spring 1968 after thinning (breast-height age 42 years)											
1	4,049	21.4	43	82	23.3	6.9	44.1	441	190	413	439
2	7,979	38.0	79	190	15.1	6.1	42.2	792	275	731	709
3	12,099	61.4	128	310	11.8	6.2	41.4	1,164	420	1,088	1,100
4	16,085	77.0	161	393	10.5	6.0	41.9	1,585	440	1,457	1,117
5	20,039	94.1	198	492	9.4	5.9	42.4	1,922	546	1,766	1,410
Fall 1972 (breast-height age 47 years)											
1	5,005	27.7	54	82	23.0	7.9	47.1	630	443	588	1,170
2	9,716	48.5	98	190	15.1	6.9	45.3	1,103	573	1,041	1,583
3	14,434	72.6	148	308	11.9	6.8	45.2	1,597	769	1,499	2,156
4	18,736	88.0	181	388	10.6	6.4	46.3	1,972	809	1,839	2,166
5	23,502	104.3	216	488	9.4	6.3	46.8	2,434	960	2,253	2,617
Fall 1977 (breast-height age 52 years)											
1	5,965	35.2	67	82	23.0	8.9	51.0	843	687	790	2,049
2	11,046	59.0	116	188	15.2	7.6	48.7	1,446	923	1,360	2,755
3	17,487	85.5	170	308	11.9	7.4	48.7	2,117	1,264	1,992	3,722
4	22,075	100.9	203	385	10.6	6.9	49.5	2,419	1,286	2,246	3,653
5	25,970	113.2	231	475	9.6	6.6	50.1	2,845	1,391	2,656	3,971
Fall 1982 (breast-height age 57 years)											
1	7,041	42.8	79	82	23.0	9.8	54.2	1,122	979	1,059	3,252
2	12,979	69.2	133	188	15.2	8.3	52.1	1,821	1,232	1,716	3,822
3	20,504	97.2	190	308	11.9	7.8	52.8	2,586	1,704	2,432	5,324
4	23,538	113.0	225	385	10.6	7.3	53.1	2,960	1,688	2,780	4,959
5	27,849	122.2	246	460	9.7	7.0	53.9	3,281	1,830	3,033	5,554

Table 2—Average stand characteristics (per-acre basis) of live trees at Snow Creek over the period of study (continued)

									Merchantable volume[c]		
Growing-stock level	Bole area	Basal area	SDI[a]	Number of trees	Average spacing	Quadratic mean diameter	Average height	Total cubic volume[b]	≥7 in d.b.h. to 5-in top	≥4 in d.b.h. to 3-in top	Scribner
	Square feet				*Feet*	*Inches*	*Feet*	-----------	*Cubic feet*	-----------	*Board feet*
Before fall 1987 thinning (breast-height age 62 years)											
1	8,447	48.1	87	82	23.0	10.4	58.7	1,388	1,240	1,317	4,450
2	15,384	78.0	148	188	15.2	8.8	56.1	2,206	1,774	2,084	5,946
3	22,917	105.5	204	305	12.0	8.2	56.5	3,015	2,175	2,855	7,118
4	27,816	122.0	240	385	10.6	7.6	56.6	3,488	2,188	3,275	6,794
5	30,503	126.0	251	445	9.9	7.2	56.7	3,632	2,205	3,409	6,963
After fall 1987 thinning (breast-height age 62 years)											
1	5,529	30.9	56	50	29.5	10.6	60.4	933	843	888	3,116
2	10,096	53.6	99	108	20.1	9.6	59.7	1,551	1,353	1,468	4,690
3	15,132	70.1	134	188	15.2	8.5	58.2	2,041	1,522	1,926	5,075
4	20,197	91.9	178	252	13.1	8.2	58.8	2,677	1,914	2,518	6,212
5	24,331	103.9	203	308	11.9	7.9	59.8	3,091	2,154	2,905	6,835
Fall 1992 (breast-height age 67 years)											
1	5,986	37.1	65	50	29.5	11.7	65.3	1,071	989	1,028	3,972
2	11,491	61.2	111	108	20.1	10.2	64.0	1,867	1,682	1,777	6,243
3	15,980	76.4	144	183	15.4	9.0	62.0	2,264	1,778	2,092	6,116
4	21,313	98.3	187	242	13.4	8.6	61.6	2,925	2,252	2,759	7,619
5	25,005	108.8	210	295	12.2	8.2	63.0	3,255	2,453	3,068	8,165

[a] SDI = stand density index.
[b] Total cubic-foot volume of entire stem, inside bark, all trees.
[c] Merchantable cubic-foot volume for all trees 7 inches d.b.h. and larger to a 5-inch top diameter inside bark; merchantable-cubic foot volume for all trees 4 inches d.b.h. and larger to a 3-inch top diameter inside bark; and Scribner board-foot volume for all trees 7 inches d.b.h. and larger to a 5-inch top diameter inside bark.

Because the original lodgepole pine plots are assumed to be a random sample of the stand, the three paired plots are assumed to be a random sample of the stand where paired ponderosa and lodgepole pine plots could be installed. The design for this subexperiment comparing the two species was, therefore, considered to be a randomized block. The b value of 1.77 (DeMars and Barrett 1987) was used with equation (1) to calculate SDIs for the ponderosa pine plots.

Measurements and Calculations

Diameters at breast height were determined for all trees before the initial thinning. Diameters and heights of all trees were taken in subsequent measurements. Diameters were measured with steel tapes, and total heights (H) were measured with height poles or Barr and Stroud optical dendrometers after the initial thinning and at 5-year intervals. Diameters and heights were recorded to the nearest 0.1 inch and 0.1 foot, respectively. Heights and diameters measured immediately after the initial thinning were used to determine coefficients in the equation (Curtis 1967),

$$\log_e H = b + m/(\text{d.b.h.}) \ . \qquad (2)$$

Equation (2) was then used to estimate heights of all plot trees before the initial thinning. Additional measurements were taken on a subsample of trees, picked initially at random from diameter class distributions of each plot, to develop local volume and bole area equations for each time of measurement. Only five of these trees per plot were initially picked at Twin Lakes. For subsequent measurements at Twin Lakes and all measurements at Snow Creek, 15 trees per plot were picked for the development of local volume and bole area measurements. These subsample trees were either climbed and measured with calipers or measured with optical dendrometers to determine diameters at 1.0 foot, 4.5 feet, 5.5 feet, and at intervals up the bole. Bark thickness was measured at 4.5 feet, and diameters inside bark at other locations were calculated assuming that the diameter inside bark:diameter outside bark ratio varied along the bole as described for ponderosa pine (Cochran 1976). Cubic volume inside bark and bole area including stump and tip were calculated for each of these trees; the stump was considered to be a cylinder, and the tip was assumed to be cone shaped. Smalian's formula was used to determine cubic volume for the bole sections. Bole area was determined assuming each bole section had the same surface as a cylinder of the same length with a diameter equivalent to the mean basal area of both ends of the section. The same trees were measured for volume and bole area each time the plots were measured, if possible. If a tree died or was removed in thinning, the tree closest to the size of the missing or dead tree at the previous measurement was selected as a replacement.

Coefficients for the cubic volume (V) and bole area (CA) equations (Schumacher and Hall 1933),

$$\log_e V = a_0 + a_1[\log_e(\text{d.b.h.})] + a_2[\log_e(H)] \ , \qquad (3)$$

and

$$\log_e CA = b_0 + b_1[\log_e(\text{d.b.h.})] + b_2[\log_e(H)] \ , \qquad (4)$$

were computed initially by using all trees measured for volume and bole area at Twin Lakes. For 1964 and later measurements at Twin Lakes, new coefficients were computed for each plot at each measurement time. New coefficients were computed for each plot at all measurement times for the Snow Creek study. Three different merchantable volumes using equations of Dahms (1983) for lodgepole pine were determined: (1) cubic-foot and (2) Scribner board-foot volumes, for all trees 7.0 inches d.b.h. and larger to a 5-inch top inside bark diameter; and (3) cubic-foot volumes for all trees 4.0 inches d.b.h. and larger to a 3-inch top inside bark diameter. These three merchantable volumes also were determined for ponderosa pine by using equations developed from sectioned tree data for ponderosa pine from several other studies (Cochran and Barrett 1995). Plot volumes and bole areas were then calculated by summing the measured and estimated tree volumes and bole areas for all trees within a plot at a given remeasurement year. To obtain plot volumes and bole areas before the initial thinning, the same equations used just after the initial thinning were used with heights determined from equation (1). Percentage of mortality and ratios of dead tree:live tree diameters were calculated for each plot for each 5-year period. Percentage of mortality was obtained for each plot by dividing the number of trees that died during the period by the number of living trees at the start of the period and multiplying the result by 100. The QMD of trees that died during each period was divided by the QMD for live trees at the start of the period to obtain the dead tree:live tree diameter ratios. 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 and gross and net cubic and board-foot volumes. The PAIs for merchantable volume include ingrowth, and the portion of merchantable volume PAIs resulting from ingrowth also were determined. The PAIs of QMDs and average heights were based on growth of surviving trees. Thirty-year mean annual gross and net basal area and volume growth (growth during the study divided by the appropriate number of years) were calculated; removals in all thinnings occurring during the 30-year period were included. Volume yields (cumulative net yields), the live standing volume at each measurement plus the live volume removed in all previous thinnings were determined. When Twin Lakes plots were expanded and thinned, thinning removals were estimated as the difference between the live basal area per acre (and volume per acre) before thinning and plot expansion and the corresponding values for the expanded plot after thinning. Net mean annual volume increments (MAI, cumulative net yields divided by age) also were calculated.

Additional Twin Lakes measurements and calculations—Heights to green crown were measured for all trees initially (spring 1960) and in fall 1964, 1969, 1974, and 1984. Live crown ratios at these dates were calculated for trees in the original plots after the 1984 thinning.

For the three paired sets of lodgepole and ponderosa pine plots, growth percentages for gross cubic volume and basal area were calculated by using gross PAIs with,

$$\text{Growth percent} = 100(\text{PAI})/[(Y_1 + Y_2)/2] \ . \tag{5}$$

Here Y_1 is the basal area or cubic volume of live trees at the beginning of the period, and Y_2 is the basal area or volume of all trees at the end of the period.

Additional Snow Creek measurements and calculations—Heights to green crown were measured on only four dates (1967, 1972, 1977, and 1983). Live crown ratios were calculated from these measurements for trees standing after the last thinning. There were no supplementary plots with constant spacing or other species.

Analyses for the LOGS Experiments

Standard analyses of variance and repeated measures analyses (SAS Institute 1988) were used to test the following hypotheses for both studies. (1) There are no differences in PAIs with GSL or period (age). (2) There are no differences in 30-year mean annual gross or net growth of basal area or volume with GSL. (3) There are no differences in cumulative net volume yields with GSL at the time of the last measurement. (4) There are no differences in live crown ratios with GSL or time of measurement. Because there are five GSL levels, up to a fourth degree polynomial can be used to describe the relation between response and GSL. Results from LOGS studies in Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) (Curtis and Marshall 1986), ponderosa pine (Cochran and Barrett 1995), and western larch (*Larix occidentalis* Nutt.) (Cochran and Seidel, 1999) indicated that linear or second degree polynomials would sufficiently describe this relation. Linear, quadratic, and lack-of-fit effects were, therefore, tested by using orthogonal polynomial methods. The coefficients used in these tests were determined by using five equally spaced levels of bole area (Bliss 1970).

Twin Lakes analyses—Data from the 1960-64 period were not used in testing hypotheses 1 and 2 because the density initially prescribed for GSL 5 was not met in 1960. Repeated measures analysis of variance (split-plot in time) was used to test the hypothesis that SDI varied identically with bole area after the thinnings before the growing season in 1965, 1970, and 1985.

For the Twin Lakes LOGS plots, regressions of the form,

$$\log_e PAI = c_0 + c_1[\log_e(SDIm_i)] + c_2(SDIm_i) + c_3[\log_e(S)] + d_1P_1 + \ldots . d_{i-1}P_{i-1}\ , \qquad (6)$$

were used to relate gross PAIs of basal area and total cubic volume to period mean stand density index (SDIm), site index (S) (Dahms 1975), and period (P_i). Dummy variables were used for periods. Observations are not independent, and this equation probably underestimates the error term. The contributions of each coefficient to the R^2 value for the complete model, therefore, were calculated instead of conducting probability tests. Similar equations were used for Douglas-fir by Curtis and Marshall (1986), for ponderosa pine by Cochran and Barrett (1998, 1995), and for western larch by Cochran and Seidel (1999). Curtis and Marshall (1986) used relative density instead of SDI. Cochran and Barrett (1995) used an age variable instead of dummy variables for periods. Cochran and Barrett (1998) did not use site index and added dummy variables for replication because the study had a randomized block design. Cochran and Seidel (in press) did not use site index but added as a variable the height PAI for the two tallest trees per plot. Site index was used here instead of height PAI for the site trees because some of these trees were lost to windfall during the last period.

Snow Creek analyses—Data from all periods were used in testing hypotheses 1 and 2. Repeated measures analysis was used to test the hypothesis that the SDI-bole area relation remained the same after each of the three thinnings.

For the Snow Creek LOGS plots, regressions of the form,

$$\log_e PAI = c_0 + c_1[\log_e(SDIm_i)] + c_2(SDIm_i) + c_3[\log_e(HPAI)]$$

$$+ \; d_1P_1 + \ldots . \; d_{i-1}P_{i-1} \;, \qquad (7)$$

were used to relate gross PAIs of basal area and total cubic volume to SDIm, survivor height PAI (HPAI), and period (P_i). A term for survivor height PAI instead of site index was used for the Snow Creek plots because high stand densities may have lowered the height growth of the site trees on some of the plots, thereby resulting in estimated site index values that were too low. All observations are not independent; therefore analyses and presentation of results followed the procedures of the Twin Lakes analyses.

Analyses of supplemental lodgepole pine plots at Twin Lakes—No statistical analyses were performed by using data from the supplemental lodgepole pine plots. These plots are not part of the LOGS experimental design and were added only to furnish some information about the influence of early spacing on tree and stand development.

Analyses of supplemental ponderosa pine plots at Twin Lakes—For the three paired sets of lodgepole and ponderosa pine plots, repeated measures analyses of variance were used to test the hypotheses that percentage of basal area and cubic-volume growth did not differ with species or period (age).

Results

Initial and Final Stand Averages for the LOGS Experiments

Twin Lakes stand averages—Before the initial thinning, average spacings for the GSLs ranged from 4.8 to 6.1 feet, SDIs ranged from 210 to 265, QMDs ranged from 3.1 to 3.7 inches, average heights ranged from 21.8 to 23.6 feet, and basal areas ranged from 89 to 110 square feet. Total cubic volumes ranged from 1,152 to 1,442 cubic feet, three GSLs had no board-foot volumes, and board-foot volumes for the other GSLs were low (table 1). Thirty-five years later, average spacings ranged from 10.9 to 37.4 feet, QMDs ranged from 7.5 to 14.4 inches, average heights ranged from 60.5 to 72.3 feet, and Scribner board-foot volumes ranged from 4,773 to 8,937 board feet (table 1).

Snow Creek stand averages—Before treatment, average spacings for the GSLs ranged from 5.2 to 6.4 feet, SDIs ranged from 268 to 317, QMDs ranged from 3.9 to 4.8 inches, average heights ranged from 26.9 to 32.4 feet, and basal areas ranged from 121 to 130 square feet. Total cubic volumes ranged from 1,152 to 1,442 cubic feet, and board-foot volumes ranged from 369 to 1,200 (table 2). Thirty years later, average spacings ranged from 12.2 to 29.5 feet, QMDs ranged from 8.2 to 11.7 inches, average heights ranged from 61.6 to 65.3 feet, and Scribner board-foot volumes ranged from 3,972 to 8,165 board feet (table 2).

The Relation Between Stand Density Index and Bole Area for the LOGS Experiments

Twin Lakes stand density index-bole area relation—There was a linear relation ($p \leq 0.10$) between SDI and bole area for the GSL plots after each of the three thinnings where plots were thinned to 4,000, 8,000, 12,000, 16,000, and 20,000 square feet of bole area (table 3, fig. 3). The SDI values differed ($p \leq 0.10$) with consecutive thinnings (table 3). The slope of the SDI-bole area relation also differed ($p \leq 0.10$) among thinnings resulting in significance ($p \leq 0.10$) of the linear component of the thinning time by treatment interaction. In all plots, the SDI values for the same bole area decreased as the average tree size became larger (fig. 3).

