State of California
The Resources Agency
Department of Forestry & Fire Protection

GROWTH & YIELD REPORT FOR THE WHISKEY SPRINGS REDWOOD COMMERCIAL THINNING STUDY

A TWENTY-NINE YEAR STATUS REPORT (1970-1999)

California Forestry
Report No. 3
February 2004

JAMES L. LINDQUIST

25% Retention

50% Retention

75% Retention

Uncut Control

SUMMARY

The response of well-stocked second-growth coastal redwood stands to three levels of commercial thinning is reported after 29 years of growth. Commercial thinning treatments left 25%, 50%, 75% and 100% (uncut control) of the original basal area (400 sq. ft.) in a 40-year old stand on the Jackson Demonstration State Forest. Stand values are given for basal area, number of trees, average diameter, and cubic foot volume and board foot volume per acre for the pre-treatment stand and five post treatment inventory dates from 1970 to 1999.

There are significant differences between the treatments in stand basal area, average diameter, and volume that have remained throughout the course of the study. Analysis of the periodic growth rate reveals strong statistical differences between the treatments in diameter growth but no significant differences in the basal area or cubic and board foot volume growth. Total yield in board foot volume was not statistically different due to the high variation but a graphical analysis suggests that the 25% retention treatment produced a lower yield than the other three treatments, including the uncut control.

Though this was not a regeneration harvest, regeneration was measured for inference to partial harvest management. The response of the understory regeneration was strongly affected by the density of the overstory canopy. A precommercial thinning study of the redwood sprouts showed a response only in the 25% overstory retention treatment.

Key Words: Sequoia sempervirens, coast redwood, commercial thinning, stand growth, stand management, sprout potential, sprout growth, stand density, stocking, forest management.

February 2004

California Department of Forestry & Fire Protection

P.O. Box 944246

Sacramento, CA 94244-2460

Web: www.fire.ca.gov

GROWTH & YIELD REPORT FOR THE WHISKEY SPRINGS REDWOOD COMMERCIAL THINNING STUDY

A Twenty-Nine Year Status Report
(1970-1999)

James L. Lindquist

James L. Lindquist is a consulting forester from Arcata, California.
This study was conducted under contract number 8CA85004.

CONTENTS

Introduction

The Whiskey Springs commercial thinning study was established as a cooperative project of the California Department of Forestry and Fire Protection (CDF) and the USDA Forest Service Redwood Sciences Lab (USFS) in 1970 on the Jackson Demonstration State Forest (JDSF) near Fort Bragg, California. The original study design included three sites, located in the redwood region. Oliver et al. (1994) reported the first 15 years of growth (1971-1985) for all three sites. This report covers the growth and yield of the overstory stand in the 12 Whiskey Springs plots for the period 1970 through 1999. A second part of this study reports on the establishment and growth of sprout regeneration established as the result of thinning the overstory.

This study provides information about the biological capabilities of redwood (*Sequoia sempervirens*) and the inherent productivity of the soil. This report describes the stand response of 40-year old well-stocked second growth redwood to four levels of thinning. The original study plan called for thinning at five-year intervals until 60 years with a final harvest at 70 years of age (Strothman 1969). The rotation age of 70 years was selected based upon the projected culmination of mean annual increment (cubic feet) for a site index of 180 (Lindquist and Palley, 1963). These later thinning entries were never carried out. These stands are now over 70 years old and analysis of the growth will help to determine an appropriate next step.

There are only a few published studies concerned with the growth of young redwood stands following silvicultural treatment. Carr (1958) reported on the four-year growth of three one-acre plots in a 77-year-old, high-site redwood stand that averaged 153,636 board feet per acre of volume. The highest 4-year volume growth percent (18.5%) was for the heavy cut where 56.6% of the volume was removed. The light cut growth percent (10.5%) with 21.3% of the volume removed was nearly that of the uncut plot (9.9%). Average periodic annual growth increment (PAI) was 3,861 (uncut), 3,254 (light cut), and 2,975 (heavy cut) board feet per acre (Carr 1958). Four years was not enough time for the crowns of individual trees to respond completely to the increased space. These results indicate that even after removing half of the stand volume, the heavy cut plot produced an average annual volume of nearly 3,000 board feet per acre.

The Caspar Creek Cutting Trials (CCCT) were established in 1960 in an 85-year old stand. When measured after 24 years, the uncut stand had the greatest PAI for the 24-year period (Lindquist 1988). This study was not an even-aged thinning, but a test of partial logging to create uneven-aged stands. Stands cut at this age did not appear to take advantage of the space created by logging.

Oliver et al. (1994) reported on the first 15-years after commercial thinning at three locations (Korbel, Crescent City, and Whiskey Springs). Results indicated that only the board foot periodic annual increment (PAI) of the 25% retention treatment (2,137 board feet/acre/year) was significantly less than the other treatments (3,017 board feet/acre/year). The greatest PAI at all three locations occurred in the 75% retention treatment; and maximum board foot growth percent was (6.6%) in the 25% retention treatment and the minimum (4.0%) in the uncut control. The PAI of basal area, cubic and board foot volume at all three locations were highest at stocking levels between 300 and 500 square feet per acre of stand basal area.

A study of new sprout growth after the thinning of these plots described height growth at 15-years of age and developed an equation to predict future growth (Allen and Barrett, 1985). This report provides additional information on the development of this new cohort.

The purpose of this study was to determine how a range of commercial thinning intensities compared when considering total yield. This growth and yield information will aid in planning silvicultural prescriptions in redwood to achieve maximum volume production and other attributes such as tree size. The analysis of sprout response provides information for multi-cohort management of redwood stands whether they are two-aged or classical single tree selection, particularly when transitioning from single to multi-aged management of a stand.

Methods and Data

Study area

The stand selected for this study is located approximately nine miles from the Pacific coast, in the drainage of the Little North Fork of Big River near the divide with the Noyo River. There is an east to northeast aspect and an elevation range from 600 to 800 feet. The old-growth stand was clearcut in the late 1920s and a nearly pure stand of second growth redwood sprouts was established. There is evidence to suggest that the area was planted with redwood seedlings after the initial harvest in the 1920s. There are small intermittent stream courses through plots 1, 2, 3, 4, and 12 that create different moisture regimes and site index than plots located higher on the slopes.

Over the period 1970 to 1985, five-year measurement intervals were maintained. There have been two measurements since 1985, in 1991 and 1999.

Study design

Twelve 0.4-acre plots (132 x 132 feet) were established in the stand. The plots were selected such that intra-plot basal area, site index, and species composition were as uniform as possible. Breast-height age of the redwood ranged from 39 to 41 years in 1970, and the site index ranged from 172 to 212 feet, using 100 years as the base age (Lindquist and Palley, 1961). Initial basal area of trees greater than 4.5 inches dbh prior to thinning averaged 401.3 ± 7.6 sq. ft. per acre. The species composition of trees by basal area was 91.2% redwood, 6.7% other conifers, and 1% hardwood. The layout of the plots and assigned treatments are shown in Figure 1.

Thinning of the plots occurred in 1970 and was based on leaving a residual stand that was 25%, 50%, or 75% of the average basal area of the uncut control plots. The central 0.2-acre (93.3 x 93.3 ft. section) of each plot was the portion of the plot that was measured. These trees were tagged and were the basis for all per acre values computed in subsequent inventories. Buffer zones around each central core plot of 0.2 acres were 19.3 ft. wide, and were treated in the same way as the tagged portion of the plot. Three plot replicates of the four treatments were assigned in a completely randomized design. None of these plots were included in the control, which necessitated adjustments for some variables. Marking of trees was done to favor healthy dominant and codominant redwoods while leaving trees well distributed on the plot. All hardwoods and any conifers less than 4.5 inches dbh were removed.

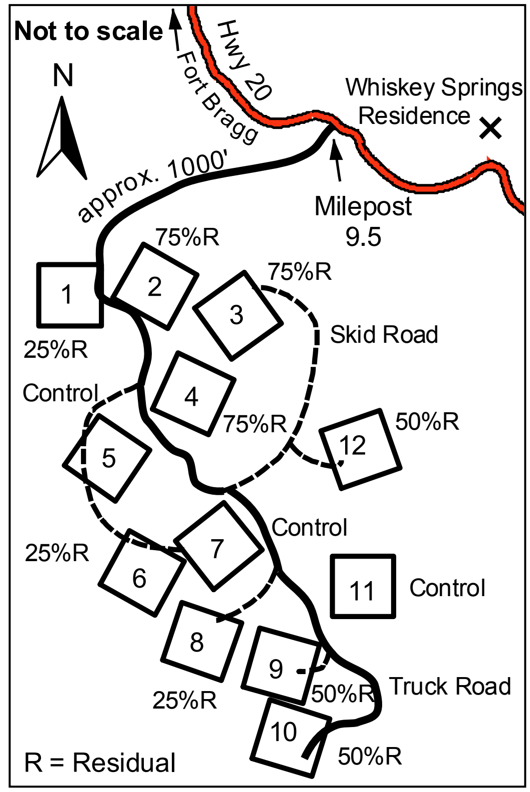

Figure 1. Whiskey Springs location and plot layout.

Uniformity of the basal area was the primary condition for plot selection in this study. The basal area in the treated plots was reduced to 100, 200, and 300 square feet per acre. All of the hardwoods were tanoak (*Lithocarpus densiflorous*) less than 4.5 inches dbh at the time of plot establishment. These trees were not recorded in the thinned plots. The prescription was originally conceived of as a crown thinning, but was modified to a low thinning to remove suppressed stems first, progressing to intermediate trees until the desired basal area was reached.

Volume computations

Evaluation of the stand volumes for all the inventories relied on linear local volume equations (Table 1) for redwood and Douglas-fir (*Pseudotsuga menziesii*). These lines were computed for each plot and inventory year. The small number of Douglas-fir required that all fir be combined. Total heights of stems were measured across the range of diameters present in the plot. These cubic and board foot tree volumes were computed from equations developed by the Redwood Yield Cooperative (Wensel and Krumland, 1987). Board foot volumes were computed by the Scribner log rule using a one-foot stump height and a top diameter of 6 inches. A constrained linear regression was computed using each tree's volume and squared dbh. The regression line was forced through a selected diameter where the tree volume was zero (cubic volume at 4 inches and the board foot volume at 10 inches). The linear equations slope and intercept were used to compute stand volume for the species as a function of the sum of the diameter squared and number of trees in the plot. The list of slope coefficients used for the computed volumes is shown in Table 1.

