

## Twenty-six-year response of ponderosa pine and Douglas-fir plantations to woody competitor density in treated stands of madrone and whiteleaf manzanita

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### ABSTRACT

Ponderosa pine (*Pinus ponderosa* Dougl.) grown in mixture with whiteleaf manzanita (*Arctostaphylos viscida* Parry) and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*) grown in mixture with Pacific madrone (*Arbutus menziesii* Pursh) in southwestern Oregon showed an increase in growth with removal of competing woody cover. Both conifer species had roughly one-third the volume at plantation ages 26–27 when grown with uncontrolled competition compared to where woody competition was completely controlled at age 2. Intermediate levels of competitors usually led to intermediate levels of growth, but this was more evident with Douglas-fir than pine. When competition was reduced or removed, height/age relationships for Douglas-fir at plantation ages 23 and 27 reflected medium site quality rather than low quality as estimated from adjacent stands, indicating that these sites are potentially more productive than perceived with uncontrolled dense woody cover. These studies support the concept that competition management may allow some poor sites of ponderosa pine or Douglas-fir to be managed on the basis of a higher site potential.

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### 1. Introduction

Southwestern Oregon includes several counties in which hot, dry summers and shallow soils lead to sites of low productivity on a large scale. In 1980, the Forestry Intensified Research (FIR) program was initiated by the College of Forestry at Oregon State University to evaluate reforestation options relevant to ponderosa pine (*Pinus ponderosa* Dougl.) and Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco var. *menziesii*) sites in southwestern Oregon where previous attempts at reforestation had resulted in high rates of plantation failure. At that time, a 110,000-ha area of lands was “withdrawn” from the productive base on federal ownerships because it could not be reforested economically following harvest. The FIR Program pursued a research mission to inquire whether future productive potential in coniferous forests might be realized if suitable regeneration could be obtained and maintained (Hobbs et al., 1992). Vegetation and its competing effects were identified as a key constraint. Tesch et al. (1992) described the general problem of need for control of non-coniferous vegetation in the southwestern Oregon climate and terrain in order to obtain survival of conifers. They also outlined

some of the unique adaptations of the sclerophyll shrubs and hardwoods toward their own survival, all of which tend to increase their importance as competitors. Zybach (2007) has recently reviewed evidence that activities of native Americans toward meeting their food and game supplies tended to promote the occurrence of sclerophyll communities which limit conifer invasion.

There is a rich literature describing positive responses of planted conifers when comparing growth in weeded versus unweeded conditions in a wide variety of climates and regions (e.g. McDonald et al., 1999; Miller et al., 2003; Rose et al., 2006; Wagner et al., 2006). Growth responses are often quantitatively linked to degree, duration and structure of competing cover, as in McDonald and Abbott (1997). In many of these, partial contributions of herbs versus woody competitors are defined, with herbs tending to have greater relative importance in early years and lower relative importance in later years. Some of the studies have monitored responses for about a decade, but few have extended beyond 20 years (McDonald and Oliver, 1984; McDonald and Abbott, 1997; Zhang et al., 2006). Most reported substantial growth gains in short terms attributable to control of herbs, but in some (but not all) circumstances longer term effects were observed when woody competitors have been removed, as in Miller et al. (2003) in loblolly pine (*Pinus taeda* L.). The importance of competitor dynamics and length of time over which influence

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persists was germane, along with patterns of divergence versus non-increasing effects in decades following treatment.

Our study examined 26–27 years of data from experiments that evaluated effects of density of whiteleaf manzanita (*Arctostaphylos viscida* Parry) on planted ponderosa pine of the same age, and also density of Pacific madrone (*Arbutus menziesii* Pursh) post-burn sprout clumps on planted Douglas-fir. The studies were on sites that were considered too poor to be managed economically for timber production. Specifically, we asked whether there was a quantitative and generalized influence of density of woody competitors on conifer growth over  $\geq 2$  decades when established concurrently. Early results of the studies have been reported previously (Ortiz-Funez, 1989; White and Newton, 1989; Hughes et al., 1990; Pabst et al., 1990; Wang et al., 1995; Hanson, 1997).

## 2. Methods

### 2.1. Study sites, design, and measurements

#### 2.1.1. Ponderosa pine/whiteleaf manzanita

The ponderosa pine study was conducted on what was perceived to be three very poor sites (Big Humbug, Little Humbug, and China Gulch, each with 600 mm precipitation) near Ruch, Oregon (42°14'N., 123°02'W.) on USDI Bureau of Land Management (BLM) land in the valley of the Applegate River. The study was located on xeric low-elevation sites with west-southwest facing slopes. Soil is a clay loam 60–90 cm deep underlain by moderately weathered metasedimentary rock. Summer climate is hot and dry; water balance deficits are roughly 427 mm by October (Johnsgard, 1963). Hughes et al. (1987), Ortiz-Funez (1989), White and Newton (1989), and Hanson (1997) have reported results from these installations at intermediate ages.

These plantations occurred in three units previously dominated by 40- to 50-year-old whiteleaf manzanita, and not recently occupied by conifers except near roadsides and isolated clumps upslope. In late 1980, the sites were cleared with a brushrake; the brush was piled in windrows and burned in an operational pilot program. In spring 1981, the soil was ripped with a crawler tractor to a depth of 45 cm along planting rows. In those rows, Douglas-fir and ponderosa pine bare-root stock were planted in a 50:50 mixture at a spacing of 3-m  $\times$  3-m or slightly closer. To encourage survival, herbaceous competition was controlled for the first 2 years by either spraying with glyphosate (first year) or hexazinone (second year) herbicide while protecting the manzanita (China Gulch) or applying paper mulch mats (Big Humbug and Little Humbug).

