The Whiskey Springs Redwood Commercial Thinning Study: A 29-Year Status Report (1970 to 1999)[1,2]

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Abstract
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 percent, 50 percent, 75 percent and 100 percent (uncut control) of the original basal area (400 ft^2 per acre) 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 were significant differences between the treatments in basal area, average diameter, and volume throughout the course of the study. Analysis of the periodic growth rate revealed strong statistical differences between the treatments in diameter growth but no significant differences in the basal area or volume growth (cubic and board foot). Total board foot volume was not statistically different between thinning treatments due to high variation but there is a trend indicating that the 25 percent retention treatment produced a lower yield than the other two treatments and 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 percent overstory retention treatment.

Key words: commercial, precommerical, redwood, regeneration, thin

Introduction

The Whiskey Springs commercial thinning study was established as a cooperative project between 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 in the redwood region. Oliver and others (1994) reported the first 15 years of growth (1970 to 1985) for all three sites (Korbel, Crescent City, and Whiskey Springs). This paper covers the growth and yield of the overstory stand in the 12 Whiskey Springs thinning plots for the period 1970 through 1999.

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The 40-year old well-stocked second growth redwood stand was commercially thinned to four levels of overstory retention to assess stand structure changes for redwood *(Sequoia sempervirens)* over a range of commercial thinning intensities. This growth and yield information will aid in planning silvicultural prescriptions in redwood to achieve volume production and tree size goals.

A second part of this study reports on the establishment and growth of sprout regeneration established as a result of thinning the overstory. The analysis of sprout response provides information for multi-cohort management of redwood stands. 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).

Methods

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 original old-growth stand was clearcut in the late 1920s and a nearly pure stand of second growth redwood sprouts was established. There is evidence suggesting 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.

Twelve 0.4-acre plots (132 by 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 ft^2 per acre. The species composition of trees by basal area was 91.2 percent redwood, 6.7 percent other conifers, and one percent 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 percent, 50 percent, or 75 percent (100, 200, 300 ft^2 per acre) of the average basal area of the uncut control plots (400 ft^2 per acre). The interior 0.2-acre section (93.3 by 93.3 ft) of each plot was measured to eliminate edge effect. Leave trees were tagged and evaluated 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. Marking of trees was done to favor healthy dominant and codominant redwoods while leaving trees well distributed on the plot. All hardwoods *(Lithocarpus densiflorous)* and any conifers less than 4.5 inches dbh were removed. Over the period 1970 to 1985, five-year measurement intervals were maintained. There have been two measurements since 1985, in 1991 and 1999.