Table 3—Probability of higher *F*-values for the repeated measures analyses of SDI values after the last three thinnings at Twin Lakes and after all thinings at Snow Creek

Source	Degrees of freedom	Probability of higher *F*-values	
		Twin Lakes	Snow Creek
GSL:[a]			
Linear	1	0.0001	0.0001
Quadratic	1	.8263	.0220
Lack of fit	2	.6470	.7614
Error	5		
Thinnings	2	.0001	.0001
Thinnings × GSL:			
Linear	2	.0004	.0001
Quadratic	2	.8470	.1644
Lack of fit	4	.4785	.1720
Error	10		
MSE:[b]			
Whole plot		74.6528	51.8573
Subplot		25.4467	45.5208

[a] GSL = growing-stock level.
[b] MSE = mean square error for analysis of variance.

Snow Creek stand density index-bole area relation—The upper limit of bole area at Snow Creek was about 5,000 square feet per acre higher than at Twin Lakes. At Snow Creek, the SDI-bole area relation was curvilinear ($p \leq 0.10$). The SDI values differed ($p \leq 0.10$) with thinning times, but a significant ($p \leq 0.10$) difference in curvature with thinning time was not detected (table 3, fig. 4).

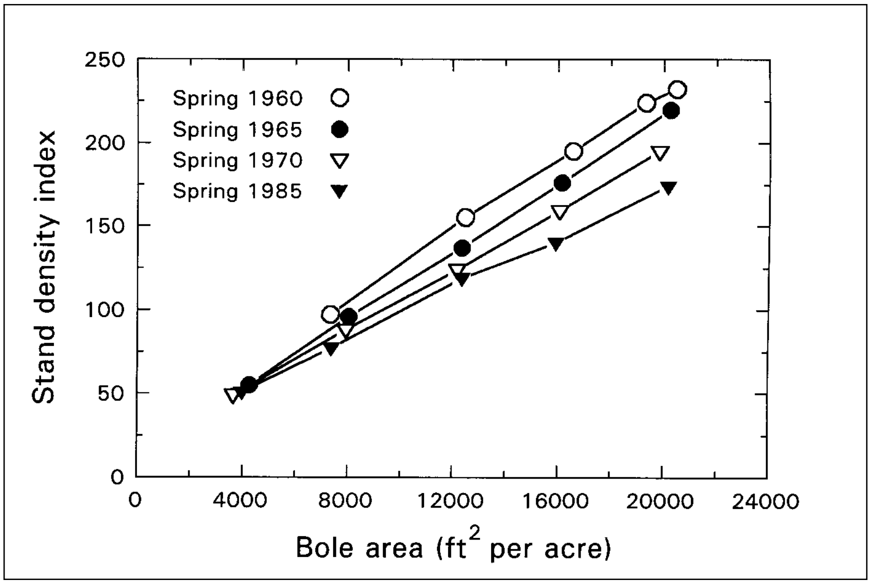

Figure 3—Stand density index versus bole area after thinning for the Twin Lakes LOGS study. Plotted points are treatment means. Data for 1960 were not used in the repeated measures analysis.

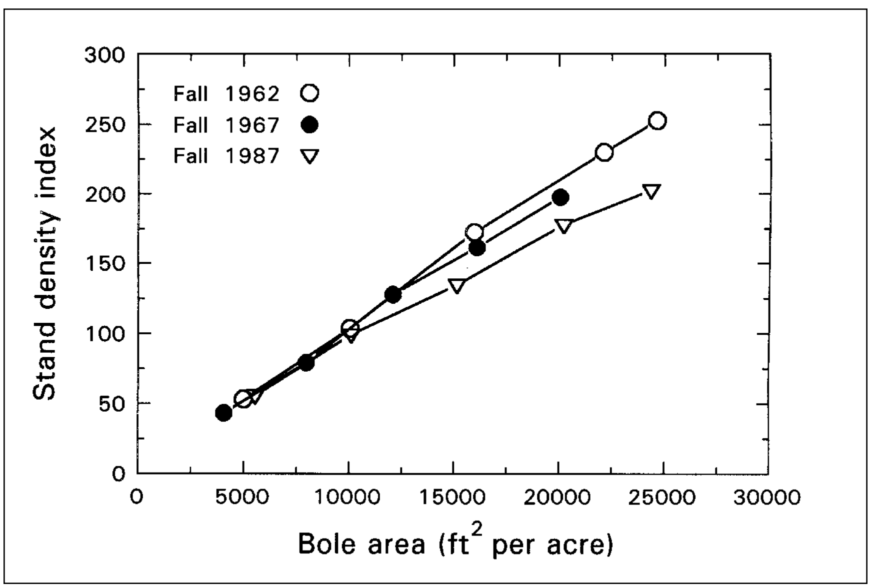

Figure 4—Stand density index versus bole area after thinning for the Snow Creek LOGS study. Plotted points are treatment means.

Mortality for the LOGS Experiments and the Supplemental Plots

Mortality observations consist of trees lost on each plot during any 5-year period. At Twin Lakes, there are 70 observations for the GSL plots, 12 observations for the spacing plots, and 15 observations for the ponderosa pine plots. At Snow Creek, there are 60 mortality observations.

Twin Lakes LOGS and supplemental plot mortality—Mortality occurred for 27 of the 70 observations for the GSL plots, 2 of the 12 observations for the spacing plots, and 1 of 15 observations for the ponderosa pine plots (table 4). No statistical analyses of mortality were performed because of the large numbers of observations with no mortality throughout much of the GSL-period matrix (table 4).

All the mortality in the 1990-94 period was windfall resulting from a single severe wind storm. For other periods, the mortality appears highest in the higher GSLs. In the first six periods, mortality occurred in only one observation for GSL 1, one observation for GSL 2, three observations for GSL 3, seven observations for GSL 4, and eleven observations for GSL 5 (table 4). The dead QMD:live QMD ratios ranged from 0.6 to 1.4 and averaged 0.8 for the first six periods. No relation of this ratio to GSL, period or tree size was evident. For the last period where windfall caused all the mortality, this dead QMD:live QMD ratio ranged from 0.5 to 1.1 and averaged 0.9. Lodgepole pine mortality in the absence of windfall occurred in only two observations where SDI was lower than 170 at the start of the period (fig. 5). The causes of this mortality other than windfall are unknown.

Snow Creek LOGS mortality—Mortality occurred for 25 of the 60 mortality observations for the Snow Creek study (table 5). Mortality was not statistically analyzed because only 6 of the 36 observations in the GSLs 1, 2, and 3 had mortality. Seven of the 12 observations in GSL 4 experienced mortality, and mortality occurred in all 12 observations for GSL 5. Eighteen of the 25 observations with mortality occurred when SDIs were 170 or greater at the start of the period (fig. 6). The dead QMD:live QMD ratio averaged 0.75, 0.93, 0.86, 0.95, 1.23, and 1.0 for periods 1 through 6, respectively. This ratio-GSL relation was not statistically tested, but it did not appear to be related to GSL. Much of the mortality in the first period (1963-67) is attributed to the pine engraver beetle (*Ips pini* (Say)), which came out of the thinning slash. Causes of mortality in periods 2 through 5 are unknown, but much of the mortality in the last period (1988-92) is due to mountain pine beetles. The mountain pine beetle population appeared to increase rapidly in the unthinned portion of the stand surrounding the plots during the last period.

Periodic Annual Increments for the LOGS Experiments

Twin Lakes LOGS periodic annual increments—All PAIs differed ($p \leq 0.10$) with period (tables 6 and 7). Survivor PAIs for QMDs decreased curvilinearly ($p \leq 0.10$) with increasing GSL, and the curve shape for this relation did not vary with period as shown by the nonsignificance ($p \leq 0.10$) of the quadratic component of the period by GSL interaction (table 6, fig. 7). Although survivor height PAIs appear to decrease with increasing GSL for several periods (fig. 8), differences were not statistically significant ($p \leq 0.10$) (table 6). Gross PAIs for basal area and gross and net PAIs for total cubic volume varied curvilinearly ($p \leq 0.10$) with increasing GSL, and the curvatures of these PAI-GSL relations did not differ ($p \leq 0.10$) with period (table 6, figs. 9 and 10).

Text continues on page 27.

Table 4—Twin Lakes mortality for each plot in each period expressed as number of trees per acre and as percentage of the number of live trees at the start of the period in parentheses

		Period							
GSL[a]	Rep[b]	1960-64	1965-69	1970-74	1975-79	1980-84	1985-94	1990-94	Total trees per acre
		Trees per acre (percent)							
1	1	0	0	0	3(3.4)	0	0	0	3
	2	0	0	0	0	0	0	8(23.1)	8
2	1	0	0	0	0	0	0	0	0
	2	0	5(0.9)	0	0	0	0	0	5
3	1	0	0	0	0	5(2.0)	0	15(10.7)	20
	2	10(1.1)	0	0	0	5(1.8)	0	10(7.1)	25
4	1	20(1.3)	0	0	0	5(1.1)	0	10(4.1)	35
	2	40(3.4)	10(0.8)	20(2.7)	10(2.1)	20(4.2)	0	0	100
5	1	30(1.9)	20(1.3)	30(3.4)	20(3.3)	15(2.5)	0	0	115
	2	90(4.8)	10(0.5)	70(5.8)	15(1.7)	30(1.2)	10(1.2)	0	225
Spacing[c]		--	0	0	0	0	0	5(6.3)	5
Spacing[c]		--	0	0	0	0	0	30(33.3)	30
Ponderosa[d]		--	--	0	0	0	0	0	0
Ponderosa[e]		--	--	5(3.8)	0	0	0	0	0
Ponderosa[f]		--	--	0	0	0	0	0	5
Total		190(1.9)	45(0.9)	125(2.2)	48(1.1)	80(2.0)	10(0.5)	78(3.7)	576

[a] GSL = growing-stock level.
[b] Rep = replication.
[c] Spacing plots added in 1963 in relatively open portions of the stand.
[d] Ponderosa plot added in 1969 and paired with lodgepole pine plot replication 1, GSL 1.
[e] Ponderosa plot added in 1969 and paired with lodgepole pine plot replication 2, GSL 1.
[f] Ponderosa plot added in 1969 and paired with lodgepole pine plot replication 2, GSL 3.

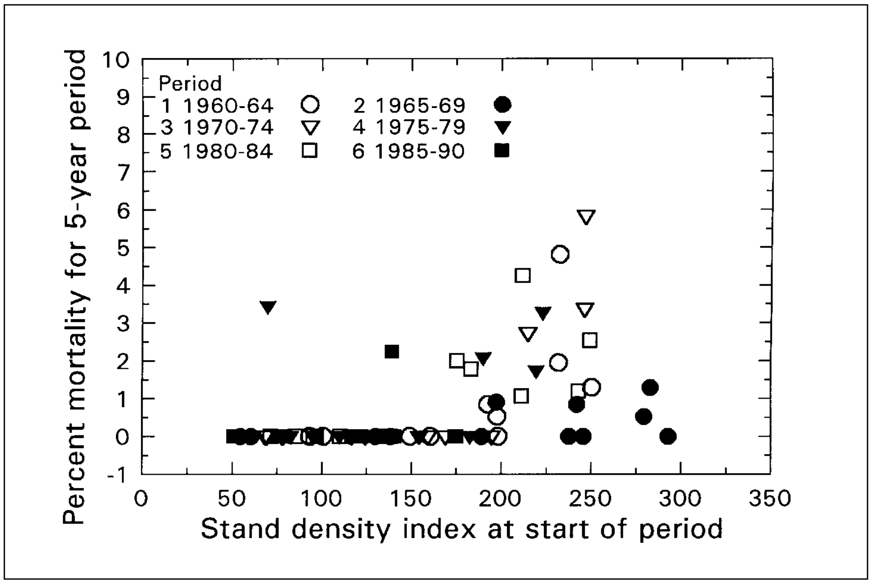

Figure 5—Percentage of mortality for each Twin Lakes LOGS study plot for the first six periods of observation as a function of SDI at the start of the period. The high mortality rates for some plots in period 7 (1990-94) are not shown.

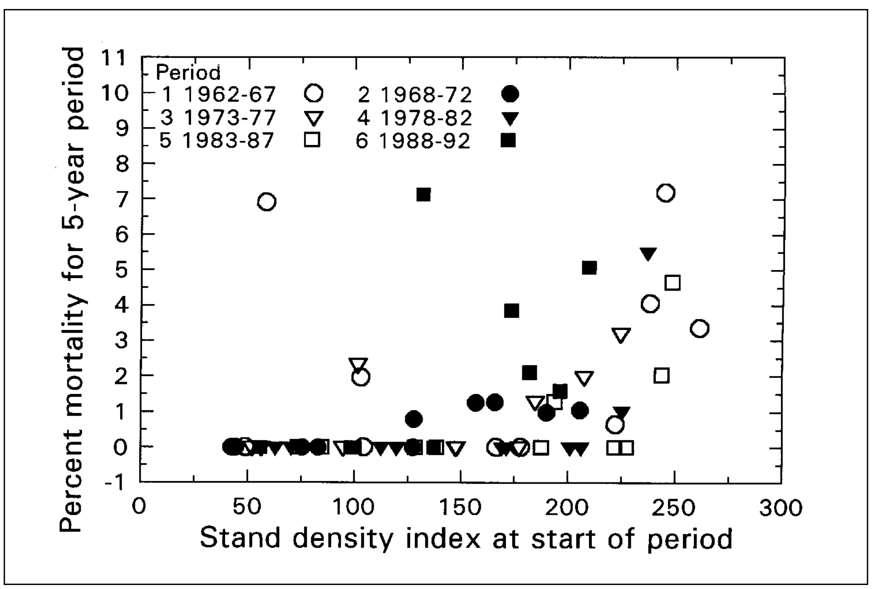

Figure 6—Percentage of mortality for each Snow Creek LOGS study plot for each period of observation as a function of SDI at the start of the period.

Table 5—Snow Creek mortality for each plot in each period expressed as number of trees per acre and as a percentage (in parentheses) of the number of live trees at the start of the period

		Period						
GSL[a]	Rep[b]	1963-67	1968-72	1973-77	1978-82	1983-87	1988-92	Total trees per acre
		Trees per acre (percent)						
1	1	0	0	0	0	0	0	0
	2	10(6.9)	0	0	0	0	0	10
2	1	0	0	5(2.3)	0	0	0	5
	2	5(2.0)	0	0	0	0	0	5
3	1	0	0	0	0	0	10(7.1)	10
	2	0	5(0.8)	0	0	5(1.3)	0	10
4	1	30(4.0)	5(1.3)	5(1.3)	0	0	5(2.1)	45
	2	5(0.7)	5(1.3)	0	0	0	10(3.8)	20
5	1	30(3.4)	5(1.0)	10(2.0)	5(1.0)	10(2.0)	5(1.6)	65
	2	55(7.2)	5(1.0)	15(3.2)	25(5.5)	20(4.6)	15(5.1)	135
Total		135(2.7)	25(0.8)	35(1.4)	30(1.1)	35(1.2)	45(2.4)	305

[a] GSL = growing-stock level.
[b] Rep = replication.

Table 6—Probability of higher *F*-values for the repeated measures analyses of variance for periodic annual increments (PAIs) of QMD, average height, basal area and total cubic volume at the Twin Lakes study for six 5-year periods beginning in spring 1965

		Probability of higher *F*-values for PAI					
				Basal area		Total cubic volume	
Source	Degrees of freedom	QMD[a]	Average height	Gross	Net	Gross	Net
GSL:[b]							
Linear	1	0.0002	0.1553	0.0047	0.0268	0.0009	0.0030
Quadratic	1	.0198	.9199	.0964	.1632	.0335	.0780
Lack of fit	2	.8845	.9783	.8135	.7238	.8773	.8874
Error	5						
Period (P)	5	.0001	.0001	.0001	.0001	.0001	.0001
P × GSL:							
Linear	5	.0300	.7190	.3842	.1413	.0012	.0050
Quadratic	5	.1980	.9537	.8405	.1247	.6038	.3126
Lack of fit	10	.1242	.7122	.4429	.0248	.6592	.1495
Error	25						
MSE:[c]							
Whole plot		.0016	.1553	.5178	.8468	560.3789	855.4343
Subplot		.0004	.0282	.0681	.1185	205.1241	274.4080

[a] GSL = growing-stock level.
[b] QMD = quadratic mean diameter of surviving trees.
[c] MSE = mean square error from analyses of variance.

