and raspberry fruits by *Botrytis cinerea* Pers Ann. Appl. Biol. 50:569–575.

MATTHEWS, R. G. 1981. Contrasting approaches to containerized seedling production. P. 115–122 *in* Proc. Canadian Containerized Tree Seedling Symp., Scarratt, J. B., C. Glerum, and C. A. Plexman (eds.). Can. Dep. Environ., O-P-10. Toronto, Ont.

PETERSON, M J , J R SUTHERLAND, AND S E TULLER. 1988. Greenhouse environment and grey mould of container-grown Douglas-fir seedlings. Can. J. For. Res. 18:974–980.

SUTHERLAND, J. R., G. M. SHRIMPTON, AND R. N. STURROCK. 1989. Diseases and insects in British Columbia forest seedling nurseries. B.C. Ministry of Forests/Forestry Canada FRDA Rep 065.

SUTTON, J. C., T. J. GILLESPIE, AND P. D. HILDEBRAND. 1984. Monitoring weather factors in relation to plant diseases. Plant Dis. 68:78–84.

ZAR, J. H. 1984. Biostatistical analysis. Prentice-Hall, Englewood Cliffs, NJ. 718 p.

Spacing and Shrub Competition Influence 20-Year Development of Planted Ponderosa Pine

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*ABSTRACT. Growth and stand development of ponderosa pine (*Pinus ponderosa*) were monitored for 20 years after planting at five different square spacings (6, 9, 12, 15, and 18 ft) in the presence or absence of competing shrubs on the westside Sierra Nevada. Mean tree size was positively correlated and stand values negatively correlated with spacing in the absence of competing shrubs. Trees growing with competing shrubs attained 76% of the diameter, 80% of the height, and 58% of the cubic volume of trees free of shrub competition when all spacings were combined. This study suggests that the major effect of shrub competition in ponderosa pine plantations on good sites is to lengthen the rotation.*

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Initial spacing has long been recognized as a fundamental question in silviculture and widely reported in the literature (Evert 1973, 1984, Sjolte-Jorgensen 1967). But reports on ponderosa pine are few, especially those dealing with the influence of tree spacing and shrubs on long-term growth on a productive site. Results of a 20-year study on the west slope of the Sierra Nevada are reported here which extend 12-year results reported earlier (Oliver 1979).

STUDY ENVIRONMENT

The plantation was established on a clearcut on the Challenge Experimental Forest, Yuba County, CA, at 2650-ft elevation, near the lower edge of the mixed-conifer forest type. Slopes range from 2 to 10%, face south and southeast, and are flat in profile. Summers are hot and dry and winters are cool and wet at this elevation. Daily average temperatures range from 75°F in July and August to 43°F in December. Annual precipitation, measured at Challenge since 1937, averages 68 in., about 98% of which falls between October and May. Soil is a deep (>5 ft), weathered Aiken Xeric Haplohumult, found extensively in the Sierra Nevada. Site Index is estimated to be 110 ft at 50 years (Powers and Oliver 1978).

FIELD DESIGN AND ESTABLISHMENT

In March 1966, 1-0 ponderosa pine from the appropriate seed zone was hand-planted at staked locations in two randomized blocks. These blocks, each containing five rectangular plots, were planted at square spacings of 6, 9, 12, 15, and 18 ft.

The effect of shrubs on tree growth at these spacings was tested by a split plot design. On one half, chosen randomly, shrubs were allowed to develop naturally. The other half was kept shrub-free. Each divided plot contained 12 trees to be measured and was surrounded by a buffer of at least 24 ft, minimally containing two rows of trees. Therefore, split plots with buffer varied in area from 0.11 ac for 6-ft spacings to 0.36 ac for 18-ft spacings. The entire experiment covered 4.31 ac.

In treated plots, woody vegetation was killed by 2,4,5-T herbicide applied by hand sprayer in the second and fourth years after planting. Subsequent shrub seedlings were grubbed out by hand. The influence of forbs and bracken fern (*Pteridium aquilinum* var. *lanuginosum*), which occupied the understory in the absence of a woody understory, was not evaluated in this study.

MEASUREMENTS AND ANALYSES

The following data were recorded for the study trees in even-numbered years:

1. Stem diameter at 1 ft, breast height (dbh), and midcrown for trees taller than 20 ft.
2. Total height.
3. Crown width—mean of two measurements—at widest diameter and at right angles.
4. Height to first live whorl.
5. Mean diameter of branches in whorl at or just above breast height.