Evaluation of shrub density effects was conducted in 0.04-ha plots containing over 30 conifer seedlings per plot and many thousands of manzanita seedlings. Shrubs were thinned to densities of 27,000, 13,500, 6720, 3360, 1700, and 0 (Trees only) shrubs per hectare (sph). Gaps in the shrub distribution were filled by interplanting nearby wildlings. The 13,500 sph density was installed in two plots in each of the three replications for a total of 7 plots per site (replication). Associated woody species, i.e. wedgeleaf ceanothus (*Ceanothus cuneatus* Nutt.), poisonoak (*Toxicodendron diversilobum* (Torr. and Gray) Greene) and sprouting Oregon white oak (*Quercus garryana* Dougl. ex Hook.), were completely removed by herbicide applications for the first 3 years (see White and Newton, 1989). Herbaceous species were also removed for the first 5 years, except for the additional 13,500 plot. This treatment was referred to as 13500HERBS, and herbaceous species were allowed to develop after the first 2 years. The statistical design was a randomized complete block with seven treatments consisting of six levels of manzanita density, one of which included herbs, and three replications.

Trees were thinned to 20 stems per plot (494 tph) at age 6, with the intention of having as close as possible to an even mixture of

pine and Douglas-fir. However, heavier mortality in Douglas-fir resulted in some plots having only pine trees. In year 21, one of the replication units (China Gulch) was subjected inadvertently to a mechanical fire hazard reduction treatment to eliminate continuity of fuel. This operation removed all the manzanita in all plots in that replication, and removed some of the remaining conifers. There is therefore an unknown influence of the fire hazard reduction treatment on mean tree size although all remaining individual trees were identified and measured. At age 26, number of pines per plot ranged from 12–20 for the Humbug units and 4–9 for China Gulch.

#### 2.1.2. Douglas-fir/madrone

The study of Pacific madrone, a hardy sclerophyllous hardwood, with Douglas-fir was on BLM land currently classified as Douglas-fir site V (site index<sub>50</sub> 17 m, King, 1966) within a slash-and-burn administrative study toward the rehabilitation of madrone-dominated sites. The site (Shoestring) was at 650-m elevation with very shallow soil but with 1080 mm precipitation, near Canyonville, OR (42°N., 123°12'W.). Following the burn, the site was planted in December 1979 with 2-year-old (2 + 0) bare-root Douglas-fir on a 2.4-m  $\times$  2.4-m or closer spacing. Very little herbaceous cover appeared in the first year, and cover was sparse the second year. The second year after planting, when madrone sprouts were the dominant vegetation and about 2 m tall, we installed a study of competitive influence of density of sprout clumps on planted Douglas-fir of the same age. This study has been reported previously by Hughes et al. (1990), Pabst et al. (1990), and Hanson (1997).

Four madrone densities were replicated with and without retention of associated shrubs and herbs in a 4  $\times$  2 randomized block factorial design on 0.04-ha square plots with three blocks. The densest sprout clump treatment (HIGH) relied on natural spacing in which clump spacing was about 2.7 m  $\times$  2.7 m (1372 clumps per hectare (cph)) with no removals. Two other densities were achieved by chemical removal of all other sprout clumps with 2,4-D directed sprays to leave clumps at spacings of 5.5-m  $\times$  5.5-m (331 cph; MED) and 7.9 m  $\times$  7.9 m (160 cph; LOW). For the fourth treatment (No madrone), all madrone clumps were removed, making four levels of madrone competition ranging from none to unrestricted.

For each level of madrone, there was a factorially combined treatment applied in year 3 in which understory herbs and shrubs were treated (or not) with a directed spray of glyphosate herbicide. The herb treatment did not control evergreen shrubs such as canyon liveoak (*Quercus chrysolepis* Liebm.) effectively, but did give temporary control of herbs and longer term control of poisonoak, deerbrush ceanothus (*Ceanothus integerrimus* Hook. and Arn.), and a few other deciduous species.

Initially, fifteen Douglas-fir seedlings were selected at random in each plot for repeated measurements of growth. At age 13, we thinned the population at that time to a planned level of 20 trees per plot (494 trees per hectare (tph) or 4.5 m  $\times$  4.5 m spacing), in all but unthinned-madrone (HIGH) plots, and tagged all trees; the originally tagged trees were retained unless suppressed by other Douglas-firs. We postponed thinning in the densest madrone plots to ensure that we would have a measurable population of conifers in the longer term; there was no obvious indication at that time of imminent intraspecific competition among the conifers in this understory situation, and that condition persisted as of time of last measurement.

### 2.2. Measurements

Diameters at 15 and 137 cm above ground (where present) of all trees of record were measured in fall each of the first 5 years,

and 7, 8, 14, 15, 23, and 27 years after planting (Douglas-fir). Heights of all trees of record were measured through age 15; the last two measurements were a random 40% sample of all diameter classes consisting of a subsample (8 trees/plot in every plot). Each time heights were measured, increments (nodes) were noted as far back as the previous measurement, if possible. Ponderosa pine are 1 year younger than the Douglas-fir, but were measured during the same calendar years. Height was measured for all ponderosa pine at each measurement time. At the last two measurements, crown length, and two-dimensional crown widths were recorded for both coniferous species. Hanson (1997) reported on the first 13 years in pine and 14 years in Douglas-fir.

A subsample of 25 manzanita per plot was tagged for permanent measurements. At each tree-measurement entry (except the most recent), tagged manzanitas were measured for basal diameter, height, and two dimensions of crown width. The earlier measurements of shrubs in the ponderosa pine study were reported by Hughes et al. (1987), White and Newton (1989), and Hanson (1997). Many of those data are illustrated in time-dependent figures in this paper.

In the year-23 measurements for the Douglas-fir study, we counted clumps and measured the largest dbh of every madrone clump in five systematically located 2.5-m radius subplots in each plot, and height of the tallest madrone stem nearest each subplot center. If more than 5 clumps occurred in the subplot, another height measurement was taken. No madrone measurements made between those reported by Hughes et al. (1990) and Pabst et al. (1990) have been previously published.