Table 7—Probability of higher *F*-values for the repeated measures analyses of variance for merchantable volume periodic annual increments (PAIs) at the Twin Lakes study for six 5-year periods beginning in spring 1965

		Probability of higher *F*-values for PAI								
		Cubic volume						Scribner board feet		
		Trees 7 in d.b.h. and larger to a 5-in top			Trees 4 in d.b.h. and larger to a 3-in top			Trees 7 in d.b.h. and larger to a 5-in top		
Source	Degrees of freedom	Gross	Net	Ingrowth	Gross	Net	Ingrowth	Gross	Net	Ingrowth
GSL:[a]										
Linear	1	0.3922	0.3676	0.0176	0.3922	0.0018	--	0.6422	0.6438	0.0159
Quadratic	1	.0306	.0488	.1934	.0306	.1088	--	.0338	.0561	.2251
Lack of fit	2	.7515	.9418	.8482	.5752	.7292	--	.7521	.8657	.7789
Error	5									
Period (P)	5	.0001	.0001	.0045	.0001	.0001	--	.0001	.0001	.0077
P × GSL:										
Linear	5	.0001	.0001	.0001	.0363	.0416	--	.0001	.0001	.0001
Quadratic	5	.0010	.0007	.0001	.3471	.6909	--	.0113	.0054	.0001
Lack of fit	10	.0191	.0055	.1607	.6502	.2267	--	.1258	.0231	.1584
Error	25									
MSE:[b]										
Whole plot		1,923	2,188	16,344	549	618	--	28,65	130,850	99,579
Subplot		360	405	7,431	267	321	--	3,469	4,056	43,112

[a] GSL = growing-stock level.
[b] MSE = mean square error from analyses of variance.

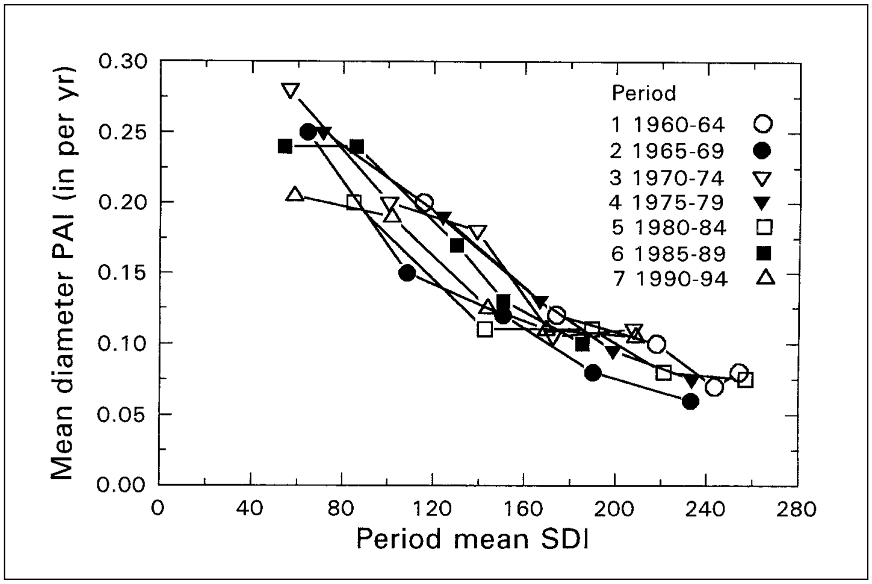

Figure 7—The relation of survivor PAIs for QMD to period mean SDI for the seven periods of the Twin Lakes LOGS study. Plotted points are treatment means.

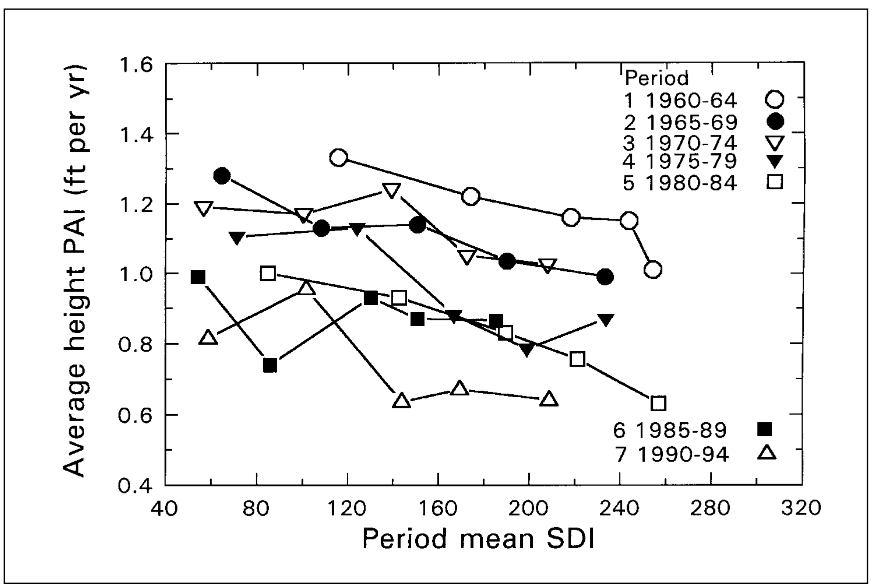

Figure 8—The relation of survivor PAIs for average height to period mean SDI for the seven periods of the Twin Lakes LOGS study. Plotted points are treatment means.

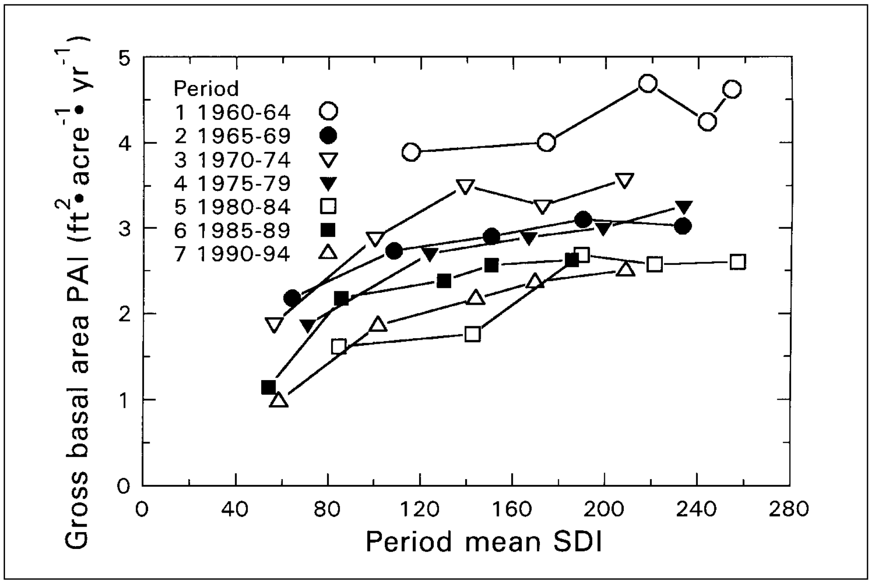

Figure 9—The relation of gross basal area PAIs to period mean SDI for the seven periods of the Twin Lakes LOGS study. Plotted points are treatment means.

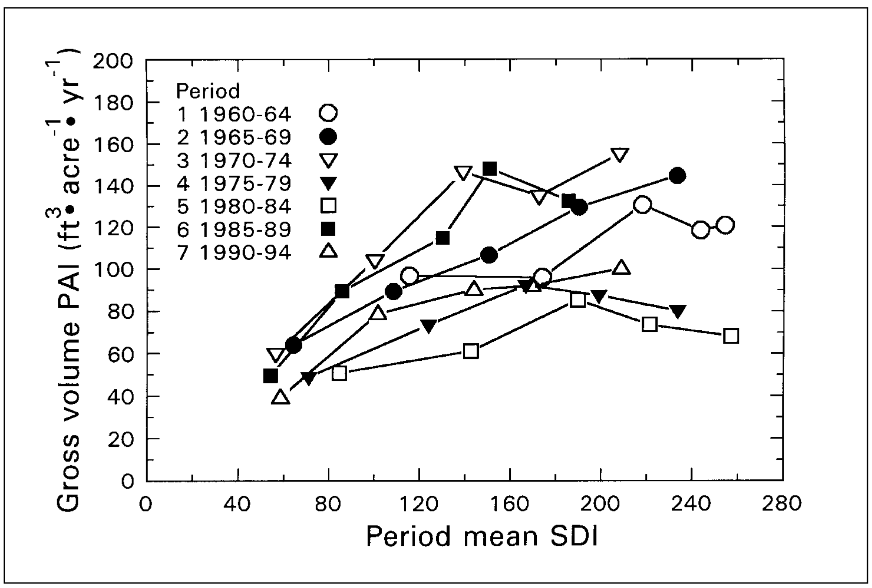

Figure 10—The relation of gross total cubic-volume PAIs to period mean SDI for the seven periods of the Twin Lakes LOGS study. Plotted points are treatment means.

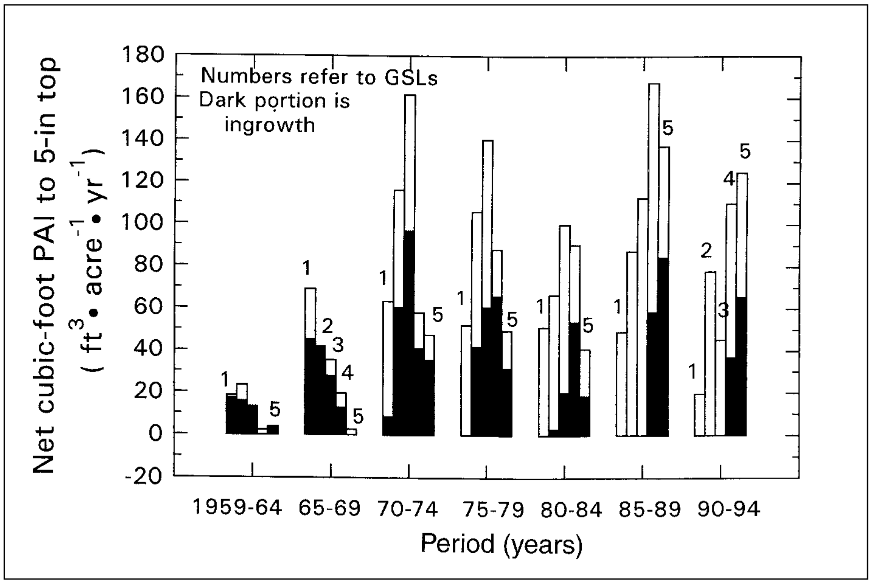

Figure 11—The relation of net merchantable cubic-volume (trees 7 inches and larger d.b.h. to a 5-inch top diameter inside bark) PAIs to GSLs for the seven periods of the Twin Lakes LOGS study. Bars represent treatment means.

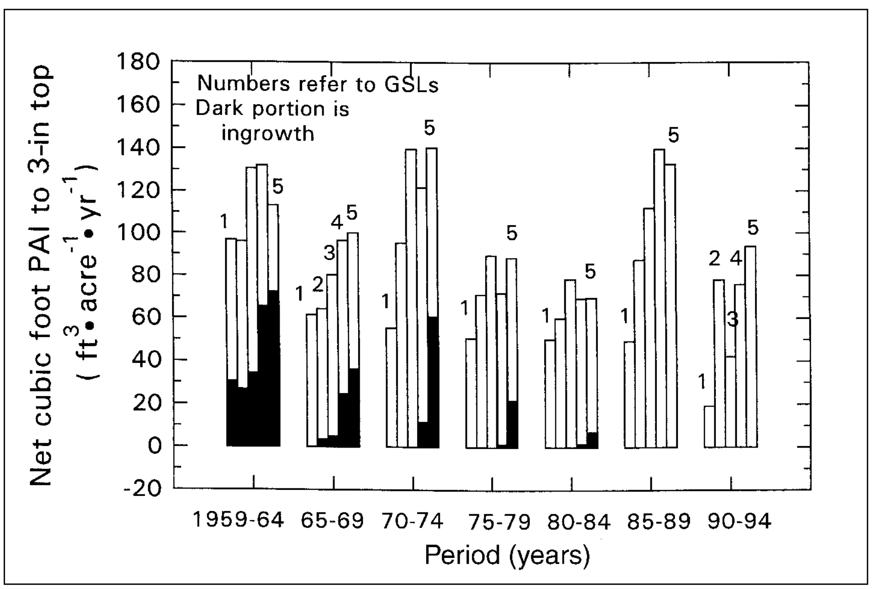

Figure 12—The relation of net merchantable cubic-volume (trees 4-inches and larger d.b.h. to a 3-inch top diameter inside bark) PAIs to GSLs for the seven periods of the Twin Lakes LOGS study. Bars represent treatment means.

Net basal area PAIs varied linearly ($p \leq 0.10$) with GSL, not curvilinearly as expected (table 6). Gross and net PAIs for merchantable cubic volume in 7-inch and larger diameter trees varied curvilinearly ($p \leq 0.10$) overall with increasing GSL (table 7, fig. 11). The PAI for merchantable cubic-volume ingrowth in 7-inch and larger diameter trees varied linearly ($p \leq 0.10$) overall with GSL. These gross, net, and ingrowth merchantable volume PAI-GSL relations appear to decrease linearly, increase linearly, vary curvilinearly, or vary erratically with GSL for varying periods (fig. 11). These variations in PAI-GSL relations for gross, net, and ingrowth merchantable volume PAI result in significance ($p \leq 0.10$) of the quadratic components of the period by GSL interaction terms. The significance ($p \leq 0.10$) of the lack-of-fit components for gross and net merchantable volume PAI indicates that considerable variation exists in these PAI-GSL relations not accounted for by a quadratic surface (table 7). Gross PAIs for merchantable cubic volume in 4-inch and larger diameter trees varied curvilinearly ($p \leq 0.10$) overall with increasing GSL (table 7, fig. 12). Net PAIs for merchantable cubic volume in 4-inch and larger diameter trees varied linearly ($p \leq 0.10$) with increasing GSL (table 7, fig. 12). Differences in slope for this PAI-GSL relation occurred as indicated by the significance ($p \leq 0.10$) of the linear component of the period by GSL interaction. Ingrowth for merchantable cubic volume in 4-inch and larger diameter trees occurred for only 10 out of 30 GSL-period combinations (fig. 12) so the repeated measures analysis was not performed for these ingrowth PAIs. Gross and net PAIs for Scribner board-foot volumes varied curvilinearly ($p \leq 0.10$) with GSL (table 7, fig. 13). These board-foot PAI-GSL relations seemed to decrease linearly with GSL for the 1965-69 period, vary curvilinearly with GSL for the 1970-74, 1975-79, 1980-84, and 1985-89 periods, and then vary erratically with GSL for the last period (1990-94) (fig. 13). These variations resulted in significance of the quadratic components of the period by GSL interaction (table 7). Significance ($p \leq 0.10$) of lack-of-fit component for net board-foot PAI indicates variation in this PAI-GSL relation not accounted for by a quadratic surface. Overall, the ingrowth portions of the board-foot PAIs increased linearly ($p \leq 0.10$) with increasing GSL (table 7), but the Scribner board-foot ingrowth PAI-GSL relation was curvilinear for some periods (fig. 13). This curvature differed ($p \leq 0.10$) with period as maximum ingrowth shifted from the lowest GSLs in 1965-69 to the highest GSLs in 1990-94 resulting in significance ($p \leq 0.10$) of the quadratic component of the period by GSL interaction.

Snow Creek periodic annual increments—Like Twin Lakes, all PAIs differed ($p \leq 0.10$) with period (tables 8 and 9). Survivor PAIs for QMDs decreased curvilinearly ($p \leq 0.10$) with increasing GSL, and the curve shape for this relation did not vary with period as shown by the nonsignificance ($p \leq 0.10$) of the quadratic component of the period by GSL interaction (table 8, fig. 14). Overall averages of survivor height PAIs did not differ ($p \leq 0.10$) significantly with GSL (table 8). These height PAIs appear, however, to generally increase with increasing GSL for two periods (1968-72, 1978-82) and decrease with GSL for the remaining periods (fig. 15). These changes in the height PAI-GSL relation with period resulted in significance ($p = 0.0002$, not shown in table) of the period by GSL interaction. Gross and net PAIs for both basal area and total cubic volume varied curvilinearly ($p \leq 0.10$) with increasing GSL, and the curvatures of these PAI-GSL relations did not differ ($p \leq 0.10$) with period (table 8, figs. 16 and 17). Gross and net PAIs for merchantable cubic volume in 7-inch and larger diameter trees and the 4-inch and larger diameter trees varied curvilinearly ($p \leq 0.10$) with increasing GSL (table 9, figs. 18 and 19). A significant ($p \leq 0.10$) difference in curvature

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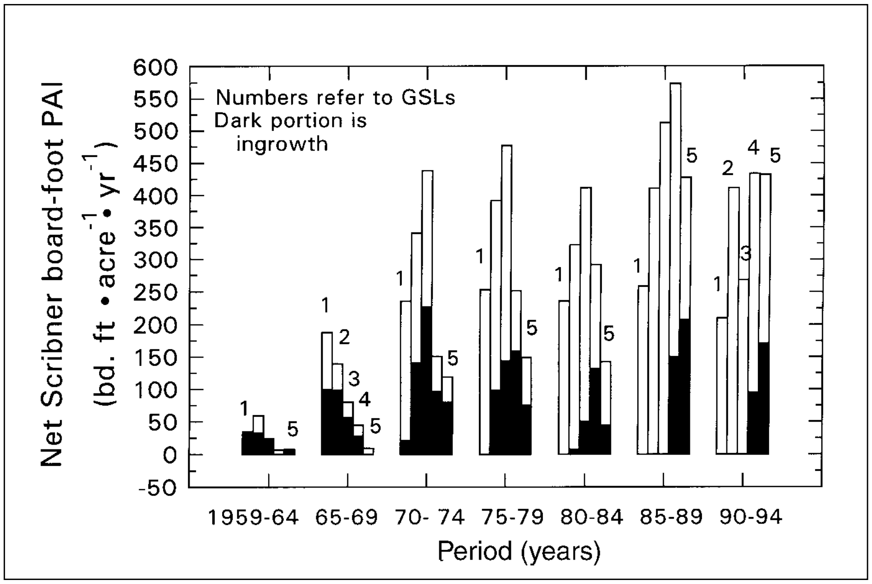

Figure 13—The relation of net Scribner board-foot PAIs to GSLs for the seven periods of the Twin Lakes LOGS study. Bars represent treatment means.