Cubic-foot volumes inside bark were determined by dividing outside bark readings by 1.1949 and computing the stem segments as truncated cones from groundline to tip. Board-foot volumes were determined from Biging (1983). Cylindrical Form Factors (CFF) were calculated as the ratio of tree volumes inside bark in ft^3 to the volume of a cylinder with a diameter equal to dbh outside bark and a length equal to total tree height.

Woody vegetation was sampled in the 10th, 14th, and 20th years in treated plots. Circular 0.0025-ac plots were established at random locations within the area containing trees to be measured. Because 25% of each area containing trees to be measured was sampled, the number of shrub sample plots varied with tree plot size. Within each plot, shrubs were measured for mean maximum crown diameter (two readings taken at right angles) and mean crown height. Dominant shrub species were whiteleaf manzanita *(Arctostaphylos viscida)*, Indian manzanita *(A. mewukka)*, deerbrush *(Ceanothus integerrimus)*, small numbers of Sierra gooseberry *(Ribes roezlii)*, and sprouts of California black oak *(Quercus kelloggii)* and tanoak *(Lithocarpus densiflora)*.

Spacing treatment means and their standard errors for each tree and stand total were calculated (Table 1), and graphs were prepared separately according to shrub treatment (Figures 1 and 2). A split-plot analysis of variance with five spacings, with and without competing shrubs, was calculated for the entire experiment at age 20 (Table 2).

Table 1. Tree means and stand totals (with their standard errors) for ponderosa pine 20 years after planting to five spacings with and without shrub understories.

Square spacing (ft)	Stem: Dbh (in.)	Stem: Avg. height (ft.)	Stem: Avg. CFF[1]	Crown: Width (ft.)	Crown: Percent	Crown: Av. branch diameter in.	Stand: Basal area (ft²/ac)	Stand: Volume total (ft³/ac)	Stand: Volume merch.[2] (bf/ac)
				Without shrubs					
6	4.7 ± <.1	25 ± 2	.424 ± .028	8 ± <1	57 ± 2	0.9 ± <.1	130 ± 21	1316 ± 252	0 ± 0
9	6.7 ± .3	30 ± 1	.368 ± .002	11 ± 1	65 ± 1	1.2 ± .1	131 ± 12	1474 ± 184	0 ± 0
12	8.1 ± .2	34 ± 1	.343 ± .006	13 ± 1	70 ± 2	1.5 ± .2	107 ± 5	1263 ± 101	324 ± 310
15	8.8 ± .3	34 ± 1	.337 ± .003	14 ± 1	74 ± 2	1.7 ± <.1	81 ± 5	932 ± 86	997 ± 954
18	10.3 ± .2	36 ± <1	.333 ± .011	16 ± 1	74 ± <1	1.7 ± <.1	78 ± 2	958 ± 1	2616 ± 51
				With shrubs					
6	4.1 ± .1	23 ± 2	.420 ± .005	7 ± <1	52 ± 2	0.7 ± <.1	102 ± 13	1027 ± 205	0 ± 0
9	5.6 ± .1	24 ± <1	.399 ± .002	9 ± <1	59 ± 1	1.0 ± <.1	93 ± 3	940 ± 3	0 ± 0
12	6.1 ± .7	26 ± 4	.408 ± .031	10 ± 1	64 ± 2	1.1 ± .1	62 ± 14	656 ± 200	0 ± 0
15	6.0 ± <.1	25 ± 1	.392 ± .009	10 ± <1	62 ± <1	1.0 ± <.1	36 ± 1	378 ± 32	0 ± 0
18	7.5 ± .4	30 ± 1	.369 ± .004	12 ± 1	68 ± <1	1.2 ± .1	41 ± 4	449 ± 52	146 ± 139

[1] Cylindrical form factor.
[2] Board feet (Scribner) from a 1-ft stump to 6-in. top for trees 10-in. dbh and larger (Biging 1983).

RESULTS

Mortality was light and had little effect on results. In the first year, 23 trees or 1.5% of all trees planted in the experiment died. These trees and those that died during the next 2 years were replaced. After 20 years, 6 measurement trees were dead, 5 of which were in the 6-ft spacing plots.

