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

PRECOMMERCIAL STOCKING CONTROL OF COAST REDWOOD

A SEVENTEEN-YEAR STATUS REPORT (1981-1998)

California Forestry
Report No. 2

JAMES L. LINDQUIST

3 YEAR-OLD CLEARCUT (1964)

1981
TREATMENTS

UNCUT
CONTROL

300 TREES
PER ACRE

2004

200 TREES
PER ACRE

100 TREES
PER ACRE

SUMMARY

Regeneration of coast redwood by stump sprouting often results in a stand condition that is very dense. A precommercial thinning of redwood sprouts allows managers to select trees and spacing that can best utilize the productivity of the site. The study of five thinning treatments with an unthinned control was initiated on a 19-year old third growth stand. Precommercial thinning was performed in 1981 with the random assignment of three 0.4-acre plots per treatment. Treatments were 100, 150, 200, 250, and 300 trees per acre plus an unthinned control. All 18 plots were measured in 1981 immediately after precommercial thinning, again in 1986 (5-year growth), and again in 1998 (12-year growth).

This study summarizes the three stand inventories and two periodic stand growth results for basal area, diameter, tree count, cubic foot, and board foot volumes. Analysis of variance (ANOVA) results indicated that despite the range of thinning, the 38-year-old stand showed no statistical differences in volume growth or yield between the thinning treatments. Heavily thinned treatments concentrated more growth on fewer trees to match the stand volume growth in the lightly thinned treatments. Consequently, the average diameters, by treatment, were statistically different. The unthinned plots had the lowest average 17-year board foot volume growth and the smallest average diameter of all the treatments.

A trend appears to be developing that indicates a drop in stand productivity for the heaviest thinning and the control. More time is needed to determine if the trend will continue. The optimal precommercial thinning density depends on a number of factors including desired stem diameter, thinning costs, timing of future treatments, and future commercial value.

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

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Introduction

This report documents the growth response of 18 precommercially thinned and control plots in the coast redwood (*Sequoia sempervirens*) forest type on the Jackson Demonstration State Forest (JDSF). These plots are located in a unit that had been clearcut as part of the 1961 Caspar Creek Cutting Trials (CCCT). This study originated in 1981 as a cooperative effort by the California Department of Forestry and Fire Protection (CDF) and the USDA Forest Service - Redwood Sciences Lab. CDF has since continued the study with a 1986 measurement and report that detailed the first five years of growth following the precommercial thinning (Lindquist, 1988). This report is an update of the study, incorporating the 1998 measurement.

Improving the productive capacity of forest stands is the primary reason why forest managers invest in timber stand improvement work. Site preparation, planting, thinning, and other cultural operations are designed to produce a positive return when considering operational and capital costs. This study is designed to determine the growth response of coast redwoods to a variety of stocking levels following precommercial thinning. David Smith defines this operation as an investment in the future growth of stands when the trees cut are so young that they have no market value (Smith, 1962).

The optimal stand density for young coast redwoods is currently unknown and a complex question. Residual stocking should be consistent with the productive capacity of the site and the species ability to utilize the space provided. Thinning too heavily may result in inefficient use of the site's productive capacity. In addition, the sprouting ability of coast redwood can result in excessive stocking and spacing problems that are not common to other conifer species. A single redwood stump may often produce more than 20 stems as the result of sprouting. The intense competition among these sprouts may eventually produce one or two codominant trees over the course of many years. Thinning is designed to accelerate this natural process.

Another characteristic of coast redwood is to produce dense, wide crowns if given abundant space, where a low density stand will expend much of its growth capacity on limbs and development of stems with a large amount of taper. Stem selection early in stand development is an important and reasonable option for the forest manager. Five stand densities, ranging from 100 to 300 trees per acre, as well as unthinned controls, were used in this study in order to gain a better understanding of a thinning schedule for coast redwood.

There were few third-growth redwood stands of an age that were ready for precommercial thinning when this study was initiated in 1981. A 14-acre unit, which had been clearcut in 1961 as part of the CCCT, was selected for the study area. In this unit, the study of tree growth and the effects of the precommercial thinning could be conducted in full sunlight without the shade of an overstory.

Methods and Data

Study design

The study is a complete random block design with three blocks. Each block contains six treatments including an unthinned control plot. Blocks 1 and 2 are located in the unburned portion of the clearcut and block 3 is located in the burned portion. The block design allows for the identification of effects due to treatments while controlling for block effects and providing replication. Eighteen plots were established in the study area as shown in Figure 1. Each plot is 0.4-acres in size. Trees were tagged and measured in the central 0.2-acre area of each plot, while leaving the trees in the 0.2-acre perimeter area as a treatment buffer. The designated treatment was applied to the entire 0.4-acre plot. In addition, there is an unthinned control in each of the three blocks. Trees were selected to retain an equal number of stems in each quadrant of the central plot and in each of the four buffer areas. Redwood was designated as the highest priority for retention, with Douglas-fir (*Pseudotsuga menziesii*), retained where suitable redwood were not available.

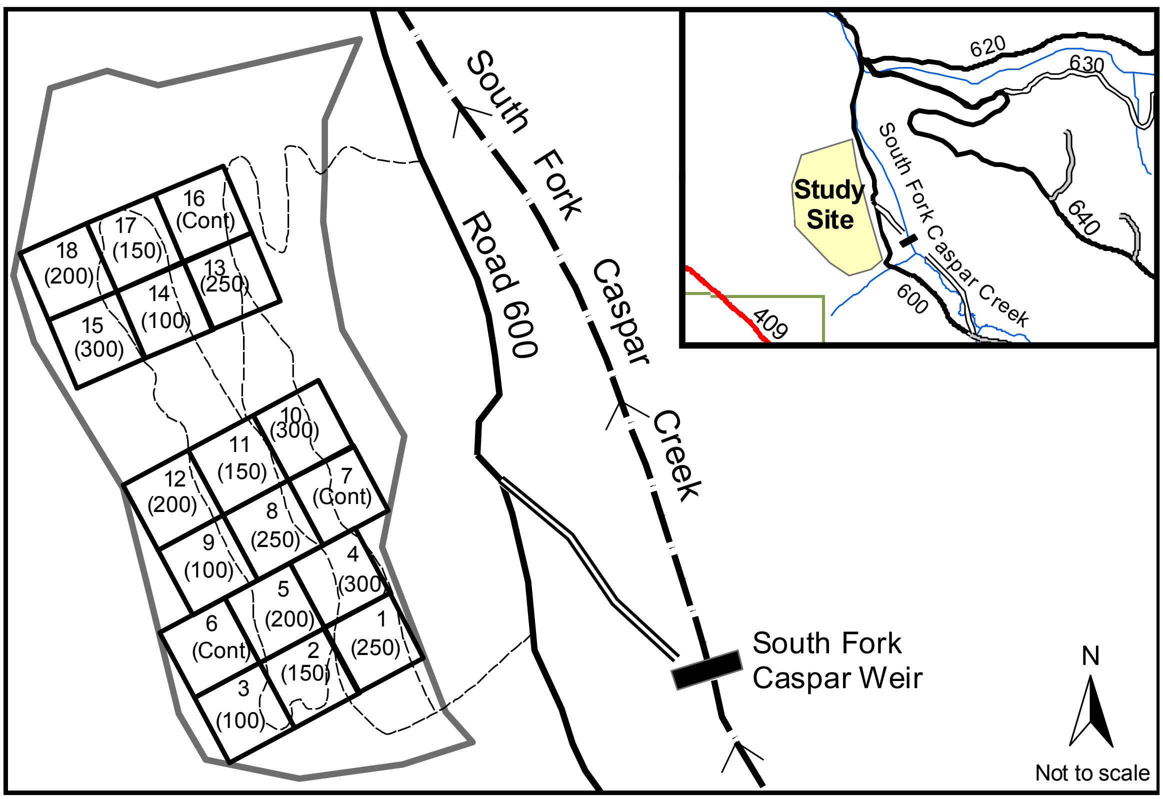

Figure 1. Study design layout for the pre-commercial thinning study.

Redwood sprout clumps were thinned to at least a 24-inch stem spacing within a single stump due to the need to distribute the trees as uniformly as possible. Trees as small as 1.5 inches in diameter were selected for retention. The primary objective in thinning redwood clumps was to achieve average spacing targets. Where spacing was adequate, thrifty trees were retained and the remaining stems were thinned from below.

The second growth stand (prior to harvest in 1961)

The second growth stand (prior to harvest in 1961) was described in a report by Malain and Burns (1962). The original 85-year old stand averaged 452 ft^2/ac of conifer basal area with a species composition of 51 percent redwood, 42 percent Douglas-fir and 7 percent other conifers. There were 143 trees per acre greater than 10.5 inches before harvest, of which 58 percent were redwood. The volume averaged 131,000 board feet per acre (Scribner). Dominant redwood trees from within the CCCT study indicated a site index of 155 to 160 at 100 years breast-high age (Lindquist and Palley 1961). The site index of the second growth stand aids in the prediction of future production.

The third growth stand (prior to precommercial thinning in 1981)

The conifer stocking present within the plots prior to precommercial thinning is shown in Table 1. These values represent a tally of stems greater than 1.5 inches dbh, greater than 4.5 inches, and greater than 10.5 inches in the central 0.2-acre for each of the 18 plots. Two small deer enclosures in block 2 contained planted Douglas-fir seedlings, but most other Douglas-fir and redwood were of natural origin.

Table 1. Pre-treatment Stand Description with Block Summaries (all values are per acre).

