Young-Growth Redwood Stands Respond Well To Various Thinning Intensities

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ABSTRACT. *Three 45- to 50-yr-old redwood* (Sequoia sempervirens) *sawtimber stands spanning a substantial portion of the species' commercial range were thinned to three stocking levels. Treatments were low thinnings leaving 25%, 50%, 75%, and 100% of the before-treatment stand density, expressed as basal area/ac. Trees were measured for dbh, and a sampling of heights was taken for volume estimations at 0, 5, 10, and 15 yr after thinning. Leave trees responded strongly to the increased growing space, in spite of the vigorous stump sprouting of cut trees. Stand growth in basal area and volume varied narrowly among treatments. Overall, volume production was significantly different only in the 25% leave plots where sites were not fully occupied by the leave trees. Results illustrate the similarity between two growth/growing stock theories which appear to conflict. We conclude that 50% of the basal area in fully stocked stands could be removed in a low thinning without significant loss in volume production. West. J. Appl. For. 9(4):106–112.*

Redwood *(Sequoia sempervirens)* is one of the most productive timber types in the United States, because of the fortunate combination of productive soils, long growing season, and inherent growth rate. Nevertheless, young-growth stands, which comprise 96% of the land in redwood available for timber harvest (California Dept. of Forestry and Fire Protection 1990), must be managed on a scientific basis to realize redwood's productive potential. Stocking control is an effective technique for accomplishing this objective.

Surprisingly few formal thinning trials have been undertaken with redwood. Carr (1958) conducted a thinning experiment in a 77-yr-old stand on Site Index 190 land (Lindquist and Palley 1963). His results suggest that young-growth redwood may respond well to thinning. But statistically valid information is lacking on its responsiveness to a variety of precisely defined stocking levels and on what might be the optimum stand density for various management objectives. We undertook to answer these questions with 15-yr results from a study of levels of growing stock in three young redwood stands spanning a substantial portion of the species' commercial range. This study is the first of its kind designed to produce guidelines for commercial thinning in young redwood. Interim results from one study location have been reported previously (Henry 1991, Lindquist 1982, 1988).

Methods

The study was installed at three locations in dense second-growth redwood originating from sprouts about 45 to 50 yr before treatment (Table 1). Species composition varied from north to south among the installations. Western hemlock *(Tsuga heterophylla)*, red alder *(Alnus rubra)*, and coast Douglas-fir *(Pseudotsuga menziesii)* in the two northerly locations, and tanoak *(Lithocarpus densiflorus)* and Pacific madrone *(Arbutus menziesii)* in the southern location were minor components. All three installations are on middle to upper northerly slopes generally less than 50%, with Site Indexes of about 180 for base age 100 (Lindquist and Palley 1963) or 125 for base age 50 (Wensel and Krumland 1986). Stands were densely stocked. Numbers of trees per acre exceeded that shown in Lindquist and Palley's (1963) yield tables by 212%, on the average, but because mean dbh was only 75% of yield table values, basal areas/ac averaged only 15% greater. The installations (Whiskey Springs—Lat. 39°22′N, Long. 123°40′W; Korbel—Lat. 40°52′N, Long. 123°58′W; and Crescent City—Lat. 41°43′N, Long. 124°08′W) all receive between 55 and 70 in. of rainfall

NOTE: We thank the Miller-Rellim Redwood Co., Simpson Timber Co., and California Department of Forestry and Fire Protection's Jackson Demonstration State Forest, on whose lands the study was done.

Table 1. Site and stand characteristics before thinning young-growth redwood stands in northwestern California.

Location	Soil taxonomy	Site index L&P[1]	Site index W&K[2]	Trees (no.)	Dbh (in.)	Basal area (ft^2/ac)
Crescent City	Mollic hapludalf	176	123	305	16.4	447
Korbel	Typic tropohumult	177	124	470	14 5	536
Whiskey Springs	Typic tropohumult	187	128	515	12.0	401

[1] Base age 100 yr (Lindquist and Palley 1963)
[2] Base age 50 yr (Wensel and Krumland 1986)

annually. Little rain falls between May and October, but the installations, 9 miles or less from the coast, are shrouded by fog most mornings during the summer.

Four stand density treatments were assigned to each of three plots in a randomized block design at Korbel and Crescent City, and in a fully randomized design at Whiskey Springs. The 12 plots were selected in the most uniform portion of each stand, were square and 0.2 ac, with a buffer strip 20 ft wide to be treated similarly. Four residual stand densities were chosen for study—25, 50, 75, and 100% of the mean basal area as measured on the three control plots at each location (100% treatment). Differences in pretreatment basal area among the three installations, therefore, caused the actual basal area stand densities to vary slightly (Table 2).