Table 8—Probability of higher *F*-values for the repeated measures analyses of variance for periodic annual increments (PAIs) of QMD, average height basal area and total cubic volume at the Snow Creek study for six 5-year periods beginning in spring 1963

		Probability of higher *F*-values for PAI					
				Basal area		Total cubic volume	
Source	Degrees of freedom	QMD[a]	Average height	Gross	Net	Gross	Net
GSL:[b]							
Linear	1	0.0001	0.4232	0.0010	0.4617	0.0001	0.0010
Quadratic	1	.0826	.7600	.0026	.0044	.0028	.0015
Lack of fit	2	.9108	.7708	.8006	.7470	.8328	.8874
Error	5						
Period (P)	5	.0001	.0002	.0001	.0001	.0001	.0001
P × GSL:							
Linear	5	.0042	.0001	.3725	.1821	.3734	.2682
Quadratic	5	.1992	.2459	.6263	.4780	.7448	.8324
Lack of fit	10	.8419	.6396	.7436	.9640	.7206	.7182
Error	25						
MSE:[c]							
Whole plot		.0005	.1553	.0862	.2564	112.5434	141.7209
Subplot		.0002	.0017	.0317	.0931	262.4595	386.5065

[a] QMD = quadratic mean diameter.
[b] GSL = growing-stock level.
[c] MSE = mean square error from analyses of variance.

Table 9—Probability of higher *F*-values for the repeated measures analyses for variance of merchantable volume periodic annual increments (PAIs) at the Snow Creek study for six 5-year periods beginning in spring 1963

		Probability of higher *F*-values for PAI								
		Cubic volume						Scribner board feet		
		Trees 7 in d.b.h. and larger to a 5-in top			Trees 4 in d.b.h. and larger to a 3-in top			Trees 7 in d.b.h. and larger to a 5-in top		
Source	Degrees of freedom	Gross	Net	Ingrowth	Gross	Net	Ingrowth	Gross	Net	Ingrowth
GSL:[a]										
Linear	1	0.0160	0.0147	0.0003	0.0001	0.0013	--	0.1471	0.1667	0.0002
Quadratic	1	.0961	.0362	.0854	.0023	.0020	--	.3103	.2240	.0850
Lack of fit	2	.7996	.7361	.4656	.7848	.5526	--	.9002	.8600	.4478
Error	5									
Period (P)	5	.0001	.0017	.0005	.0001	.0001	--	.0001	.0001	.0009
P × GSL:										
Linear	5	.7799	.9330	.2812	.2405	.2977	--	.8769	.9631	.2082
Quadratic	5	.6524	.7733	.8601	.8767	.9489	--	.5719	.7550	.8702
Lack of fit	10	.9785	.9867	.9281	.8328	.7311	--	.8790	.9052	.9384
Error	25									
MSE:[b]										
Whole plot		583	2,188	1,327	89	138	--	17,648	11,267	6,299
Subplot		551	405	4,133	247	400	--	5,418	8,708	22,868

[a] GSL = growing-stock level.
[b] MSE = mean square error from analyses of variance.

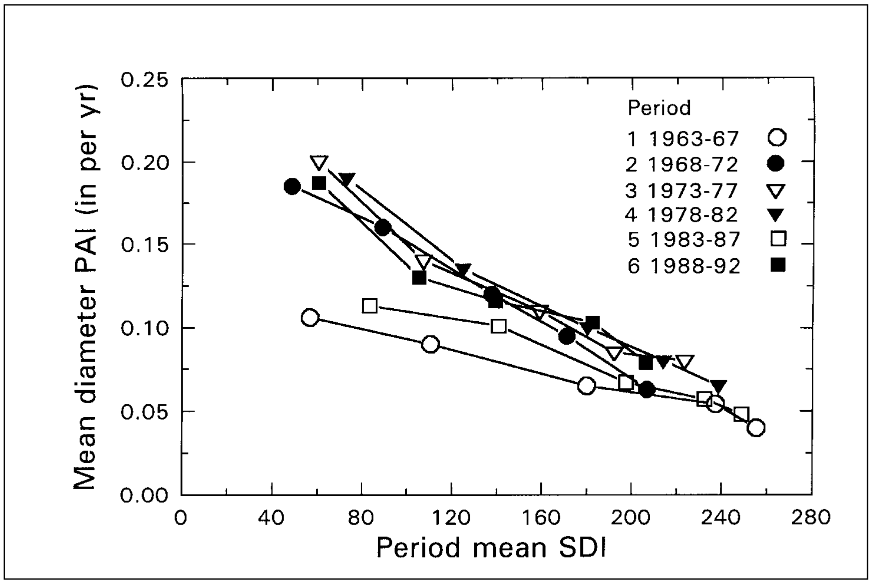

Figure 14—The relation of survivor PAIs for QMD to period mean SDI for the six periods of the Snow Creek LOGS study. Plotted points are treatment means.

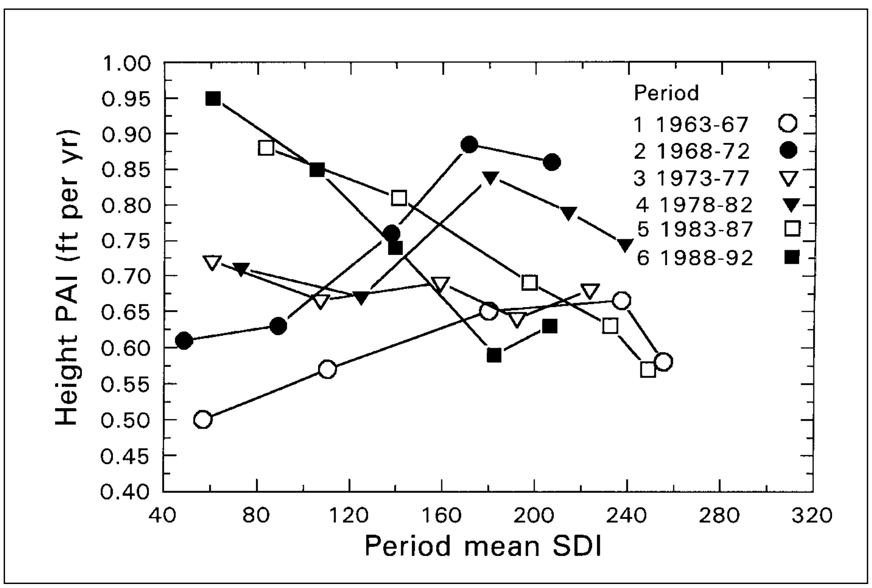

Figure 15—The relation of survivor PAIs for average height to period mean SDI for the six periods of the Snow Creek LOGS study. Plotted points are treatment means.

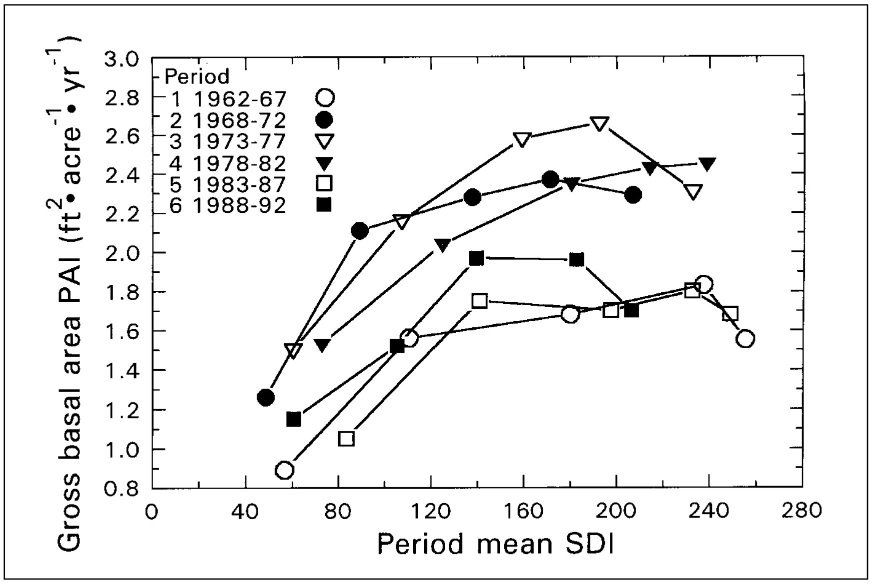

Figure 16—The relation of gross basal area PAIs to period mean SDI for the six periods of the Snow Creek LOGS study. Plotted points are treatment means.

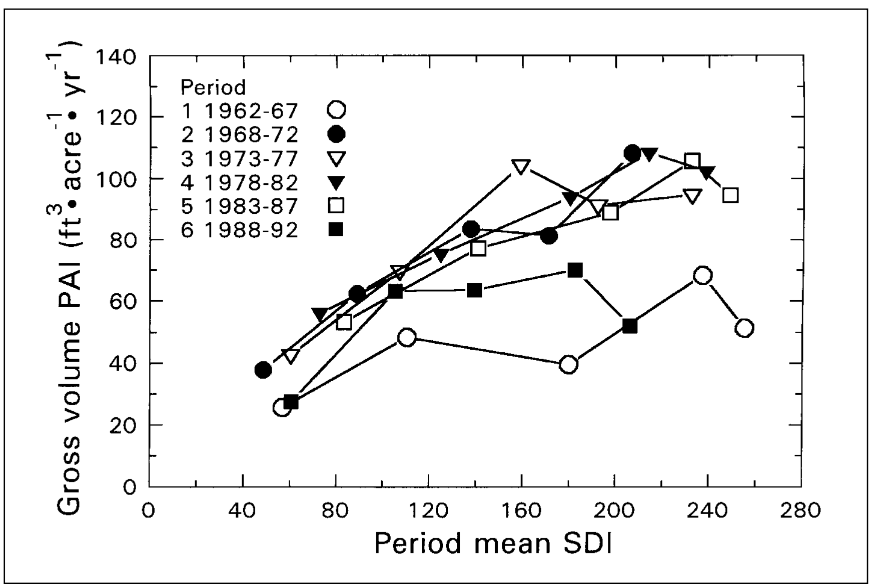

Figure 17—The relation of gross total cubic-volume PAIs to period mean SDI for the six periods of the Snow Creek LOGS study. Plotted points are treatment means.

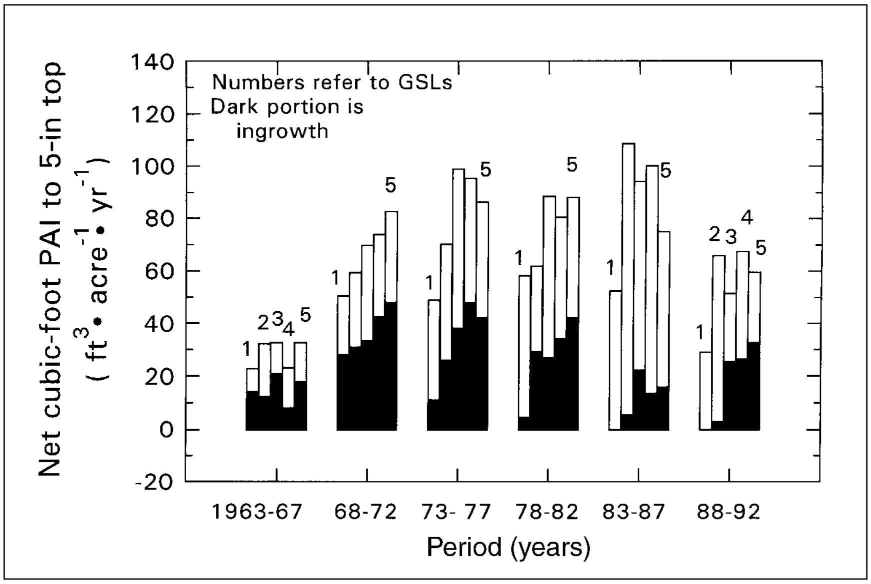

Figure 18—The relation of net merchantable cubic-volume (trees 7-inches and larger d.b.h. to a 5-inch top diameter inside bark) PAIs to GSLs for the six periods of the Snow Creek LOGS study. Bars represent treatment means.

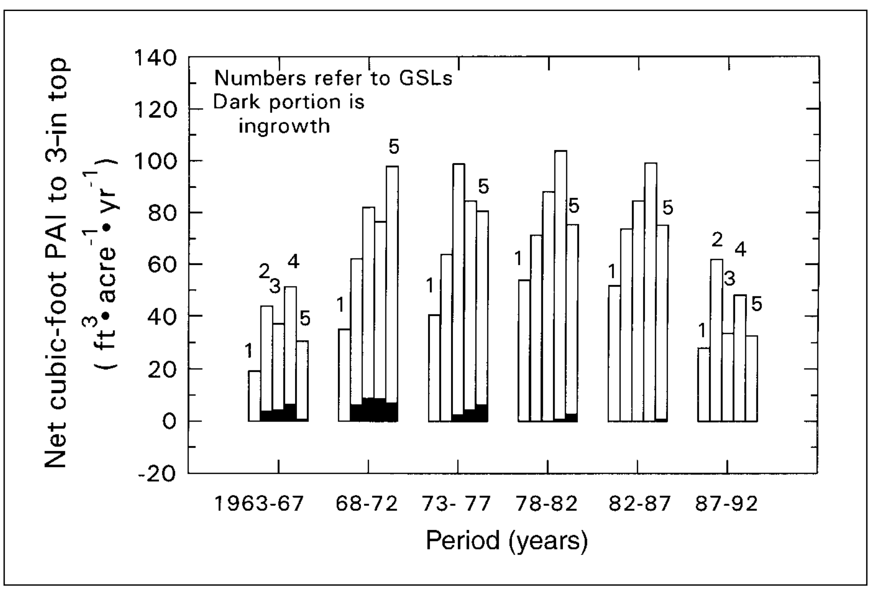

Figure 19—The relation of net merchantable cubic-volume (trees 4-inches and larger d.b.h. to a 3-inch top diameter inside bark) PAIs to GSLs for the six periods of the Snow Creek LOGS study. Bars represent treatment means.

with period for these PAIs was not detected (table 9). Ingrowth PAIs for merchantable cubic volume in 7-inch and larger diameter trees varied curvilinearly ($p \leq 0.10$) with GSL, and this curvature did not vary ($p \leq 0.10$) with period (table 9, fig. 18). Ingrowth for merchantable cubic volume in 4-inch and larger diameter trees occurred for only 14 out of 30 GSL-period combinations (fig. 19) so the repeated measures analysis was not performed for these ingrowth PAIs. Although gross and net PAIs for Scribner board-foot volumes appeared to vary linearly or curvilinearly with GSL for different periods (fig. 20), no significant ($p \leq 0.10$) differences were detected (table 9). The ingrowth portions of the board-foot PAIs increased curvilinearly ($p \leq 0.10$) with increasing GSL (table 9, fig. 20), and this curvature did not differ ($p \leq 0.10$) with period.

Thirty-Year Mean Annual Growth (1970-94) for the LOGS Experiments

Results for mean annual growth of the LOGS plots match the whole plot analyses (analyses of GSL) for PAIs (tables 6, 7, 8, and 9). Results of these analyses, therefore, are not shown.