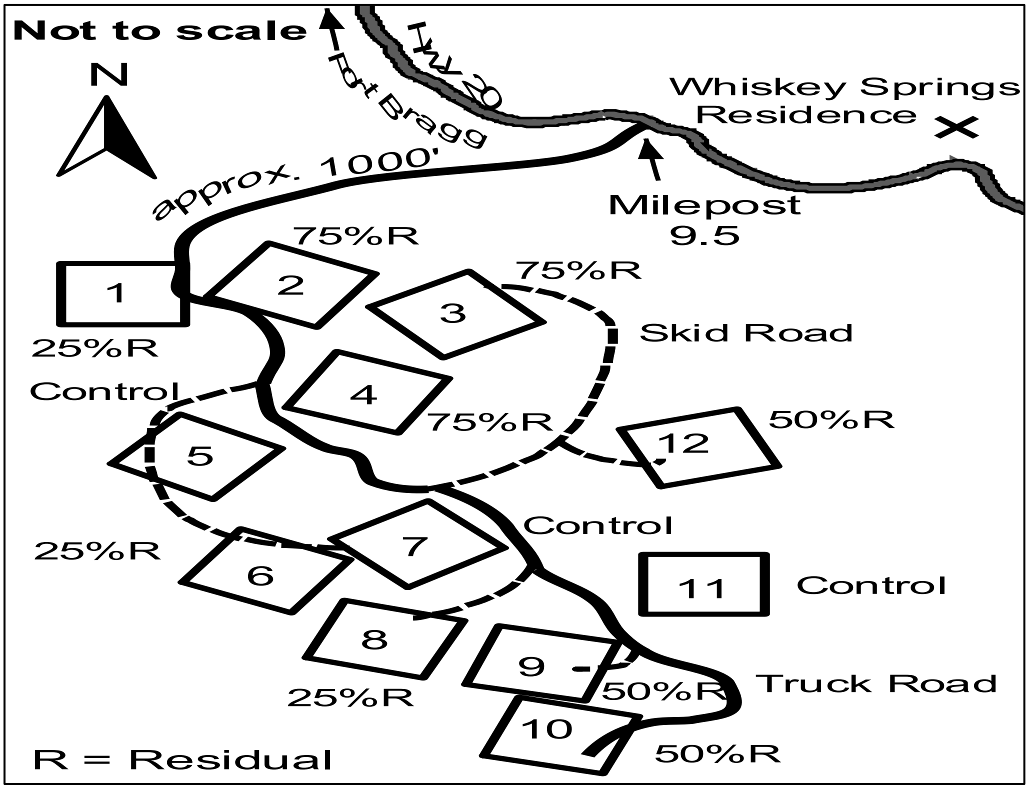

Figure 1—Whiskey Springs location and plot layout.

Evaluation of the stand volumes for all the inventories relied on linear local volume equations for redwood and Douglas-fir *(Pseudotsuga menziesii)*, computed for each plot and inventory year. The small number of Douglas-fir required that all fir be combined. These cubic and board foot tree local volumes were computed from standard equations developed by the Redwood Yield Cooperative (Krumland and Wensel l979). Board foot volumes were computed by the Scribner log rule using a one-foot stump height and a top diameter of 6 inches.

Results and Discussion

Initial Stand Conditions

The average pre-treatment basal area of all plots was 401.3 ± 7.6 ft^2 per acre (range 392 to 410 ft^2 per acre). 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 refer only to conifers. Analysis of variance tests (ANOVA) of the pre-harvest stands indicated that a block design was not required.

Prior to thinning, the thinned plots had similar diameter distributions. Trees less than 10.5 inches dbh are 45 percent to 49 percent of the total numbers of stems. Thinning removed nearly all the stems less than 10.5 inches from the 25 percent and 50 percent retention treatments and only a small percent in the 75 percent retention treatment. The uncut plots averaged about 150 more stems per acre than the treated plots with 72 percent 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 before thinning, 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. 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.

Within the 25 percent retention treatment, thinning removed 75 percent of the basal area, and 72 percent of the cubic foot volume. The 75 percent retention treatment removed only 20 percent of the cubic volume and 10 percent of the board foot stand.

Repeated measurement of the total heights of dominant redwood in these plots shows that the estimates of site index have remained stable over the 29 years of measurements. Site index estimates of treatments with 25 percent and 75 percent retention are virtually the same in all years. 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. This is accounted for in later analyses so that treatment effects may be tested. Testing the site data against the ages of the stands showed no statistical differences.

Basal Area

Basal area growth over a 29-year period for trees greater than 4.5 inches was similar for each treatment *(fig. 2)*. The 25 percent retention treatment added about 150 ft^2 per acre of growth, the 50 percent and 75 percent treatments added an average of 201 ft^2 per acre, and the control increased by 174 ft^2 per acre. Maximum periodic annual increment (PAI) for all harvested stands was in the period of 46 to 51 years of age, which was five to 10 years after cutting the thinning treatment *(fig. 3)*. There was a highly significant difference in basal area growth between treatments in the first growth period of 41 to 46 years ($p = 0.001$). All other growth periods showed no significant differences in periodic basal area growth between the treatments. This was explained by the increased variation within the treatments and the similarity of the PAI between all but the 25 percent 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 4* shows the relationship of initial basal area and PAI for the 29-year period. This trend agrees with Oliver and others' (1994) findings for the first 15 years of this study.

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. 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 ($p = 0.000$).

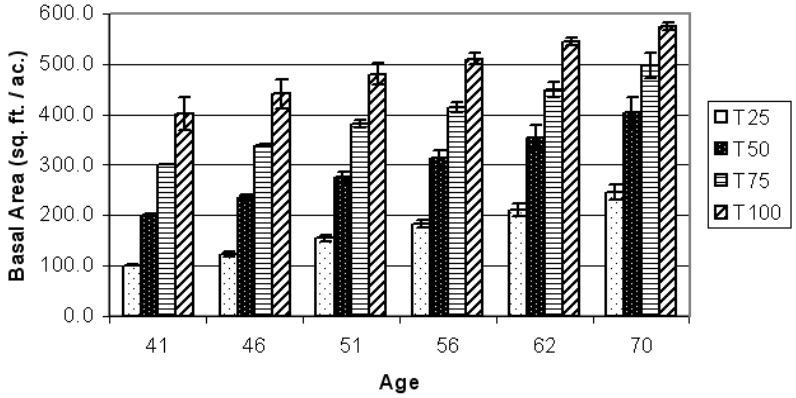

Figure 2—Average stand basal area of trees >4.5" dbh by age and treatment. Error bars are one standard deviation.