		Trees > 1.5 inches			Trees > 4.5 inches			Trees > 10.5 inches				
	Plot	Number of Trees	Basal Area (sq. ft.)	Average Diameter (in.)	Number of Trees	Basal Area (sq. ft.)	Average Diameter (in.)	Number of Trees	Basal Area (sq. ft.)	Average Diameter (in.)		
Block 1	1	870	200.2	6.5	465	183.0	8.5	60	48.9	12.2	Block 1	
	2	505	113.1	6.4	250	99.4	8.5	45	37.0	12.3		Redwood (>1.5 inches)
	3	450	112.1	6.8	240	98.1	8.7	45	39.6	12.7		Number of Trees
	4	785	133.8	5.6	335	112.7	7.8	35	32.2	13.0		87.3%
	5	1095	175.9	5.4	570	150.4	6.9	10	7.2	11.5		Basal Area
	6	700	137.1	6.0	305	124.5	8.6	50	36.8	11.6		96.6%
	Average	734	145.4	6.1	361	128.0	8.2	41	33.6	12.2		
	Std. Dev.	239	35.5	0.5	131	33.1	0.7	17	14.1	0.6		
Block 2	7	885	135.1	5.3	345	113.0	7.7	25	17.7	11.4	Block 2	
	8	910	126.3	5.0	305	99.7	7.7	30	29.7	13.4		Redwood (>1.5 inches)
	9	695	117.3	5.5	250	98.9	8.5	35	32.4	13.0		Number of Trees
	10	960	124.6	4.9	310	98.2	7.6	35	26.3	11.7		60.5%
	11	860	168.7	6.0	350	148.1	8.8	80	59.5	11.7		Basal Area
	12	1185	164.4	5.0	445	132.5	7.4	25	19.7	12.0		86.5%
	Average	916	139.4	5.3	334	115.1	8.0	38	30.9	12.2		
	Std. Dev.	160	21.8	0.4	65	20.9	0.6	21	15.1	0.8		
Block 3	13	630	163.5	6.9	295	149.2	9.6	95	87.5	13.0	Block 3	
	14	395	94.4	6.6	160	82.7	9.7	60	58.1	13.3		Redwood (>1.5 inches)
	15	740	136.4	5.8	321	117.1	8.2	35	33.8	13.3		Number of Trees
	16	690	122.3	5.7	275	103.4	8.3	35	34.8	12.6		82.8%
	17	475	167.4	8.0	320	161.3	9.6	105	102.2	13.4		Basal Area
	18	535	66.2	4.7	160	52.5	7.7	20	17.3	12.6		94.8%
	Average	578	125.0	6.3	255	111.0	8.9	58	55.6	13.0		
	Std. Dev.	132	39.5	1.1	76	40.8	0.9	35	33.4	0.4		
	Between Block P-Values	0.02 S	0.56 NS	0.09 NS	0.17 NS	0.65 NS	0.12 NS	0.36 NS	0.15 NS	0.05 NS		

S = significant at alpha .05, NS = not significant

Diameter distributions for the three blocks are shown in Table 2. This table provides an understanding of the stand structure within the blocks. Block 2 had the heaviest concentration of Douglas-fir (approximately 40 percent), with 916 stems per acre, while blocks 1 and 3 averaged about 15 percent Douglas-fir. The northwest half of the study area, encompassing block 3, was burned following the clear-cutting of the original second growth stand. The burning resulted in a dense growth of blue blossom (*Ceanothus thyrsiflorus*) that has since declined in site occupancy. Redwood sprouts in block 3 produced the fewest stems per acre, but possessed a diameter distribution with many larger stems. Redwood sprouts, in contrast to natural seedlings, represented 91 percent of all of the redwood regeneration prior to thinning in 1981.

Table 2. Pre-treatment Stand Diameter Distributions

Diameter Class (inches)	Trees Per Acre Block 1	Block 2	Block 3
2	186.0	290.0	159.0
3	105.0	166.5	97.5
4	82.0	114.0	66.0
5	66.0	80.0	42.5
6	66.0	73.0	41.5
7	54.0	49.0	36.0
8	57.0	41.0	33.5
9	50.0	36.0	28.5
10	27.5	28.0	14.0
11	16.0	19.0	15.0
12	12.5	6.0	16.0
13	6.0	7.5	13.5
14	2.5	3.5	4.0
15	1.5	1.5	6.5
16	2.5	1.0	1.5
17	0.0	0.0	1.0
18	0.0	0.0	1.5
Total	734.5	916.0	577.5

Analysis of variance (ANOVA) tests for number of trees, basal area, and average diameter of the three diameter limits, are shown at the bottom of Table 1. Only the number of stems greater than 1.5 inches exhibited a significant difference (.05 level) between blocks. The Scheffe test, for testing mean differences, indicated that the 338 stem difference between blocks 2 and 3 are significant at the .05 level. The difference is the result of block 2 having about four times as many small Douglas-fir in the 2 to 5-inch diameter classes than in blocks 1 and 3. In 1981 only a few Douglas-fir were greater than 5.5 inches in diameter, and all stems with diameters greater than the 6-inch class were redwood. Before thinning, the stand was 76.9 percent redwood by number of trees and they accounted for 92.6 percent of the basal area in trees greater than 1.5 inches. Douglas-fir comprised 96 percent of all non-redwood conifer stems. All stems greater than 10.5 inches in diameter prior to thinning were redwood.

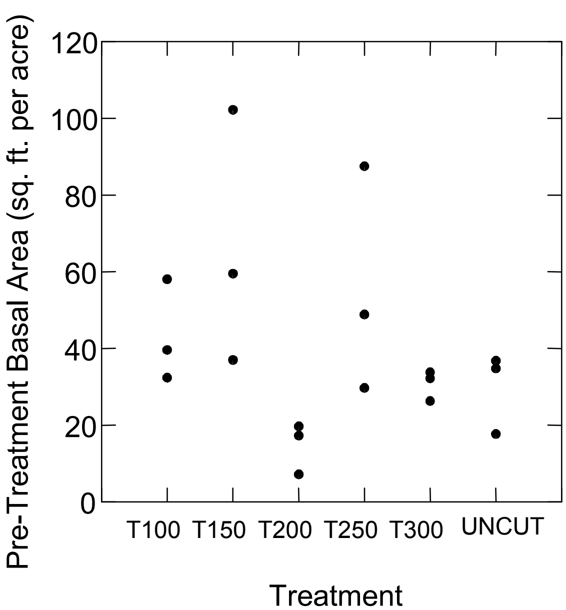

Figure 2. Graph of pre-treatment plot basal areas, for trees greater than 10.5 inches, by treatment.

No significant differences were detected between pre-harvest treatment groups, as would be expected with a randomized and replicated design. As Figure 2 illustrates, however, random chance has placed an inordinate amount of Douglas-fir in the plots assigned to T200. This was reflected in the pre-treatment basal area values for trees greater than 10.5 inches. This difference in T200 was accounted for in the analyses below.

Site index and stand age

The initial report for the CCCT study indicated that the clearcut block was logged in 1961. The maximum age of young conifer stems in this study was expected to have been 20 years at the time of the PCT. After the PCT was completed, a number of dominant and codominant redwoods were cored for breast-high age and measured for total height. Redwood site index was determined from site curves, where site index is the total height at 100 years of age (Lindquist and Palley, 1961). The average age of the trees cored from within these stands was determined to be 18.7 ± .3 years in October of 1981. Summaries of the average ages, total heights, and site indices for 1981, 1986, and 1998 are shown in Table 3 for the three blocks.

Table 3. Summaries of the average ages, total heights, and site indices for 1981, 1986, and 1998 for the three blocks.

Plot	1981 BHAge (yrs)	1981 Height (ft)	Site	1986 Height (ft)	Site	1998 Height (ft)	Site
Block 1							
1	19.4	60.2	180	72.7	177	101.7	183
2	18.5	49.0	165	60.4	158	92.1	169
3	19.0	53.2	169	63.9	164	87.6	164
4	19.2	51.7	164	64.2	163	82.1	154
5	19.2	47.7	157	58.9	158	89.1	166
6	18.5	54.4	176	66.1	170	93.0	171
Average	19.0	52.7	169	64.4	165	90.9	168
Std. Dev.	0.4	4.5	8	4.9	7	6.5	9
Block 2							
7	18.5	50.4	173	61.7	164	88.3	158
8	17.9	49.4	171	61.7	165	95.1	174
9	18.1	50.7	172	64.9	170	99.5	180
10	18.2	50.9	172	64.9	169	97.1	177
11	19.2	51.4	164	63.6	163	92.0	170
12	18.8	57.1	179	68.7	173	93.0	171
Average	18.5	51.7	172	64.3	167	94.2	172
Std. Dev.	0.5	2.8	5	2.6	4	4.0	8
Block 3							
13	19.2	57.6	177	73.6	179	104.4	187
14	19.8	58.2	172	77.0	182	108.9	193
15	18.2	55.9	183	71.8	183	106.5	190
16	18.6	56.4	180	70.9	178	97.4	177
17	18.3	63.4	199	78.6	193	111.7	197
18	17.8	55.3	185	69.9	179	95.1	174
Average	18.7	57.8	183	73.6	182	104.0	186
Std. Dev.	0.7	2.9	9	3.5	6	6.5	9

ANOVA tests for differences between blocks indicated that tree ages by plot were not significantly different at any of the three measurement dates. Total heights and site indices between blocks in 1981 were significantly different (p-value=0.016). Total heights and site indices in 1986 and 1998 exhibited highly significant differences (p-values of 0.000 and 0.006 respectively). The Scheffe tests of the block's average heights and sites indicated that block 3 (burned) had average tree heights and site indices that were significantly different from blocks 1 and 2. Estimates of average site index have risen from 2 to 4 feet between 1986 and 1998. Within each block, the site index has remained quite stable over the 17-year period since the plots were established. The average 12-year periodic height growth of dominant and co-dominant redwood since 1986 ranged from 28.2 feet in block 1 and 30.4 feet in block 3. No significant differences in site index were detected between treatments.

Volume computations

Local volume equations were developed to account for local conditions and allow for predictions that did not require a total height measurement for each tree. These equations were structured to predict total volume per plot. Individual tree volume was computed for each redwood and Douglas-fir tree with a height measurement, using the Krumland and Wensel (1979) equations for cubic and Scribner board foot. These equations use diameter at breast height and total tree height in the calculation of stem volume to a specified upper stem diameter (4" for cubic volume and 6" for board foot volume).