Twin Lakes mean annual growth—Mean annual growth rates for gross basal area (fig. 21) and gross and net total cubic volume (fig. 22) increased curvilinearly ($p \leq 0.10$) with increasing GSL. Mean annual growth for net basal area and for net cubic volume in 4-inch and larger trees appeared to vary curvilinearly with increasing GSL, but only a significant ($p \leq 0.10$) linear variation was detected (table 6, fig. 21). Gross and net mean annual growth of merchantable cubic volume in 7-inch and larger trees increased curvilinearly ($p \leq 0.10$) with increasing GSL (tables 7 and 10). Gross mean annual growth of merchantable cubic volume in 4-inch and larger trees and gross and net Scribner board-foot volume varied curvilinearly ($p \leq 0.10$) with increasing GSL (tables 7 and 10).

Snow Creek mean annual growth—Mean annual growth rates for gross and net basal area (fig. 23) and gross and net total and merchantable cubic volumes (fig. 24) increased curvilinearly ($p \leq 0.10$) with increasing GSL (tables 8, 9, and 11). Significant ($p \leq 0.10$) differences in gross and net Scribner board-foot volume with GSL were not detected (tables 9 and 11).

Net Yields for the LOGS Experiments

Net yields include trees removed in thinnings. All net cubic-volume yields at Twin Lakes and both total cubic-volume yield and cubic-volume yield in trees 4 inches and larger at Snow Creek varied curvilinearly ($p \leq 0.10$) with GSL (tables 12 and 13, figs. 25 and 26). Net Scribner board-foot yields at Twin Lakes also varied curvilinearly ($p \leq 0.10$) with GSL (table 12, fig. 27). Net cubic-volume yields for trees 7 inches and larger at Snow Creek varied linearly ($p \leq 0.10$) with GSL, whereas variation in Scribner board-foot yields with GSL at Snow Creek were not detected (table 13, fig. 28).

Net Mean Annual Increments for the Levels-of-Growing-Stock

The MAIs were not analyzed statistically because values for each measurement are in part dependent on the values of the previous measurement. Analysis of net MAIs for the last measurement would be the same as the analyses of variances of accompanying yields (tables 12 and 13).

Twin Lakes mean annual increments—Net total cubic-volume MAIs (fig. 29) seem to have culminated for the lowest GSL. Net cubic volume for the higher GSLs seemed to increase rapidly until age 38 years and then to change gradually with further increases in age. With the exception of the lowest GSL and those GSLs that did not

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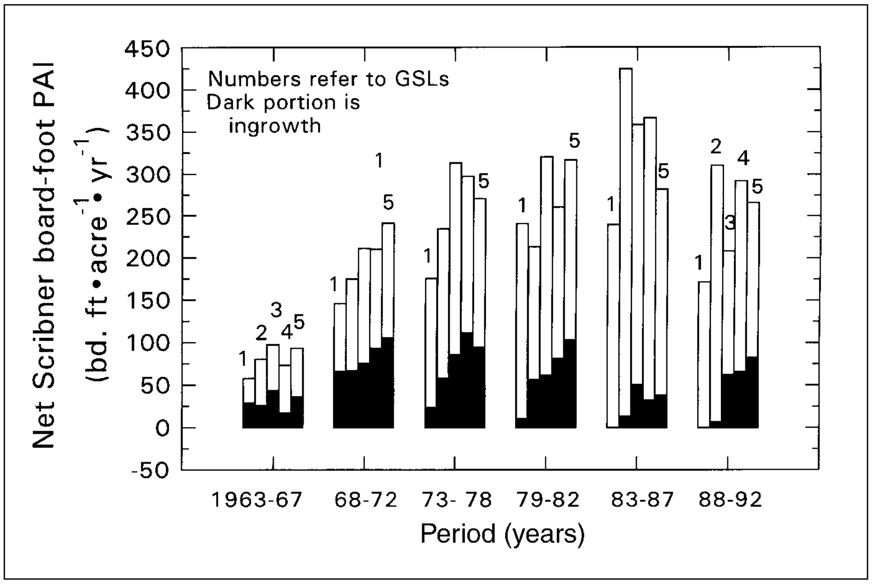

Figure 20—The relation of net Scribner board-foot PAIs to GSLs for the six periods of the Snow Creek LOGS study. Bars represent treatment means.

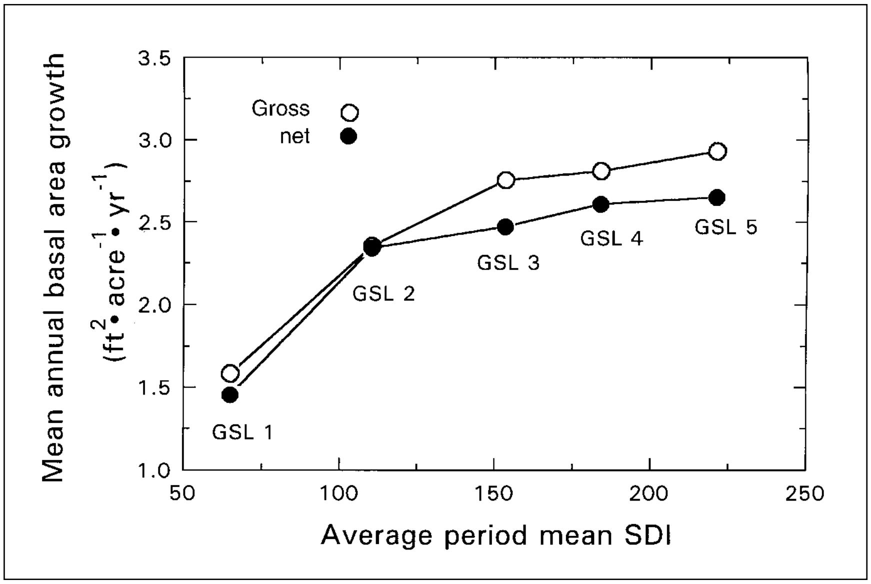

Figure 21—Mean annual gross and net basal area growth for each GSL during the last six periods (30 years) of the Twin Lakes LOGS study. Plotted points are treatment means.

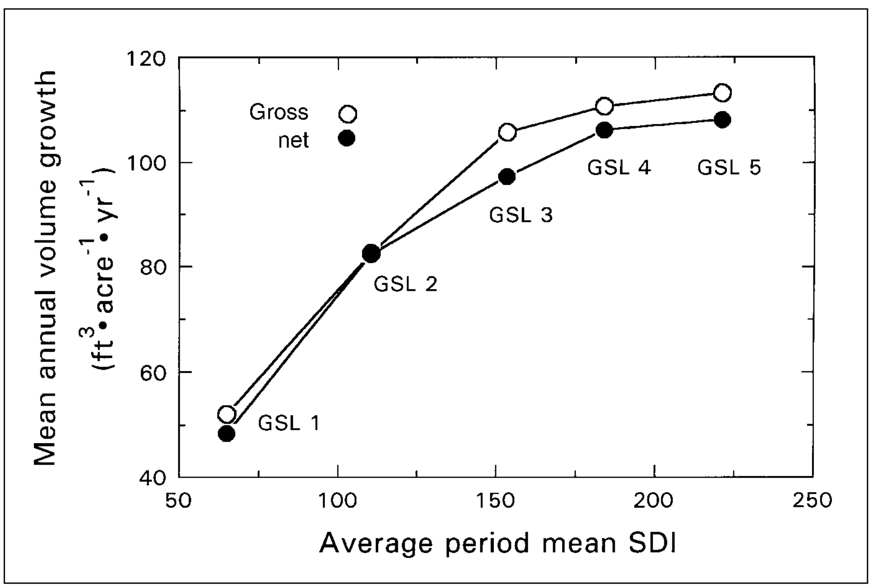

Figure 22—Mean annual gross and net total cubic-volume growth for each GSL during the last six periods (30 years) of the Twin Lakes LOGS study. Plotted points are treatment means.

Table 10—Mean annual growth (1965-94) including ingrowth for the Twin Lakes LOGS and spacing plots

	Thirty-year mean annual growth							
	Total cubic volume[a]		Trees ≥7 in d.b.h. to a 5-in top[b]		Trees ≥4 in d.b.h. to a 3-in top[c]		Scribner board feet[d]	
Treatment	Gross	Net	Gross	Net	Gross	Net	Gross	Net
	Cubic feet						*Board feet*	
GSL:[e]								
1	52.0	48.4	54.1	50.6	49.5	46.0	232	217
2	82.5	82.5	79.6	79.6	76.2	76.2	336	336
3	105.8	97.3	106.6	99.3	98.6	90.4	394	364
4	110.8	106.2	91.0	89.0	99.7	95.9	297	291
5	113.2	108.2	67.1	67.1	111.6	104.2	213	213
Spacing	61.8	44.7	61.0	44.9	59.4	42.8	291	220

[a] Total cubic-foot volume of entire stem, inside bark, all trees.
[b] Merchantable cubic-foot volume for all trees 7 inches d.b.h. and larger to a 5-inch top diameter inside bark.
[c] Merchantable cubic-foot volume for all trees 4 inches d.b.h. and larger to a 3-inch top diameter inside bark.
[d] Scribner board-foot volume for all trees 7 inches d.b.h. and larger to a 5-inch top diameter inside bark.
[e] GSL = growing-stock level.

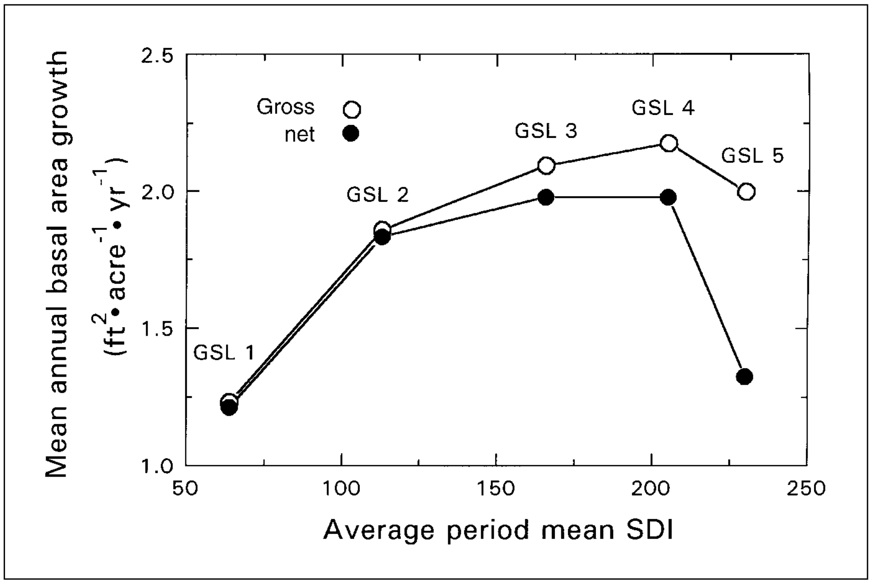

Figure 23—Mean annual gross and net basal area growth for each GSL during all six periods (30 years) of the Snow Creek LOGS study. Plotted points are treatment means.

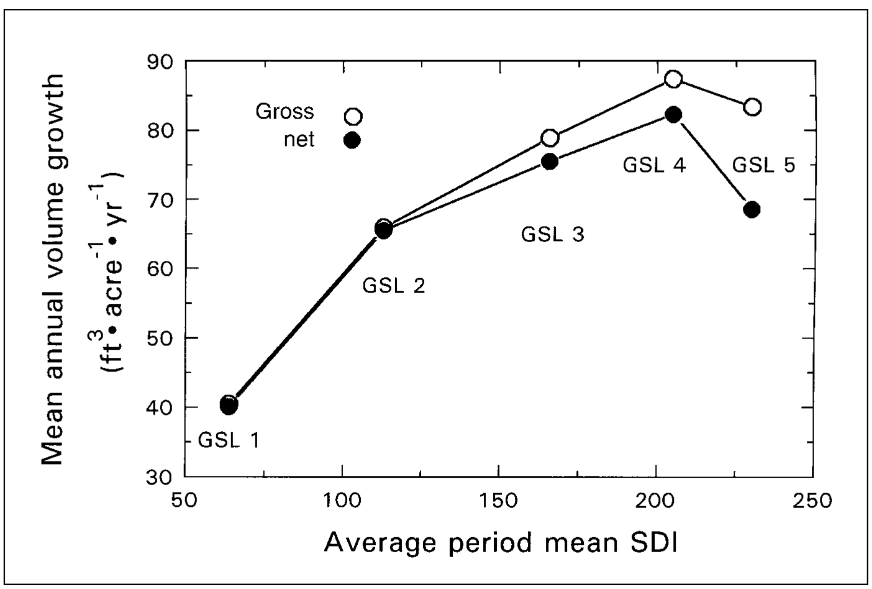

Figure 24—Mean annual gross and net total cubic-volume growth for each GSL during all six periods (30 years) of the Snow Creek LOGS study. Plotted points are treatment means.

Table 11—30-year mean annual growth (1962-92) including ingrowth for the Snow Creek LOGS study

	30-year mean annual growth							
	Total cubic volume[a]		Trees ≥7 in d.b.h. to a 5-in top[b]		Trees ≥4 in d.b.h. to a 3-in top[c]		Scribner board feet[d]	
Treatment	Gross	Net	Gross	Net	Gross	Net	Gross	Net
	Cubic feet						*Board feet*	
GSL:[e]								
1	40.4	40.1	43.6	43.6	38.2	38.0	172	172
2	65.9	65.4	66.4	66.4	63.2	62.7	240	240
3	78.9	75.5	77.0	72.6	75.4	70.6	268	252
4	87.4	82.3	76.4	73.4	81.5	77.2	260	250
5	83.8	68.7	78.0	70.7	80.4	65.4	266	245

[a] Total cubic-foot volume of entire stem, inside bark, all trees.
[b] Merchantable cubic-foot volume for all trees 7 inches d.b.h. and larger to a 5-inch top diameter inside bark.
[c] Merchantable cubic-foot volume for all trees 4 inches d.b.h. and larger to a 3-inch top diameter inside bark.
[d] Scribner board-foot volume for all trees 7 inches d.b.h. and larger to a 5-inch top diameter inside bark.
[e] GSL = growing-stock level.

Table 12—Probability of higher *F*-values for the analyses of variance of cumulative net volume yields at Twin Lakes in fall 1994

Source	Degrees of freedom	Probability of higher *F*-values for yield: Total cubic volume	Merchantable volume[a]: Trees ≥7 in d.b.h. to 5-in top	Merchantable volume[a]: Trees ≥4 in d.b.h. to 3-in top	Merchantable volume[a]: Scribner board feet
GSL:[b]					
Linear	1	0.0038	0.5564	0.0165	0.2527
Quadratic	1	.0291	.0454	.0669	.0481
Lack of fit	2	.7351	.9088	.7308	.8036
Error	5				
MSE[c]		138,771.288	353,838.8	235,334.8	5,001,439.9
C.V.%[d]		8.76	24.2	13.1	25.5

[a] Merchantable cubic-foot volume for all trees 7 inches d.b.h. and larger to a 5-inch top diameter inside bark; merchantable cubic-foot volume for all trees 4 inches d.b.h. and larger to a 3-inch top diameter inside bark; and Scribner board-foot volume for all trees 7 inches d.b.h. and larger to a 5-inch top diameter inside bark.
[b] GSL = growing-stock level.
[c] MSE = mean square error from analyses of variance.
[d] C.V.% = coefficient of variation.

Table 13—Probability of higher *F*-values for the analyses of variance of cumulative net volume yields in fall 1992 at Snow Creek

Source	Degrees of freedom	Probability of higher *F*-values for yield: Total cubic volume	Merchantable volume[a]: Trees ≥7 in d.b.h. to 5-in top	Merchantable volume[a]: Trees ≥4 in d.b.h. to 3-in top	Merchantable volume[a]: Scribner board feet
GSL:[b]					
Linear	1	0.0684	0.0541	0.0391	0.2316
Quadratic	1	.0561	.1034	.0970	.2518
Lack of fit	2	.9028	.6357	.5614	.7721
Error	5				
MSE[c]		803,264.181	2,685,362.7	2,808,450.2	29,055,696.3
C.V.%[d]		9.30	17.4	10.8	22.9

[a] Merchantable cubic-foot volume for all trees 7 inches d.b.h. and larger to a 5-inch top diameter inside bark; merchantable cubic-foot volume for all trees 4 inches d.b.h. and larger to a 3-inch top diameter inside bark; and Scribner board-foot volume for all trees 7 inches d.b.h. and larger to a 5-inch top diameter inside bark.
[b] GSL = growing-stock level.
[c] MSE = mean square error from analyses of variance.
[d] C.V.% = coefficient of variation.