Table 1. Local volume line LVL) coefficients for redwood and Douglas-fir. Values shown are the average regression slope for the three plots for each treatment and year of inventory.
Functions are: Cubic Vol. = 16 + Coefficient*(K&W Vol) and Board Foot Vol. = 100 + Coefficient*(K&W Vol).

Treatment	Age	Year	RW (cubic ft.)	RW (board ft.)	DF (cubic ft.)	DF (board ft.)	Site Index
25	41	1970	0.187580	1.27463	0.239020	1.79231	189.8
25	46	1975	0.199120	1.36517	0.235028	1.76198	191.3
25	51	1980	0.210427	1.45999	0.245537	1.79714	194.8
25	56	1985	0.214461	1.50031	0.241206	1.76627	195.9
25	62	1991	0.218286	1.54557	0.266495	1.97121	192.4
25	70	1999	0.232475	1.68639	0.285465	2.13846	190.8
50	41	1970	0.181050	1.19982	0.000000	0.00000	184.7
50	46	1975	0.191286	1.29657	0.000000	0.00000	188.5
50	51	1980	0.197743	1.35138	0.000000	0.00000	186.4
50	56	1985	0.203775	1.40056	0.274734	2.02811	184.5
50	62	1991	0.212639	1.48318	0.278255	2.05481	180.3
50	70	1999	0.228182	1.62786	0.289398	2.14443	181.4
75	41	1970	0.200787	1.46928	0.239020	1.79231	186.0
75	46	1975	0.207750	1.47839	0.275940	2.05398	189.5
75	51	1980	0.218714	1.57819	0.297406	2.22310	188.2
75	56	1985	0.228121	1.60573	0.317894	2.37558	188.1
75	62	1991	0.243107	1.74599	0.341957	2.58032	188.0
75	70	1999	0.263530	1.93278	0.358446	2.73181	190.8
100	41	1970	0.176327	1.21911	0.239020	1.79231	165.8
100	46	1975	0.179780	1.23845	0.216906	1.79928	173.9
100	51	1980	0.178929	1.20449	0.210225	1.63469	173.9
100	56	1985	0.196912	1.36644	0.256237	1.90086	170.0
100	62	1991	0.206951	1.44998	0.273982	2.02216	165.9
100	70	1999	0.220342	1.55899	0.281985	2.09980	167.2

* K&W is Krumland and Wensel (1987).

Results and Discussion

Initial stand conditions

Descriptive statistics of the plots prior to thinning are summarized in Tables 2 and 3. The number of trees and basal area per acre for trees greater than 4.5 inches dbh include both conifers and hardwoods, but the volumes in Table 2 refer only to conifers. Average post-treatment basal area for the treatments ranged from 392 to 410 square feet per acre. The greatest variation was in the uncut plots with a coefficient of variation (CV) of 8.6%, and a mean of 403 square feet per acre. The average basal area of all plots was 401.3± 7.6 square feet per acre.

For the variables listed in Table 2, statistical differences between the treatments occurred only in average diameter of trees greater than 10.5 inches. The variation of some variables within treatments may effectively mask any difference between treatments. Analysis of variance tests (ANOVA) of the pre-harvest stands indicated that a block design was not required.

Table 2. Preharvest average stand conditions of three plots in the four treatments. Except for the volumes, all conifers and hardwoods are included. Statistical differences between treatments are tested by the F(3,8,.05)=4.07.

		Trees > 4.5 inches				Trees > 10.5 inches			
Treatment	Site Index	Basal Area (sq. ft.)	Number of Trees	Average Diameter (in.)	Cubic Vol. (cubic ft.)	Basal Area (sq. ft.)	Number of Trees	Average Diameter (in.)	Bd. Ft. Vol. (board ft.)
25%	189	399	488	12.3	12,198	320	215	16.5	49,254
SD	11	16	80	1.0	1,210	37	33	0.3	9,555
50%	184	410	488	12.4	12,070	323	242	15.7	47,480
SD	7	23	55	0.9	1,831	44	42	0.4	10,868
75%	195	392	467	12.5	12,807	326	247	15.5	51,893
SD	19	24	70	1.3	2,078	55	32	0.6	12,199
100%	180	403	628	10.9	11,205	282	240	14.7	35,210
SD	8	35	71	0.5	342	36	22	0.4	6,616
F Values	0.86	0.27	3.41	1.94	0.59	0.67	0.55	9.82*	1.63
Average per acre values of conifers removed by thinning									
25%		286	403	11.4	8,780	118	123	13.3	30,367
50%		196	297	11.0	5,678	123	107	14.6	14,733
75%		89	217	8.7	2,571	41	42	13.4	5,190

*Significantly different

The average removal, by treatment, shows the portion of the stands cut in order to reach the desired residual basal area (Table 2). Within the 25% retention treatment, thinning removed 75% of the basal area, and 72% of the cubic volume. The 75% retention treatment removed only 20% of the cubic volume and 10% of the board foot stand.

The diameter distributions in Table 3 show that prior to thinning, the thinned plots had similar diameter distributions. Trees less than 10.5 inches dbh are 45% to 49% of the total numbers of stems. Thinning removed nearly all the stems less than 10.5 inches from the 25% and 50% retention treatments and only a small percent in the 75% retention treatment. The uncut plots averaged about 150 more stems per acre than the treated plots with 72% of the trees less than 10.5 inches. The average stand diameter of the control was about 1.5 inches less than the treated plots, and the board foot volume of the control was about 14,330 less than the average of the pre-treatment volume of the other plots (Table 2). This may be due to the fact that the three control plots were located higher on the slope and had the lowest average site of any of the treatments.

Table 3. Diameter distributions (average number of stems per acre in 1970) before and after treatment.

	Preharvest Values				Residual Values			
Dbh (in.)	25%	50%	75%	Control	25%	50%	75%	Control
4	15.0	10.0	16.5	34.0	0.0	0.0	0.0	34.0
5	61.6	41.7	45.0	71.7	0.0	0.0	0.0	71.7
6	40.0	31.7	41.7	76.7	0.0	0.0	0.0	76.7
7	33.3	33.3	25.0	63.3	0.0	0.0	0.0	63.3
8	33.3	46.7	26.7	63.3	0.0	0.0	0.0	63.3
9	28.3	28.3	25.0	48.3	0.0	0.0	11.7	48.3
10	31.6	26.7	36.7	95.0	0.0	1.7	21.7	95.0
11	35.0	25.0	25.0	40.0	1.7	3.3	15.0	40.0
12	28.3	25.0	28.5	38.3	5.0	5.0	21.7	38.3
13	25.0	30.0	26.7	36.7	3.3	16.7	23.3	36.7
14	18.3	10.0	23.3	35.0	1.7	3.3	21.7	35.0
15	15.0	26.7	30.0	20.0	0.0	16.7	26.7	20.0
16	3.3	23.3	16.7	20.0	0.0	16.7	16.7	20.0
17	16.7	10.0	21.7	11.7	3.3	5.0	20.0	11.7
18	11.7	8.3	25.0	5.0	1.7	6.7	23.3	5.0
19	6.7	13.3	16.7	18.3	5.0	6.7	15.0	18.3
20	6.7	13.3	8.3	5.0	5.0	11.7	6.7	5.0
21	6.7	8.3	6.7	1.7	3.3	8.3	6.7	1.7
22	3.3	8.3	1.7	5.0	1.7	6.7	1.7	5.0
23	5.0	1.7	0.0	1.7	1.7	1.7	0.0	1.7
24	6.7	3.3	3.3	0.0	3.3	3.3	3.3	0.0
25	3.3	1.7	3.3	3.3	1.7	1.7	3.3	3.3
26	1.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
27	0.0	1.7	0.0	0.0	0.0	0.0	0.0	0.0
28	3.3	0.0	0.0	0.0	3.3	0.0	0.0	0.0
29	3.3	1.7	0.0	0.0	3.3	1.7	0.0	0.0
30	0.0	1.7	0.0	0.0	0.0	1.7	0.0	0.0

Site index

Repeated measurement of the total heights of dominant redwood in these plots shows that the estimates of site index has remained stable over the 29 years of measurements (Figure 2). There is some movement in the values of the average heights of the dominant trees since it was not possible to re-measure exactly the same set of trees. Site index estimates of treatments 25% and 75% are virtually the same in all years.

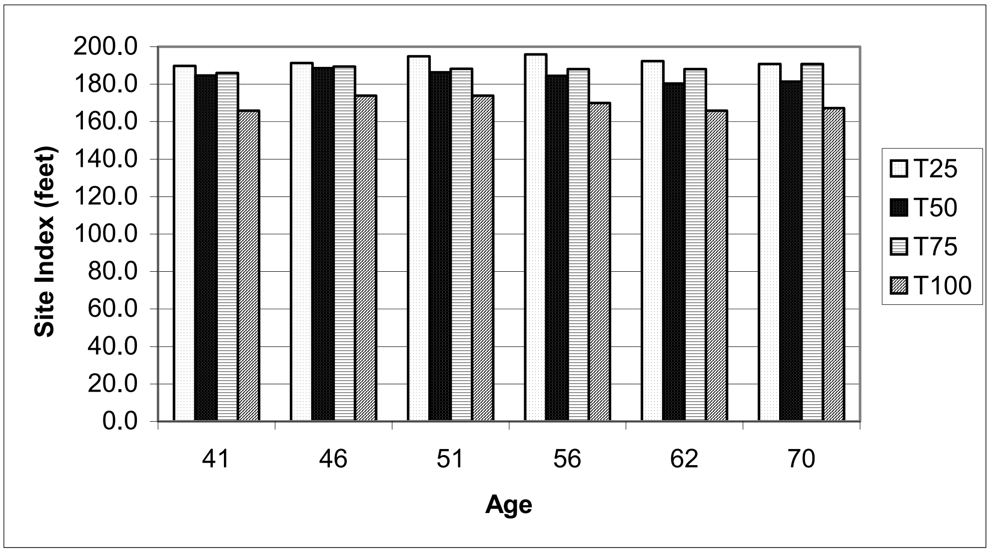

Figure 2. Average site index of dominant redwood by age and treatment.

The control had the lowest average site index. An ANOVA of these site estimates showed highly significant differences between treatments, with the uncut plots different than the thinned treatments. Testing the site data against the ages of the stands showed no statistical differences. The averages of the 12 plots for the six measurement ages ranged from a low in 1970 of 181.6 feet to a high in 1980 of 185.8 feet.