### 2.3. Statistical analyses

#### 2.3.1. Ponderosa pine

Analyses of the ponderosa pine data were based on a randomized complete block design evaluating seven vegetation treatments in which one replication was confounded by fuel treatment that removed all shrubs and a fraction of measurable trees at age 21. To determine treatment effects at age 26, analyses of variance were run for year-26 height, dbh, basal diameter, volume/tree (calculated from equations in Walters et al., 1985), base of live crown, and crown ratio. All ANOVAs were performed using PROC MIXED in SAS<sup>®</sup> (Littell et al., 1996; SAS Institute Inc., 2003) with block (site) as a random effect. Due to heterogeneity of variance, dbh, basal diameter, and volume were log-transformed prior to analyses. Tukey's test for nonadditivity was used to determine if there were block  $\times$  treatment interactions. These tests indicated significant block  $\times$  treatment interactions for dbh, basal diameter, volume, and crown ratio so data were re-analyzed utilizing only the Big and Little Humbug sites. Bonferroni's adjusted means tests were used to compare ANOVA means.

In addition to ANOVA, linear regression was used to evaluate the relationship between original manzanita density and ponderosa pine height, dbh, basal diameter, volume, crown ratio, and base of live crown at age 26. Original manzanita density was used instead of year-22 density, because manzanita had been removed at China Gulch. Because the manzanita data were calculated at the plot level, regressions were based on plot means rather than individual trees. Crown ratio and base of live crown were regressed against manzanita height, diameter, and crown width to examine those relationships. The independent variable (original density of manzanita) was log-transformed prior to analyses for Big and Little Humbug, but the dependent variable was log-transformed for China Gulch. Data were analyzed using PROC MIXED in SAS<sup>®</sup>, and differences in both intercepts and slopes were tested among blocks. In addition, PROC REG in SAS<sup>®</sup> was used to develop

regression equations of plot mean height, basal diameter, dbh, and stem volume/tree as dependent variables and time since planting as the independent variable.

To determine treatment differences for manzanita, ANOVAs for year-22 manzanita height, basal diameter, and crown width were performed using PROC MIXED in SAS<sup>®</sup> with block as a random effect. Because manzanita had been removed at China Gulch, only Little and Big Humbug sites were used. Basal diameter and crown width were log-transformed prior to analyses due to heterogeneity of variance.

#### 2.3.2. Douglas-fir

As with the ponderosa pine data, ANOVA and regression were used to analyze the data. The ANOVAs analyzed year-27 data as a  $2 \times 4$  factorial. Regressions examined the relationship between year-27 height, dbh, basal diameter, and volume/tree and the independent variable madrone clumps per hectare based on year-23 measurements. Regression was also used to chart growth with years and madrone densities.

For the ANOVAs, PROC MIXED in SAS<sup>®</sup> was used with block as a random variable. Because there were some differences in number of Douglas-fir per hectare, stem density of dominant Douglas-fir per hectare was tested as a covariate. It was not significant ( $p > 0.14$ ) for height, diameters, or volume, so data were re-analyzed without the covariate. For height and volume, the log transformation was needed to adjust for heterogeneity of variance. For crown ratio and base of live crown, stem density of dominant Douglas-fir per hectare was a significant covariate. This resulted from the two unthinned (HIGH) plots in one of the blocks. When those were deleted, the covariate was no longer significant. Because of this confounding, we decided to not analyze crown ratio and base of the live crown further.

The regression analyses with year-23 clumps per hectare as the independent variable used PROC MIXED in SAS<sup>®</sup> with block as a random variable for fitting various size parameters, and the dependent variables were log-transformed. Tests for differences among the blocks were not significant ( $p > 0.13$ ), so only a single regression equation was developed for all of the blocks. With time as the independent variable, PROC MIXED and REG were used. Tests indicated that there were significant differences among the blocks in time, so equations were developed for each block. The best-fit equations were selected based on  $r^2$  values and examination of residual and predicted values.

### 2.4. Site index projections

The Shoestring site adjacent to the study plots supported a few Douglas-fir  $\geq 65$  years old of natural origin growing in gaps between similar-aged madrone clumps. Site index (King, 1966) was calculated from these trees to be 17.3 m at 50 years breast height age when mixed with madrone populations of about the same age regenerated after fire. We projected measures of site index (King, 1966) for the study site with and without removal of madrone. To simplify the comparison of growth under a range of competitor levels with King's (1966) site curves, we merged non-herb with herb treatments. Our trees took 8.5–10 years to reach breast height (based on total age), depending upon replication and madrone density. On the average, the No madrone plots reached breast height about 0.5 year earlier than the HIGH density madrone plots and the trees on blocks A and B 1 year earlier than block C. For comparative purposes, we used breast height total ages 16 and 20 for blocks A and B and 15 and 19 for block C for years-23 and -27 measurements, respectively. In addition, our estimates were based on the overall average for each treatment, rather than the top 99 tph that King (1966) used for site index estimates. Our site

index values would be somewhat higher if based on only the largest 99 tph.

### 3. Results

#### 3.1. *Ponderosa pine*

Where the shrubs had been completely removed, dbh and volume/tree were significantly greater than where original manzanita densities were 1700 sph or more (Table 1); heights were greater than where shrub density was >6720 sph. ANOVA means of heights and diameters (Table 1) for the treatments where manzanita remained at any spacing were no longer significantly different from each other despite their having been different in earlier years (White and Newton, 1989; Hanson, 1997).