Spacing

Spacing strongly influenced all tree and stand characteristics 20 years after planting in plots maintained free of shrubs (Table 2). Differences among spacings in these characteristics have continued to enlarge (Figures 1 and 2) since the last report at age 12 (Oliver 1979).

Mean stand dbh at age 20 was 4.7 in. for 6-ft spacing plots compared with 10.3 in. for 18-ft spacing plots (Table 1). Over this same range of spacings, mean height varied from 25 to 36 ft. Crown size, as measured by crown width and percent live crown, was greater for widely spaced trees than for those more narrowly spaced. Crowns ranged in width from 8 ft in the 6-ft spacing plots to a mean of 15 ft in the two widest spacings where crowns have yet to close. Live crowns were 74% in the 15- and 18-ft plots, but were progressively more restricted at progressively narrower spacings.

Quality of the stem for lumber production can be estimated from branch diameter and cylindrical form factor (CFF). Mean branch diameter almost doubled from 0.9 in. for trees spaced 6 by 6 ft to 1.7 in. for trees spaced 18 by 18 ft. All branches of closely spaced trees in shrub-free plots were dead by age 14. Tree stems were less cylindrical at wider spacings than they were at narrower ones. CFF decreased from 0.424 for trees spaced 6 ft apart to 0.333 for trees spaced 18 ft apart.

In contrast to mean tree characteristics, stand totals of basal area and volume/ac tended to be negatively correlated with spacing (Table 1). Exceptions to this tendency were: (1) basal area/ac of 9-ft spacing plots which equalled that of 6-ft spacing plots—about 130 ft²; (2) basal area/ac of 15- and 18-ft spacing plots which had similar basal areas/ac—about 80 ft²; (3) total stem volumes/ac of 9-ft