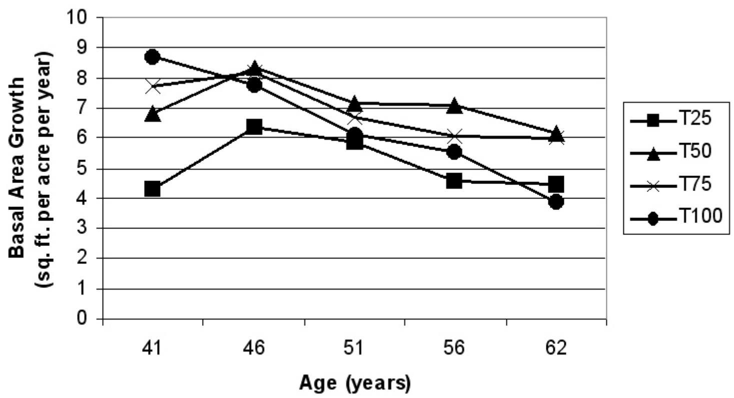

Figure 3—Periodic annual growth of basal area for trees greater than 4.5 inches dbh.

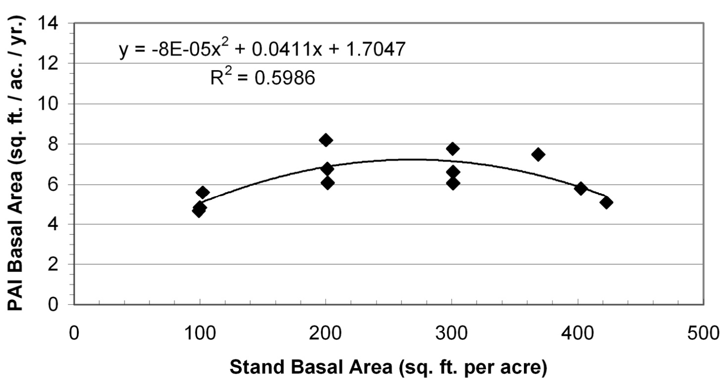

Figure 4—Basal area PAI based on 29 years of post treatment growth, as a function of initial basal area. For trees greater than 4.5 inches dbh.

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Diameter growth in the residual stand for each treatment has remained consistent over the five growth periods in the 29 years of measurement. The periodic growth percent peaked in the 1975 to 1980 period for the 25 percent and 50 percent retention treatments and then slowly decreased. In the 75 percent treatment plots, the periodic growth dropped consistently. Graphic expression of these growth trends by treatment and age is shown in *figure 5*. Growth of the residual trees was most obvious for the 25 percent retention treatment.

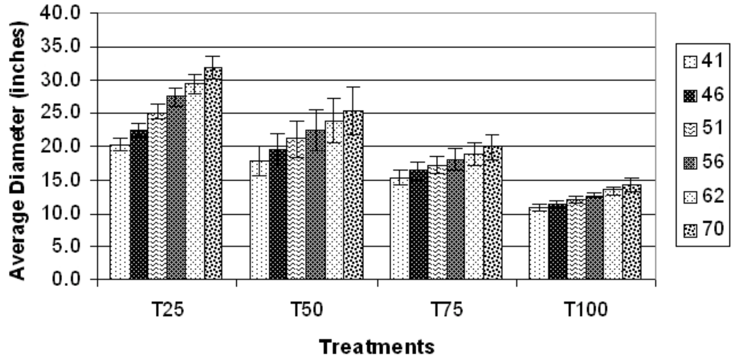

Figure 5—Average diameter of trees greater than 4.5". Error bars are one standard deviation.

Cubic Volume

Cubic volume for trees 4.5 inches diameter and greater over time is shown in *figure 6*. 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 five-year increments and last two periods are six and eight years long. Volume for the 75 percent basal area retention lags behind the control until 1991 (age 62). 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 percent retention treatment was statistically different than the lighter cut 75 percent retention treatment and the control.