Height (Fig. 1), dbh, and volume/tree (Fig. 2) of ponderosa pine were substantially affected by manzanita despite the pine being dominant over manzanita for most of their lives.  $R^2$  values for these curves were all greater than 0.95. For most of the curves, the quadratic term for year was significant, but some of the curves indicated that this term was non-significant, even though tree growth was not linear. Pine height also displayed poor growth at ages 21 and 22 reflecting the severely prolonged summer drought at that time, but depression of growth was not obviously related to treatment (see data points, Fig. 1). Plot means illustrated slow-down and recovery superimposed on fitted curves, and this was best seen with the Trees only data in Fig. 1. Pine showed a variable tendency for growth in early years to decrease with each increment of manzanita, both in height and diameter. The poorest growth was shown in the 13500HERBS manzanita treatment. Although this effect was significant in early years (White and Newton, 1989), it was no longer significant, even though the means indicated these trees were the shortest and smallest at plantation age 26. In Figs. 1 and 2, it appeared that the Humbug sites were slowing in growth whereas, the China Gulch sites were accelerating. It was not certain if this was a mathematical artifact of the curve generation or a response to the removal of the manzanita at the China Gulch site.

Based on regressions, mean pine volume/tree (Fig. 3) was significantly, negatively correlated with original manzanita density. However, if the Trees only plots were not included in the regression, the relationship was not significant ( $p > 0.05$ ) for the intact (Humbug) units, a pattern that has persisted for the last two measurements. Regressions relating pine crown ratio to manzanita size and density were not significant. If the Trees only plots were removed, there was a significant ( $p = 0.04$ ), positive

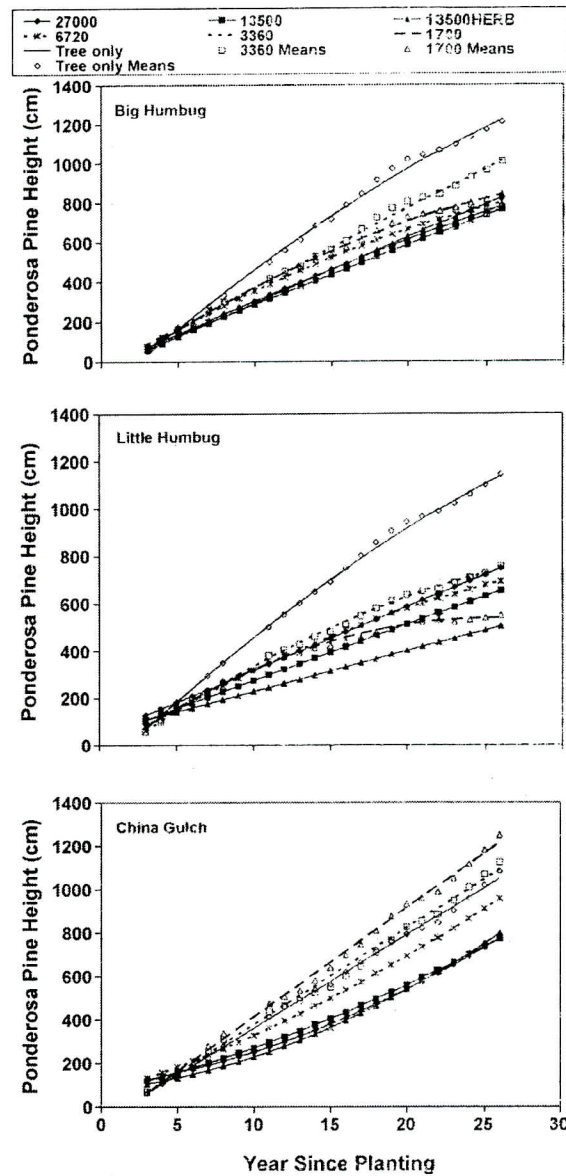


Fig. 1. Trend lines from regression analyses and selected treatment means for total height for ponderosa pine at Big Humbug, Little Humbug, and China Gulch from the manzanita study. Treatment numbers in the legend are original manzanita sph.

Table 1

P values and least-squared means comparisons from ANOVAs for year-26 ponderosa pine data

Treatment	Probability for F tests for manzanita treatment effects					
	Height 26	dbh 26	BD 26	Volume/tree 26	Base live crown 26	Crown ratio 26
Treatment	0.0090	0.0022	0.0129	0.0162	0.0031	0.1234
Manzanita per hectare	Least-squared means					
	cm	mm	mm	m <sup>3</sup>	cm	
27,000	792b <sup>a</sup>	164b	226b	0.064b	204ab	0.66a
13,500	743b	160b	223b	0.059b	185b	0.66a
13,500HERB	715b	145b	197b	0.042b	181b	0.63a
6720	810b	160b	220b	0.060b	201b	0.67a
3360	953ab	183b	249ab	0.089b	228a	0.70a
1700	843ab	168b	225b	0.059b	225a	0.62a
Trees Only	1175a	258a	350a	0.21a	262a	0.76a

Means for diameters and volume have been back-transformed from log values. Manzanita densities are given as of the time of establishment.

<sup>a</sup> Means within column followed by the same letter are not significantly different at  $p = 0.05$  using Bonferroni's adjusted means comparisons.