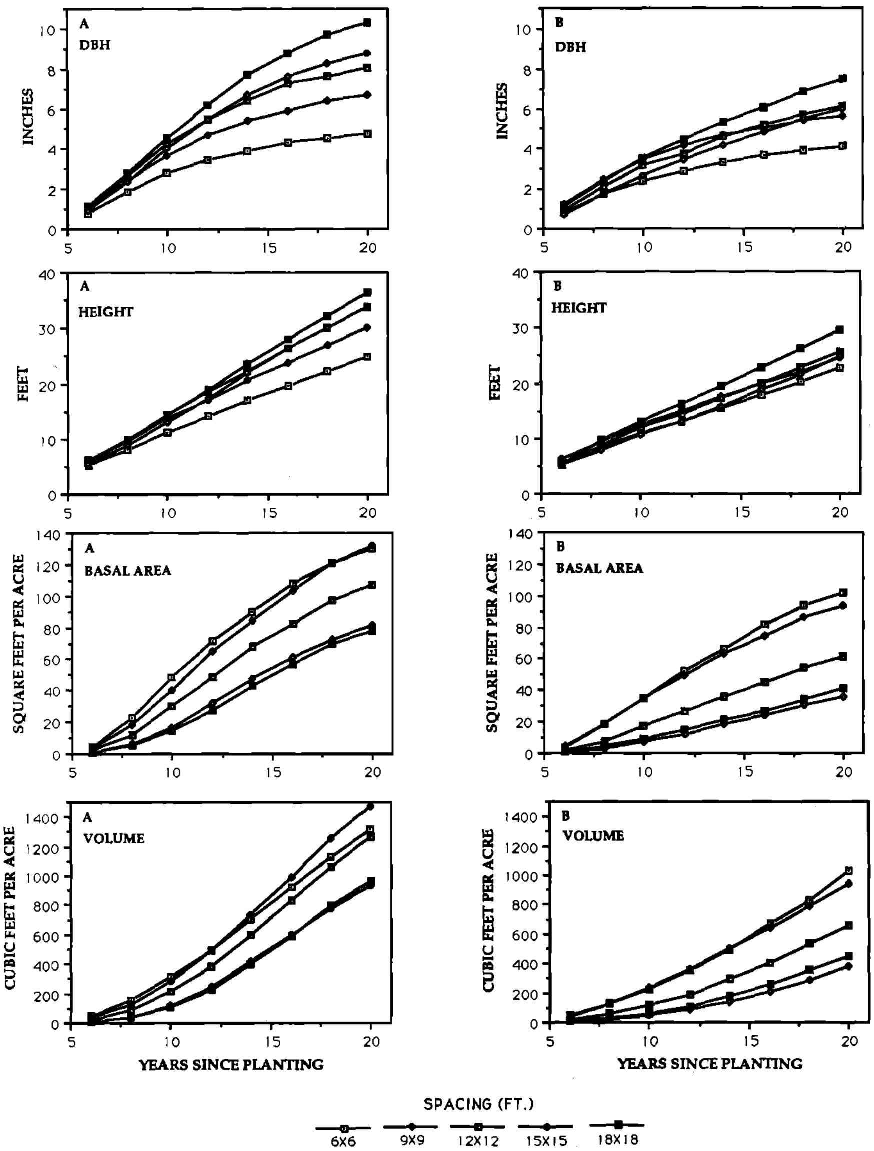

Figure 1. Tree and stand characteristics for ponderosa pine planted to five initial spacings and growing for 20 years without (A) and with (B) shrub competition on a productive site.

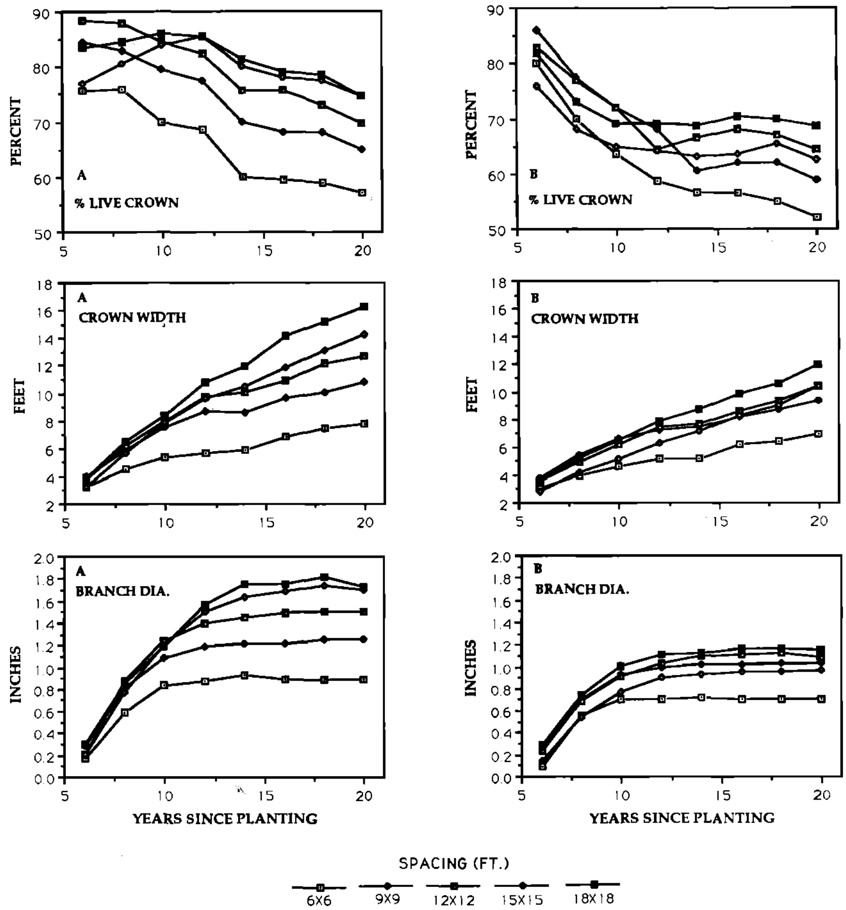

Figure 2. Crown characteristics for ponderosa pine planted to five initial spacings and growing for 20 years without (A) and with (B) shrub competition on a productive site.

spacing plots which contained more volume than 6-ft spacing plots—1474 vs 1316 ft^3/ac; and (4) the volume of 958 ft^3 in 18-ft spacing plots which had surpassed the 932 ft^3 found in 15-ft spacing plots.

Shrubs

Trees competing with shrubs were significantly smaller in all tree and stand characteristics than were trees growing without such competition (Table 2). On average, trees in shrub plots were 75% of the diameter, 80% of the height, 63% of the basal area/ac, and 53% of the volume/ac of trees in plots free of shrubs. The disparity in all tree and stand characteristics increased at wider spacings. For example, the percentage loss in total volume/ac for each spacing at 20 years was:

Square spacing (ft)	Volume loss (%)
6	22
9	36
12	48
15	59
18	53

Shrubs restricted crown size. Crown widths and live crown percents were both significantly smaller in shrub plots regardless of spacing (Table 2). At the closest spacing, adjacent crowns were touching by year 16 whether shrubs were present or not. At the 9-ft spacing, however, crown closure was delayed from the 16th until the 20th year On average, no crowns of trees spaced wider than 9 ft were closed at age 20 when shrubs were present. In contrast, crowns had closed by the 18th year at the 12-ft spacing when shrubs were absent.