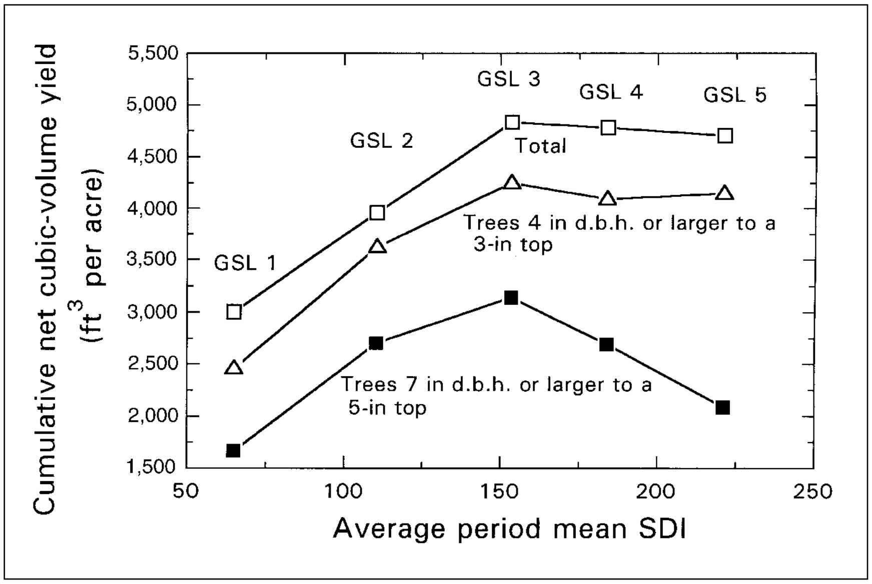

Figure 25—Cumulative net cubic-volume yields (total and merchantable), including thinnings, for the Twin Lakes LOGS study in fall 1994. Plotted points are treatment means.

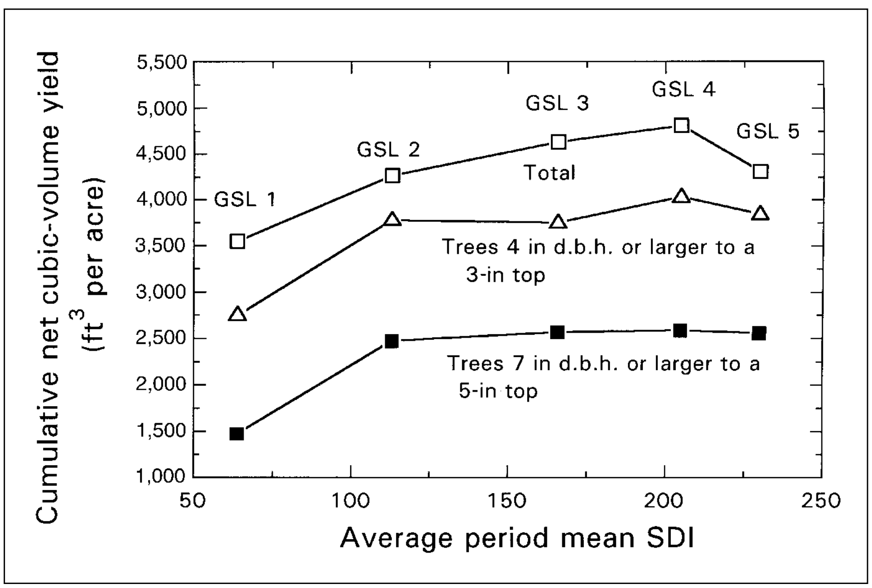

Figure 26—Cumulative net cubic-volume yields (total and merchantable), including thinnings, for the Snow Creek LOGS study in fall 1992. Plotted points are treatment means.

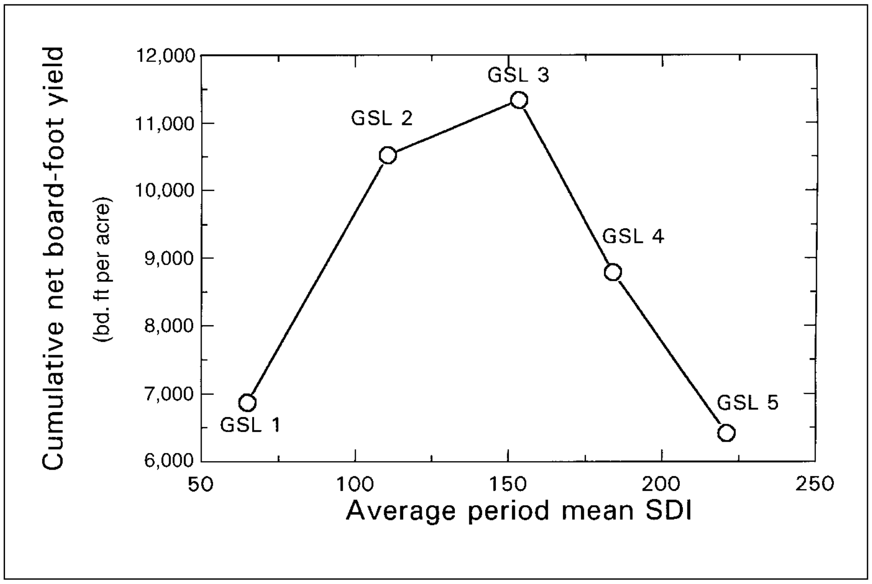

Figure 27—Cumulative net Scribner board-foot yields, including thinnings, for the Twin Lakes LOGS study in fall 1994. Plotted points are treatment means.

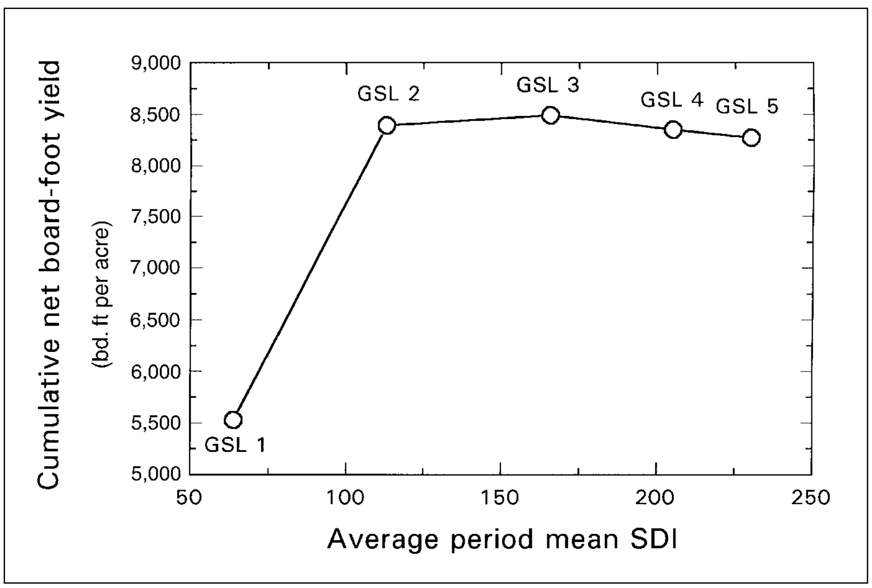

Figure 28—Cumulative net Scribner board-foot yields, including thinnings, for the Snow Creek LOGS study in fall 1992. Plotted points are treatment means.

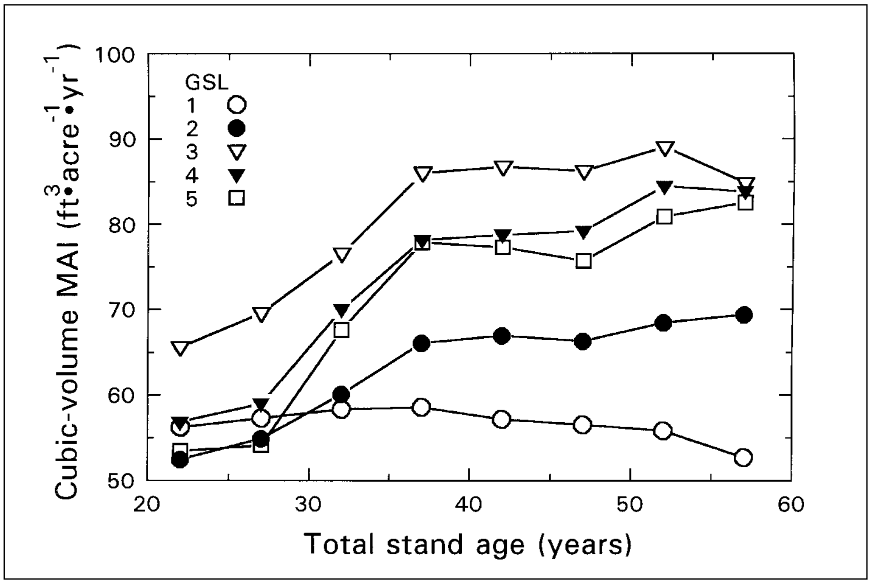

Figure 29—Mean annual increments of total cubic volume, including thinnings, for each GSL and stand age at Twin Lakes. Plotted points are treatment means.

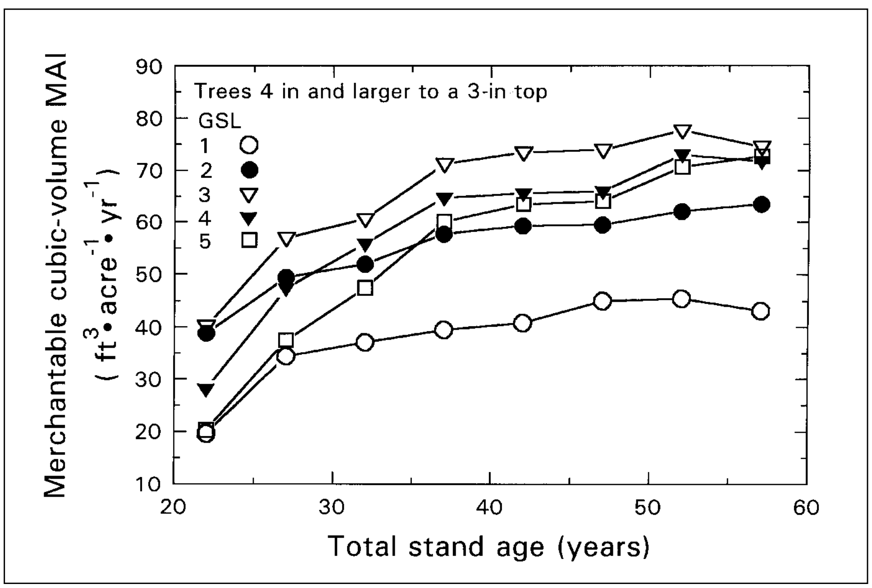

Figure 30—Mean annual increments of merchantable cubic volume (trees 4 inches and larger d.b.h. to a 3-inch top diameter inside bark), including thinnings, for each GSL and stand age at Twin Lakes. Plotted points are treatment means.

experience windfall in the last period, net total cubic-volume MAIs seem to still be gradually increasing at age 58 when last measured. Net merchantable cubic-volume MAIs for trees 4 inches and larger in diameter and for trees 7 inches and larger seem to still be gradually increasing with age for the GSLs where blowdown did not occur in the last period (figs. 30, 31). All board-foot MAIs (fig. 32) are still generally increasing with age at age 58 years; GSLs 1 and 3 seem to be leveling off somewhat probably because of the windfall mortality in these GSLs during the last period (table 4).

Snow Creek mean annual increments—Total cubic-volume MAIs and cubic-merchantable-volume MAIs for trees 4 inches and larger began decreasing at age 72 years except for GSL 2 (figs. 33 and 34); no mortality occurred for GSL 2 in the last period (table 5). Mean annual increments for merchantable cubic volume in 7-inch and larger trees and for board-foot volume are still increasing at age 77 years for all GSLs (figs. 35 and 36).

Crown Ratios for the LOGS Experiments

Twin Lakes crown ratios—Live crown ratios of trees surviving after the last thinning (1984) decreased linearly ($p \leq 0.10$) with increasing GSLs, and these ratios differed ($p \leq 0.10$) with time (table 14, fig. 37). The slope of the crown ratio-GSL relation became steeper with each succeeding time of measurement as indicated by the significance ($p \leq 0.10$) of the linear component of the time by GSL interaction.

Snow Creek crown ratios—Overall, the live crown ratio-GSL relation for trees surviving after the last thinning (1987) was linear ($p \leq 0.10$). Significance ($p \leq 0.10$) of the lack of fit term, however, indicates a significant amount of variation was not accounted for by the linear and quadratic surfaces. Inconsistency is also apparent in the significance ($p \leq 0.10$) of the linear and quadratic components of the time by GSL interaction (table 14). Crown ratios differed ($p \leq 0.10$) with time and by the 1982 crown ratios appeared to decrease curvilinearly with increasing GSL (table 14, fig. 38).

Growth of Supplemental Lodgepole Pine Spacing Plots

The spacing plots were not part of the original experiment, and spacings were not randomly assigned to plots. No statistical tests, therefore, were performed comparing growth rates of spacing and GSL plots. Some general observations, however, are appropriate. Lower numbers of trees per acre on the spacing plots before thinning resulted in larger average tree sizes in the spacing plots than in the LOGS plots in spring 1965. Because of the larger tree sizes in the spacing plots in 1965, corresponding board-foot values are considerably larger, even though cubic-foot volume for the spacing plots is lower than all of the LOGS plots (table 1). Even after the 1970 thinning, which lowered the tree numbers in the GSL 1 plots to 70 TPA, the average tree size for the 85 TPA in the spacing plots is still larger. Fifteen years later, the 69 live TPA in the GSL 1 plots had about the same average size as the 85 TPA in the spacing plots (table 1).

Gross mean annual growth for the LOGS and spacing plots for 1965-94 varied considerably (table 10). Average values for gross mean annual growth of total and merchantable cubic volume were lower for the spacing plots than all GSLs but GSL 1. Net mean annual growth of total and merchantable cubic volume for the spacing plots were lower than for all the GSLs. Average values for mean annual growth of Scribner board-foot volume were higher for the spacing plots than for GSLs 1 and 5.

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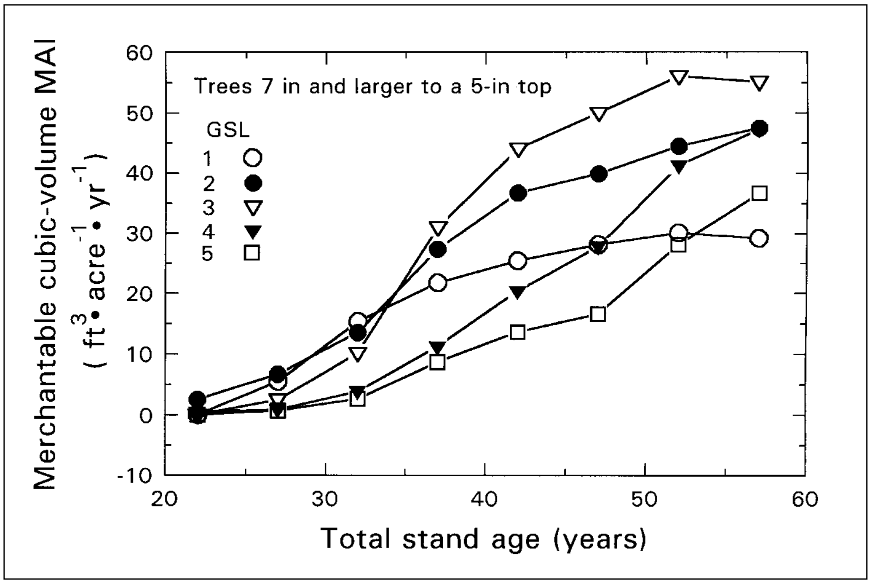

Figure 31—Mean annual increments of merchantable cubic volume (trees 7 inches and larger d.b.h. to a 5-inch top diameter inside bark), including thinnings, for each GSL and stand age at Twin Lakes. Plotted points are treatment means.