The volume of each plot was calculated by utilizing a linear regression of the stem volume as a function of the diameter squared. These regressions are constrained to intercept the diameter square axis at a point where the stem volume is zero. In this study, the cubic volume equations express a zero volume for a tree whose diameter squared is 10 or less. The zero-volume point for the board foot equations was 50 or less. As a consequence of this constraint on the volume equations, a tree less than 3.16 inches in diameter had no cubic volume and a tree less than 7.07 inches in diameter had no board foot volume. These local volume lines were computed by using stem volumes and diameters of 10 to 20 redwood trees in each plot. All plots were combined to compute the Douglas-fir coefficients since many of the plots did not have sufficient numbers of Douglas-fir trees to compute a reliable volume line. There were a few grand fir (*Abies grandis*) stems within the set of plots, and the coefficients for Douglas-fir were used for this species. The average stand volume coefficients used in the 1998 computations of plot volumes are shown in Table 4.

Table 4. Average stand volume coefficients used in the 1998 computations of plot volumes.

		Cubic Volume		Board Foot Volume	
Species	No. Plots	B (slope)	A (intercept)	B (slope)	A (intercept)
Redwood	18	0.15138	-1.5137	0.8745	-43.725
Douglas-fir	15	0.17659	-1.7659	1.13999	-56.999
Grand fir	1	0.17659	-1.7659	1.13999	-56.999

Calculation of the species volume per acre used the following function:
Volume = B X (stand basal area)/0.005454 + (-A X No. Trees)

Analysis

Treatments in this study are the reduction of stand density, as measured by the number of trees per acre. Response to treatments may be exhibited in the average standing volume, periodic growth, mean annual growth as a function of basal area, average diameters, ingrowth, and mortality. Simply identifying differences between treatments is not the only intent of this study. Identification of a suitable stocking level to either maximize yield or accelerate the production of larger trees may be of practical use to forest landowners and managers. The data from three plots in each treatment were averaged and the variation expressed by the mean and standard deviation for the three inventory dates 1981, 1986, and 1998. The 1984 measurements are not included in the analysis of inventory and growth since it represented only the first three years of the five-year growth period.

The statistical analysis relies upon the use of ANOVA to determine differences in response as the result of various levels of treatment. Blocks are included as a factor in the ANOVA to account for block effects. Other factors are considered and, where appropriate and not influenced by treatment effects, are accounted for using analysis of covariance (Gomez and Gomez 1984). Specific treatment differences are identified by the Scheffe test of multiple contrasts (SMC). SMC is only appropriate when the ANOVA indicates a significant difference in treatments overall (Neter, Wasserman, and Kutner 1985).

Results and Discussion

The plot responses to the treatments are summarized in Table 5. Periodic annual increment (PAI) by average diameter, basal area, volume, and numbers of trees are shown in Table 6.

Table 5. Plot responses to the treatments.

		Trees >1.5"				Trees >10.5"			
Plot	Year	No. (trees/ac.)	BA (sq.ft./ac.)	QMD (in.)	Cubic Vol. (cubic ft.)	No. (trees/ac.)	BA (sq.ft./ac.)	QMD (in.)	Bd. Ft. Vol. (board ft.)
100 trees/acre									
3	1981	75	48.0	10.8	699	35	30.3	12.6	1,791
	1984	110	75.2	11.2	1,243	60	61.0	13.6	4,166
	1986	110	91.8	12.4	1,609	70	80.7	14.5	6,022
	1998	110	179.1	17.3	4,860	95	175.3	18.4	25,373
9	1981	110	55.6	9.6	734	35	30.7	12.7	1,680
	1984	110	85.9	12.0	1,399	75	73.4	13.4	4,564
	1986	110	105.4	13.6	1,707	85	96.7	14.4	6,066
	1998	110	224.9	19.4	5,834	110	224.9	19.4	30,364
14	1981	100	64.9	10.9	977	50	52.8	13.9	3,277
	1984	100	106.2	13.9	2,090	70	98.5	16.1	8,664
	1986	100	131.8	15.5	2,612	75	124.9	17.5	11,313
	1998	95	261.1	22.4	7,513	85	255.7	23.5	40,882
150 trees/acre									
2	1981	150	85.2	10.2	949	40	35.4	12.7	1,741
	1984	150	116.5	11.9	1,776	110	103.6	13.1	6,107
	1986	150	139.9	13.1	2,275	120	130.0	14.1	8,496
	1998	150	264.6	18.0	7,091	140	260.5	18.5	35,302
11	1981	155	76.8	9.5	1,066	60	47.6	12.1	2,449
	1984	150	124.0	12.3	2,010	85	101.3	14.8	6,449
	1986	150	157.5	13.9	2,663	90	133.5	16.5	9,211
	1998	145	295.6	19.3	7,016	125	286.3	20.5	34,665
17	1981	150	127.9	12.5	2,118	105	113.0	14.0	7,623
	1984	150	185.8	15.1	3,637	130	178.3	15.9	15,313
	1986	150	218.0	16.3	4,566	135	212.1	17.0	20,307
	1998	150	385.7	21.7	12,020	145	382.7	22.0	65,579
200 trees/acre									
5	1981	205	67.7	7.8	836	20	14.2	11.4	748
	1984	205	113.4	10.1	1,779	85	72.0	12.5	4,488
	1986	205	146.4	11.4	2,213	115	113.5	13.5	6,760
	1998	205	303.6	16.5	7,798	185	296.0	17.1	37,783
12	1981	200	62.6	7.6	983	25	18.3	11.6	1,223
	1984	195	105.7	10.0	1,945	70	58.1	12.5	4,323
	1986	195	132.2	11.1	2,527	125	110.5	12.7	8,535
	1998	190	246.8	15.4	6,333	160	235.0	16.4	28,922
18	1981	200	51.8	6.9	647	20	18.3	12.9	1,040
	1984	195	88.5	9.0	1,461	55	52.7	13.3	3,655
	1986	190	109.9	10.0	1,962	85	84.4	13.5	6,392
	1998	165	215.6	14.1	5,535	130	205.6	17.0	26,121

		Trees >1.5"				Trees >10.5"			
Plot	Year	No. (trees/ac.)	BA (sq.ft./ac.)	QMD (in.)	Cubic Vol. (cubic ft.)	No. (trees/ac.)	BA (sq.ft./ac.)	QMD (in.)	Bd. Ft. Vol. (board ft.)
250 trees/acre									
1	1981	275	126.4	9.2	1,911	65	51.4	12.0	2,905
	1984	275	179.5	10.9	3,281	170	147.1	12.6	10,747
	1986	255	205.0	12.1	3,867	180	177.9	13.5	14,012
	1998	250	376.5	16.6	11,140	225	360.2	17.1	54,885
8	1981	255	79.4	7.6	935	45	39.8	12.7	1,887
	1984	255	122.4	9.4	1,961	70	72.6	13.8	4,769
	1986	255	147.8	10.3	2,405	100	106.6	14.0	6,905
	1998	255	275.0	14.1	7,178	190	252.5	15.6	32,397
13	1981	255	133.3	9.8	2,021	100	99.2	13.5	6,251
	1984	255	193.9	11.8	3,697	150	175.9	14.7	14,638
	1986	255	229.0	12.8	4,661	150	206.1	15.9	19,195
	1998	240	394.2	17.4	11,348	185	378.5	19.4	57,542
300 trees/acre									
4	1981	305	114.4	8.3	1,427	55	55.0	13.5	2,922
	1984	305	177.9	10.3	2,638	120	127.3	13.9	7,942
	1986	300	209.5	11.3	3,471	150	165.8	14.2	11,529
	1998	300	353.7	14.7	8,260	215	328.7	16.7	37,374
10	1981	305	83.9	7.1	1,042	45	35.1	11.9	1,846
	1984	305	123.2	8.6	2,049	75	67.2	12.8	4,700
	1986	305	148.3	9.4	2,558	110	101.7	13.0	7,170
	1998	265	263.3	13.5	7,102	165	232.1	16.1	31,240
15	1981	300	98.5	7.8	1,362	40	35.4	12.7	2,110
	1984	300	149.9	9.6	2,559	105	97.5	13.0	6,917
	1986	300	181.2	10.5	3,367	135	136.5	13.6	10,715
	1998	300	326.6	14.1	9,510	195	294.3	16.6	43,086
Unthinned Control									
6	1981	870	153.8	5.7	1,587	80	59.1	11.6	2,921
	1984	840	207.4	6.7	2,962	130	110.6	12.5	7,339
	1986	865	231.2	7.0	3,415	155	137.9	12.8	9,282
	1998	560	333.1	10.4	8,362	205	260.9	15.3	32,152
7	1981	805	126.6	5.4	1,239	15	11.1	11.6	582
	1984	795	158.5	6.0	2,210	65	47.6	11.6	3,227
	1986	805	174.7	6.3	2,483	80	62.5	12.0	4,255
	1998	545	265.3	9.4	6,187	180	178.5	13.5	19,394
16	1981	760	140.2	5.8	1,686	55	48.2	12.7	3,030
	1984	745	198.2	7.0	3,011	125	113.7	12.9	8,168
	1986	755	225.6	7.4	3,820	150	144.9	13.3	11,734
	1998	475	344.8	11.5	9,931	215	296.8	15.9	44,416

Table 6. Average and standard deviation for inventory values for each thinning treatment in 1981, 1986, and 1998. Average periodic annual growth of the 5-, 12-, 17-year growth periods. All values are reported on a per acre basis.