Treatments were created by removing hardwoods and, then, thinning the softwoods from below, favoring redwoods. After damaged trees and trees of poor vigor were removed, thinning progressed upward through the diameter classes, with some compromise to attain a reasonably uniform spacing, until the target basal area was achieved. Cut trees were limbed and bucked, and the merchantable logs skidded from the study plots by crawler tractors. All hardwood and conifer stems less than 4.5 in. dbh were felled. Slash was lopped and left in place. One installation was logged each year between 1971 and 1973.

Measurements and Analysis

Immediately after thinning, all trees were tagged, were described by species, and were measured for dbh to the nearest 0.1 in. Total height to the nearest foot was measured on 6 to 15 randomly selected trees. Breast-height age of 2 to 5 dominants on each plot was measured to determine site index. Diameters and heights were remeasured on the same trees after 5, 10, and 15 growing seasons.

Mean plot characteristics based on trees larger than 4.5 in. dbh after thinning (Table 2) and after each remeasurement were calculated as follows:

Table 2. Mean stand characteristics and standard errors by treatment immediately after thinning three young-growth redwood stands in northwestern California and 15 yr later (trees larger than 4.5 in. dbh).

Location	Treatment	Trees (ac)	Dbh (in.)	Net basal area (ft^2/ac)	Net volume Cubic[1] (ft^3/ac)	Net volume Bf[2] (Scribner/ac)
				After thinning		
Crescent City	25	52	19 6±0.5	107±2	3,413±99	17,915±528
	50	95	20 3±0.6	211±4	6,823±154	36,109±1312
	75	155	19 6±1.4	316±7	10,250±439	53,710±4159
	100	297	16.2±0.6	421±11	13,450±488	64,120±4134
Korbel	25	53	20.9±1.2	124±2	4,175±218	22,422±1917
	50	125	19.2±0 8	249±6	8,427±406	44,396±2950
	75	185	19 3±0.4	373±7	12,327±407	64,505±2944
	100	437	14.5±0.5	496±9	16,022±1127	71,436±6903
Whiskey Springs	25	45	20.3±0.6	100±1	3,413±235	18,887±2276
	50	120	17 9±1 3	201±1	6,392±403	30,928±3275
	75	240	15 3±0.7	301±0	10,256±573	46,695±3880
	100	630	10.9±0.3	408±24	11,206±198	35,210±3820
				15 years later		
Crescent City	25	52	28 4±1.0	225±5	8,065±278	49,620±2601
	50	93	26 3±0 7	349±13	13,120±326	79,776±1732
	75	155	23 2±1 7	443±12	17,408±1058	101,933±8502
	100	265	19 0±0.5	522±14	19,903±487	110,947±5230
Korbel	25	53	29.8±1.3	255±6	9,716±201	60,383±2319
	50	125	24 7±1 5	407±12	16,294±973	97,452±8489
	75	183	22 9±0 8	521±6	20,591±674	119,418±4646
	100	388	16 9±0 4	601±9	22,591±153	120,568±3769
Whiskey Springs	25	45	27 4±0 8	183±4	7,277±465	45,384±3212
	50	120	22 4±1 8	313±10	11,586±1303	66,134±9926
	75	235	18.1±0.9	414±5	16,757±694	86,899±5866
	100	588	12 7±0.2	511±6	17 208±1095	71 229±7548

[1] 1-ft stump to 5 0-in top diameter inside bark for trees larger than 4.5 in dbh.
[2] 1-ft stump to 8 0-in top diameter inside bark for trees larger than 10 5 in. dbh

- Mean dbh—quadratic mean diameter.
- Cubic volume—cubic-foot volumes (ft^3) from a 1-ft stump to a 5-in. top inside bark (Krumland and Wensel 1978) were estimated from measured dbh and total height. Local volume equations were computed for each treatment, species, and inventory date for each plot. These regression lines were computed using the tree volume and basal area of the trees whose heights were measured.
- Board-foot volume—board feet (bf) (Scribner) from a 1-ft stump to an 8-in. top inside bark (Krumland and Wensel 1978). Board-foot volumes were calculated using a method similar to that used for cubic-foot volumes.