Growth and yield

Average treatment inventory values for the stands in terms of trees greater than 4.5 inches dbh (cubic foot) and greater than 10.5 inches dbh (board foot, Scribner) are summarized in Table 4. The individual plot results are given in Table 5.

Table 4. Average and standard deviation values for the three plots by overstory treatment and inventory year. Values are expressed on a per acre basis for the stands larger than 4.5 and 10.5 inches in dbh.

	Trees >4.5 inches dbh				Trees>10.5 inches dbh				
Year	BA (sq.ft. / ac.)	Trees per Acre	QMD (in.)	Cubic Vol. (cu.ft. / ac.)	BA (sq.ft. / ac.)	Trees per Acre	QMD (in.)	Bd. Ft. Vol. (bd.ft. / ac.)	Site
	25% Overstory								
1970	100.4	45.0	20.3	3,417.7	100.4	45.0	20.3	18,887	195.7
std. dev.	1.5	5.0	1.0	401.4	1.5	5.0	1.0	3,942	9.4
1975	122.2	45.0	22.4	4,429.7	122.2	45.0	22.4	25,767	192.0
std. dev.	4.2	5.0	0.9	562.4	4.2	5.0	0.9	5,065	16.0
1980	153.9	45.0	25.1	5,923.3	153.9	45.0	25.1	35,816	196.9
std. dev.	5.5	5.0	1.1	848.3	5.5	5.0	1.1	6,580	16.9
1985	183.3	45.0	27.4	7,277.3	183.3	45.0	27.4	45,384	195.3
std. dev.	7.3	5.0	1.3	804.8	7.3	5.0	1.3	5,564	16.1
1991	210.8	45.0	29.4	8,597.7	210.8	45.0	29.4	55,298	191.1
std. dev.	12.1	5.0	1.4	462.6	12.1	5.0	1.4	2,958	6.5
1999	246.3	45.0	31.8	10,675.0	246.3	45.0	31.8	71,231	190.8
std. dev.	15.8	5.0	1.8	1,046.5	15.8	5.0	1.8	7,606	11.7
	50% Overstory								
1970	200.9	118.3	17.8	6,392.0	200.0	116.7	18.0	30,928	191.1
std. dev.	0.7	30.1	2.2	697.6	1.3	27.5	2.2	5,672	12.3
1975	235.1	118.3	19.4	8,014.3	235.1	118.3	19.4	41,669	189.9
std. dev.	5.8	30.1	2.6	1,084.4	5.8	30.1	2.6	8,556	14.2
1980	276.8	118.3	21.1	9,849.0	276.8	118.3	21.1	54,169	187.7
std. dev.	10.4	30.1	2.8	1,517.3	10.4	30.1	5.8	12,013	
1985	312.6	118.3	22.4	11,586.0	312.1	116.6	22.5	66,134	184.5
std. dev.	17.6	30.1	3.1	2,257.1	18.3	27.5	3.0	17,192	12.1
1991	355.2	118.3	23.9	13,656.0	355.2	118.3	23.9	81,647	176.9
std. dev.	22.8	30.1	3.3	3,005.3	22.8	30.1	3.3	24,322	15.7
1999	404.4	118.3	25.4	16,982.0	404.4	118.3	25.4	104,697	181.4
std. dev.	30.6	30.1	3.6	4,173.0	30.6	30.1	3.6	34,012	14.0
	75% Overstory								
1970	300.9	238.3	15.3	10,255.7	285.9	205.0	15.9	44,695	191.1
std. dev.	0.1	38.2	1.2	992.5	19.7	20.0	0.9	6,720	16.1
1975	339.5	238.3	16.3	12,276.0	329.3	218.3	16.7	59,012	189.5
std. dev.	3.2	38.2	1.3	1,226.9	9.3	25.6	1.2	8,880	16.1
1980	380.5	238.3	17.2	14,593.3	371.9	221.7	17.6	73,676	188.1
std. dev.	7.6	38.2	1.4	1,566.2	8.6	30.1	1.5	11,824	16.1
1985	414.0	235.0	18.1	16,757.3	407.1	221.7	18.5	86,899	188.1
std. dev.	8.9	37.7	1.6	1,202.1	8.5	30.1	1.5	10,160	9.0
1991	450.3	233.3	18.9	19,381.0	445.4	223.3	19.3	105,461	186.2
std. dev.	16.1	35.1	1.7	1,586.8	16.2	32.5	1.8	14,509	8.3
1999	498.4	233.3	19.9	23,549.7	492.5	221.7	20.3	133,878	190.5
std. dev.	25.3	35.1	1.9	2,061.2	25.4	30.1	1.9	18,739	5.8
	100% Overstory								
1970	401.7	626.7	10.9	11,205.7	282.5	240.0	14.7	35,210	180.3
std. dev.	32.5	72.8	0.5	342.2	35.7	21.8	0.4	6,616	
1975	441.6	623.3	11.4	12,971.3	331.1	263.3	15.2	45,048	175.6
std. dev.	28.9	76.4	0.5	837.4	27.4	25.2	0.5	8,133	7.4
1980	480.4	613.3	12.0	15,024.7	377.1	276.7	15.8	57,173	172.7
std. dev.	20.5	76.4	0.5	1,484.1	25.1	29.3	0.6	11,030	9.3
1985	511.1	588.3	12.6	17,208.0	417.3	285.0	16.4	71,229	170.0
std. dev.	11.2	46.5	0.4	1,896.2	24.3	34.6	0.7	13,073	15.5
1991	544.3	556.7	13.4	19,461.7	459.5	288.3	17.2	86,616	165.8
std. dev.	7.4	57.9	0.6	2,640.6	17.2	40.7	1.0	17,216	14.2
1999	575.5	523.3	14.2	22,585.0	500.4	286.7	17.9	108,334	167.5
std. dev.	8.7	59.6	0.9	3,344.1	23.8	33.3	1.2	23,934	16.6

Landscape table 5 from excel on this page.

Basal area

Basal area growth over a 29-year period for trees greater than 4.5 inches was similar for each treatment (Figure 3). The 25% retention treatment added about 150 square feet per acre of growth, the 50% and 75% treatments added an average of 201 square feet per acre, and the control increased by 174 square feet per acre. Maximum PAI for all harvested stands was in the period of between 46 to 51 years of age, which was the 5 to 10 years after cutting (Figure 4). There was a highly significant difference in basal area growth between treatments in the first growth period of 41-46 years (p=0.001). All other growth periods showed no significant differences in periodic basal area growth between the treatments. This is explained by the increased variation within the treatments and the similarity of the PAI between all but the 25% treatment. Over the entire 29-year growth period, there was no significant difference in basal area growth between the four treatments. Over a period of 29 years, over 200 suppressed trees have died in the control, which reduced the basal area growth. Figure 5 shows the relationship of initial basal area and PAI for the 29-year period. This trend agrees with Oliver's et al. (1994) findings for the first 15 years of this study.

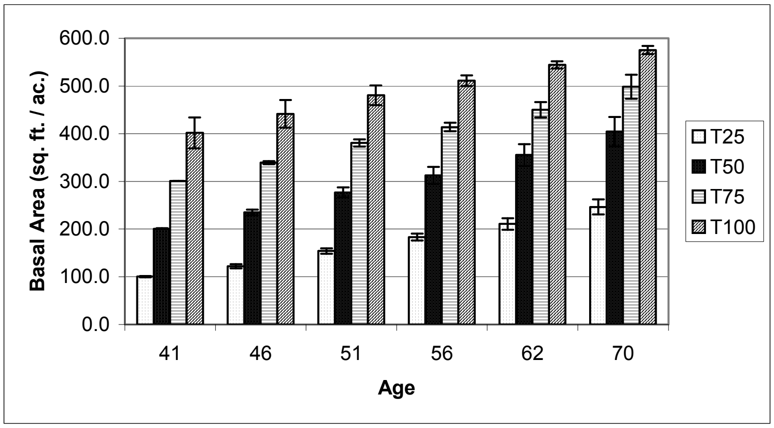

Figure 3. Average stand basal area of trees > 4.5" dbh by age and treatment. Error bars are one standard deviation.

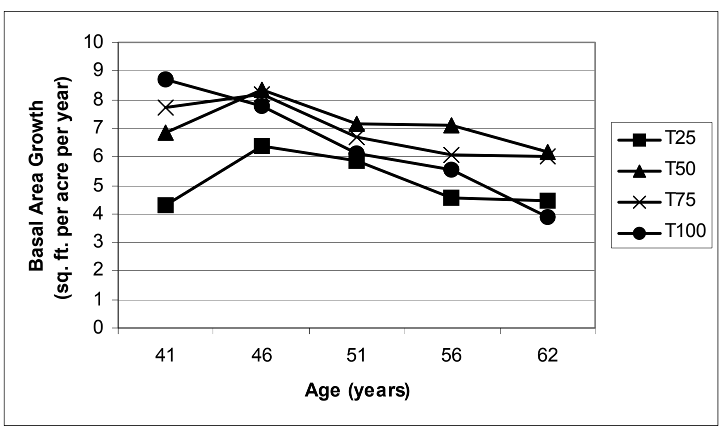

Figure 4. PAI of basal area for trees greater than 4.5 inches dbh.

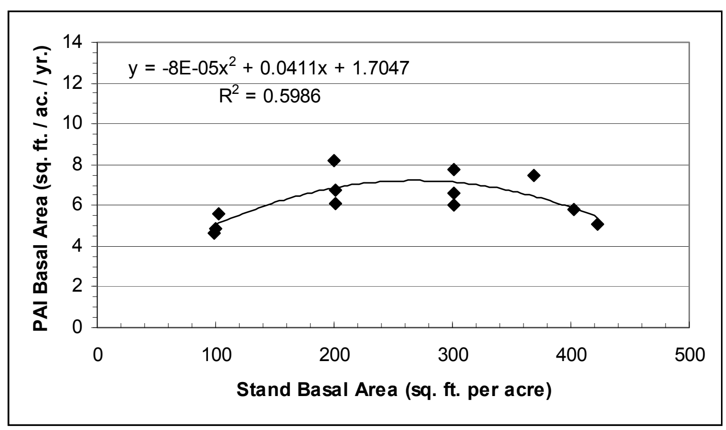

Figure 5. Basal area PAI based on 29 years of post treatment growth, as a function of initial basal area. For trees greater than 4.5 inches dbh.