Treatment		Year	Trees >1.5" No. (trees/ac.)	BA (sq.ft./ac.)	QMD (in.)	Cubic Vol. (cubic ft.)	Trees >10.5" No. (trees/ac.)	BA (sq.ft./ac.)	QMD (in.)	Bd. Ft. Vol. (board ft.)
100	Inventory	1981	95.0	56.2	10.4	803	40.0	37.9	13.1	2,249
		std. dev.	18.0	8.5	0.7	151	8.7	12.8	0.7	892
		1986	106.6	109.6	13.8	1,976	76.9	100.7	15.5	7,800
		std. dev.	5.8	20.3	1.6	553	7.6	22.4	1.8	3,042
		1998	105.0	221.7	19.7	6,069	96.7	218.6	20.4	32,206
		std. dev.	8.7	41.1	2.6	1,342	12.6	40.6	2.7	7,917
	Annual Change	86 - 81	2.3	10.7	0.7	235	7.4	12.6	0.5	1,110
		98 - 86	-0.1	9.3	0.5	341	1.7	9.8	0.4	2,034
		98 - 81	0.6	9.7	0.5	310	3.3	10.6	0.4	1,762
150	Inventory	1981	151.7	96.6	10.7	1,378	68.3	65.3	12.9	3,938
		std. dev.	2.9	27.4	1.6	644	33.3	41.7	1.0	3,211
		1986	150.0	171.8	14.4	3,168	115.0	158.5	15.8	12,671
		std. dev.	0.0	41.0	1.7	1,226	22.9	46.4	1.6	6,622
		1998	148.3	315.3	19.7	8,709	136.7	309.8	20.3	45,182
		std. dev.	2.9	62.9	1.9	2,868	10.4	64.4	1.7	17,667
	Annual Change	86 - 81	-0.3	15.0	0.7	358	9.3	18.6	0.6	1,747
		98 - 86	-0.1	12.0	0.4	462	1.8	12.6	0.4	2,709
		98 - 81	-0.2	12.9	0.5	431	4.0	14.4	0.4	2,426
200	Inventory	1981	201.7	60.7	7.4	822	21.7	16.9	11.9	1,004
		std. dev.	2.9	8.1	0.5	168	2.9	2.4	0.8	240
		1986	196.7	129.5	10.8	2,234	108.3	102.8	13.2	7,229
		std. dev.	7.6	18.4	0.7	283	20.8	16.0	0.5	1,146
		1998	186.7	255.3	15.3	6,555	158.3	245.5	16.8	30,942
		std. dev.	20.2	44.6	1.2	1,147	27.5	46.1	0.4	6,087
	Annual Change	86 - 81	-1.0	13.8	0.7	282	17.3	17.2	0.3	1,245
		98 - 86	-0.8	10.5	0.4	360	4.2	11.9	0.3	1,976
		98 - 81	-0.9	11.4	0.5	337	8.0	13.4	0.3	1,761
250	Inventory	1981	261.7	113.0	8.9	1,622	70.0	63.5	12.7	3,681
		std. dev.	11.3	29.3	1.1	598	27.8	31.6	0.8	2,283
		1986	255.0	193.9	11.7	3,644	143.3	163.5	14.5	13,371
		std. dev.	0	41.7	1.3	1,144	40.4	51.3	1.3	6,170
		1998	248.3	345.2	15.9	9,888	200.0	289.5	17.3	48,274
		std. dev.	7.6	60.9	1.6	2,349	21.8	61.3	1.8	13,814
	Annual Change	86 - 81	-1.3	16.2	0.6	404	14.7	20.0	0.4	1,938
		98 - 86	-0.6	12.6	0.4	520	4.7	10.5	0.2	2,909
		98 - 81	-0.8	13.7	0.4	486	7.6	13.3	0.3	2,623
300	Inventory	1981	303.3	98.9	7.7	1,277	46.7	41.8	12.7	2,293
		std. dev.	2.9	15.2	0.6	206	7.6	11.4	0.8	561
		1986	301.7	179.7	10.4	3,132	131.7	134.7	13.6	9,805
		std. dev.	2.9	30.6	1.0	500	20.2	32.1	0.6	2,318
		1998	288.3	314.5	14.1	8,291	191.7	285.0	16.5	37,233
		std. dev.	20.2	46.4	0.6	1,204	25.2	49.0	0.3	5,924
	Annual Change	86 - 81	-0.3	16.2	0.5	371	17.0	18.6	0.2	1,502
		98 - 86	-1.1	11.2	0.3	430	5.0	12.5	0.2	2,286
		98 - 81	-0.9	12.7	0.4	413	8.5	14.3	0.2	2,055
UNCUT	Inventory	1981	811.7	140.2	5.6	1,504	50.0	39.5	12.0	2,178
		std. dev.	55.3	13.6	0.2	235	32.8	25.2	0.6	1,383
		1986	808.3	210.5	6.9	3,239	128.3	115.1	12.7	8,424
		std. dev.	55.1	31.1	0.6	686	41.9	45.7	0.6	3,813
		1998	526.7	314.4	10.4	8,160	200.0	245.4	14.9	31,987
		std. dev.	45.4	42.9	1.1	1,880	18.0	60.6	1.3	12,512
	Annual Change	86 - 81	-0.7	14.1	0.3	347	15.7	15.1	0.1	1,249
		98 - 86	-23.5	8.7	0.3	410	6.0	10.9	0.2	1,964
		98 - 81	-16.8	10.2	0.3	392	8.8	12.1	0.2	1,753

Some general observations can be made about the results. Over time, average stand diameter increased with lower treatment density. Stand density was not statistically different after 17 years. However, a trend is developing that appears to indicate a drop in stand productivity for the heaviest thinning and the control. Another measurement will be necessary to confirm this conclusion. Additionally, the species composition of a given stand apparently dictates the opportunities for precommercial thinning and the expected response.

Diameter and diameter growth

Average stand diameter is expressed as quadratic mean diameter (QMD), the diameter of the tree of average basal area. Average stand diameter is a function of ingrowth, mortality, and the radial growth of stems. Changes in both the numbers of trees per acre and stand basal area influence the diameter increment. The average diameter of trees greater than 1.5 inches and trees greater than 10.5 inches for the 18 plots are shown in Table 5. The average values of diameter by treatment class are shown in Table 6, along with periodic annual increment of diameter.

The average stem diameter for trees greater than 1.5 inches immediately after thinning in 1981, ranged from 5.6 inches (control) to 10.7 inches (T150); a range of 5.1 inches (Figure 3). This exhibited a highly significant difference between treatments, due partially to removal of most of the smallest trees in the heavily thinned plots. This difference remained significant in 1986 and 1998, due to the greater number of slow-growing small stems in the control and higher residual-density treatments. Changes in average stand diameter were also affected by increased mortality of suppressed Douglas-fir. The range of average diameters in 1998 increased to 9.3 inches, partially due to the rapid radial growth in the T100 and T150 treatments.

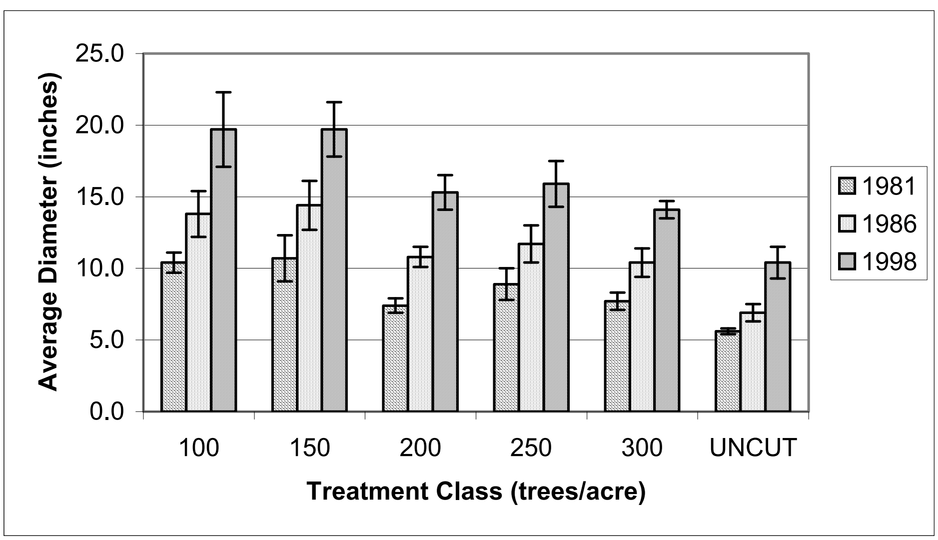

Figure 3. Average stand diameter for trees greater than 1.5” dbh. Error bars are one standard deviation.

Examination of periodic annual increment (Table 6) revealed no significant difference between treatments in the 1981-86 period but a highly significant difference in the 1986-98 period. Board foot stand values were not significantly different between treatments at the time of first measurement after thinning. Average diameters of these larger stems were not affected by thinning. Diameters of these larger trees ranged from 11.9 to 13.1 inches.

The number of trees greater than 10.5 inches in 1981, averaged across all treatments, was 48.6 trees per acre. By 1986, there was a significant difference in diameter between the control and the T150 plots (3.1 inches). The 1998 results indicated a highly significant difference between the control plots and those within T100 and T150 (about 5.5 inches). This pattern is similar to that exhibited by trees greater than 1.5 inches.

Stand basal area and basal area growth

Stand basal area (Figure 4) is a useful variable to consider in the evaluation of growth because it is highly correlated to stand volume. In 1981, immediately after thinning, the differences between treatments were highly significant for stands greater than 1.5 inches (Table 6).

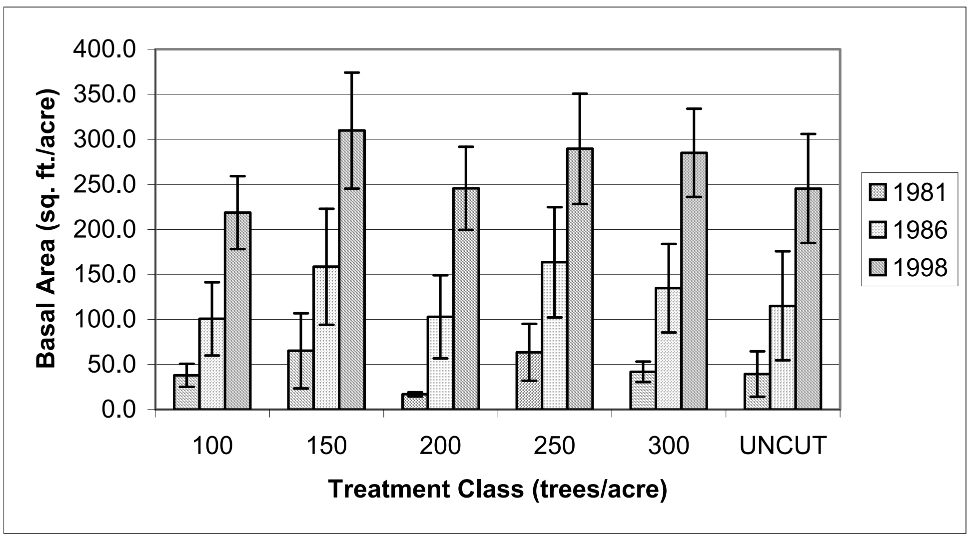

Figure 4. Average basal area for trees greater than 10.5” dbh.
Error bars are one standard deviation.