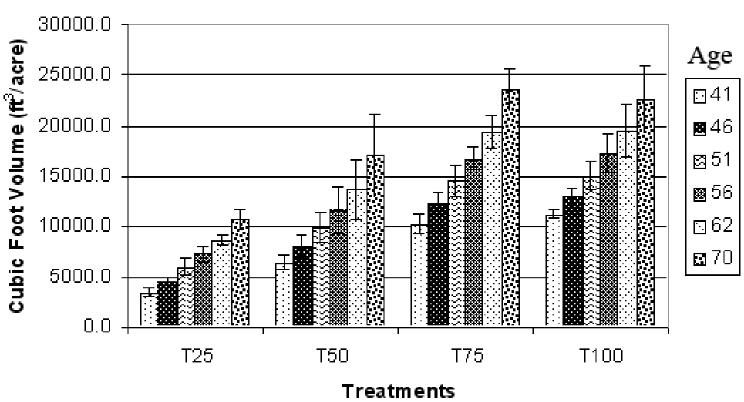

Figure 6—Cubic volume per acre over time by treatment. Error bars are one standard deviation.

Although cubic volume was different, the periodic cubic foot growth in each treatment was uniform with a significant difference in only the period 1970 to 1975 when the Scheffe comparison test indicated a significant difference between the 25 percent 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 *(fig. 7)*.

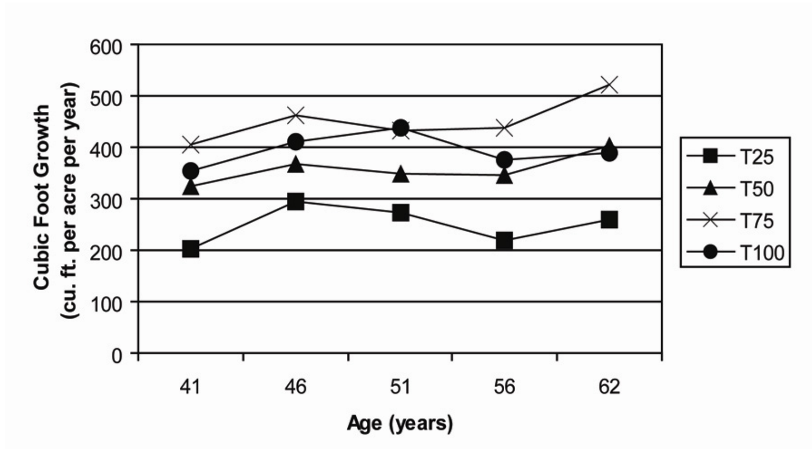

Figure 7—Cubic foot periodic volume growth.

A plot *(fig. 8)* of stand density index (SDI; Reineke 1933) 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.

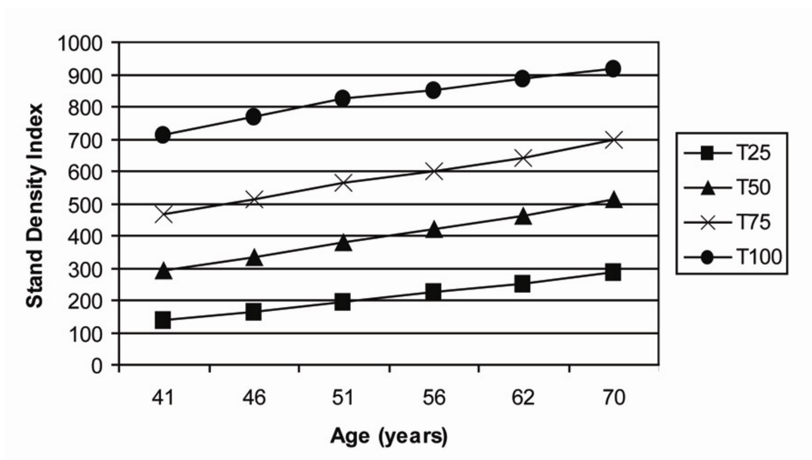

Figure 8—Cubic foot periodic volume growth.

When periodic cubic foot increment was plotted *(fig. 9)* over the initial stand basal area, there was a quadratic form with the maximum at 300 square feet per acre. Cubic-foot increment indicated that for each thinning level, the growth generally peaked five to 10 years after thinning, and then dropped slightly over the remaining periods. The 75 percent 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 percent 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 *(fig. 9)* was partially the result of the loss of many small trees that were part of the cubic foot inventory.