The portion of the stand diameter distribution greater than 10.5 inches dbh was used to calculate board-foot inventory. In the 25% and 50% retention treatments, all trees smaller than this limit were removed in the thinning. The more lightly thinned 75% retention treatment and control retained small trees that subsequently grew past the 10.5 inch dbh threshold so that basal area increased due to both ingrowth and survivor growth. The 29-year PAI of basal area for trees greater than 10.5 inches dbh was not significantly different between treatments (p=0.06).

Number of trees

The average number of trees per acre were not significantly different prior to thinning except for the control, which averaged about 150 more trees per acre. As a result of the random assignment of treatments, the three plots with the greatest number of stems and lowest site quality became the control. Distributions of stems before and after thinning of each treatment are shown in Table 2. Changes in the stem diameter distributions as the result of growth are shown in Table 6. In 1999, after 29 years of growth, all 45 trees in the 25% retention treatment were greater than 20.0 inches dbh and the average diameter was nearly 32 inches, an increase of 11.5 inches. The 50% retention treatment had 118.3 trees per acre at the beginning and end of the 29 years. The 75% retention treatment lost 5 trees greater than 4.5 inches. The control plots showed the most change, with high mortality in the smaller diameter classes. By 1985, 39 trees had died, and by 1999, 103 trees had been lost to mortality.

Table 6. Average number of trees per acre by diameter class for each treatment in 1985 and 1999.

Diameter	1985				1999			
Class	25%	50%	75%	100%	25%	50%	75%	100%
5	0.0	0.0	0.0	43.3	0.0	0.0	0.0	20.0
6	0.0	0.0	0.0	63.3	0.0	0.0	0.0	35.0
7	0.0	0.0	0.0	73.3	0.0	0.0	0.0	50.0
8	0.0	0.0	0.0	46.7	0.0	0.0	0.0	35.0
9	0.0	0.0	5.0	38.3	0.0	0.0	6.7	35.0
10	**0.0**	**0.0**	**8.3**	**45.0**	**0.0**	**0.0**	**5.0**	**38.3**
11	0.0	0.0	8.3	35.0	0.0	0.0	11.7	26.7
12	0.0	0.0	16.7	38.3	0.0	0.0	13.3	36.7
13	0.0	0.0	21.7	38.3	0.0	0.0	15.0	33.3
14	0.0	3.3	18.3	21.7	0.0	0.0	11.7	26.7
15	0.0	8.3	13.3	30.0	0.0	0.0	8.3	8.3
16	0.0	8.3	15.0	20.0	0.0	1.7	16.7	33.3
17	6.7	6.7	11.7	21.7	0.0	6.7	15.0	11.7
18	1.7	8.3	25.0	13.3	0.0	10.0	11.7	23.3
19	3.3	6.7	13.3	6.7	0.0	6.7	18.3	18.3
20	**0.0**	**6.7**	**11.7**	**15.0**	**3.3**	**8.3**	**6.7**	**11.7**
21	0.0	11.7	13.3	10.0	3.3	6.7	11.7	3.3
22	0.0	6.7	15.0	10.0	3.3	10.0	8.3	8.3
23	3.3	6.7	16.7	10.0	0.0	5.0	20.0	6.7
24	1.7	11.7	10.0	0.0	1.7	5.0	8.3	6.7
25	3.3	15.0	0.0	5.0	0.0	10.0	10.0	3.3
26	1.7	1.7	1.7	5.0	1.7	5.0	11.7	6.7
27	1.7	6.7	5.0	0.0	0.0	8.3	6.7	3.3
28	3.3	1.7	1.7	0.0	6.7	11.7	5.0	1.7
29	5.0	3.3	3.3	1.7	0.0	6.7	1.7	6.7
30	**3.3**	**0.0**	**0.0**	**0.0**	**1.7**	**3.3**	**0.0**	**5.0**
31	1.7	1.7	0.0	1.7	3.3	3.3	5.0	0.0
32	1.7	0.0	0.0	0.0	0.0	1.7	3.3	0.0
33	0.0	0.0	0.0	1.7	3.3	1.7	1.7	0.0
34	0.0	0.0	0.0	0.0	3.3	1.7	0.0	0.0
35	0.0	1.7	0.0	0.0	1.7	0.0	0.0	1.7
36	1.7	0.0	0.0	0.0	0.0	1.7	0.0	1.7
37	1.7	1.7	0.0	0.0	5.0	0.0	0.0	0.0
38	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.7
39	1.7	0.0	0.0	0.0	0.0	1.7	0.0	0.0
40	**1.7**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**
41	0.0	0.0	0.0	0.0	1.7	0.0	0.0	0.0
42	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
43	0.0	0.0	0.0	0.0	1.7	1.7	0.0	0.0
44	0.0	0.0	0.0	0.0	1.7	1.7	0.0	0.0
45	0.0	0.0	0.0	0.0	1.7	0.0	0.0	0.0

Diameter

The most obvious effect produced by the thinning was the immediate increase of the quadratic mean diameter, in proportion to the amount of overstory reduction. Average diameters for trees greater than 4.5 inches were not significantly different prior to thinning (Table 2). In the two heaviest thinnings, the large increase in residual diameter was the result of cutting nearly all of the stems less than 11 inches. After the thinning in 1970 the average stand diameters were statistically different in each treatment (p=0.000). Average stand diameters remained statistically different in each treatment for all inventory dates. The Scheffe pairwise comparison test indicated that the average stand diameters in the control were different than the 25% (p=0.000) and 50% (p=0.001) retained treatments in 1999.

Table 7. Periodic annual increment by treatment for two minimum tree sizes.

		Trees > 4.5 inches					Trees > 10.5 inches				
Years	Period (years)	Basal Area (ft^2/ac./yr.)	Growth Percent (per year)	QMD (in./ac./yr.)	Cubic Volume (ft^3/ac./yr.)	Growth Percent (per year)	Basal Area (ft^2/ac./yr.)	Growth Percent (per year)	QMD (in./ac./yr.)	Board Foot Volume (bf./ac./yr.)	Growth Percent (per year)
25% Overstory											
1970-75	5	4.3	3.9	2.10	203.4	5.2	4.3	3.9	2.10	1,309	6.2
1975-80	5	6.3	4.6	2.70	298.7	5.8	6.3	4.6	2.70	2,076	6.5
1980-85	5	5.9	3.9	2.30	270.8	4.1	5.9	3.5	2.30	1,914	4.7
1985-91	6	4.6	2.3	1.97	220.0	2.8	4.6	2.3	1.97	1,652	3.3
1991-99	8	4.5	1.9	2.40	259.7	2.7	4.5	1.9	2.40	1,983	3.2
1970-99	29	5.0	2.9	11.47	250.4	3.6	5.0	2.9	11.47	1,803	4.0
50% Overstory											
1970-75	5	6.8	3.1	1.47	324.5	4.5	6.8	3.2	1.47	2,148	5.9
1975-80	5	8.3	3.3	1.67	366.9	4.1	8.3	3.3	1.67	2,500	5.2
1980-85	5	7.2	2.4	1.33	347.4	3.3	7.2	2.4	1.33	2,393	4.0
1985-91	6	7.1	2.1	1.47	345.0	2.7	7.1	2.2	1.47	2,585	3.5
1991-99	8	6.2	1.6	1.57	403.2	2.7	6.2	1.6	1.57	2,881	3.1
1970-99	29	7.0	2.3	7.48	361.7	3.1	7.0	2.3	7.48	2,544	3.7
75% Overstory											
1970-75	5	7.7	2.4	0.96	404.0	3.6	9.1	2.8	0.73	2,463	5.5
1975-80	5	8.2	2.3	0.93	463.5	3.4	8.5	2.4	0.93	2,933	4.4
1980-85	5	6.7	1.7	0.90	432.8	2.8	7.1	1.8	0.86	2,645	3.3
1985-91	6	6.1	1.4	0.80	437.3	2.4	6.4	1.5	0.80	3,094	3.2
1991-99	8	6.0	1.3	1.03	521.1	2.4	5.9	1.3	1.06	3,537	3.0
1970-99	29	6.8	1.7	4.62	458.4	2.7	7.2	1.8	4.38	3,002	3.4
100% residual											
1970-75	5	8.0	1.9	0.56	353.1	2.9	9.7	3.2	0.50	1,962	4.9
1975-80	5	7.8	1.7	0.63	410.7	2.9	9.2	2.6	0.67	2,451	4.8
1980-85	5	6.1	1.2	0.53	436.7	2.3	8.0	2.0	0.60	2,791	4.4
1985-91	6	5.5	1.1	0.80	375.6	2.4	7.0	1.6	0.73	2,565	3.2
1991-99	8	3.9	0.7	0.83	390.4	1.8	5.1	1.1	0.76	2,727	2.8
1970-99	29	6.0	1.2	3.35	392.4	2.3	7.5	1.9	3.26	2,525	3.5

Diameter growth in the residual stand for each treatment has remained consistent over the five growth periods in the 29 years of measurement. Table 7 shows that periodic growth percent peaked in the 1975-80 period for the 25% and 50% retention treatments and then slowly decreased. In the 75% treatment plots, the periodic growth dropped consistently. Graphic expression of these growth trends by treatment and age is shown in Figure 6. Growth of the residual trees was most obvious for the 25% retention treatment.

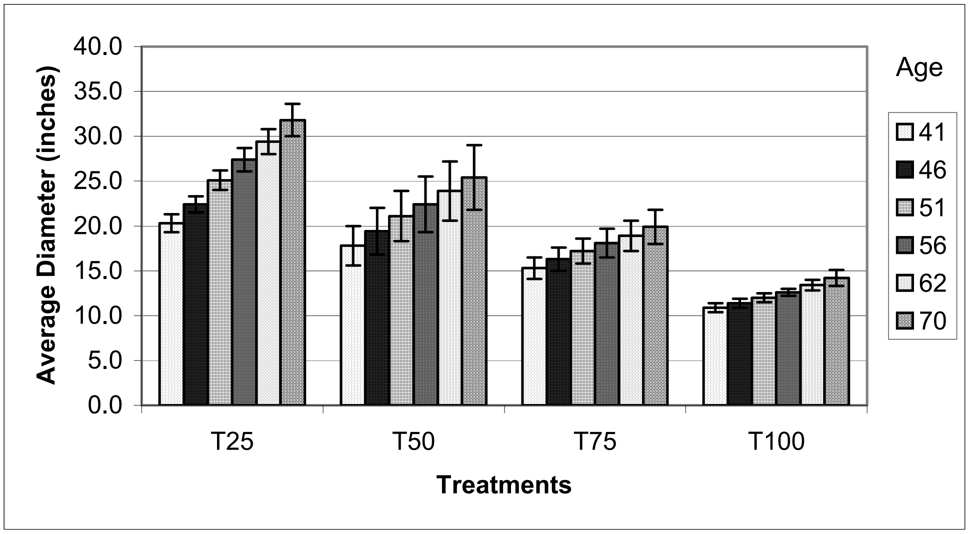

Figure 6. Average diameter of trees greater than 4.5”. Error bars are one standard deviation.