The basal area of trees greater than 10.5 inches (Figure 4) was not significantly different between treatments in 1981, in spite of the fact that thinning changed the number of stems in each treatment (Table 6). These values ranged from a low of 16.9 square feet in T200 to a high of 65.3 square feet per acre in T150, with an average of 44.2 ± 26.8 square feet per acre. The 1986 inventory also showed no significant differences between treatments despite the fact that the average basal area in thinned stands increased by a factor of 4.3. By 1986, an average of 67.8 trees per acre passed the 10.5-inch threshold. Average stand basal area in 1998 (Table 7) again showed no significant difference between treatments.

Table 7. Analysis of variance for basal area (sq. ft. per acre, trees > 10.5”) inventory in 1998.
N: 18   Multiple R: 0.860

Source	Sum-of-Squares	df	Mean-Square	F-ratio	P
Block	2068.578	1	2068.578	1.221	0.295
Treatment	18915.927	5	3783.185	2.233	0.131
Pre-BA10	18871.893	1	18871.893	11.141	0.008
Error	16939.214	10	1693.921		

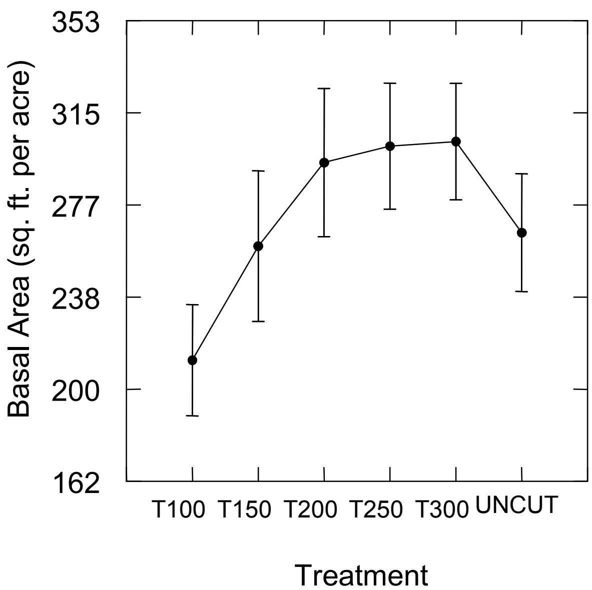

Figure 5. Basal area treatment means for trees greater than 10.5 inches for 1998. ANOVA includes block factor and pre-harvest basal area (>10.5”) as concomitant variable.

Despite the highly significant differences in the number of trees retained in the stands after treatment, the basal area was not significantly different after 17 years. The trees have adjusted to the space provided by thinning. However, there is an apparent response trend developing when both block and pre-treatment large tree inventory are considered (Figure 5). Figure 6 illustrates that pre-harvest basal area in trees greater than 10.5 inches is an important covariate. Pre-harvest basal area is correlated to 1998 basal area (0.66), cubic volume (0.66), and board foot volume (0.78).

The lowest initial residual basal area (trees greater than 1.5”) was in T100, and the largest in the control plots. The Scheffe pairwise comparison tests indicated that all of the treatments were significantly lower than the control area and many were significantly different from each other. By 1998, inventory differences were not significantly different.

The most recent periodic basal area growth in all treatments except T100 was greater than the control, but not statistically significant. Periodic basal area growth for the 17-year period shows no significant differences but all thinned treatments have higher basal area growth than the uncut plots (Tables 5 and 6).

For trees greater than 10.5 inches in diameter, the unthinned control plots had an average basal area growth of 205.9 square feet for the 17-year period. This was only 25 square feet greater than for the T100 treatment. There was heavy mortality of small diameter Douglas-fir in the unthinned plots of blocks 1 and 2, which produced a reduction in basal area. Variation between three plots in each treatment, shown by standard

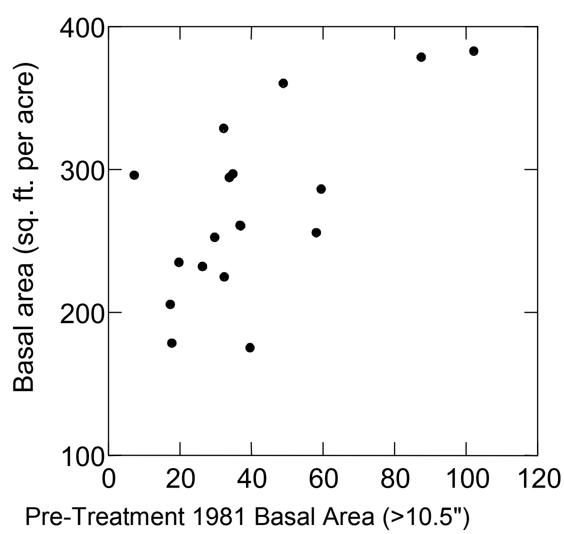

Figure 6. Relationship between 1998 basal area (trees > 10.5 inches) and 1981 pre-treatment basal area.

deviation (SD), is low and uniform across the range of treatments.

The portion of basal area growth attributable to ingrowth will continue to increase in the lightly thinned and uncut treatments for some time. The more heavily thinned stands exhibited higher levels of radial growth on fewer but larger stems, resulting in no apparent difference in basal area growth between the treatments. As these stands age, it will be of interest to see if longer rotations in lightly thinned treatments are able to produce greater stand basal area than in the heavily thinned treatments, where ingrowth has nearly ceased by age 38. A strictly statistical view of the results as of 1998 is that little is gained in terms of basal area yield and periodic growth by precommercially thinning. Additional time is needed for the effects of the treatments on basal area to be revealed or fully distinguished.

Cubic-foot inventory and growth

Cubic volume was computed for all trees greater than 1.5 inches at breast height. Except for the unthinned plots, there were very few stems smaller than 4.5 inches diameter. No ingrowth was observed in terms of cubic volume (trees greater than 1.5 inches). Table 5 indicates that the number of trees has remained constant through time, except in the unthinned plots where mortality has reduced the number of trees. Average cubic-foot inventory was not statistically different between treatments within the 1981, 1986, or 1998 (Table 8) inventories. The non-significant differences between treatments shown by the ANOVA indicated little was gained by precommercial thinning. Plot variation within treatments was large (Figure 7 error bars). Figure 7 illustrates that a trend is developing, similar to basal area (Figure 5), where although not statistically significant yet, the two least-stocked treatments appear to exhibit lower cubic foot productivity. This indicates a possible relationship between stocking level and cubic volume productivity that should be monitored into the future.

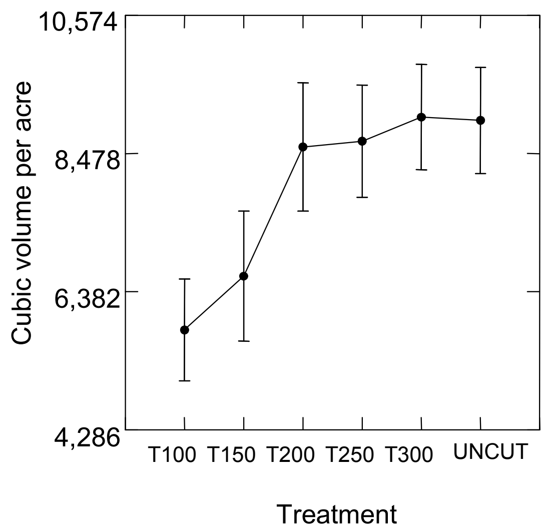

Figure 7. Cubic volume treatment means for 1998. ANOVA includes block factor and pre-harvest basal area (>10.5”) as concomitant variable.

Table 8. Analysis of variance for cubic volume per acre inventory in 1998.
N: 18 Multiple R: 0.759

Source	Sum-of-Squares	df	Mean-Square	F-ratio	P
Treatment	2.36960E+07	5	4739194.722	2.676	0.087
Block	274960.137	1	274960.137	0.155	0.702
Pre-BA10	2.01839E+07	1	2.01839E+07	11.398	0.007
Error	1.77090E+07	10	1770896.300		

The growth within Block 3 (burned) was clearly highest when the cubic volume plot data in Table 5 were ranked. The greatest volume of all the plots was found in plot 17 of T150. Except for plot 18 of

T200, the plots in block 3 had the largest volume in each treatment. Most of the plots in this block also had very few Douglas-fir. The stand volumes for plots in block 2 were the lowest. This was probably due to a greater percentage of Douglas-fir in the block. Many of the Douglas-fir trees that were retained were relatively small understory stems that had not been capable of taking advantage of the increased growing space created by precommercial thinning.

The cubic volume response to thinning in terms of the 5, 12, and 17-year periodic growth rate is shown in Table 6. The ANOVA of the data for each of these growth periods showed no difference between treatments. The smallest 17-year periodic growth was in T100 and the largest in T250.

Board-foot inventory and growth

Board-foot volumes were computed for trees greater than 10.5 inches dbh. These values are shown in Tables 5 and 6 and in Figure 8. Over time, board-foot inventories were affected somewhat by in-growth of smaller trees into the 10.5-inch class. This effect was greatest in the lower density treatments. The board-foot values for each of the three inventory dates indicated no significant differences between treatments (Table 9). Adjusting the average treatment means for block and starting inventory effects (Figure 9), the relationship, although not statistically significant, appears to be that T250 has produced the maximum board foot volume after seventeen years.