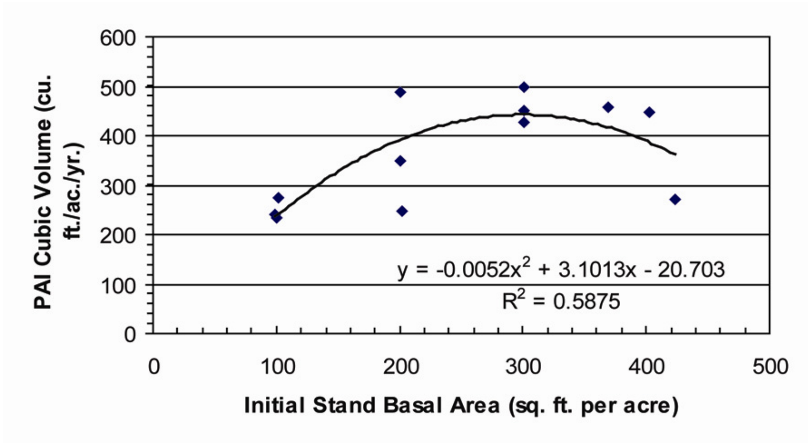

Figure 9—Cubic volume 29-year growth after commercial thinning as a function of initial basal area.

Board Foot Growth and Yield

Many aspects of the results observed for cubic volume were similar for 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 percent and 75 percent treatments (p = 0.044 in 1999).

Site index is a significant covariate (P = .039) *(fig. 10)*. Random assignment of treatments to plots resulted in the control plots averaging about 71 percent (14,330 board feet per acre less) of the pre-treatment volume in the treated areas. The control plots are located higher on the slope, which is reflected in their lower site values. Despite these differences in the initial volumes there were no statistically significant differences in the cubic and board foot volumes of the treatment sites. Site index is correlated to the pre-treatment board foot volume ($r^2 = 0.772$).

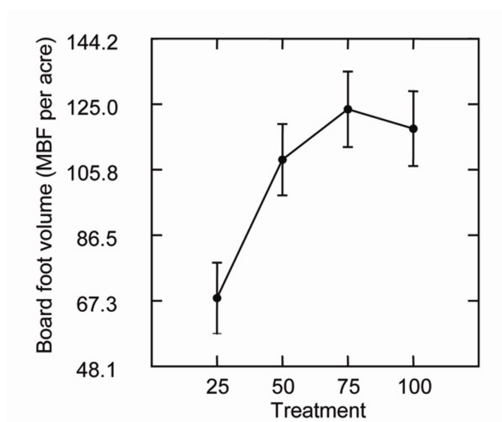

Figure 10—Board foot volume treatment means for 1999.

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 percent retention treatment where the stand volume increased 200 percent, an annual increase of 3,002 board feet per acre per year. 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 percent of the original basal area and leaving only 118 trees per acre, the

50 percent retention treatment grew by 238 percent or 2,544 board feet per acre per year. The 25 percent retention treatment grew 276 percent or 1,803 board feet per acre per year.

The plot of board foot increment *(fig. 11)* 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 *(fig. 9)*. 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. There is no evidence of culmination in any of the treatments. The four treatments showed a gradual increase across the 29 years.

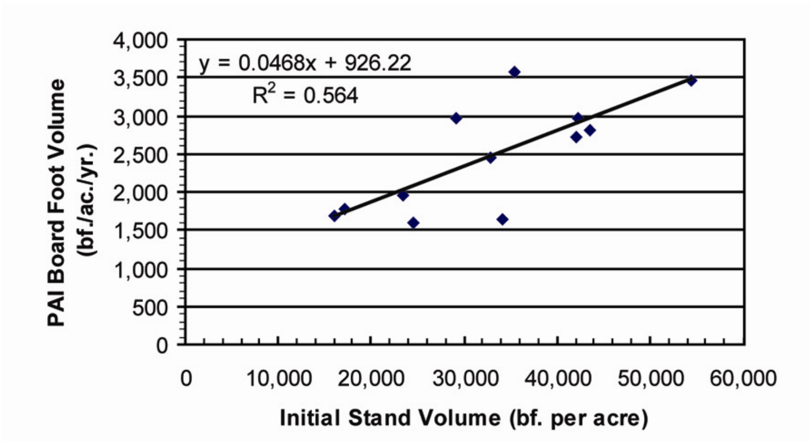

Figure 11—Mean annual increment of board foot volume including commercial harvest yield.