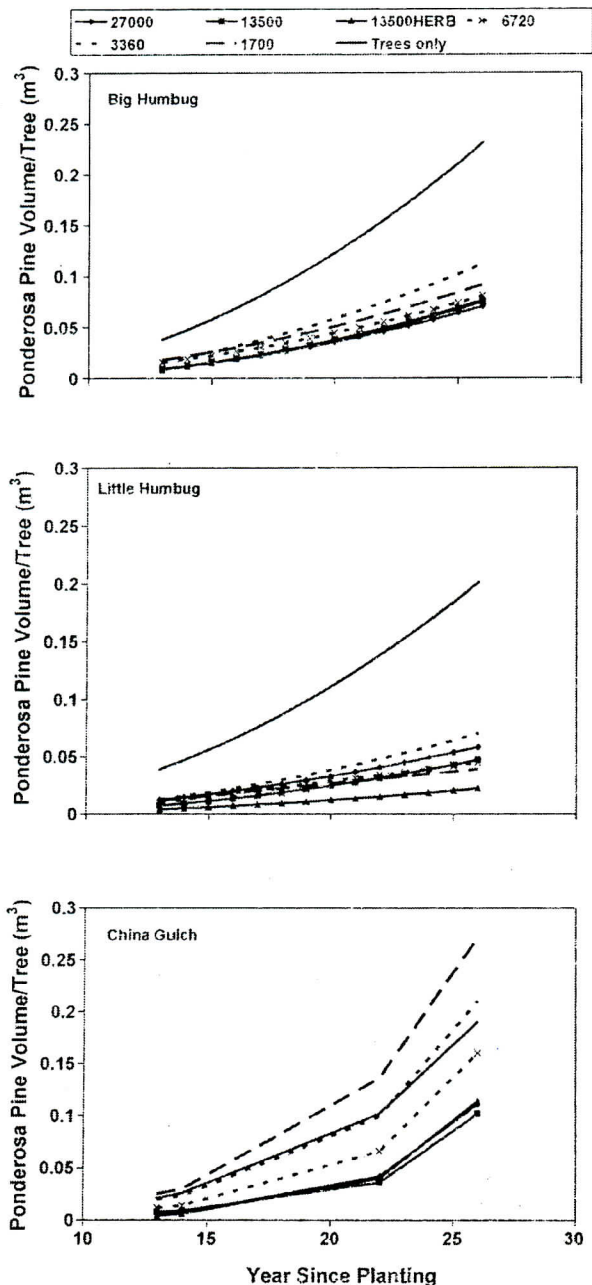


Fig. 2. Trend lines from regression analyses for volume/tree for ponderosa pine at Big Humbug and Little Humbug and means for China Gulch from the manzanita study. Treatment numbers in the legend are original manzanita sph.

correlation between base of live crown and manzanita height, but the  $r^2$  value was low (0.29).

Manzanita had reached the point of crown overlap at most densities. Crown and basal diameters of manzanitas were significantly ( $p < 0.05$ ) and negatively correlated with original manzanita density as they approached crown overlap. Gaps within individual manzanita crowns were common at age 26 owing to suppression by pine or crowding by other shrubs. Analyses indicated no significant differences among treatments for manzanita heights (Table 2), but diameters increased as density decreased.

Manzanita crown covers, estimated from shrubs per hectare and crown spread, have increased steadily until mortality of branches and entire shrubs became common. Through age 22,

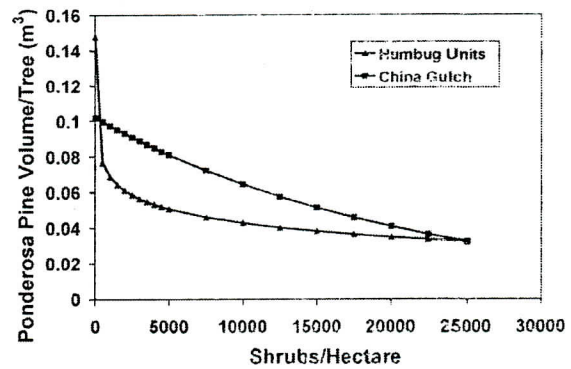


Fig. 3. Relationship between volume/tree year 26 and manzanita density year 22 for ponderosa pine from the manzanita study.

Table 2

P values and least-squared means comparisons from ANOVAs for year-22 average size of manzanita

Treatment	Probability for F tests for manzanita treatment effects		
	Height 22	BD 22	Crown width 22
	0.3206	<0.0001	0.0052
Manzanita per hectare	Least-squared means		
	cm	mm	cm
27,000	236a <sup>a</sup>	37.3c	109b
13,500	227a	40.2c	100b
13,500HERB	232a	44.2b	114b
6720	236a	48.1b	145ab
3360	261a	60.4a	166ab
1700	249a	60.1a	219a

Means for diameter and width have been back-transformed from log values. Manzanita densities are given as of the time of establishment.

<sup>a</sup> Means within column followed by the same letter are not significantly different at  $p = 0.05$  using Bonferroni's adjusted means comparisons.

cover measures from Fig. 4 indicated that whereas crown cover in year 8 ranged from 20 to <100% across the manzanita densities, by age 22, the range was 55 to >100%, and only the 1700 and 3360 shrubs per hectare plots were at less than 90%. This resulted in an increase in contrast between the lowest shrub densities and Trees only, and decreased contrasts among shrub densities. Because crown cover estimates were based on crown spread without an indication of foliage density, cover estimates were probably greater than actual manzanita cover.

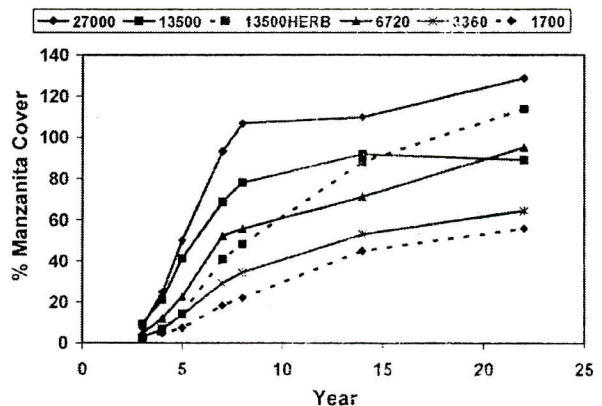


Fig. 4. Treatment means for manzanita crown cover through time. Treatment numbers in the legend are original manzanita sph.

3.2. Douglas-fir

Twenty-seven years after establishment, the ANOVAs indicated that only the HIGH density of madrone caused a significant reduction in Douglas-fir height, but the intermediate densities of madrone had reduced diameter and volume/tree (Table 3). Height, dbh, and volume of Douglas-fir were still showing signs of understory control at age 23 ( $p < 0.026$ ), although the differences between the herb and no herb treatments were not great. They became non-significant at age 27 (Table 3). Regression analyses indicated that slopes of the Douglas-fir height curves based on madrone density were not different between the two herb treatments, indicating that trees were exhibiting the same relationship with madrone density with or without the presence of herbaceous plants.