Periodic annual increments (PAIs) were examined for statistical differences by two-way analysis of variance for repeated measurements (Table 3) (SAS 1988). Randomized blocks were used at Korbel and Crescent City, but a preliminary analysis showed that blocking was not statistically significant ($P > 0.10$), allowing all installations to be analyzed as completely randomized designs. Differences of special interest were tested further by Tukey's multiple comparison procedure after determining from Bartlett's test that variances were homogeneous. The probability that differences were due to chance was set at 0.05.

Linear regressions modeled trends of 15-yr PAIs in dbh, net stand basal area, and net stand ft^3 and bd-ft volume to stand basal area at the beginning of the period. Separate coefficients were fit for each location using indicator variables (Table 5).

Results

All growth parameters measured were significantly ($P < 0.01$) related to stand treatment, growth period, and location (Table 3). In general, growth rates for a given treatment were greatest at Korbel and least at Whiskey Springs (Figure 1, Table 4).

Diameter Growth

Averaged over the 15-yr period, mean PAI dbh of all trees declined as stand density increased—from 0.55 in. at 25% leave to 0.15 in. at 100% leave (Table 4, Figure 1A). The following equation form describes the curvilinear relationship for trees living through the 15-yr period.

$$PAI\ DBH = b_0 - b_1(\ln BA)$$

$$R^2 = 0.950 \quad S = 0.04 \text{ in.}$$

where $PAI\ DBH$ = annual dbh growth for the 15-yr period in inches, $\ln BA$ = natural logarithm of stand basal area at beginning of period in ft^2/ac, and coefficients b_0 and b_1 are as presented in Table 5.

Growth differences between treatments were less at the higher leave densities, such that for the first 10 yr, 25% and 50% leave densities were significantly different from each other and from the higher leave densities ($P < 0.05$), but 75% and 100% leave densities were not significantly different. During the last 5-yr period, diameter growth was statistically different among all treatments.

Basal Area Increase

Levels of leave densities had a statistically significant, but surprisingly small, influence on mean net PAI basal area/ac over the 15-yr period. Plots with 25% leave basal area grew 7.3 ft^2/ac, whereas plots with 50% leave basal area grew 9.1 ft^2—the most of any treatment. Growth declined at higher leave densities with 75% leave growing 8.6 ft^2 and growth of 100% leave dropping below that of 25% leave to 6.8 ft^2/ac (Table 4, Figure 1B). This relationship was described by the quadratic equation:

$$PAI\ BA = b_0 + b_1(BA) - b_2(BA)^2$$

$$R^2 = 0.688 \quad S = 0.94 \text{ ft}^2\text{/ac}$$

where $PAI\ BA$ = annual basal area increment for the 15-yr period in ft^2/ac, and coefficients b_0, b_1 and b_2 are as presented in Table 5.

The pattern of differences among the treatments changed with time period. For the first 5-yr period, basal area growth was similar for all but the 25% leave, which was significantly less. For the second 5-yr period, peak growth was obtained by 50% leave, which was significantly different from the lowest net growth obtained by 100% leave. During the last 5 yr, growth of 100% leave was significantly less than all other treatments ($P < 0.05$) at 5.6 ft^2, whereas 25% leave was second only to 50% leave at 8.3 ft^2/ac.

Volume Growth

PAI in net ft^3/ac, similar to basal area, varied significantly ($P < 0.05$) but narrowly among leave stand densities (Table 4), and the pattern was similar at each location (Figure 1C). Over the 15 yr, 25% leave produced significantly less volume

Table 3. Analysis of variance of tree and stand characteristics after thinning young-growth redwood stands in northwestern California.

		Probability of a greater 'F' value when characteristic was:							
					Volume				
			Basal area		Total		Merch		
Source	Df	Dbh (in.)	Net (ft^2/ac)	Gross	Net (ft^3/ac)	Gross	Net (bf/ac)	Gross
Location (L)	2	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Treatment (T)	3	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Growth period	2	<0.01	0.14	0.21	<0.01	<0.01	<0.01	<0.01
$L*T$	6	0.59	0.29	0.44	0.82	0.92	0.97	0.98

Table 4. Annual increments for 15 years after thinning three young-growth redwood stands in northwestern California (trees larger than 4.5 in. dbh).