Volume yield and growth

The two diameter limits of 4.5 and 10.5 inches describe respectively, the cubic and board foot volume inventories. While the cubic measure is a more precise unit of the total stand increment, the board foot measure is more easily converted into economic value for the landowner.

Random assignment of treatments to plots resulted in the control plots averaging about 71% (14,330 board feet per acre less) of the pre-treatment volume in the treated areas. Despite these differences in the initial volumes there were no statistically significant differences in the cubic and board foot volumes of the treatment sites (Table 2). Site index is correlated to the pre-treatment board foot volume (r^2=0.772). The control plots are higher on the slope, which is reflected in their lower site values (Table 2, Figure 2).

Cubic Volume

Cubic volume over time is shown in Figure 7. There was a very consistent increase across the five growth periods. Some distortion exists in the graph since the periods between 1970 and 1985 were 5-year increments and last two periods are 6 and 8 years long. The 75% retention volume lags behind the control until 1991. The thinning created cubic volumes that were significantly different across the six inventory dates (p=0.002). The Scheffe multiple comparison tests for 1999 showed that the 25% retention treatment was statistically different than the lighter cut 75% retention treatment and the control.

Although cubic volume was different, the periodic cubic foot growth in each treatment was uniform with a significant difference in only the period 1970-75 when the Scheffe comparison test indicated a significant difference between the 25% retention treatment and the control. The trend of cubic foot volume growth over stand age showed a relatively flat linear trend with an initial increase after thinning and periodic variation (Figure 8). A plot (Figure 9) of stand density index (SDI; Reineke 1933)

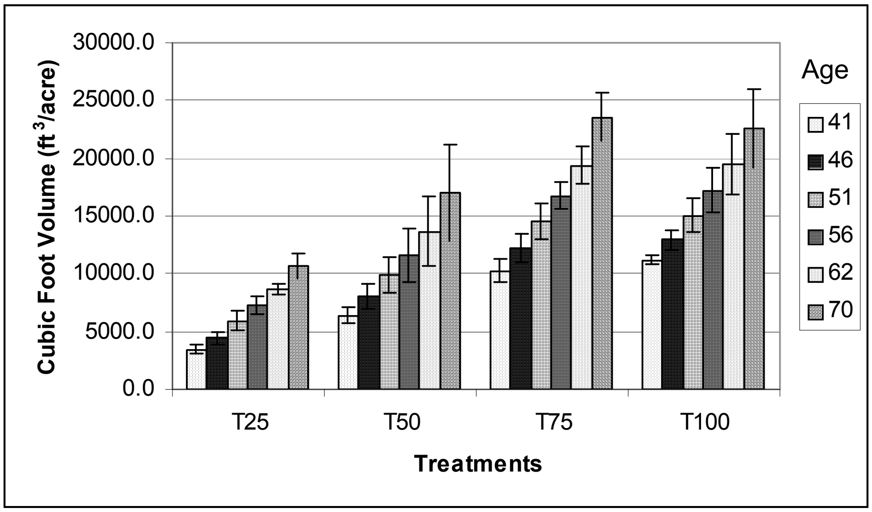

Figure 7. Cubic volume per acre over time by treatment.
Error bars are one standard deviation.

over time indicates a linear increase. The maximum biomass carrying capacity, which is estimated to be 1,000 SDI for redwood (Reineke 1933), has not been reached even by the control. This explains why the cubic stand volume, which is highly correlated with stand biomass, is still increasing.

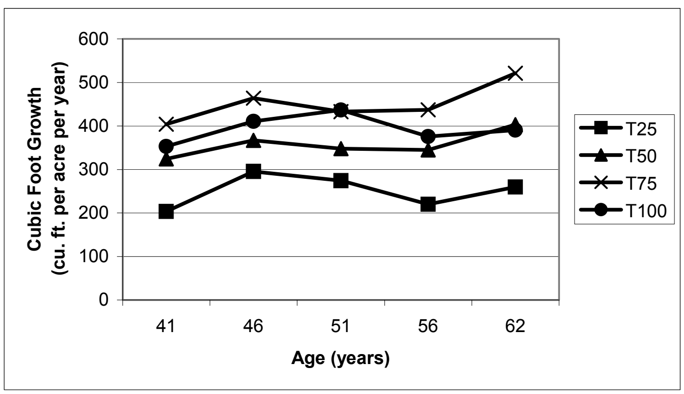

Figure 8. Cubic foot periodic volume growth.

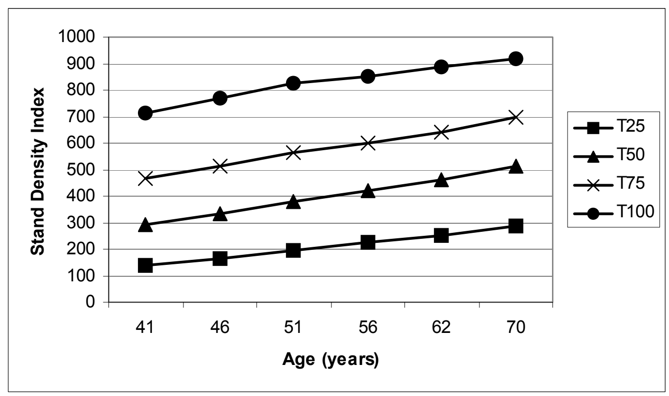

Figure 9. Stand density index over time.

When periodic cubic foot increment was plotted (Figure 10) over the initial stand basal area, there was a quadratic form with the maximum at 300 square feet per acre. Cubic-foot increment (Table 7) indicated that for each thinning level, the growth generally peaked 5 to 10 years after thinning, then dropped slightly over the remaining periods. The 75% retention treatment consistently had the highest growth (458 ft^3/acre/year) over the 29 years, a result of the good site and the presence of large diameter trees. The poorest rates were in the 25% retention treatment (250 ft^3/acre/year) where there were only 45 trees per acre. The relatively low cubic volume growth per unit of basal area in the control (Figure 10) was partially the result of the loss of many small trees that were part of the cubic foot inventory.

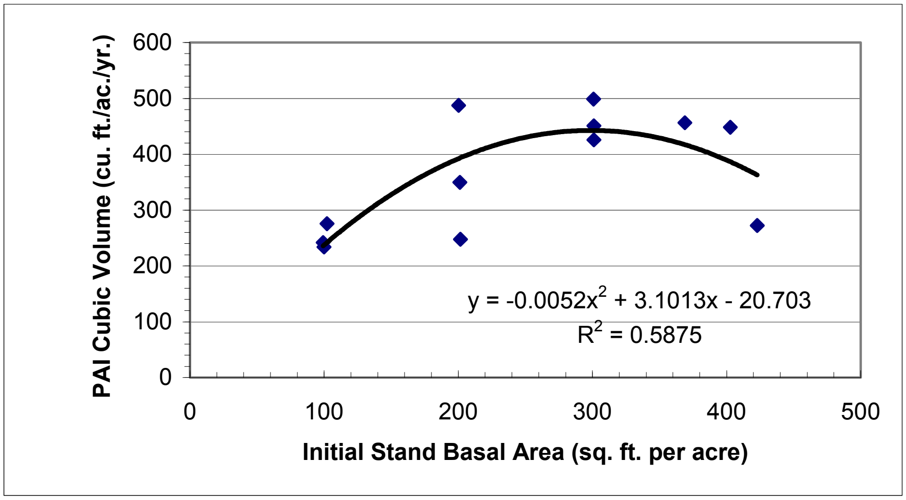

Figure 10. Cubic volume 29-year growth after commercial thin as a function of initial basal area.

Board Foot Volume

Many aspects of the results observed for cubic volume were similar for board foot volume. Expressing stand volume in terms of board feet is useful to landowners because it facilitates economic evaluation. In this region, most log sales are made in terms of board foot measure. Prior to thinning, the plot volumes were not significantly different. Prior to thinning, the control averaged 14,332 board feet per acre less than the treatments, whose means were all within 2,700 board feet of each other. After 29

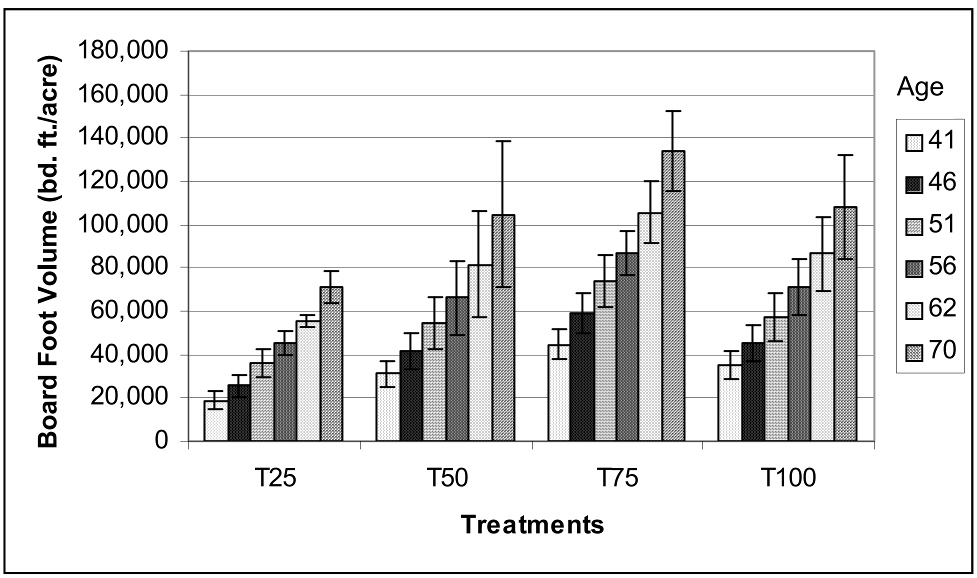

Figure 11. Board foot volume per acre over time by treatment. Error bars are one standard deviation.

years, the control had 3,600 board feet per acre more volume than the 50% retention treatment, and 25,500 board feet per acre less than the 75% retention treatment. Figure 11 shows the progression of stand volume between 1970 and 1999. The parallel and nearly equal track of the 50% retention treatment and control is apparent in this graphic, while the 75% retention treatment is clearly the highest and the 25% retention is clearly the lowest in term of board foot volume.