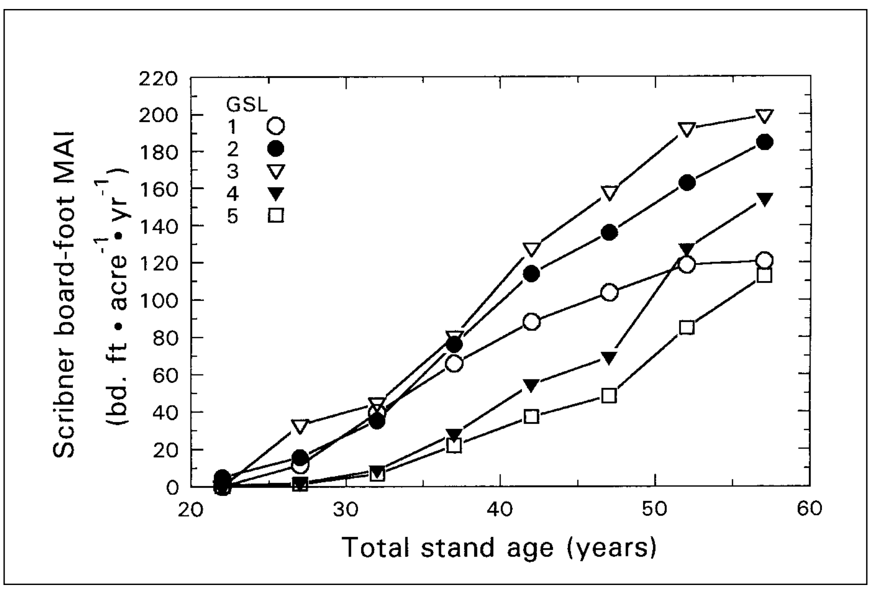

Figure 32—Mean annual increments of Scribner board feet, including thinnings, in trees 7 inches and larger d.b.h. to a 5-inch top diameter inside bark for each GSL and stand age at Twin Lakes. Plotted points are treatment means.

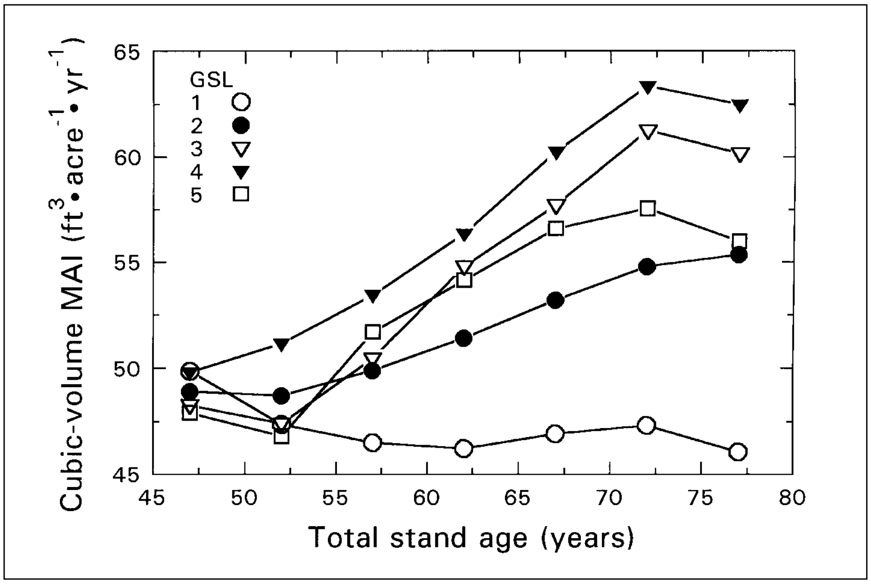

Figure 33—Mean annual increments of total cubic volume, including thinnings, for each GSL and stand age at Snow Creek. Plotted points are treatment means.

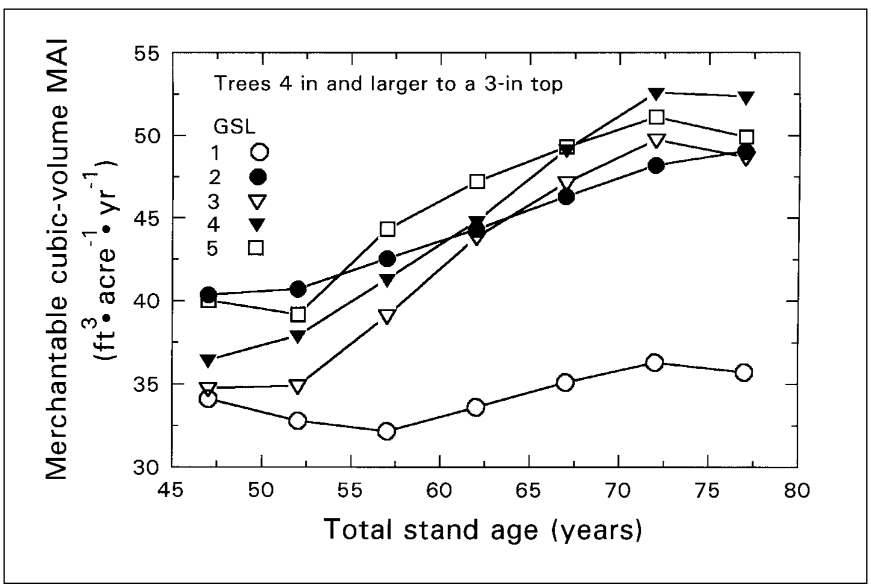

Figure 34—Mean annual increments of merchantable cubic volume (trees 4 inches and larger d.b.h. to a 3-inch top diameter inside bark), including thinnings, for each GSL and stand age at Snow Creek. Plotted points are treatment means.

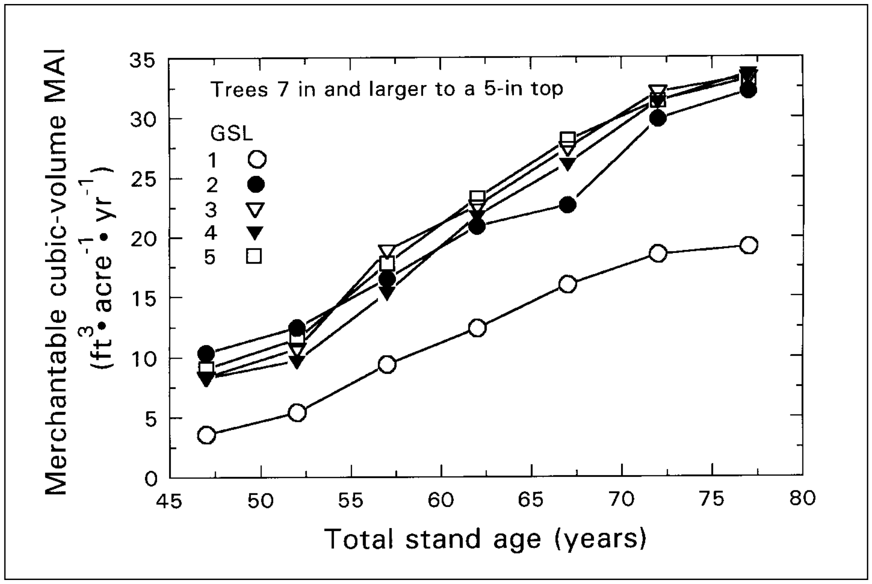

Figure 35—Mean annual increments of merchantable cubic volume (trees 7 inches and larger d.b.h. to a 5-inch top diameter inside bark), including thinnings, for each GSL and stand age at Snow Creek. Plotted points are treatment means.

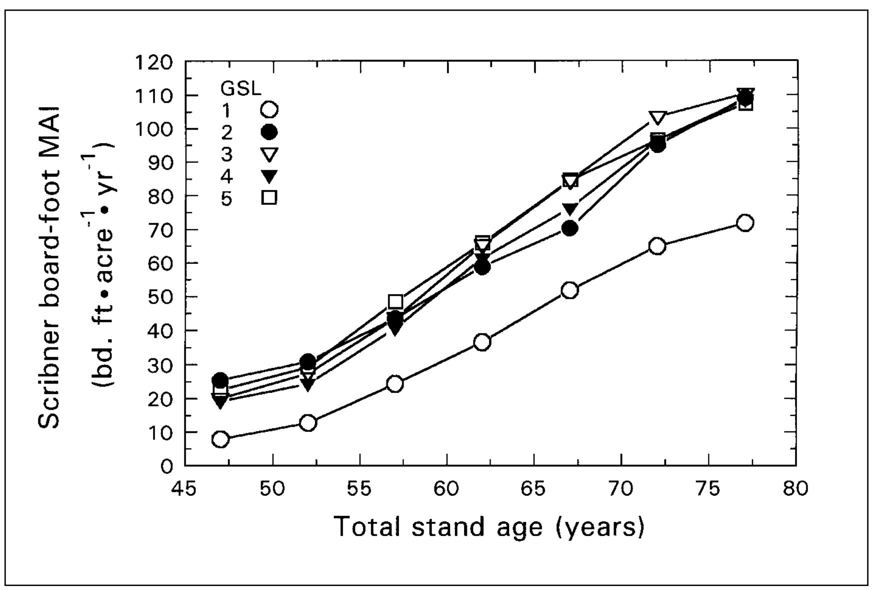

Figure 36—Mean annual increments of Scribner board feet, including thinnings, in trees 7 inches and larger d.b.h. to a 5-inch top diameter inside bark for each GSL and stand age at Snow Creek. Plotted points are treatment means.

Table 14—Probability of higher *F*-values for the repeated measures analyses of live crown ratios in 1960, 1964, 1969, 1974, and 1984 for trees standing after the 1984 thinning that were present on the plots initially before enlargement at Twin Lakes and for live crown ratios at Snow Creek in 1967, 1972, 1977, and 1963 for trees standing after the 1987 thinning

	Twin Lakes		Snow Creek	
Source	Degrees of freedom	Probability of higher *F*-values	Degrees of freedom	Probability of higher *F*-values
GSL:[a]				
Linear	1	0.0012	1	0.0486
Quadratic	1	.9279	1	.7115
Lack of fit	2	.5971	2	.0784
Error	5		5	
Time	4	.0001	3	.000
Time × GSL:				
Linear	4	.0001	3	.0003
Quadratic	4	.4219	3	.0862
Lack of fit	8	.7136	6	.6337
Error	20		15	
MSE:[b]				
Whole plot		.0039		.0023
Subplot		.0005		.0006

[a] GSL = growing-stock level.
[b] MSE = mean square error from repeated measures analysis.

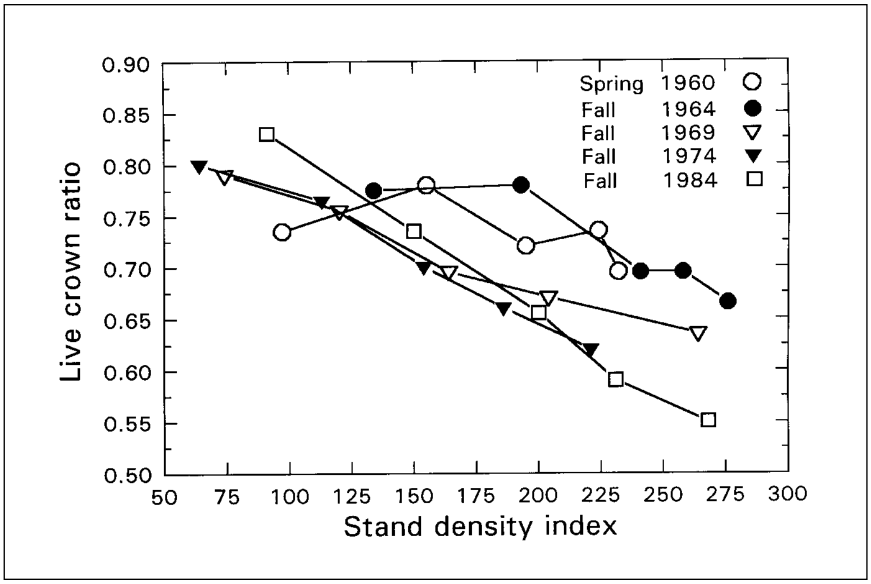

Figure 37—The relation of live crown ratios for the Twin Lakes LOGS study to SDI for trees standing after the 1984 thinning that were also on the plots before the plots were expanded. Plotted points are treatment means.

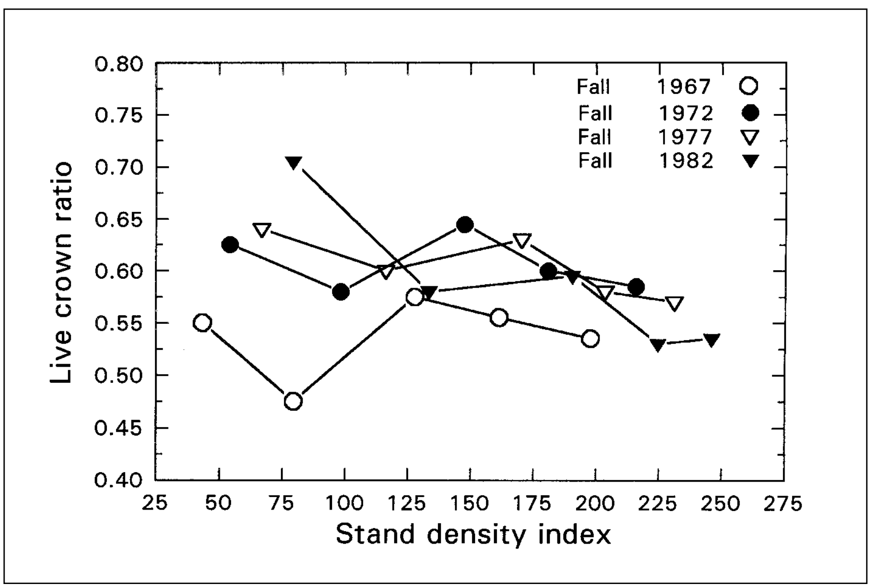

Figure 38—The relation of live crown ratios for the Snow Creek LOGS study to SDI for trees standing after the 1987 thinning. Plotted points are treatment means.

Table 15—Probability of higher *F*-values for the repeated measures analyses of variance of percentage of increases in annual growth of basal area and total cubic volume for lodgepole and ponderosa pine at Twin Lakes for five 5-year periods starting in spring 1970

Source	Degrees of freedom	Probability of higher *F*-values	
		Basal area	Total cubic volume
Replication	2	0.2513	0.1917
Species (S)	1	.0999	.0212
Error	2		
Period (P)	4	.0001	.0001
P × S	4	.7451	.0332
Error	16		
MSE:[a]			
Whole plot		.6259	.3365
Subplot		.2958	.2326

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

Table 16—Average percentage of annual growth rates for lodgepole and ponderosa pine at Twin Lakes

Period	Basal area			Total cubic volume		
	Lodgepole pine	Ponderosa pine	Difference	Lodgepole pine	Ponderosa pine	Difference
	Percent					
1970-74	6.0	6.5	0.5	9.2	10.4	1.2
1975-79	4.4	5.2	.8	5.1	7.5	2.4
1980-84	3.2	4.6	1.4	4.4	5.1	.7
1985-89	3.3	4.2	.9	5.7	7.6	1.9
1990-94	2.8	3.5	.7	3.6	4.4	.8

Table 17—Coefficients from regression analysis of Twin Lakes LOGS data for equation (6)[a], R^2 values for these individual coefficients, and R^2 values for the complete model

	Volume		Basal area	
Coefficient	Estimate	$(R^2)^b$	Estimate	$(R^2)^b$
c_0	-16.0770	--	-14.6891	--
c_1	1.7056	0.3721	1.4190	0.5087
c_2	-.0065	.0801	-.0057	.0265
c_3	2.7791	.0149	1.9592	.0455
d_1	.0367	.0353	.5475	.0750
d_2	.1980	.0253	.4125	.0433
d_3	.3981	.1248	.4500	.0917
d_4	-.1593	.0044	.2787	.0390
d_5	-.4060	.1304	.0000	.0020
d_6	.3628	.0588	.1578	.0113
Model R^2		.8461		.8430

[a] $\log_e PAI = c_0 + c_1[\log_e(SDIm_i)] + c_2(sdim_i) + c_3[\log_e(\text{site index})] + d_1P_1 + \ldots + d_{i-1}P_{i-1}$.
[b] R^2 values for individual coefficients are contributions to the model R^2.

Table 18—Coefficients from regression analysis of Snow Creek LOGS data for equation (7),[a] R^2 values for these individual coefficients, and R^2 values for the complete model

	Volume		Basal area	
Coefficient	Estimate	$(R^2)^b$	Estimate	$(R^2)^b$
c_0	-0.7784	--	-4.3689	--
c_1	1.1021	0.4458	1.1729	0.3879
c_2	-.0042	.0412	-.0060	.1322
c_3	.1764	.0553	.0005	.0116
d_1	-.1538	.1396	-.0945	.0743
d_2	.3721	.0066	.2778	.0472
d_3	.3920	.0147	.2999	.1056
d_4	.4087	.0349	.2228	.1064
d_5	.3399	.0512	-.1073	.0113
Model R^2		.7815		.8755

[a] $\log_e PAI = c_0 + c_1[\log_e(SDIm_i)] + c_2(sdim_i) + c_3[\log_e(HPAI)] + d_1P_1 + \ldots + d_{i-1}P_{i-1}$.
[b] R^2 values for individual coefficients are contributions to the model R^2.