All parameters exhibited strong trends of decreasing Douglas-fir size with increasing year-23 madrone density ( $p < 0.05$ ) (Figs. 5 and 6). Trends of volume/tree over time (Fig. 7) continued to diverge in Douglas-fir growing with different levels of madrone clumps. Patterns did differ somewhat among replications, primarily related to the differences in numbers of madrone clumps resulting from recovery of treated clumps and seedling recruitment.

**Table 3**  
P values and least-squared means from ANOVAs for year-27 Douglas-fir Shoestring data

	Probability for F tests for treatment effects			
	Height 27	dbh 27	BD 27	Volume/tree 27
Density	0.0025	<0.0001	<0.0001	0.0001
Understory	0.2626	0.3755	0.5916	0.3791
Dens*und	0.8310	0.8091	0.8406	0.7546

Madrone density	Least-squared means			
	cm	mm	mm	m <sup>3</sup>
HIGH	1059b <sup>a</sup>	123c	161c	0.06c
MEDIUM	1202a	155b	206b	0.10b
LOW	1309a	173b	231b	0.13ab
No madrone	1335a	195a	267a	0.16a

Understory	Least-squared means			
	cm	mm	mm	m <sup>3</sup>
Removed	1248a	165a	219a	0.11a
Present	1195a	158a	214a	0.10a

Means have been back-transformed for height and volume.  
<sup>a</sup> Means within column followed by the same letter are not significantly different at  $p = 0.05$  using Bonferroni's adjusted means comparisons.

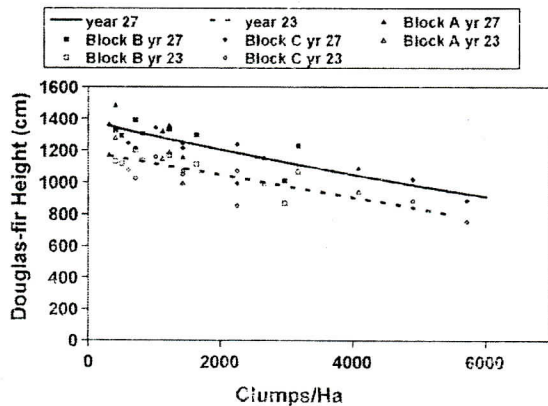


Fig. 5. Regression lines and block means for Douglas-fir total heights years 27 and 23 for the madrone study. Clumps/ha is madrone density in year-23.

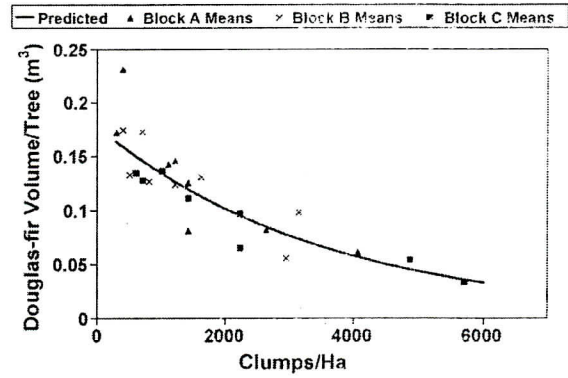


Fig. 6. Regression line and block means for Douglas-fir volume/tree for year 27 for the madrone study. Clumps/ha is madrone density in year 23.

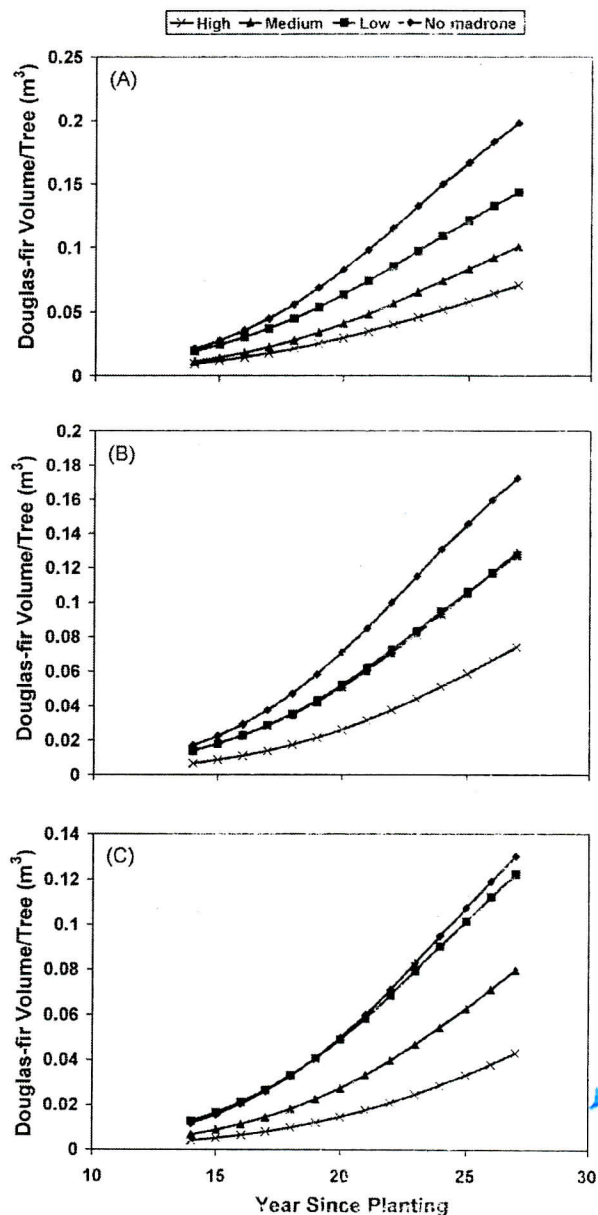


Fig. 7. Trend lines from regression analyses for Douglas-fir volume/tree (A) Block A, (B) Block B, and (C) Block C from the madrone study.