Stem quality, as measured by branch diameter and CFF, was improved at the wider spacings in plots containing shrubs compared with those without. Branch diameters ranged from 0.7 in. for trees spaced 6 ft apart to 1.2 in. for trees spaced 18 ft apart, averaging 71% of the diameter of tree branches in shrub-free plots By 12 years, nearly all branches at breast height were dead regardless of spacing and, as a result, size differences among spacings were less than in shrub-free plots. CFF was 10% higher over all spacings in plots with shrubs than in similar trees in plots without shrubs. Again, differences among spacings were not as pronounced as they were in shrub-free plots.

DISCUSSION

Twenty-year development of brush-free ponderosa pine in this spacing trial was in general accordance with that reported by Evert (1971) and Sjolte-Jorgensen (1967). Although differences in tree characteristics among spacings are expected to remain constant (Sjolte-Jorgensen 1967), differences in total stem volume and basal area/ac among spacings are expected to narrow over time (Evert 1971, Cromer and Pawsey 1957).

Firm recommendations on spacing remain tentative. In terms of lumber production, the narrow spacing of 6 ft by 6 ft is too narrow without precommercial thinning. Stem quality considerations aside, diameter growth is slow, and the next wider spacing has overtaken it in cubic volume production. The widest spacing of 18 by 18 ft, on the other hand, appears too wide although it produces the greatest board foot volumes by age 20 (Table 1). Although diameter growth is rapid, time to first commercial entry may be delayed because volume production and basal area/ac may never match that of plots with trees more closely spaced if such stands suffer

Table 2. Analysis of variance of tree and stand characteristics of ponderosa pine 20 years after planting to five spacings with and without shrub understories.

		Probability of chance differences when characteristic was:							
Source	Df	Dbh (in.)	Height	Crown width	Live crown (%)	Branch diameter (in.)	Basal area (ft^2/ac)	Total volume (ft^3/ac)	Cylindrical form factor
			.... (ft)						
Block (BL)	1	0.25	0.03	0.58	1.00	0.13	0.04	0.01	0.35
Spacing (SP)	4	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.04
BL*SP	4	0.41	0.16	0.91	0.56	0.67	0.17	0.08	0.22
Shrubs (SH)	1	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
SP*SH	4	0.03	0.13	0.30	0.22	0.04	0.68	0.87	0.19

damage or mortality. If, however, intermediate cuttings are not planned and a diverse stand structure is desired for wildlife, esthetics, or other considerations, the widest spacing is likely to be appropriate. Present market conditions and an intermediate harvest suggest that the 12- or 15-ft spacings are best. The 12-ft spacing plots without shrubs, for instance, achieved a mean stand diameter only 21% less and a cubic volume only 14% less than the maximum found in this study.

Shrub seeds germinated abundantly, and seedlings grew rapidly on plots where they were allowed to develop. By the 10th year, shrub cover averaged 77% and stabilized there during the next 10 years. Shrubs continued to grow in height, however, from 4.6 ft in the 10th year to an average of 8.5 ft in the 20th year. Few ponderosa pines were overtopped by shrubs owing to the rapid growth in height of the pines, and the complete site preparation that had eliminated all existing shrubs and nearly all hardwood sprouts.

The presence of competing shrubs has slowed growth and improved stem quality markedly at all spacings. The practical significance of this growth loss becomes apparent when current trends in mean dbh are projected to first commercial entry for the three intermediate spacings with and without competing shrubs. A thinning from below is assumed when mean stand dbh is 12 in.