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 12* shows the adjusted treatment means for yield.

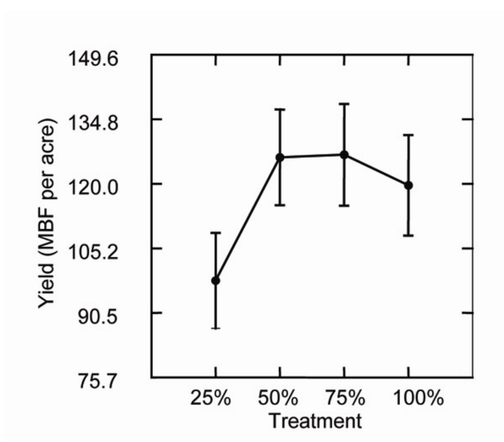

Figure 12—Yield treatment means adjusted by site as a covariate.

Understory Regeneration

The commercial thinning harvest in 1970 created an opportunity to study the effects of the varying amounts of overstory on redwood sprout development in the understory over 29 years of growth. 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 regeneration study was initiated in 1972, two years after the commercial thinning. Six of the nine thinned plots were examined in three overstory levels. The number of sprout clumps, sprouts, and the height of the tallest sprout were measured. These data were used initially to describe and test a method of sampling for redwood sprouts (Lindquist 1979).

In 1986 an understory redwood sprout inventory was made of all nine commercially thinned plots and a precommercial thinning study was established in the 25 percent and 50 percent retention treatments. Plots were established and subdivided into four 0.1-acre plots prior to precommercial thinning 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. The retained trees were subsequently measured in 1986, 1991 and 1999.

A large number of sprouts had developed in all treatments, by 1972, ranging from a low of 2,052 sprouts per acre (75 percent retention treatment) to 8,123 (25 percent retention treatment). The 1986 inventory showed a reduction to 268 in sprouts per acre (75 percent retention treatment) and 1,719 sprouts per acre (25 percent retention treatment).

In 1986 both average sprout diameter and height were much larger where 25 percent of the stand was retained than where 50 percent was retained (2.1 inches dbh vs. 0.9 inches and 17.9 feet vs. 6.9 feet). The sprouts in the 75 percent retention treatment were so severely impacted that subsequent measurements were not warranted.

The precommercial thinning treatments appear to have had no effect within the 50 percent overstory retention treatment but appear to have had an effect in the 25 percent overstory retention treatment. In 1986, the 25 percent overstory retention treatment showed no significant difference between precommercial thinning treatments ($p = 0.164$) and there was a difference in 1999 ($p = 0.048$). The 300 stems per acre precommercial target have shown the maximum diameter growth.

The total height of all trees measured indicated highly significant differences ($p = 0.000$) between the 25 percent overstory and 50 percent overstory treatments in all three inventory years. At age 29 these heights were 32.6 feet and 15.2 feet respectively.

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 percent, 50 percent, and 75 percent of the average stocking of the three control plots, which was 401 ft^2 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.

This study showed 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. By 1999, the average diameters ranged from 14.2 inches in the control to 31.8 inches in the 25 percent retention treatment, a difference of 17.6 inches. The highest thinning intensity produced the highest radial growth. Intensive thinning from below is capable of producing larger diameter trees relatively quickly in stands at 40 years-of-age. Despite good diameter growth in the 25percent retention treatment, a 75 percent reduction of basal area did not produce total growth at a rate consistent with the site potential. The 50 percent retention treatment, with twice the initial basal area, had a net board-foot growth that was 140 percent of the 25 percent retention treatment.

The relationship between understory growth and overstory density indicated that growth of redwood regeneration was inversely proportional to overstory canopy. The average height of the dominant redwood understory sprouts was 48 feet at 29 years-of-age. This was 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 2004a). The time needed to produce trees of commercial size under stands even as lightly stocked as the 25 percent retention treatment with 45 trees per acre will be much longer than under full sunlight. A sub-study of precommercial thinning treatments of the redwood sprouts showed an effect only in the most heavily thinned overstory condition. The results of this study, including data tables, are discussed in greater detail in Lindquist (2004b).

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