Madrone height and crown width on individual stems did not vary significantly among the treatments where some madrone remained (Table 4). These treatments had significantly taller and larger madrones than the No-madrone treatment, where madrone originated primarily from germinants after study installation. Excluding the No-madrone treatment, there was a trend of decreasing madrone stem diameters as madrone density increased. Comparing madrone densities from year-23 measurements and earlier results was problematic because of difficulties in identifying clumps. In the earlier studies, clumps were difficult to distinguish, because at the time of study layout, foliage covered many of the stumps, and some stumps could have been missed. By year-23, the stumps had rotted and were no longer visible, again making it difficult to identify clumps.

### 3.3. Site index projections

Site index projections from all blocks and treatments at the Shoestring study site were higher than those estimated from the surrounding stand ( $SI_{50} = 17.3$  m) (Table 5). The highest indices were from the No-madrone plots, and indices decreased as madrone density increased. Projections from the year-23 data were slightly greater than those using year-27 heights.

**Table 4**

*P* values and least-squared means from ANOVAs for year-23 madrone Shoestring data

	Probability for <i>F</i> tests for treatment effects		
	Height 23	dbh 23	Crown width 23
Density	<0.0001	<0.0001	0.0001
Understory	0.7665	0.1031	0.5109
Dens*und	0.6925	0.2370	0.4890
Madrone density	Least-squared means		
	cm	mm	cm
HIGH	766a <sup>a</sup>	67.1b	201a
MEDIUM	787a	84.6ab	249a
LOW	819a	93.2a	286a
No madrone	305b	17.9c	97b
Understory			
	Removed	617a	51.6a
Present	630a	59.6a	200a

Means have been back-transformed.

<sup>a</sup> Means within column followed by the same letter are not significantly different at  $p = 0.05$  using Bonferroni's adjusted means comparisons.

**Table 5**

Estimated site index for treatments on Douglas-fir/madrone competition study site corresponding to King (1966)

	Clump density (Tmt)	Year-23 height (m)	Year-27 height (m)	Basis: King (1966)	
				Year-23 $SI_{50}$	Year-27 $SI_{50}$
Block A	No madrone	12.3	14.2	31	29
	LOW	11.7	13.4	29	27
	MEDIUM	10.3	12.0	27	24
	HIGH	9.7	11.2	24	23
Block B	No madrone	11.6	13.6	29	29
	LOW	11.4	13.1	29	27
	MEDIUM	11.2	13.0	28	26
	HIGH	9.7	11.2	24	23
Block C	No madrone	10.5	12.3	26	25
	LOW	11.0	12.7	27	26
	MEDIUM	9.6	11.2	24	22
	HIGH	8.2	9.6	20	19

Based on all planted trees, years 23 and 27.

## 4. Discussion

Removal of manzanita and madrone increased growth of pine and Douglas-fir. Growth increases have continued through 26–27 years after treatment. Whereas the over-all effect of the woody competitors was highly significant, differences between levels of competition varied. Differences between life-forms of competitors and/or climate were associated to some degree with different patterns of effect on conifers. The height of ponderosa pine increased sharply between the lowest levels of whiteleaf manzanita shrubs and complete removal, and volume/tree increased in larger proportion even though the shrubs never exceeded 3 m in height, over which the pines were always dominant. Whereas differences among manzanita densities were important at age 13 (Hanson, 1997) the principal differences at age 26 were between any level of manzanita and total removal. Differences in height of Douglas-fir remained small between No madrone and the lowest level of co-dominant hardwoods; differences in volume/tree between No madrone and the lowest densities had increased since age 14. Heights were more or less negatively linear with density of sprout clumps, a factor not previously reported. Differences in volume/tree were proportionally greater throughout the range of hardwood density evaluated at age 23, with the largest gains in volume/tree observed at the lowest densities of madrone (Fig. 6).

Zwieniecki and Newton (1996) noted that the two sclerophyllous species growing in these competition experiments had access to water held in bedrock that was inaccessible to conifers, and were thus able to transpire and presumably photosynthesize for several weeks longer in the growing season. Even though these two woody species differed in being understory versus co-dominant, both transpire late in the growing season when soil- and bedrock-held water was difficult for conifers to extract.

Several authors have reported varying effects of different competitors on conifer growth. Harrington and Tappeiner (2004) reported increments in height and volume growth of Douglas-fir remarkably like our data showing responses to madrone densities when tanoak densities were reduced by half, three-quarters and complete removal, as shown in Fig. 8. Summarizing several competition studies, Wagner (2000) indicated that maximum growth gains occurred with low levels of competing vegetation. McDonald and Abbott (1997) reported that even a light amount of shrubs decreased ponderosa pine growth in a study on different quality sites in northern California. In a southeastern US loblolly pine study, Glover and Quicke (1999) observed that any reduction in water oak density resulted in increased pine growth, but sweet

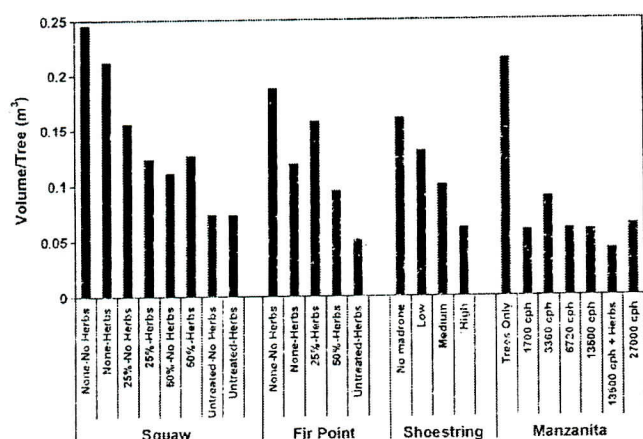


Fig. 8. Treatment means for volume/tree for Douglas-fir age 25 (Squaw, from Harrington and Tappeiner, 2004), age 24 (Fir Point, from Harrington and Tappeiner, 2004), and age 27 (Shoestring) and ponderosa pine age 26 (Manzanita). Volumes are calculated from Bruce and DeMars (1974) for Squaw and Fir Point and from Walters et al. (1985) for Shoestring and Manzanita. For Squaw and Fir Point, percentages refer to 25 and 50% of original tanoak density.