Square spacing (ft)	Shrubs present	Shrubs absent
	.... (yr)	
9	50	37
12	36	29
15	32	25

Shrub competition appears to add 7 years to the time for first commercial entry for the 12- and 15-ft spacings and more years for the 9-ft spacing. Expressed in another way, shrub competition has reduced yields the equivalent of about 20 Site Index units (Powers and Oliver 1978)—from Site Index 110 to Site Index 90 (based on yields at age 20 from Oliver and Powers 1978). This translates to a loss of 1500 ft^3/ac, or 20%, at age 40 years for trees spaced 12 by 12 ft. Losses are likely to be proportionally greater on poorer sites than on better ones (McDonald and Oliver 1984). Barrett (1982) demonstrated a loss of production equivalent to 20 Meyer (1938) site index units or 32% in yield at 40 years in central Oregon. Greater losses of 69% were found for a plantation under severe shrub competition on a marginal timber site in California's North Coast Range (Oliver 1984) (Data on file at the Pacific Southwest Forest and Range Experiment Station, USDA Forest Service, Redding, CA).

Close initial spacing was not an effective tool to capture the site's resources from severe shrub competition. The interaction between spacing and shrub competition was weak for most attributes (SP*SH in Table 2), and what did exist appears to result from intertree competition being dominant at close spacings and shrub competition being dominant at wide spacings. Barrett (1982) found a similar relationship in central Oregon. I could not establish that shrub coverage was declining at closer spacing, but the techniques used in this study were not designed to measure this change well. Even if shrub amounts are declining in plots with closely spaced trees, the resulting loss in growth makes this technique unacceptable.

Tree crowns will close eventually for stands with shrub understories at all spacings, and when they do, an increasing proportion of the site's resources will be captured by the trees. Eventually, stand growth rates should equal that of trees free of shrubs—the Type I growth response of Snowdon and Waring (1984). From this likely scenario it follows that, given time, plots which had shrub understories will possess the same standing volume as shrub-free plots. The significant impact of shrub competition on this productive site, therefore, is a time delay which can cause a substantial loss in plantations managed on short rotations. □

LITERATURE CITED

BARRETT, J. W. 1982. Twenty-year growth of ponderosa pine saplings thinned to five spacings in central Oregon. USDA For. Serv. Res. Pap. PNW-301. 18 p.

BIGING, G. S. 1983. Volume tables for young-growth mixed conifers of northern California based upon the stem analysis data. Rev. Draft. Calif. For. Yield Coop. Univ. Calif. Res. Note 7. 60 p.

CROMER, D. A. N. AND C. K. PAWSEY. 1957. Initial spacing and growth of *Pinus radiata*. For. Timber Bur. Bull. 36. Canberra, Australia. 42 p.

EVERT, F. 1971. Spacing studies—a review. Can. For. Serv. For. Manage. Inst. Inform. Rep. FMR-X-37. 95 p.

EVERT, F. 1973. Annotated bibliography on intitial tree spacing. Can. For. Serv. For. Manage. Inst. Inform. Rep. FMR-X-50. 149 p.

EVERT, F. 1984. An update (1970/71–1982) of the annotated bibliography on initial tree spacing. Can. For. Serv. Petawawa Natl. For. Inst. Inform. Rep. PI-X-44. 157 p.

MCDONALD, P. M., AND W. W. OLIVER. 1984. Woody shrubs retard growth of ponderosa pine seedlings and saplings. P. 65–89 *in* Proc. 5th annual forest vegetation management conf. For. Veg. Manage. Conf., Redding, CA.

MEYER, W. H. 1938. Yield of even-aged stands of ponderosa pine. USDA Tech. Bull. 630. 59 p.

OLIVER, W. W. 1979. Early response of ponderosa pine to spacing and brush: Observations on a 12-year-old plantation. USDA For. Serv. Res. Note PSW-341. 7 p.

OLIVER, W. W. 1984. Brush reduces growth of thinned ponderosa pine in northern California. USDA For. Serv. Res. Pap. PSW-172. 7 p.

OLIVER, W. W., AND R. F. POWERS. 1978. Growth models for ponderosa pine: I. Yield of unthinned plantations in northern California. USDA For. Serv. Res. Pap. PSW-133. 21 p.

POWERS, R. F., AND W. W. OLIVER. 1978. Site classification of ponderosa pine stands under stocking control in California. USDA For. Serv. Res. Pap. PSW-128. 9 p.

SJOLTE-JORGENSEN, J. 1967. The influence of spacing on the growth and development of coniferous plantations. Int. Rev. For. Res. 2:43–94.

SNOWDON, P., AND H. D. WARING. 1984. Long-term nature of growth responses obtained to fertilizer and weed control applied at planting and their consequences for forest management. P. 701–711 *in* Proc. symp. on site and productivity of fast growing plantations. Vol 2. IUFRO. Pretoria, S. Afr.