Testing the board-foot volume by ANOVA for each inventory year shows that after thinning, there were significant differences at the P=.05 level. The Scheffe multiple comparisons tests showed that in all five tests the difference was between the 25% and 75% treatments (p=0.044 in 1999). Site index is a significant covariate (Table 8, Figure 12) for reasons discussed at the beginning of the volume yield and growth section.

Table 8. Analysis of variance for board foot volume in 1999.

N: 12 Multiple R: 0.884 Squared multiple R: 0.781

Source	Sum-of-Squares	df	Mean-Square	F-ratio	P
Treatment	5.62841E+09	3	1.87614E+09	5.872	0.025
Site	2.04027E+09	1	2.04027E+09	6.385	0.039
Error	2.23672E+09	7	3.19531E+08		

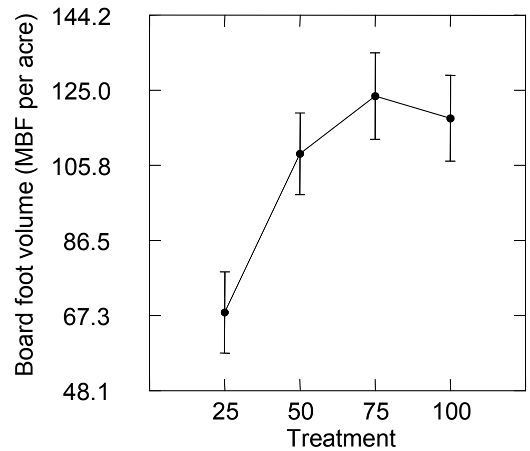

Figure 12. Board foot volume treatment means for 1999.

Growth (board feet) was not significantly different between treatments for any of the periods. The greatest board foot growth in the 29-year period was in the 75% retention treatment where the stand volume increased 200 percent, an annual increase of 3,002 board feet per acre per year (Table 7). The control increased 207 percent or 2,525 board feet per acre per year over the 29 years. Despite the reduction of the stand by 50% of the original basal area and leaving only 118 trees per acre, the 50% retention treatment grew by 238 percent or 2,544 board feet per acre per year. The 25% retention treatment grew 276 percent or 1,803 board feet per acre per year.

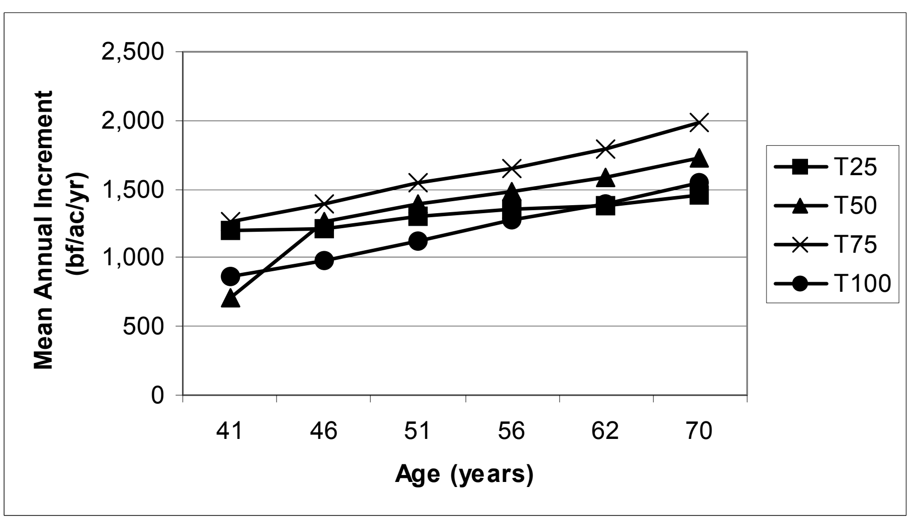

Figure 13. Board foot volume 29-year growth after commercial thin as a function of initial stand volume.

The plot of board foot increment (Table 7, Figure 14) as a function of initial post-harvest volume, reveals a linear trend. There is no apparent flattening of the board foot PAI similar to that found in the cubic volume stand (Figure 10). Culmination of the mean annual increment (CMAI) is the age when average volume growth peaks. Analysis to determine if the CMAI had been reached was conducted by adding the standing inventory to the volume removed by thinning, and then dividing by stand age. The values were then averaged for each treatment. The age range covered was 41 to 70 years and is shown in Figure 14. There is no evidence of culmination in any of the treatments. The four treatments showed a gradual increase across the 29 years.

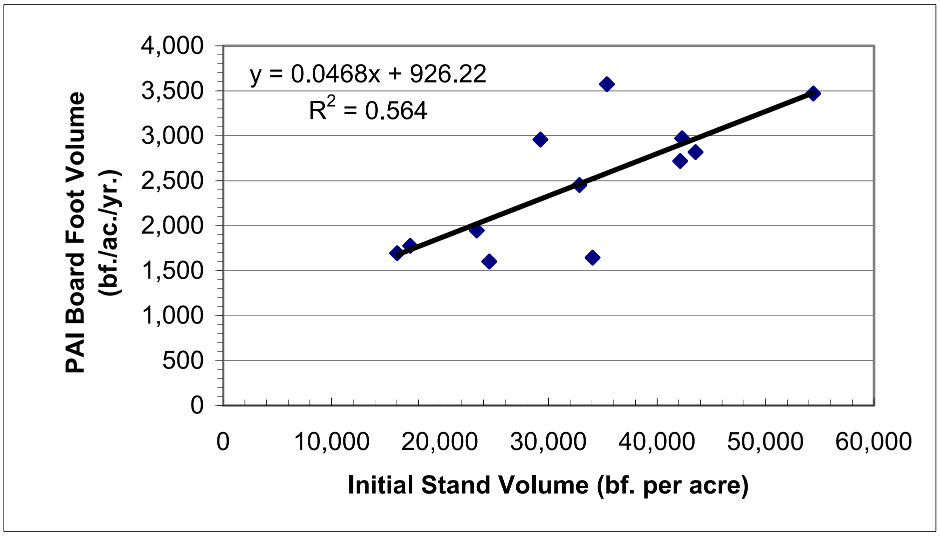

Figure 14. Mean annual increment of board foot volume including commercial harvest yield.

An alternative way of looking at periodic volume growth rates is to consider growth as a percentage of the initial stand volume. Table 7 shows the annual growth rate for the five periods and Table 9 shows the compound annual growth rate for the 29-year period. Across all four treatments, the growth rates generally dropped over time. The annual growth rates ranged from 3.7 to 4.7 percent over the entire 29-year period with the 25% retention treatment growth having the highest growth rate and the 75% retention treatment having the lowest. Yield is the total production of a stand and in this case is the sum of the 1999 stand volume and what was harvested in 1970. An ANOVA of yield, including site as a significant covariate (p=0.024), did not show the treatments to be significantly different (p=0.283). Figure 15 shows the adjusted treatment means for yield.

Table 9. Board feet per acre growth, yield and percent growth.

	Treatments			
Item	25%	50%	75%	100%
Pre-treatment volume	49,254	47,480	51,893	35,210
Volume cut in 1970	30,367	16,552	5,198	0
Post-treatment volume	18,887	30,928	46,695	35,210
Volume in 1999	71,231	104,627	133,878	108,334
Net growth	52,334	73,699	89,183	73,124
Gross yield	101,598	121,179	139,076	108,334
Percent of uncut (%)	93.8%	111.9%	128.4%	100.0%
Compound growth (%)	4.7%	4.3%	3.7%	4.0%

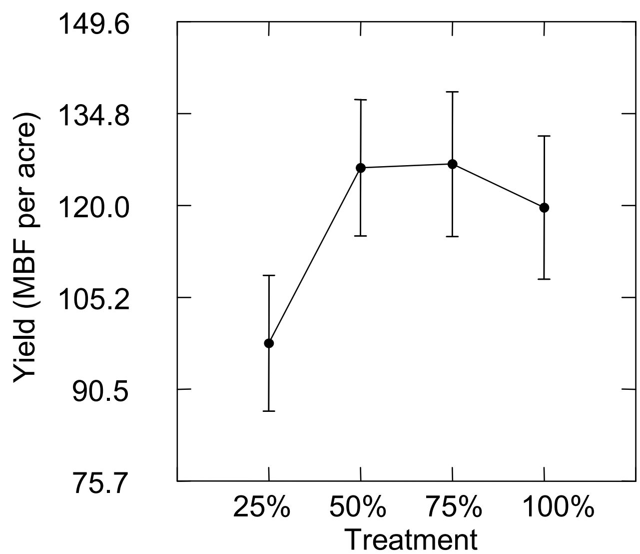

Figure 15. Yield treatment means adjusted by site as a covariate.

To establish the value of this thinning study, it is important to consider the effects of the treatments on the gross yields. Trees greater than 10.5 inches dbh have a market value, and the intent of commercial thinning is to remove a product that will at least pay for the harvest. In addition, there is an attempt to maintain or enhance growth on the residual stand. By combining information from other tables in this report it is possible to express the trends in gross growth to define the relative value of the thinning treatments (Table 9, Figure 15). The 25% retention treatment had the lowest net volume growth for the 29 years, but all of the growth was formed on large trees that averaged 31.8 inches dbh in 1999. Clearly the 25% retention treatment's residual basal area was reduced below what the site could efficiently use. Responses of the 50% retention treatment, 75% retention treatment and control plots were similar once average responses were adjusted for site.

Understory regeneration

The commercial thinning harvest in 1970 created an opportunity to study the effects of the varying amounts of overstory on the redwood sprouts in the understory. Although the commercial thinning was not designed to promote regeneration, the removal of the trees at various intensities created a stand situation similar to other partial harvest methods such as selection, transition or shelterwood. The 29 years of growth of these understory sprouts is an indication of the effect that an overstory has on the growth of the regeneration. The availability of light in the early life stages of regeneration is the principal environmental factor in the growth of redwood stands on the north coast. Chapman's discussion of silvicultural systems suggests that the failure to use a silvicultural system suitable to the desired species' ecological and silvicultural requirements is a serious mistake in forest management (Chapman 1950). In this study, three overstory levels were examined for survival and growth. In addition, a precommercial thinning study was added in 1986.