Location	Treatment (% leave)	Dbh[1] (in.)	Net basal area[2] (ft^2/ac)	Net volume: Cubic[3] (ft^3/ac)	Net volume: Cubic[3] (%)	Net volume: Bf[4] (Scribner/ac)	Net volume: Bf[4] (%)
Crescent City	25	0.59	7.8	310	5.9	2114	7.0
	50	0.40	9.2	420	4.5	2911	5.4
	75	0.24	8.4	477	3.6	3215	4.4
	100	0.17	6.7	430	2.6	3122	3.7
Korbel	25	0.60	8.7	369	5.8	2531	6.8
	50	0.37	10.5	524	4.5	3537	5.4
	75	0.24	9.9	551	3.5	3661	4.2
	100	0.16	7.0	438	2.3	3275	3.6
Whiskey Springs	25	0.47	5.5	258	5.2	1766	6.0
	50	0.30	7.5	346	4.0	2347	5.2
	75	0.19	7.5	433	3.3	2680	4.2
	100	0.12	6.8	400	2.9	2401	4.8

1 Standard error from pooled variance is ±0.04 in.
2 Standard error from pooled variance is ±1.1 ft^2/ac
3 1-ft stump to 5.0 in top diameter inside bark for trees larger than 4.5 in dbh. Standard error from pooled variance is ±74 ft^3/ac.
4 1-ft stump to 8.0 in top diameter inside bark for trees larger than 10.5 in. dbh. Standard error from pooled variance is ±475 bf/ac

(312 ft^3/ac/yr) than was produced by any of the other treatments which averaged 447 ft^3/ac/yr and did not differ significantly among themselves. The relationship was described by the quadratic equation:

$$PAI\ FT^3 = b_0 + b_1(BA) - b_2(BA)^2$$
$$R^2 = 0.590 \qquad S = 66\ ft^3/ac$$

where $PAI\ FT^3$ = annual volume increment for the 15-yr period from a 1-ft stump to a 5-in. top inside bark in ft^3/ac, and coefficients b_0, b_1, and b_2 are as presented in Table 5.

Cubic volume growth tended to peak at 75% leave during the first 10 yr and at 50% leave during the last 5 yr at all locations.

The pattern of PAI bf/ac was similar to that of ft^3/ac in that the 25% leave produced significantly less—2137 bf—than did the higher leave densities, which averaged 3017 bf. Highest board-foot volumes tended to be produced at 75% leave during all periods and at all locations. Similar to PAI basal area and cubic-foot volume, the quadratic equation described this relationship well:

$$PAI\ BF = b_0 + b_1(BA) - b_2(BA)^2$$
$$R^2 = 0.619 \qquad S = 427\ bf/ac$$

where $PAI\ BF$ = board feet (Scribner) from a 1-ft stump to an 8-in. top inside bark, and coefficients b_0, b_1, and b_2 are as presented in Table 5.

Volume growth percents compounded over 15 yr, like absolute growth, were strongly related with treatment. When averaged for all locations, percent growth in ft^3 was 5.6 for the 25% leave, dropping about 1% for each increase in leave stand density to 2.7% for the 100% leave. Board-foot volume growth percents were about 1% higher for a given treatment than were cubic growth percents. Values declined from 6.6% at 25% leave to 4.0% at 100% leave.

Mortality

Mortality per acre over the 15-yr period averaged by location for each thinning level was:

Percent leave	Trees	Volume (ft^3)
25	0	0
50	1	78
75	2	88
100	40	288

Unthinned plots (100% leave) suffered the bulk of the mortality, but it was an insignificant 1.4% of the initial stand volume. Intertree competition was assumed to be the primary cause of mortality because tree death was almost entirely confined to trees of smaller diameters in the unthinned stands. Few differences in the pattern of mortality were observed among locations.

Discussion

Leave trees responded strongly to the increased growing space made available by thinning. Leave trees grew 3.7 times faster at 25% leave and 2.4 times faster at 50% leave when compared to diameter growth at 100% leave. This response is especially impressive considering the possible influence of sprout competition discussed below. Diameter growth response over the 15 yr of observation was such that 50% of the basal area was removed in a low thinning without reducing volume growth/ac significantly ($P < 0.05$). Although not statistically significant, volume production tended to peak at a current basal area stand density of about 350 ft^2/ac. This density was established initially in the 75% leave treatment and reached by the 50% leave treatment after 10 yr of growth. Because mortality was concentrated on trees of small diameter in subordinate crown classes, it had little influence on the stand density-volume growth relationship. Both gross and net PAI in volume declined at 100% basal area leave.