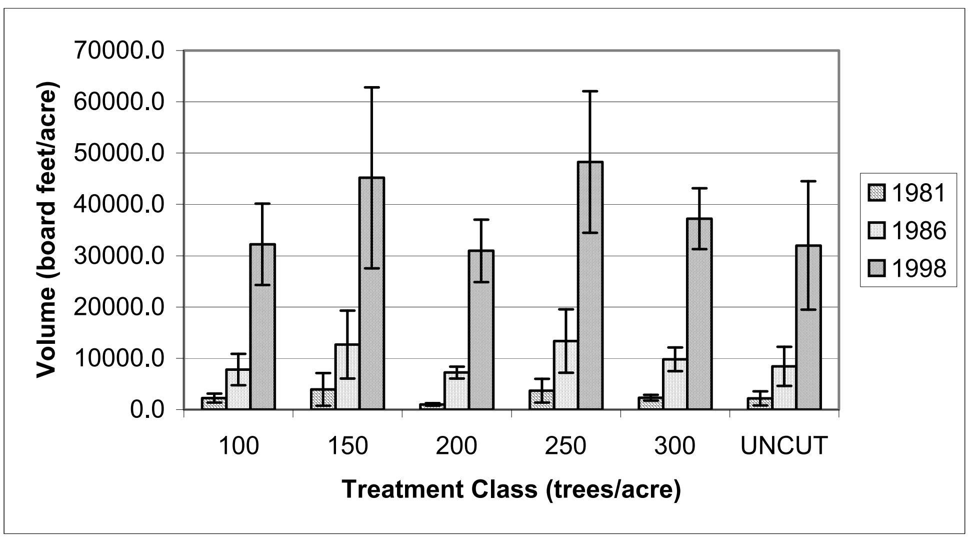

Figure 8. Average board foot per acre volumes (Scribner). Error bars are one standard deviation.

Table 9. Analysis of variance for board foot volume inventory in 1998.
N: 18 Multiple R: 0.903

Source	Sum-of-Squares	df	Mean-Square	F-ratio	P
Treatment	2.70464E+08	5	5.40928E+07	1.087	0.429
Block	1.71297E+08	2	8.56487E+07	1.722	0.233
Pre-BA10	2.94656E+08	1	2.94656E+08	5.923	0.038
Error	4.47759E+08	9	4.97510E+07		

The rapid diameter growth increase in the more heavily thinned plots has allowed them to keep pace with total volume growth in the more heavily stocked treatments. The process of thinning has left a stand comprised of vigorous redwood sprouts larger than 10.5 inches dbh. These trees, primarily in the T100 and T150, have responded by growing an average of 7.25 inches between 1981 and 1998. The result was that the thinning treatments to date have not shown statistically significant volume growth differences between treatments. The relative seventeen-year growth trend was the same pattern as that for standing volume shown in Figure 9, with T250 exhibiting the maximum annual growth.

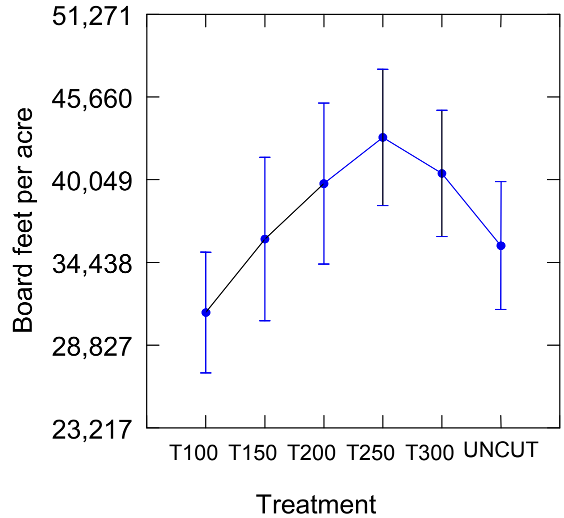

Figure 9. Board foot volume treatment means for 1998. ANOVA includes block factor and pre-harvest basal area (>10.5") as concomitant variable.

Tree size

The 20 largest trees in each post-thinned plot were followed through the last twelve years of the study to determine what effect tree size had upon stand volume production. These 20 trees in the 0.2-acre plot were analogous to treatment T100 when expanded to a trees-per-acre value. This allowed a comparison of the T100, as a baseline, with the denser treatments. Average treatment board-foot inventory values for 1986 and 1998 and the 12-year periodic growth are summarized in Table 10. For 1986, the ANOVA indicated there was no significant difference between the treatments for the largest 20 trees in the plots. The portion of average stand volume represented by these trees was 88.4 ± 7.3 percent. By 1998, the volume of the largest 20 trees in each plot was different between treatments, with the T150 and the unthinned control being statistically significant. The percent of 1998 volume produced by the largest 20 trees ranged from 100.0 percent in T100 to 62.6 percent in the unthinned control plots.

Table 10. Average board foot volumes per acre by treatment of all trees >10.5" dbh and of the 20 largest trees in each plot. Data is for 1986 and 1998 and shows periodic annual growth. Largest 20 trees per plot equates to 100 trees per acre.

	1986 values			**1998 values**			**12 year PAI**		
Trmt.	**Largest 20**	**All**	**Percent**	**Largest 20**	**All**	**Percent**	**Largest 20**	**All**	**Percent**
	bdft/ac	**bdft/ac**		**bdft/ac**	**bdft/ac**		**bdft/ac/yr**	**bdft/ac/yr**	
100	7,800	7,800	100.0	31,836	31,836	100.0	2,003	2,003	100.0
150	11,334	12,671	89.4	37,586	45,182	83.2	2,188	2,709	80.7
200	6,656	7,229	92.1	22,958	30,942	74.2	1,358	1,976	68.7
250	10,590	13,371	79.2	32,040	48,274	66.4	1,788	2,871	62.3
300	8,471	9,805	86.4	25,007	37,233	67.2	1,378	2,286	60.3
500	6,999	8,424	83.1	20,015	31,987	62.6	1,093	1,964	55.7

The periodic annual volume increment of the largest 20 trees was significantly different between treatments. The difference between T150 and the unthinned control was statistically significant. The board-foot periodic increment of the 20 largest trees in the unthinned control was only 55.5 percent of all trees. Diameter growth was important in the comparison of volume growth in the 12-year period. The average diameter of the stand in T100 increased from 15.5 inches to 20.6 inches, or 5.1 inches. In the unthinned control, the average diameter increased from 13.3 inches to 16.6 inches, or 3.3 inches. Stand density in the unthinned plots seemed to have adversely affected growth of the large trees. The larger trees in the plots tended to contribute a lower percentage of PAI with increasing stand density (Table 10). Additional time is needed to determine if this trend will reveal itself as statistically significant.

Ingrowth and mortality

Ingrowth and mortality using lower diameter limits of 4.5 and 10.5 inches were analyzed in a previous study (Lindquist, 1988). The current study uses a lower diameter limit of 1.5 inches in order to provide an understanding of the Douglas-fir mortality observed in the small diameter classes. A summary of the ingrowth and mortality during stand development is shown in Table 11. Data from this table show that in the greater than 1.5-inch stand, ingrowth was still occurring on a limited scale and the ingrowth was primarily Douglas-fir.

Table 11. Summary of the ingrowth and mortality by plot for the 12 year period 1986 - 1998.
Values are expressed on a per acre basis.

		Ingrowth								**Mortality**		
		Stand > 1.5"				**Stand > 10.5"**						
Treatment	**Plot**	**No. of Trees**	**Basal Area**	**Average Diameter**	**Percent Redwood**	**No. of Trees**	**Basal Area**	**Average Diameter**	**Percent Redwood**	**No. of Trees**	**Basal Area**	**Percent Redwood**
100	3	5.0	1.3	7.0	0.0	25.0	27.9	14.3	20.0	0.0	0.0	0.0
	9	0.0	0.0	0.0	0.0	25.0	24.6	13.4	20.0	0.0	0.0	0.0
	14	0.0	0.0	0.0	0.0	10.0	8.1	12.2	0.0	5.0	1.4	0.0
	Avg.	**1.7**	**0.4**	**7.0**	**0.0**	**20.0**	**20.2**	**13.3**	**16.7**	**1.7**	**0.5**	**0.0**
150	2	5.0	1.4	7.2	0.0	20.0	19.5	13.4	50.0	0.0	0.0	0.0
	11	0.0	0.0	0.0	0.0	35.0	29.2	12.4	0.0	5.0	1.6	0.0
	17	0.0	0.0	0.0	0.0	10.0	10.1	13.6	100.0	0.0	0.0	0.0
	Avg.	**1.7**	**0.5**	**7.2**	**0.0**	**21.7**	**19.6**	**13.1**	**30.7**	**1.7**	**0.5**	**0.0**
200	5	5.0	1.5	7.3	0.0	70.0	74.2	13.9	64.0	0.0	0.0	0.0
	12	5.0	1.2	6.5	0.0	35.0	33.4	13.2	85.7	5.0	0.5	0.0
	18	15.0	3.6	6.6	33.3	45.0	46.9	13.8	77.7	25.0	1.6	0.0
	Avg.	**8.3**	**2.1**	**6.9**	**20.1**	**50.0**	**51.5**	**13.6**	**73.2**	**10.0**	**0.7**	**0.0**
250	1	5.0	1.0	6.1	100.0	45.0	43.2	13.3	78.0	10.0	2.2	100.0
	8	0.0	0.0	0.0	0.0	90.0	76.0	12.4	33.3	5.0	0.6	100.0
	13	15.0	2.8	5.9	100.0	35.0	24.7	12.9	71.4	15.0	0.5	0.0
	Avg.	**6.7**	**1.3**	**6.0**	**99.5**	**56.7**	**48.0**	**12.9**	**52.9**	**10.0**	**1.1**	**70.1**
300	4	35.0	9.0	6.9	0.0	70.0	71.2	13.7	86.0	5.0	13.7	86.0
	10	10.0	2.0	6.1	0.0	55.0	55.4	13.6	45.0	40.0	4.3	12.0
	15	25.0	5.3	6.2	40.0	60.0	52.9	12.7	100.0	10.0	0.6	0.0
	Avg.	**23.3**	**5.4**	**6.4**	**14.3**	**61.7**	**59.8**	**13.3**	**78.3**	**18.3**	**6.1**	**33.8**
UNCUT	6	45.0	9.7	6.3	0.0	55.0	48.2	12.7	81.8	310.0	25.5	34.0
	7	60.0	13.0	6.3	16.6	100.0	77.4	11.9	80.0	260.0	13.5	81.0
	16	5.0	0.6	4.6	0.0	70.0	59.8	12.5	100.0	290.0	14.6	93.0
	Avg.	**36.7**	**7.8**	**5.7**	**9.0**	**75.0**	**61.8**	**12.4**	**86.7**	**287.0**	**17.8**	**71.4**

Ingrowth past the 10.5-inch board-foot volume threshold was contributing substantially to stand growth for the 12-year period between 1986 and 1998. As the residual tree density increased for a treatment, the percentage of ingrowth by redwood also increased. For T100 and T150, there was an average ingrowth of 15.8 Douglas-fir trees versus 5.0 redwoods per acre. Redwood ingrowth in the four treatments denser than T150 showed an average of 45.0 redwood versus 15.9 Douglas-fir per acre that grew past the 10.5-inch limit. The ability of smaller Douglas-fir to grow past this diameter limit was retarded by a relatively dense canopy.