Survival and Growth

The regeneration study was initiated in 1972, two years after the commercial thinning. Six of the nine thinned plots were examined and all residual trees and stumps were measured and mapped. All stumps and trees were described by a set of horizontal and vertical coordinates. The number of sprout clumps, sprouts, and the height of the tallest sprout were recorded. These data were used initially to describe and test a method of sampling for redwood sprouts (Lindquist 1979). Results of this initial 1972

Table 10. Sprout regeneration in the thinned Whiskey Springs plots. Numbers of clumps and sprouts in 1972 are from six mapped plots. The 1986 results are from a tally of all living sprouts in all thinned plots. Values are on a per acre basis.

	1972 Results		1986 Diameter distributions (inches)									
Plot	Clumps	Sprts.	0	1	2	3	4	5	>5	Total	Avg. dbh (in.)	Avg. Ht. (ft.)
			(number per acre)									
25% Treatment												
1	930	6,842	472	478	170	65	30	5	5	1,225	2.2	17.6
6	2,068	10,550	830	957	355	125	43	10	10	2,330	1.8	15.6
8	1,184	6,977	425	665	260	168	57	22	5	1,602	2.4	20.5
Avg.	1,411	8,123	576	700	262	119	43	12	7	1,719	2.1	17.9
SD	578	2,103	222	241	93	52	14	9	3	562	0.3	2.5
50% Treatment												
9	1,022	4,360	527	353	45	0	0	0	0	925	0.9	9.4
10	968	5,705	565	437	113	17	0	0	0	1,132	1.1	10.9
12	- -	- -	437	348	20	20	0	0	0	825	0.8	9.1
Avg.	995	5,032	510	379	59	12	0	0	0	961	0.9	9.8
SD	38	951	66	50	48	11	0	0	0	157	0.2	1.0
75% Treatment												
2	- -	- -	395	207	18	0	0	0	0	620	0.6	8.0
3	- -	- -	55	35	5	0	0	0	0	95	0.6	6.9
4	585	2,052	78	10	0	0	0	0	0	88	0.3	6.0
Avg.	585	2,052	176	84	8	0	0	0	0	268	0.5	7.0
SD	- -	- -	190	107	9	0	0	0	0	305	0.2	1.0

spout tally are shown in Table 10. In 1986 an understory redwood sprout inventory was made of all nine thinned plots after the seasonal growth period. Live sprouts taller than 4.5 feet were tallied by diameter classes and are shown in Table 10. The breast high diameter and total height of the largest sprout on each stump was measured and recorded.

A large number of sprouts had developed in all treatments, by 1972, ranging from a low of 2,052 sprouts per acre (75% retention treatment) to 8,123 (25% retention treatment). A decrease in the spatial distribution of sprouts with increasing overstory density was indicated by the absence of sprouts on one plot in the 50% treatment and two out of three plots on the 75% treatment. A comparison of the 1972 and 1986 inventories show change of the understory population. For the 25% and 50% retention treatments, the total number of living sprouts in 1986 was nearly equal to the number of sprout clumps in 1972. This is, perhaps, an indication of self-thinning within the clumps occurring in the understory.

In 1986 both average sprout diameter and height were much larger where 25% of the stand was retained than where 50% was retained (2.1 inches dbh vs. 0.9 inches and 17.9 feet vs. 6.9 feet). Sprouts were also more numerous in the 25% retention treatment than the 50% retention treatment (181 stems per acre vs. 12 for sprouts greater than 3 inches). The sprouts in the 75% retention treatment were so severely retarded that subsequent measurements were not warranted.

Precommercial Thin

After the sprout tally of 1986, each plot in the 25% and 50% retention treatments was subdivided into four 0.1-acre plots prior to precommercial thinning of the 16-year-old understory. Treatments leaving 200, 300, 400 trees per acre and an unthinned quadrat were assigned at random in the six plots. This

Table 11. Data of precommercially thinned understory redwood trees in 1986, 1992, and 1999 from 24 one-tenth acre plots. Treatment is the number of trees left per acre with number of trees and (n) being trees per 1/10 acre plot. The (n) is number of redwoods subsampled for total height.

		1986 (age 16)				1991 (age 21)				1999 (age 29)			
Plot	Treatment	No. Trees	Avg. dbh (inches)	Avg. Ht. (feet)	(n)	No. Trees	Avg. dbh (inches)	Avg. Ht. (feet)	(n)	No. Trees	Avg. dbh (inches)	Avg. Ht. (feet)	(n)
1	200	21	2.84	19.7	21	21	2.61	25.9	17	20	4.38	26.6	11
	300	30	2.97	24.5	29	30	3.81	29.9	18	30	4.59	34.5	16
	400	40	2.03	16.6	36	40	2.62	20.5	25	40	2.99	27.3	18
	Uncut	17	1.68	14.1	11	17	2.04	17.3	14	17	2.16	20.0	6
6	200	23	2.51	17.9	18	23	3.13	22.0	14	22	3.59	27.2	14
	300	33	3.19	24.2	29	33	4.15	33.5	23	33	5.07	42.9	16
	400	39	2.82	22.9	33	39	3.44	27.1	28	39	3.99	37.4	22
	Uncut	70	2.00	18.1	34	70	2.24	23.2	32	69	2.43	26.1	22
8	200	23	2.92	21.4	18	23	3.44	24.7	18	23	3.89	31.2	14
	300	35	3.61	29.9	26	35	4.56	37.2	27	35	5.25	41.7	19
	400	38	2.61	23.2	34	38	3.13	26.9	28	39	3.58	31.1	21
	Uncut	50	2.19	20.9	31	50	2.53	26.4	25	51	2.60	34.9	18
9	200	20	1.11	10.5	19	20	1.42	11.6	12	20	1.75	16.1	19
	300	30	0.96	10.2	28	30	1.16	10.9	30	30	1.29	13.0	20
	400	41	0.84	8.8	40	41	1.09	9.9	40	40	1.26	12.1	22
	Uncut	38	1.15	13.0	25	38	1.58	13.8	28	39	1.75	16.1	19
10	200	21	1.28	11.3	21	21	1.65	12.7	21	21	2.05	15.5	17
	300	29	1.11	10.3	29	29	1.45	11.9	28	31	1.82	15.8	20
	400	35	1.54	13.4	35	35	1.88	14.4	32	40	2.18	18.2	37
	Uncut	42	1.56	13.8	37	42	1.88	14.6	25	43	2.16	16.9	20
12	200	20	0.88	9.7	20	20	1.30	11.5	18	20	1.46	16.4	11
	300	30	0.84	9.4	30	30	1.27	11.6	23	30	1.64	14.9	23
	400	40	1.05	10.9	40	40	1.33	13.3	30	37	1.59	14.6	27
	Uncut	18	0.78	8.9	15	18	1.33	10.6	14	18	1.68	13.4	13

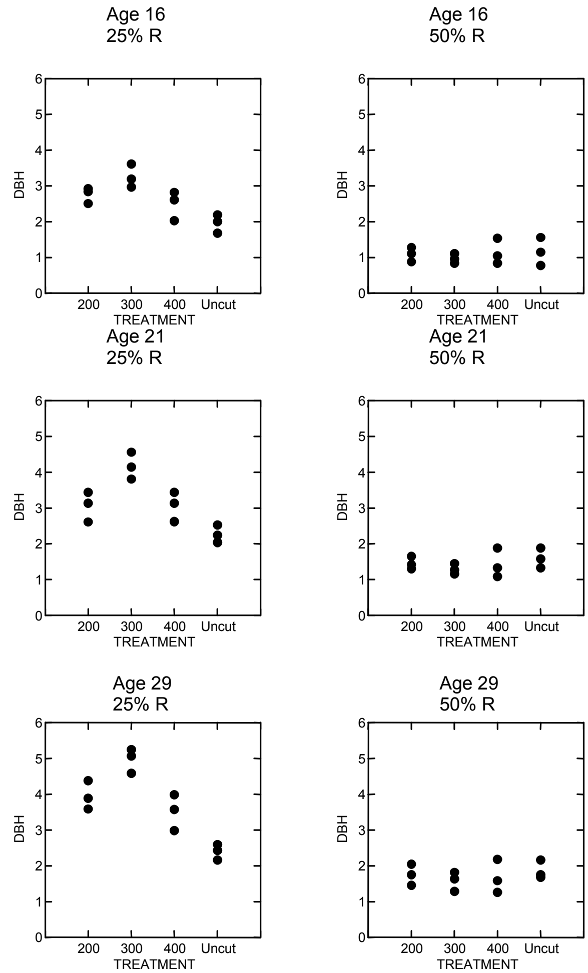

Figure 16. Plots of total understory sprout diameters (in.) by precommercial thinning treatment. Left and right columns are 25% and 50% overstory treatments respectively; rows are sprout ages.

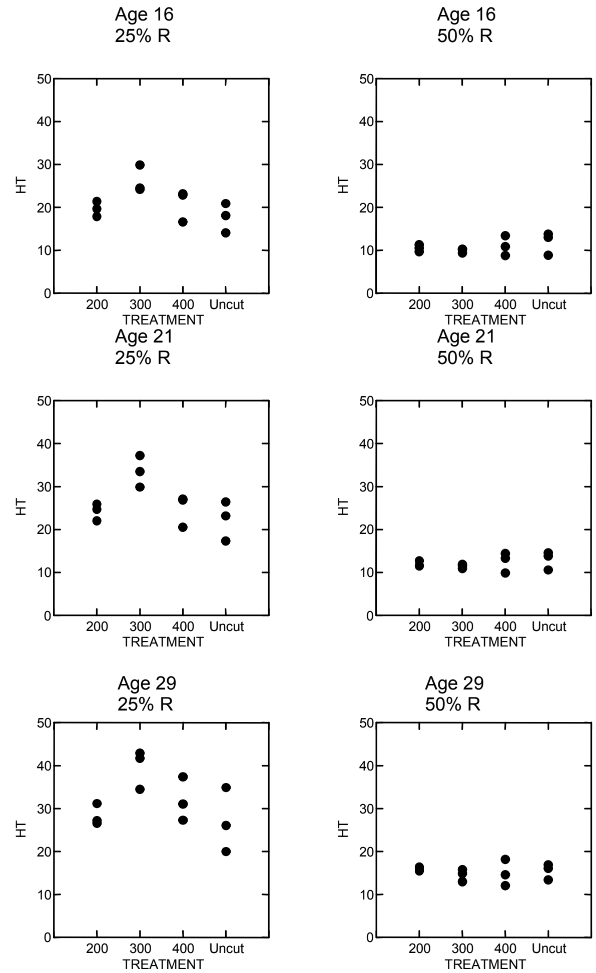

Figure 17. Plots of total understory sprout heights (ft.) by precommercial thinning treatment. Left and right columns are 25% and 50% overstory treatments respectively; rows are sprout ages.

thinning favored redwood and was intended to retain a well-distributed understory of the largest trees. The retained trees were mapped and subsequently measured in 1986, 1991 and 1999 with the results shown in Table 11. Average diameters in Table 11 were for the total number of trees in the treatment while average heights were for the tallest sprouts in a clump. Graphic displays are shown for average diameters (Figure 16) and heights (Figure 17) of trees in the three inventories for both the 25% and 50% retention overstory canopies. The number of stems by species after the 1986 thinning of the subplots was 783 redwood, 6 Douglas-fir, 4 grand fir, and 1 hemlock. Hemlock increased to 10 by 1999 while the other species numbers had not changed in 13 years. None of the redwood stems were considered seedlings. There was a very homogenous redwood sprout stand that developed after the overstory was thinned.