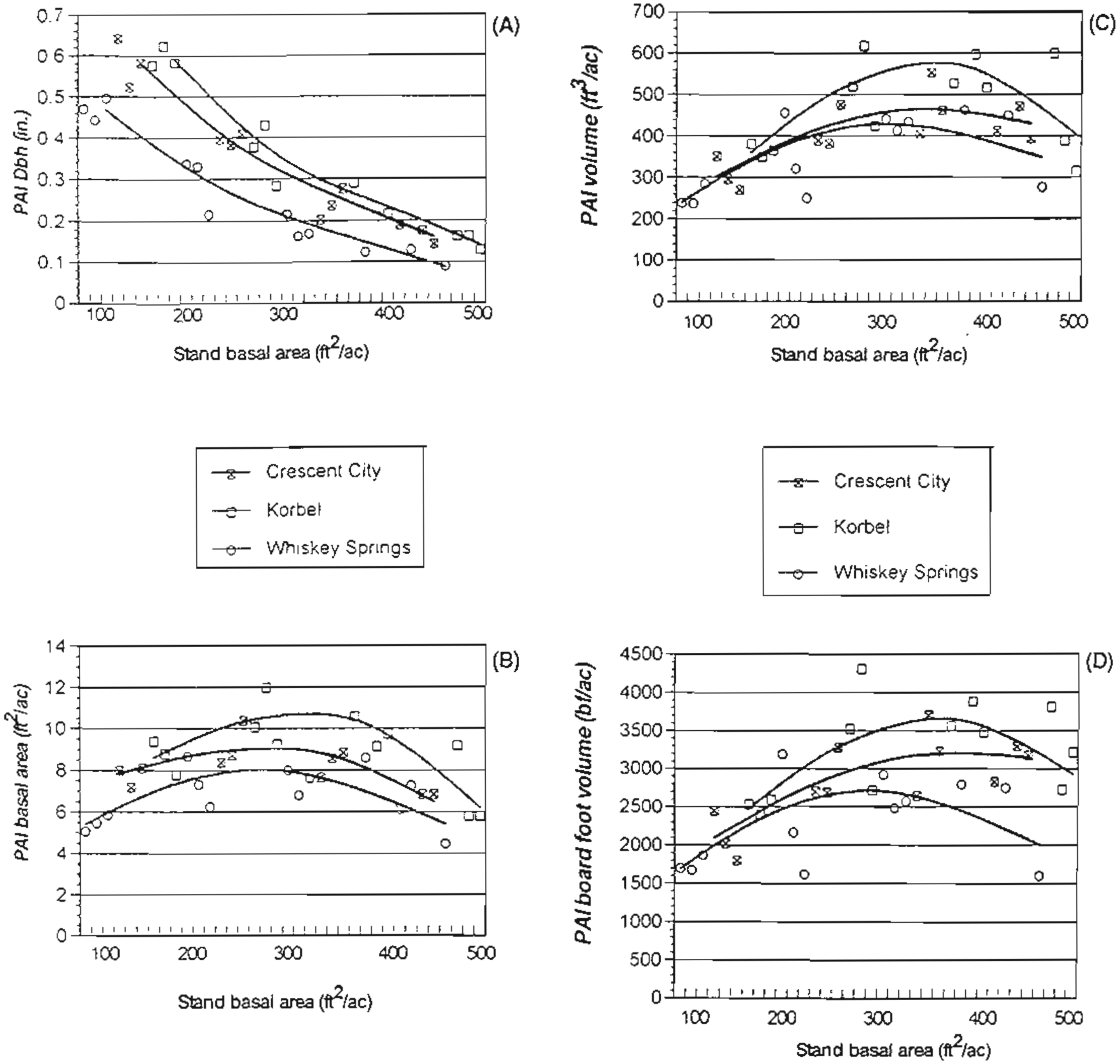

Figure 1. Commercial thinning of three stands of young-growth redwood in northwestern California strongly influenced periodic annual increments (PAI) in (A) diameter, (B) net basal area, and (C) net cubic-foot and (D) board-foot volumes for 15 yr.

The stand density-volume growth relationship found here suggests that the conflicting theories of Langsaeter (Daniel, Helms and Baker 1979) and Assmann (1970) may simply be two ways of looking at the same phenomenon. Forest managers realize that only large response differences can be measured operationally—those usually found statistically significant in studies such as the one reported here. Managers reading this paper would recognize that the volume growth response found for 50%, 75%, and 100% leave suggests that these densities are in Langsaeter's Zone III, within which the growth is nearly static, in spite of increasing stand density. The lower volume production at 25% leave would suggest that this treatment is either in Zone I or II, within which annual growth increases with increasing stand volume.