Most of the mortality had occurred among small redwood and Douglas-fir in the unthinned control plots. There had been some limited redwood blowdown in plots 4 and 6. A single 22-inch redwood was blown over in plot 4. This was the only loss of a large redwood in a treated plot. In plot 6, a large tree from off the plot fell across the plot and killed or damaged a number of redwood and Douglas-fir. In the unthinned control plots, suppressed stems in dense redwood sprout clumps have died. In unthinned control plot 16, 93 percent of the mortality was suppressed redwood.

Growth percentages

The periodic stand increment values for 1981-86 and 1986-98 are shown in Table 6. Expression of these values as a percentage periodic annual increment is shown in Table 12. The percentages are computed by the Pressler formula, which uses the average of the initial and terminal inventory as the

Table 12. Periodic annual increment (PAI) and growth percentages for cubic and board foot volumes by plot and treatment for the 5-year (1981 - 1986) and the 12-year (1986 - 1998) growth period.

		Cubic foot volume				**Board foot volume**			
Treatment	**Plot**	**1981-86**		**1986-1998**		**1981-86**		**1986-98**	
		PAI	**Pct.**	**PAI**	**Pct.**	**PAI**	**Pct.**	**PAI**	**Pct.**
100	3	322	15.8	271	8.4	846	21.7	1,613	10.3
	9	341	15.9	344	9.1	877	22.6	2,025	11.1
	14	522	18.2	408	8.1	1,607	22.0	2,464	9.4
	Avg.	**395**	**16.6**	**341**	**8.5**	**1,110**	**22.1**	**2,034**	**10.3**
	StDev.	**110**	**1.4**	**68**	**0.5**	**431**	**0.5**	**426**	**0.8**
150	2	455	16.4	401	8.6	1,351	26.4	2,234	10.2
	11	533	17.1	363	7.5	1,352	23.2	2,121	9.7
	17	913	14.6	621	7.5	2,537	18.2	3,773	8.8
	Avg.	**634**	**16.1**	**462**	**7.8**	**1,747**	**22.6**	**2,709**	**9.2**
	StDev.	**245**	**1.3**	**139**	**0.6**	**684**	**4.2**	**923**	**1.3**
200	5	443	18.1	655	9.3	1,202	32.0	2,585	11.6
	12	505	17.6	317	7.2	1,462	30.0	1,699	9.1
	18	392	20.2	298	7.9	1,070	28.8	1,644	10.1
	Avg.	**447**	**18.6**	**423**	**8.1**	**1,245**	**30.3**	**1,976**	**10.3**
	StDev.	**57**	**1.4**	**201**	**1.1**	**199**	**1.6**	**528**	**1.3**
250	1	773	13.5	606	8.1	2,221	26.3	3,406	9.9
	8	481	17.6	395	8.3	1,004	28.8	2,124	10.8
	13	932	15.8	557	7.0	2,589	20.4	3,196	8.3
	Avg.	**729**	**15.6**	**519**	**7.8**	**1,938**	**25.1**	**2,909**	**9.7**
	StDev.	**229**	**2.0**	**110**	**0.7**	**829**	**4.3**	**688**	**1.3**
300	4	694	16.7	399	6.8	1,721	23.8	2,154	8.8
	10	512	16.8	379	7.8	1,065	23.6	2,006	10.4
	15	673	17.0	512	8.0	1,721	26.8	2,698	10.0
	Avg.	**626**	**16.8**	**430**	**7.5**	**1,502**	**24.8**	**2,286**	**9.8**
	StDev.	**100**	**0.1**	**72**	**0.6**	**379**	**1.8**	**364**	**0.9**
UNCUT	6	683	14.6	412	7.0	1,272	20.9	1,906	9.2
	7	497	13.4	309	7.1	735	30.4	1,262	10.7
	16	764	15.5	509	7.2	1,741	23.6	2,724	7.9
	Avg.	**648**	**14.5**	**410**	**7.1**	**1,249**	**24.9**	**1,964**	**9.3**
	StDev.	**137**	**1.1**	**100**	**0.2**	**503**	**4.9**	**732**	**1.4**

basis against which annual growth is expressed. The average annual increment for the first 5-year period after thinning ranged from 14.5 to 18.6 percent cubic volume, and from 22.1 to 30.3 percent board-foot volume. The highest individual plot percentages occurred in T200. As expected, average annual increment expressed as a percentage, had declined over time. Cubic increment ranged from 7.1 to 8.6 percent, and board-foot volume increment ranged from 9.2 to 10.3 percent. As the stand volume increases, there is often a drop in the periodic growth percentage despite an increase in the periodic volume. This is due to the increase in diameter to which the periodic increment is compared.

Diameter distributions in 1998

The effects of thinning and the subsequent growth on the diameter distributions are shown in Table 13. The heavy treatments T100 and T150 each had about 25 percent of the residual stems less than 16 inches, but in the unthinned plots, 86 percent of the stems were below 16 inches. Most trees removed were small and suppressed, but more small stems were retained as the number of stems required to meet the denser treatment levels increased. These small trees were at a competitive disadvantage at the time of thinning and their status has not improved as the overstory trees have expanded their crowns.

Table 13. Diameter distribution of the 1998 data by treatment. The average number of stems per acre and standard deviations by one inch diameter class is given.

Diameter	100		150		200		250		300		UNCUT	
Class (in.)	Trees/Ac.	StDev.	Trees/Ac.	StDev.	Trees/Ac.	StDev.	Trees/Ac.	StDev.	Trees/Ac.	StDev.	Trees/Ac.	StDev.
2											18.3	10.4
3					1.7	2.9			3.3	2.9	45.0	25.0
4							3.3	2.9	8.3	2.9	55.0	5.0
5					1.7	2.9	3.3	5.8	13.3	2.9	40.0	21.8
6					1.7	2.9	5.0	5.0	8.3	5.8	38.3	5.8
7	1.7	2.9	1.7	2.9	5.0	0.0	3.3	5.8	11.7	2.9	40.0	26.5
8			1.7	2.9	5.0	0.0	5.0	5.0	16.7	2.9	33.3	16.1
9			1.7	2.9	6.7	7.6	15.0	8.7	13.3	5.8	30.0	17.3
10	5.0	5.0	6.7	2.9	6.7	2.9	13.3	11.6	18.3	5.8	26.7	2.9
11	3.3	2.9	3.3	2.9	3.3	5.8	15.0	10.0	6.7	2.9	28.3	12.6
12	3.3	2.9	6.7	7.6	8.3	2.9	13.3	15.3	10.0	10.0	25.0	8.7
13	1.7	2.9	8.3	5.8	15.0	13.2	16.7	7.6	25.0	8.7	20.0	5.0
14	5.0	5.0	1.7	2.9	15.0	5.0	16.7	7.6	20.0	15.0	26.7	17.6
15	5.0	5.0	5.0	5.0	18.3	7.6	15.0	13.2	31.7	11.6	26.7	5.8
16	8.3	5.8	6.7	7.6	20.0	8.7	16.7	5.8	25.0	0.0	23.3	15.3
17	11.7	10.4	5.0	5.0	16.7	5.8	30.0	21.8	20.0	13.2	18.3	7.6
18	5.0	5.0	15.0	10.0	26.7	2.9	15.0	8.7	15.0	15.0	13.3	15.3
19	8.3	10.4	11.7	12.6	8.3	2.9	15.0	13.2	10.0	10.0	6.7	2.9
20	8.3	7.6	10.0	8.7	10.0	5.0	6.7	7.6	3.3	5.8	5.0	5.0
21	5.0	5.0	16.7	5.8	6.7	2.9	10.0	0.0	6.7	2.9	1.7	2.9
22			10.0	5.0	3.3	2.9	6.7	5.8	5.0	5.0	3.3	5.8
23	5.0	5.0	6.7	7.6	1.7	2.9	5.0	5.0	5.0	5.0		
24	1.7	2.9	11.7	7.6	1.7	2.9	8.3	14.4	5.0	5.0		
25	6.7	7.6	3.3	5.8	1.7	2.9	3.3	5.8	3.3	2.9		
26	11.7	12.6	3.3	5.8	1.7	2.9	3.3	2.9				
27			3.3	5.8			1.7	2.9				
28			3.3	2.9								
29	3.3	5.8					1.7	2.9			1.7	2.9
30			3.3	2.9								
31	3.3	2.9	1.7	2.9								
Total	**105.0**		**148.3**		**186.7**		**248.3**		**288.3**		**526.7**	

This table also showed the number of stems that were available for recruitment into the board-foot stand. Treatments T100 and T150 had only a few stems remaining to pass the 10.5-inch threshold. All of the other treatments will have board-foot ingrowth for a number of years, but this will slow as the crown canopy continues to slow the radial growth of suppressed trees.

The role of Douglas-fir in the stand

Prior to thinning in 1981, Douglas-fir accounted for 23% of the stems and 7% of the basal area while redwood made up 77% of the stems and 93% of the basal area. Thinning removed many of the small trees. After thinning, Douglas-fir accounted for 26% of the residual stems and 7% of the basal area for stems greater than 1.5 inches. After thinning in 1981 there were no Douglas-fir larger than 10.5 inches and by 1986 only one Douglas-fir had grown into this class. Most mortality in the thinned plots between 1981 and 1986 was small diameter Douglas-fir.