The average diameters in 1986, 1991, and 1999 shown in Table 11 revealed highly significant differences (p=0.000) between the 25% and 50% overstory treatments in each year. In 1986, at 16 years of age, the average diameter of the 25% overstory retention was 2.5 inches and for the 50% overstory retention it was 1.1 inches. Average diameter growth (Table 12) for the 25% overstory retention between 1986 and 1999 was 1.06 inches and for the 50% overstory it was 0.61 inches. At age 29 the average diameters had increased to 3.5 and 1.7 inches respectively. The largest sprout diameter in 1999 was 10.4 inches and only 12 stems in the three 25% overstory retention plots exceeded 7.5 inches. In the 50% overstory retention plots, the largest diameter was 5.9 inches, and only 3 trees exceeded 4.5 inches. At age 29, board foot volume had not been produced and in the 50% overstory retention treatment very little cubic volume had been produced. An examination of figure 16 shows that precommercial thinning treatments had no effect within the 50% overstory retention treatment but appear to have had an effect in the 25% overstory retention treatment. In 1986 for the 25% overstory retention treatment, there was no significant difference between precommercial thinning treatments (p=0.164) and there was in 1999 (p=0.048). The 300 stems per acre precommercial target have shown the maximum diameter growth.

Table 12. Average diameters and heights of understory redwood sprouts by overstory treatment over time. Crown classifications are from 1986 inventory. MAI is average height growth at that age.

		25% Overstory Treatment						50% Overstory Treatment					
		Diameter (in.)			Height (ft.)			Diameter (in.)			Height (ft.)		
Year (Age)	Crown Class	No. trees	Avg.	Std. Dev.	Avg.	Std. Dev.	MAI	No. trees	Avg.	Std. Dev.	Avg.	Std. Dev.	MAI
1986	Dom	43	4.8	1.1	32.2	6.1	2.0	0					
(16)	Codom	82	3.4	0.5	26.2	4.7	1.6	28	2.3	0.4	18.2	3.2	1.1
	Int	96	2.4	0.5	20.1	4.0	1.3	93	1.5	0.3	13.1	2.3	0.8
	Sup	96	1.5	0.4	14.0	3.2	0.9	217	0.9	0.4	9.1	2.2	0.6
1991	Dom	35	5.9	1.0	41.6	8.6	2.0	0					
(21)	Codom	81	4.1	0.6	32.2	6.6	1.5	23	2.9	0.7	20.1	1.4	1.0
	Int	82	3.0	0.7	23.9	4.6	1.1	83	1.8	0.4	14.4	2.4	0.7
	Sup	72	1.9	0.6	16.5	4.5	0.8	190	1.1	0.4	10.3	2.8	0.5
1999	Dom	44	6.6	1.6	48.2	10.1	1.7	0					
(29)	Codom	58	4.9	0.9	38.2	9.4	1.3	18	3.5	1.0	24.4	5.3	0.8
	Int	60	3.5	0.8	27.9	7.4	1.0	69	2.1	0.5	16.9	3.6	0.6
	Sup	44	2.3	0.8	19.8	6.3	0.7	135	1.5	0.5	12.9	3.7	0.4

The effect of overstory density on the understory height growth was apparent from the tree crowns. Most of the crowns of trees considered dominant in the understory in 1986 now show a more rounded top, rather than the pointed conical top characteristic of trees open to direct sunlight. The lateral branches appeared to be showing more growth than the terminal leader. The total height of all trees measured (Table 11) indicated highly significant differences (p=0.000) between the 25% overstory and 50% overstory treatments in all three inventory years. Average height of measured trees in 1986 was 21.4 feet in the 25% retention treatment, and 10.9 feet in the 50% retention treatment area. At age 29 these heights were 32.6 feet and 15.2 feet respectively. Mean annual height growth (Table 12) had dropped for the 25% overstory from 1.3 feet per year at 16 years to 1.1 feet per year at 29 years. Comparable reductions in the 50% overstory treatment were from 0.7 feet to 0.5 feet. The dominant stems in the 25% overstory treatment showed a decline in mean annual height growth from 2.0 feet per year in 1986 to 1.7 feet per year in 1999. As the overstory density continues to increase, it is expected that the rate of decline will increase. Figure 17 shows a trend for height that is similar to that for diameter in figure 16. The greatest sprout height growth occurred where 300 trees per acre were retained by the precommercial thinning treatment, although not significant (p=0.180).

Conclusions

Periodic response to the commercial thinning of a well-stocked 41-year old second growth redwood stand was determined by implementing six measurements over a 29-year period. The basal area was reduced by thinning to retain 25%, 50%, and 75% of the average stocking of the three control plots, which was 401 square feet per acre. Tests of the plots prior to thinning showed no significant differences between the plot basal area and a simple random assignment of treatments was adopted. Differences in growth attributed to site quality between treatments were accounted for in the board foot volume analysis.

One primary observation as a result of this study was that young-growth redwood stands are very productive and respond well to a range of stocking levels. Thinning produced a substantial increase in the average diameter of the residual stands. Average diameter increase as a result of thinning ranged from 8.0 inches the 25% retention treatment to 2.6 inches in the 75% retention treatment. By 1999, the average diameters ranged from 14.2 inches in the control to 31.8 inches in the 25% retention treatment, a difference of 17.6 inches. The most severe thinning produced the highest rate of radial growth, largely replacing the volume that had been removed. Intensive thinning from below is capable of producing larger diameter trees relatively quickly in stands at 40 year-of-age. Despite good diameter growth in the 25% retention treatment, a 75% basal area reduction did not produce total growth at a rate consistent with the site potential. The 50% retention treatment, with twice the initial basal area, had a net board-foot growth that was 140 percent of the 25% retention treatment.

Considering only total volume production, a reasonable option based on the results of this study, is to not prescribe a commercial thinning intermediate treatment. Except for the lower diameter growth, the unthinned plots compare favorably in basal area and volume production. In the control and lightly thinned areas, there were some indications (Figure 4) that basal area growth was beginning to slow. The board-foot MAI is still rising and does not yet indicate a culmination at age 70. Yield tables for unmanaged redwood (Lindquist and Palley 1963) show a maximum cubic-foot MAI for site 180 at 90 years and for site 200 at 70 years. Site index averages about 185 in these plots. Comparable culmination of board foot for site 180 does not occur before 100 years, and for site 200, culmination is at 90 years (Lindquist and Palley 1963). Overall, the trend in stand volume increment in this study seems to be comparable to the yield table values.

The relationship between understory growth and overstory density indicates that growth of redwood regeneration is inversely proportional to overstory canopy. The average height of the dominant redwood understory sprouts is 48 feet at 29 years-of-age. This is nearly 20 feet shorter than the average height of 24-year old dominant redwood in a clear-cut block with full sunlight in Caspar Creek (Lindquist 2004). The time needed to produce trees of commercial size under stands even as lightly stocked as the 25% retention treatment with 45 trees per acre will be much longer than following a clear cut where there is full sunlight. A sub-study of precommercial thinning treatments of the redwood sprouts showed an effect only in the most heavily thinned overstory condition.

Literature Cited

Allen, G. M. and M.M. Barrett. 1985. A model of third growth coastal redwood sprout establishment and growth under various of overstory removal. Unpubl. report; California State University, Humboldt. McIntre-Stennis No.74. Arcata,Ca. 46 p.

Carr, S. B. 1958. Growth Increase In Young Redwood Stands After Thinning. Journal of Forestry. Vol. 56 (7): 512.

Chapman, H.H. Forest Management. 1950. The Hildreth Press. Bristol, Conn. 582 p.

Krumland, B. and L. Wensel. 1979. Volume and taper relationships for redwood, Douglas-fir and other conifers in the north coast of California. Cooperative Redwood Yield Research Project. Res. Note 9. 66 p.

Lindquist, J. L., and M. N. Palley. 1961. Site Curves For Young-Growth Coastal Redwood. California Forestry and Forest Products. 26:1-4

Lindquist, J. L. and M. N. Palley. 1963. Empirical Yield Tables For Young-Growth Redwood. Bull. 796. Univ. of California College Of Agriculture, Agricultural. Exp. Station, Berkeley, CA. 47 p.

Lindquist, J. L. 1979. Sprout Regeneration of Young-Growth Redwood: sampling methods compared. U.S. Forest Service Research Note PSW-337. Pacific SW Forestry and Range Experiment Station. 8 p.

Lindquist, J. L., 1988. The Caspar Creek Cutting Trials. California Department Forestry and Fire Protection State Forest Notes. No. 99. 25 p.

Lindquist, J. L. 2004. Precommercial stocking control of coast redwood: a seventeen-year status report (1981-1998). California Department of Forestry and Fire Protection. California Forestry Report (2) 26p.

Oliver, William W., J. L. Lindquist, and R. O. Strothmann. 1994. Young-Growth Redwood Stands Respond Well to Various Thinning Intensities. Western Journal of Applied Forestry. Vol. 9 No. 4. 106 - 112.

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

Strothmann, R. O. 1969. Study plan for testing thinning to four levels of growing stock in previously unmanaged young-growth redwood stands about 35 years of age. Unpublished study plan of USFS PSW-1203, Arcata, CA.

Arnold Schwarzenegger
Governor
State of California

Michael Chrisman
Secretary for Resources
The Resources Agency

Andrea E. Tuttle
Director
California Department of Forestry and Fire Protection