On the other hand, scientists and academics searching for precise biological relationships may recognize Assmann's "natural critical stocking density" when results are presented as in Figure 2. A maximum volume increment is realized at a specific thinning intensity, according to Assmann, and production drops off at greater and lesser intensities. Most field research, this study included, fails to demonstrate the statistical significance of Assmann's theory, probably because of the high variances inherent in such studies. Assmann proposes that the basal area that results in 95% of the maximum for that stand or site be the "critical" or target stand density. For the young-growth redwoods in this study, the critical density for the 15-yr thinning interval is between 58% and 92% of the 100% leave stand density or between 236 and

Table 5. Values for coefficients b_0, b_1 and b_2 for equations expressing periodic annual increment (PAI) as a function of stand basal area after thinning three young-growth redwood stands in northwestern California.

Growth measure and location	Values for coefficients		
	b_0	b_1	b_2
PAI dbh			
Crescent City	2.03364	0 30849	—
Korbel	2.14043	0 32049	—
Whiskey Springs	1.64978	0 25542	—
PAI ba			
Crescent City	5.39549	0.03055	0.00010
Korbel	4.36860	0 04472	0.00008
Whiskey Springs	1.73033	0 04547	0 00008
PAI ft^3			
Crescent City	115 3886	2.15645	0.00330
Korbel	49.8467	3 14145	0.00479
Whiskey Springs	26.2029	2.58107	0.00413
PAI bf			
Crescent City	1001 40	12 4135	0 01722
Korbel	891 325	15.8725	0.02324
Whiskey Springs	388 580	15.8292	0.02704

374 ft^2/ac of basal area. If 5% is considered the threshold of practical (as contrasted with statistical) significance, then the range of basal areas from 236 to 374 ft^2/ac could be Langsaeter's Zone III.

Redwood has the unique feature of sprouting profusely from the stump and root crowns (Olson and Fiske 1983). Sprouting response after 1 yr at Whiskey Springs was reported by Lindquist (1979) and after about 10 yr at all three locations by Allen and Barrett (1985). After about 10 yr when Allen and Barrett sampled stumps at each installation, they found that 69% of the sampled stumps had sprouted. And they, as did Lindquist, concluded that the correlation with residual stand density was weak. Subsequent height growth of dominant sprouts, however, was strongly correlated with residual stand density. As predicted by Allen and Barrett's growth model, dominant sprout heights at 15 yr would be 31 ft in 25% leave plots, 16 ft in 50% leave plots, and 11 ft in 75% leave plots.

Possibly, growth differences among treatments found in this study are underestimated because of redwood's ability to sprout. Sprout growth which was related to leave stand density could counteract the influence of stocking level on individual tree growth. Restricted growth of overstory trees

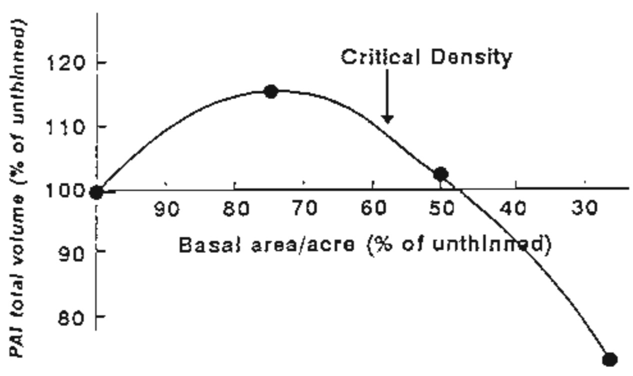

Figure 2. Assmann's (1970) critical stocking density based on the mean growth response 15 yr after thinning three stands of young-growth redwood in northwestern California.

caused by understory competition has been well documented in the dry interior forests where competition is principally for moisture (Stewart et al. 1984). Evidence of similar relationships has been documented in the mesic coastal forests, as well. If moisture competition is a factor, taller sprouts (31 ft at 15 yr in 25% leave plots) would compete more vigorously with the leave trees than would shorter sprouts (11 ft in 75% leave plots) and, thus, could reduce growth differentially on the leave trees. Nevertheless, because cut stands always sprout, this potential growth reduction should be considered characteristic of the species.

The three stands studied are not representative of average young-growth redwood in the region. The sites were more productive and the stand densities before thinning much greater than average for the region (Lindquist and Palley 1963). Resulting stand volumes and growth rates were, therefore, greater than those usually found. We believe, however, that the growth/growing stock relationships described are representative of most well-stocked young-growth stands in the region.

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