The 1998 inventory for trees greater than 1.5 inches showed that Douglas-fir accounted for 23% of the stems and 10% of the basal area in the treated plots. The data indicated that the majority of mortality had been small Douglas-fir, but the larger Douglas-fir were showing improved diameter growth and were increasing their share of the stand basal area. The 1998 inventory for trees greater than 10.5 inches also showed that Douglas-fir accounted for 12% of the trees and 8% of the board foot volume. For the total number of trees greater than 1.5 inches in the unthinned plots, Douglas-fir averaged 31% in blocks 1 and 2 but only 2% in block 3.

There was a difference between blocks in the composition of Douglas-fir due to the burning after logging of the portion of the original clearcut where block 3 was located. When this study was installed in 1981, the blue blossom was beginning to die out but was still extremely dense and about 20 to 25 feet tall. There were a few Douglas-fir under this brush cover that were spindly, and many of these were knocked down by dying brush. Consequently, the only trees to choose for the residual stand were from clumps of vigorous redwood sprouts that had been able to grow in height to keep ahead of the brush. Three of the six plots in block 3 had no Douglas-fir in the residual stand. The unthinned plot in block 3 had only 10 trees per acre of Douglas-fir, with an average diameter of 5.0 inches. Only plot 13(T250) and plot 18(T200) had Douglas-fir that will contribute much to the yield of the plot.

Block 3, as indicated by the 1998 plot volumes, had the highest volumes in five of six treatments. In the unburned portion of block 2 adjacent to block 3, Douglas-fir accounted for nearly 40% of the 900 plus stems per acre in 1981. In 1998, there was a higher percentage of Douglas-fir in the plots in block 2 than in the other two blocks.

The stands were 38 years old as of 1998 and the contribution of Douglas-fir was just starting to be important to the volume development of the stands. Aggressive growth of redwood sprouts and brush retarded the early growth of Douglas-fir. The Douglas-fir that survived was located where there was an opening in the canopy and these trees were showing good height and diameter growth.

Site index of dominant Douglas-fir from curves (base age at 100 years) at 30 years breast high age ranged from 180 to greater than 200; the 3 block averages are 200, 205, and 201. Most of the trees were between 85 and 95 feet tall, but six exceeded 100 feet. The redwood site index for dominant trees in 1998, as shown in Table 3, averaged 168, 172, and 186 in the 3 blocks. The higher local site index of Douglas-fir was consistent with other information about site indices in this area from the CCCT data in 1962.

Comparison between estimated and measured yield

Growth and yield results from the unthinned control, T250, and T300 were compared with unmanaged stands of similar ages and sites in the redwood yield tables by Lindquist and Palley (1963). The comparisons were not direct since the estimated values from the yield tables were produced from unmanaged second growth stands, but they provided an indication of differences in yield to be expected. The values of T250 and T300 were used since they represent the least amount of disturbance to the original stand structure in 1981.

The estimated yields were interpolated from the International board foot tables for trees greater than 10.5 inches using the average breast-high age and site index of the treatments. The estimated International 1/4 volumes were adjusted to the Spaulding volume rule by the volume ratio percentages recommended in the yield table. The Scribner volume tables used in this study were similar to the Spaulding rule and were considered directly comparable. The estimated volumes from the yield table were consistently greater than the actual 1998 volumes by an average of 2,694 board feet (Table 14); a difference of 7%.

Table 14. Yield comparison between Bulletin 796 yield table values versus the 1998 data for the control, T250, and T300 treatments.

Treatment	Age	Site	Estimated International Volume	Average DBH	Volume Ratio	Spaulding 1998	Scribner 1998
UNCUT	38	168.7	42,044	18.4	82.0	34,443	31,987
T300	38	173.7	46,959	18.8	85.0	39,915	37,233
T250	38	181.3	54,749	19.1	86.0	47,080	44,136

A second comparison of these results considered the 12-year periodic board foot growth with the growth estimated from an equation of 10-year periodic growth in Bulletin 831 (Lindquist and Palley, 1967). This equation used breast-high age, site index, and total basal area at the initial age to predict the 10-year stand growth based on the International ¼ inch log rule. The estimated volumes were adjusted with a volume ratio to express the volume in Spaulding log rule units. The estimated 10-year growth was increased by a factor of 1.2 to compare with the 12 years of actual growth from 1986 to 1998. Average 12-year periodic board foot growth for the predicted Spaulding and actual Scribner rules for the five treatments and the untreated plots are shown in Table 15.

The most apparent feature of the comparisons of periodic growth rates is that the actual measured values of all treatments exceed the predicted rates of growth by 785 to 1,023 board feet per acre per year. The uncut control, however, also exceeded the Bulletin 831 estimates of growth by 683 board feet per acre per year. This seems to indicate that the value of thinning, as derived from this equation, is quite variable. This also emphasizes the need to calibrate the use of unmanaged stand yield tables with the appropriate data and not treat yield table values as a surrogate for a control.

Table 15. Comparison of Bulletin 831growth values with 1998 12-year PAI values.

Treatment	Bull. 831 (Spaulding)	Measured (Scribner)	Actual - Estimated (12-year)	Actual - Estimated (Annual)
T100	14,891	24,406	9,515	793
T150	20,232	32,511	12,279	1,023
T200	14,289	23,713	9,424	785
T250	22,243	34,446	12,203	1,017
T300	17,277	27,428	10,151	846
UNCUT	15,367	23,563	8,196	683

Conclusions

This study provides some valuable insight into the effective use of precommercial thinning in young robust redwood stands. Most of the results related to inventory and growth measures do not exhibit a statistically significant difference between treatments. Variability within treatments, while common in the redwood forest type, results in finding more subtle differences between treatments problematic.

The treatments appear equal due to the ability of redwood to take advantage of space created by thinning. Figures 7 and 9 demonstrate that volume as a function of treatment resulted in a highly variable result that is not statistically significant at age 38. There are apparent trends in the graphs that suggest a thinning level of 250 or more trees per acre for cubic foot volume and 250 trees per acre for board foot volumes to maximize site utilization.

Less volume in the unthinned control relative to the thinned may be the result of high density, inhibiting the gross yield of the stand. The results for the largest 100 trees indicate that the average diameter of these trees greater than 10.5 inches in the unthinned control plots was 2 inches less than in T300 and 5 inches less than those in T150. It appears that an over-abundance of sprouts in these young stands prevents the stand from reaching maximum stand diameter growth.

Maximum diameter growth occurs in the most heavily thinned plots that have a high percentage of redwood. Volume growth in the large diameter trees of the T100 and T150 treatments is keeping these plots growing at a rate that is equal to the more heavily stocked plots. For a short rotation strategy of 60 years, thinning to these levels while retaining mostly redwood sprouts in the stand structure seems to be a reasonable strategy for increasing the size of crop trees. However, Figures 7 and 9 suggest that as the stand develops there may be a drop in productivity for T100 and T150.

Production of redwood heartwood is a prime economic consideration. Allowing the crop trees to increase in diameter at an optimum rate may be most profitable from the standpoint of volume and lumber grade. The lightly stocked treatments can achieve maximum diameter growth, but may also produce stems with large, wide and spreading branches. In addition, the relationship between branches and heartwood production is unclear (Gartner, et. al., 2002). The plots were thinned at 19 years of age, which may be older than desired. Earlier thinning would result in a stand of small crowns that may take longer to close. Allowing redwood to develop as an open grown stem may result in the production of a highly tapered stem with an over abundance of growth dedicated to branch wood.

The sequence of stands from the original old-growth to the present third-growth provides a view of changes that occurred as a result of logging history. There is no information about the old-growth structure of the study area relative to species composition. The second-growth stand that was harvested in 1961 was reported to have been about 50 percent redwood basal area 40 percent Douglas-fir, and 10 percent grand fir. These percentages were similar for number of trees, but redwood was only 40 percent of the total board foot volume of 131 MBF. In the current third growth stand, there has been an abrupt change in the species composition of the stand. The number of trees in species other than redwood has dropped sharply. The first inventory of the current stand was 19 years after the clearcut and Douglas-fir stems accounted for about 25 percent of the stand. Other conifers are virtually eliminated from the stand composition. This is in contrast to partially logged stands of the Caspar Creek Cutting Trials where about 75 percent of the regeneration was grand fir (Lindquist, 1988). The full sunlight in the clearcut provided the level of light that Douglas-fir requires for growth and regeneration. However, the large number of redwood stump sprouts and heavy brush growth in the burned portion of the study (block 3) resulted in heavy competition for the Douglas-fir and many did not get the height growth necessary to survive in the overstory.

This study demonstrates that Douglas-fir was suppressed by vigorous growth of brush following burning of the harvest unit after clearcutting. Douglas-fir growth is also retarded when redwood stocking levels are high, due to the rapid initial growth capacity of the sprouts. However, this is a high Douglas-fir site and Douglas-fir will be an increasing percentage of the stand volume as the stand matures. If rotations are longer than 60 years, Douglas-fir will have adequate time to make an important contribution to the stand yield.

This is the second young stand developed at this location. The site index estimates derived from the height growth of dominant redwood and Douglas-fir that were free of canopy competition do not suggest any loss of productive capacity. These sites can sustain the productive pace that is described in this study where there are a large number of redwood stumps to provide a vigorous crop of sprouts and there is sufficient light for young redwood and Douglas-fir to grow aggressively.

The ANOVA results indicate that despite the range of thinning, the 38-year old stand shows no statistical differences in volume yield or growth between the thinning treatments. However, the decline in volume yield for the unthinned plots seems to indicate the need to reduce the density of regeneration early in the rotation. While this study provides some insight into production at various levels of stocking, the optimum stocking level is still an open question. More time will be required to see if growth rates can be maintained. In time, if smaller codominant and intermediate trees can continue to exhibit good radial growth, the more heavily stocked treatment may yield total greater volume than the lighter stocked treatments.

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