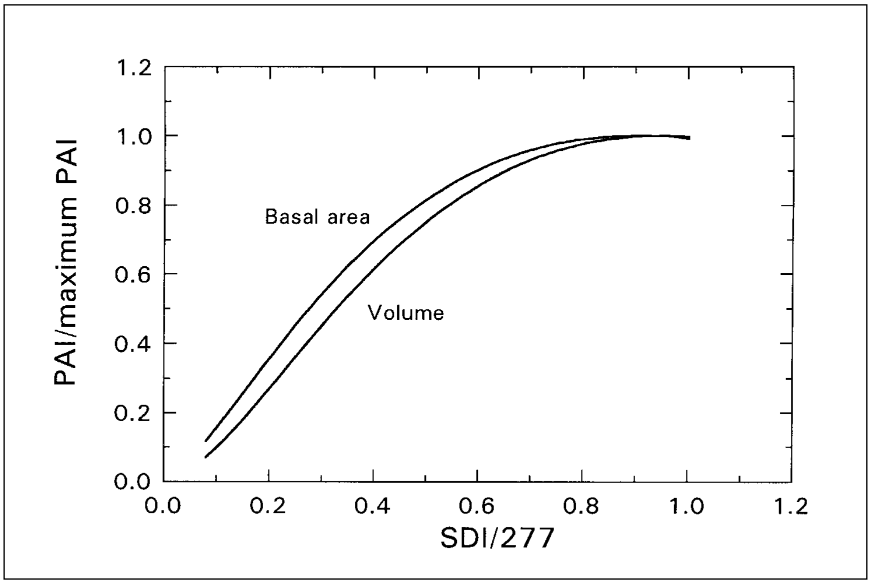

Figure 39—Gross PAIs of basal area and total cubic volume divided by the maximum gross PAI as a function of SDI divided by the SDI for a normal stand. Plots obtained from smoothed Twin Lakes data.

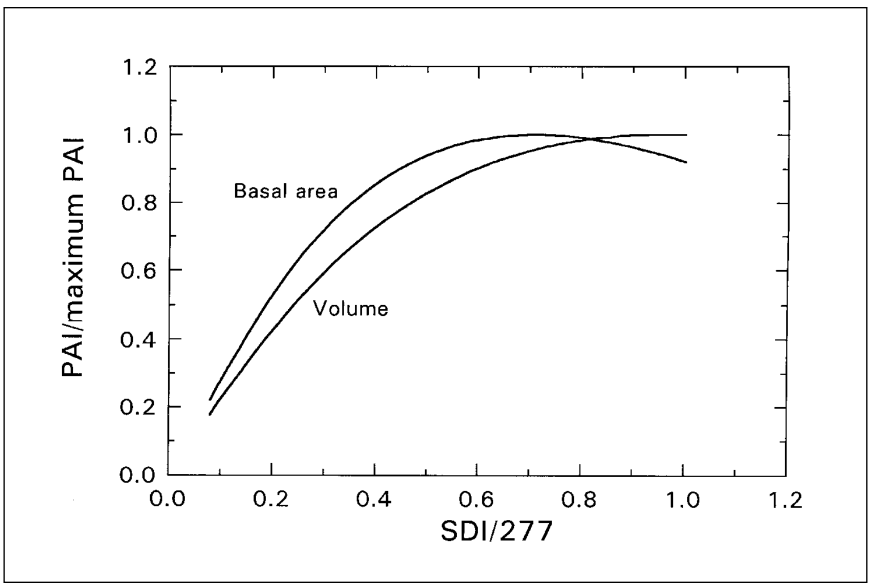

Figure 40—Gross PAIs of basal area and total cubic volume divided by the maximum gross PAI as a function of SDI divided by the SDI for a normal stand. Plots obtained from smoothed Snow Creek data

Growth Percentages for the Supplemental Ponderosa Pine Plots and the Three Adjacent Lodgepole Pine LOGS Plots

Growth percentages for gross basal area and cubic volume varied ($p \leq 0.10$) with period but were higher ($p \leq 0.10$) for ponderosa pine (tables 15 and 16). Differences in percentage of cubic-volume growth between the two species varied erratically with stand age (table 10), thereby resulting in significance ($p \leq 0.10$) of the age by species interaction term (table 15).

Growth Patterns for the Levels-of-Growing Stock Experimentst

Gross PAI-SDI relations for basal area and volume smoothed by fitting equations (6) and (7) to Twin Lakes and Snow Creek LOGS data, respectively, seem to be curvilinear (tables 17 and 18). When gross PAIs were calculated by using these equations for stand densities ranging up to SDI 277, the normal stand density for lodgepole pine in south-central Oregon, PAIs reached a plateau at SDIs lower than 277. Plots of the ratio PAI:maximum PAI for SDIs ranging up to 277 versus the ratio SDI:normal SDI produced convex curvilinear curve shapes (figs. 39 and 40). These plots depict the fraction of maximum gross PAI captured at various fractions of normal stand density. These plots assume that fits of equations (6) and (7) adequately describe the PAI-SDI relations up to SDI 277 even though 277 is slightly beyond the upper limits of the data.

Twin Lakes growth patterns—Plots of gross PAI ratios determined by using equation (6) versus SDI/277 show a rapid increase in the fraction of PAI captured as SDI is increased from low levels to 50 or 60 percent of normal SDI (fig. 39). As SDI increases further, rates of increase in observed PAI:maximum PAI begin to decline, leveling off at SDI 262 (SDI/maximum SDI = 0.95) for gross cubic-volume PAI and SDI 249 (SDI/maximum SDI = 0.90) for gross basal area PAI.

Snow Creek growth patterns—The plot of gross basal area PAI/maximum basal area PAI shows a rapid increase in the fraction of PAI captured as SDI is increased from low levels to about 40 percent of normal SDI (fig. 40). As SDI increases further, rates of increase in observed gross basal area PAI:maximum PAI begin to decline, leveling off at SDI 197 (SDI/normal SDI = 0.71). As SDI increases beyond 197, the amount of basal area captured is reduced, and at an SDI of 277, only about 92 percent of the maximum gross basal area seems to be produced (fig. 40). The plot of gross volume PAI/maximum PAI increases rapidly with increasing stand density until 50 percent of normal stand density, but the ratio continues to increase until SDI 262 (SDI/277 = 0.95) and then levels off (fig. 40).

Discussion and Conclusions

Dahms (1971) believed that a given level of bole area represented a nearly constant level of competition. A given SDI also is thought to represent a constant level of competition across a range of stand diameters. Mulloy (1944) reported that bole area was proportional to SDI for a large number of red pine (*Pinus resinosa* Ait.) and white pine (*Pinus strobus* L.) plots; the scatter of points in his figures, however, are extensive, and there seems to be considerable divergence for low SDI values. The significant ($p \leq 0.10$) decrease in slope for the SDI-bole area relation with succeeding thinnings or increasing tree size found in the Twin Lakes LOGS study (table 3, fig. 3) and the curvilinear SDI-bole area relation found with the higher upper limit of bole area levels at Snow Creek (table 3, fig. 4) indicate that SDI and bole area are not equivalent. The SDI-bole area relation was curvilinear and also changed with tree size in a larch LOGS study (Cochran and Seidel,1999). Stand density index and some other closely related measures have a common interpretation as comparisons of area occupied or available to an average tree in an observed stand with that available to the average tree in normal stand of the same QMD. Similarly, CCF is a widely used and nearly equivalent measure that can be interpreted as a comparison of area available to the average tree with crown area of open grown trees of the same d.b.h. The linear relations between $\log_e$ (TPA) and $\log_e$ (QMD) in stands of near-maximum ("normal") density, and between $\log_e$ (crown width) and $\log_e$ (d.b.h.) for open grown trees (Curtis 1970), plus the fact that in normal stands, SDI and CCF have approximately constant values independent of site index and age, indicate that SDI and CCF are preferable to bole area as measures of relative competition across a range of tree sizes and ages. They are also much more widely used.

The near absence of mortality because of mountain pine beetles at SDIs below 170 at Twin Lakes (fig. 5) and the low instances of mortality at SDIs below 170 at Snow Creek (fig. 6) confirms the findings of others (Mitchell and others 1983, Peterson and Hibbs 1989). Plots in both studies are surrounded by unthinned stands, and the build-up of beetle populations in the unthinned areas probably influenced mortality levels that occurred in the thinned plots. Managing lodgepole pine at densities that do not exceed an SDI of 170 when 9-inch diameter trees are present evidently lowers the probability of serious mountain pine beetle outbreaks.

The concave curvilinear decrease in diameter growth with increasing stand density (figs. 7 and 14) is commonly found in thinning and LOGS studies and produces large differences in tree diameters with treatments over time. Higher live crown ratios (figs. 37 and 38) usually develop with increased growing space also. More pronounced differences in crown ratios with GSL were found in the young Twin Lakes stand than in the old Snow Creek stand. The influence of early spacings on tree diameters is evident when diameters of the LOGS and spacing plots at Twin Lakes are compared (table 1). Stands of large-diameter trees with high live crown ratios can be produced in a short period through density management at early stand ages. Such stands may be preferred habitat for some wildlife species, and it might be important to grow these stands on a portion of the landscape (Hayes and others 1997) even though the large limb sizes and perhaps greater stem taper for the trees might reduce their value (Ballard and Long 1988).

No significant ($p \leq 0.10$) relation of height growth to stand density was found (figs. 8 and 15) in these studies. This is an insensitive comparison, because only two replications were available and because some height growth measurements were made with height poles, which are inherently inaccurate. The response of height growth to spacing was erratic in a study in northeastern Oregon (Cochran and Dahms 1998). Like the Snow Creek results (fig. 15), height growth seemed to increase with spacing during some periods, decrease with spacing during other periods, and not differ with spacing during still other periods in the northeastern Oregon study where spacing treatments were initiated at a young age. Mixed results for height growth response to thinning have been reported for other lodgepole pine studies (Johnstone 1985), and site quality, stand age, and past stand history all may influence height growth response of lodgepole pine after thinning.

The curvilinear increases in gross basal area and gross total cubic-volume growth with increasing stand density (figs. 9, 10, 16, 17, 39, and 40) have been found in other thinning and LOGS studies. Finding that maximum gross PAIs for basal area and total cubic volume occurred below the normal stand SDI (figs. 39 and 40) is, however, unusual.

The tapering off of gross cubic-volume PAIs at a relatively low stand density coupled with higher mortality at the higher stand densities resulted in GSL 3 (Twin Lakes) and GSL 4 (Snow Creek) producing the maximum cumulative net cubic-volume yields (figs. 25 and 26). Dahms (1964) indicates a net total cubic-volume yield of 4,018 cubic feet per acre for the highest lodgepole pine site in south-central Oregon at 57 years, and a net yield of 3,633 cubic feet per acre at 77 years for intermediate sites. Dahms' net total cubic-volume yield for the high site is lower than the cumulative net total cubic-volume yield of the three highest GSLs at 57 years in the Twin Lakes study (fig. 25) and his net total cubic yield for the intermediate site is lower than the cumulative net total cubic-volume yield for the four highest GSLs of the Snow Creek study at 77 years (fig. 26).

Merchantable cubic-volume PAIs of 7-inch and larger trees shifted from intermediate GSLs early in the Twin Lakes study to the highest GSL during the last period (figs. 11 and 13) primarily because of ingrowth. Maximum cumulative total and merchantable cubic-volume and board-foot yields, however, occurred at the intermediate GSL for the Twin Lakes study (figs. 27 and 28). Merchantable cubic volumes are highly related to tree size, and there was a lot of variation in tree size and merchantable volume growth within treatments for the Snow Creek study. Consequently, no significant ($p \leq 0.10$) differences in gross or net Scribner board-foot PAIs or cumulative net board-foot yields were detected at Snow Creek (tables 9 and 13). Merchantable and total cubic-volume PAIs and cumulative net yields do differ with GSL at Snow Creek (tables 9 and 13), but there seems to be little difference in these net yields between the four highest GSLs (fig. 26).

Dahms (1964) found that net total cubic-volume MAIs culminated at 70 years for unmanaged lodgepole stands in south-central Oregon. Values for these net cubic-volume MAIs ranged from 23.6 to 71 $ft^3 \cdot acre^{-1} \cdot yr^{-1}$. Higher net cubic-volume MAIs were found in the Twin Lakes study for the three highest GSLs (fig. 29) even though culmination perhaps has occurred only for GSL 1. Apparent culminations for GSLs 3 and 4 at Twin Lakes (fig. 29) likely are due to windfall mortality in the last period. Comparisons of the MAI curves for Snow Creek (figs. 33, 34, 35, 36) with mortality (table 5) indicates that apparent culmination of MAIs for all GSLs except GSL 2 is due to mortality in the last period (1988-92). No mortality occurred in the last period for GSL 2, and the MAIs for this GSL have not culminated even though the stand was 77 years old in 1992. Curtis (1994) examined estimates of MAIs for Douglas-fir obtained from four yield models using several management regimes. These models predicted a later culmination of MAI with density control but only small differences in volume production with and without commercial thinning. Perhaps some thinning regimes increase net cubic-volume production more for lodgepole pine than for Douglas-fir by eliminating the tendency of natural lodgepole pine stands to stagnate or by reducing mortality rates more for lodgepole pine than Douglas-fir. Results might have been somewhat different if GSLs had been defined as constant SDIs. The fact that constant bole area results in declining SDI over time probably tends to depress MAI with advancing age.

Rotation ages on National Forest lands are defined as the approximate age of MAI culmination (Public Law 94-588). This study has not continued long enough to determine the approximate age of culmination with certainty for either cubic or board-foot volume. Reduction of lodgepole pine mortality by properly managing stand density should, however, increase the age at which culmination of net MAI occurs.

Ponderosa pine outgrew lodgepole pine for the range of stand ages where the growth of both species was examined (33 to 58 years). The ponderosa pine plots were, however, on slightly sloping topography, and ponderosa pine should not be planted on lodgepole pine sites on flats and basins. Lodgepole pine female cones (Sorensen and Miles 1974) and new germinants are more frost tolerant than those of ponderosa pine (Cochran and Berntsen 1973), and ponderosa pine on flats usually becomes established under a lodgepole pine canopy (Cochran 1984). Most planted ponderosa pine seedlings do not develop normally when planted in openings on lodgepole pine flats. Repeated radiation frosts during the growing season retard the growth rates of planted ponderosa pine seedlings, and they take the form of stunted bushes. Planted lodgepole pine seedlings on these sites are not significantly damaged by radiation frost (Cochran 1984).

Spacings for precommercial thinnings depend in part on future markets. For these thinned plots, diameters of the smallest and largest trees were about 78 and 122 percent of the plot QMD. If no trees smaller than 5.8 inches could be sold, stand QMD would be 7.4 inches, and the largest trees would be 9 inches at the time of commercial entry. Because stands would be susceptible to severe mountain pine beetle mortality at SDIs greater at 170 with the presence of 9-inch trees, the SDI should not exceed 170 at the first commercial entry. Rearranging equation (1) and solving for TPA for an SDI of 170 and a QMD of 7.4 inches produces 287 TPA or a spacing of 12.3 feet. A reasonable leave tree density after this and future commercial entries would be SDI 114. Keeping the stand between SDI 114 and 170 (41 and 61 percent of the normal 277) should result in capturing between 63 and 87 percent of the total cubic-volume production (figs. 39 and 40). Similar reasoning can be used to develop other precommercial thinning levels if some larger minimum salable size is anticipated. If much smaller trees can be sold and a commercial entry can be made before the largest trees reach 9 inches d.b.h., then an SDI of 207 (75 percent of the normal 277) can be considered as a reasonable target for the first commercial entry and spacings after precommercial thinning can be estimated from the estimated QMD associated with the minimum salable tree size.

Unmanaged lodgepole pine stands in south-central Oregon are relatively short lived in part because of SDI-tree size-pine beetle relations. Few stands are older than 120 years, and few trees exceed 15 inches d.b.h. The QMDs for unmanaged stands seldom exceed 10 inches. Early spacing control coupled with later commercial thinnings to keep stand densities between SDI 114 and SDI 170 should reduce mortality considerably, allow most of the wood produced to be captured by salable trees, and greatly increase QMDs and live crown ratios over unmanaged stands at the same age. These stands would be more pleasing visually and their rotation ages may be longer. The impact of thinning lodgepole pine on various species of wildlife should be investigated.

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 per acre (ft^2 per acre)= 0.2293 square meter per hectare
1 cubic foot per acre (ft^3 per acre) = 0.06997 cubic meter per hectare
1 tree per acre = 2.471 trees per hectare

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