gum densities had to be reduced below about 1800 tph before pine showed a significant response. In a Douglas-fir competition study in Oregon, Rose et al. (2006) found that controlling woody vegetation increased individual tree volume 117% at one site, but not another; the site with the large response had heavy concentrations of tall-growing woody cover whereas the site with weak response had light woody cover with heavy herb competition. These varying results in the pattern of response indicate that conifer responses to woody competition will undoubtedly vary among sites, dominant competitor species, early herb dominance, and crop species.

Zhang et al. (2006), Powers and Reynolds (1999), and McDonald and Abbott (1997) reporting on competition experiments with ponderosa pine on a wide variety of sites have shown large variability in the way different competing species and different sites respond to tree spacing, herbicide treatment, and fertilization. In all instances, significantly higher growth rates were seen over an extended period following early hardwood/shrub removal versus other silvicultural treatments, but long-term patterns of periodic annual increment varied based on site quality, stand density, and density of hardwoods or shrubs in competition. In our studies, crop tree spacing was wide enough so that conifer crown closure had not yet occurred where woody competitors were present, and as conifers become more dominant as dictated by hardwood density, one may expect continued growth increases until conifer crowns close if and when they become fully dominant. Where madrone was absent, crown closure was nearly complete in our 494 tph plots.

Control of herbs has widely been reported as having a long-term influence on conifer yield. Harrington and Tappeiner (2004) noted on similar sites that the herb effect persisted for at least 20 years, but only in the absence of tanoak. Long-term studies by Miller et al. (2003, loblolly pine) in the southeastern USA made clear that early herb competition influenced long-term conifer yield when compared with complete removal. They also showed that effects of herbs and woody species differed in degree of influence with stand age and woody plant development, and this effect appeared in both these experiments under very different site conditions. Newton and Preest (1988) and Rosner and Rose (2006, Douglas-fir) on productive sites in the Pacific Northwest demonstrated that growth rates differed strongly in the first decade after controlling herbs. Quicke et al. (1999) observed some continued increase in

growth differences after age 10 following early herb control, and Cain (1999) observed a slight decrease in effect of hardwood density when herbs were initially controlled. On the cooler sites of boreal forests (e.g. Boateng et al., 2006) and in an array of sites in the Pacific Northwest, a pattern of continued divergence shows up in yield, as reported on better sites by Rosner and Rose (2006) while evidence of divergence following herb control disappeared in our studies.

We do not have a good explanation for decreasing effect of herb competition. Late arrival of herbs, suppression of herbs by increasing canopy and mortality within the measured stands could influence specific effects. Previous studies have indicated that to obtain the maximum increases in growth from removal of herbaceous vegetation, control needs to occur in the first years of plantation establishment (Newton and Preest, 1988; Rosner and Rose, 2006; Rose et al., 2006). None of our plots had appreciable herb cover in their first 2 years. Quicke et al. (1999) reported the height growth gains from herbaceous control were no longer significant by age 15, and that early gains might not be maintained throughout a rotation. They speculated that loss of early herbaceous competition effects may be related to the declining effect of herbs below expanding conifer cover. Their work related to very young stands in which mortality was not a factor, but others have reported that early gains from vegetation control may diminish in time as suppressed trees in untreated plots die and are no longer part of the sample (Biring et al., 2003; Heineman et al., 2007). Some changes in our experiments did occur within populations of measured trees. In the Douglas-fir study, this may have been the result of pre-commercial thinning and the selection process. Natural mortality in the ponderosa pine may have had a disproportionate effect on saplings of different sizes. Moreover, for the ponderosa pine study, the loss of the China Gulch replication resulted in only two replications available for ANOVAs, and that decreased our ability to detect statistical differences for all tests. The 13500HERB plot on which herbs developed after the first year continued to have the smallest trees, but our over-all ability to evaluate potential response to herbs was limited.

Another way that our results differed from previously reported results for the ponderosa pine study was that tree size was no longer significantly different among the manzanita densities. Although the loss of the China Gulch replication would have also affected these statistical tests, the means for diameter and volume/tree indicated that there were decreasing differences among the densities, i.e. if any manzanita were present, it matters little *how much* there was in terms of pine growth. Examination of periodic annual volume/tree increment (pai) (Fig. 9) indicated that there were differences among the treatments and replications, but these were not consistent among the manzanita densities. The Trees only plots exhibited increases in pai at year-26 over all of the sites. At China Gulch, pai increased more rapidly after the removal of manzanita in year 21. At the Humbug sites, pai trends among the treatments with manzanita varied, and at this time, we have no explanation for the trends.

Another factor influencing the impacts of competition was climate. The prolonged summer droughts of 2001 (years 22–23) and 2002 (years 23–24) affected the two coniferous species of our studies similarly, and we had no opportunity to measure whether recharge of soil and bedrock occurred between years. The result for both species was an abrupt decrease in height growth in the 2 years of measurement bracketing 2002; the reduction was similar for the two species despite their differences in sites and elongation habits. Both species have recovered to their original growth trends by the 2006 measurement.

Thus far, we have not observed negative effects of removal of shrubs or hardwoods expressed in terms of conifer growth or vigor

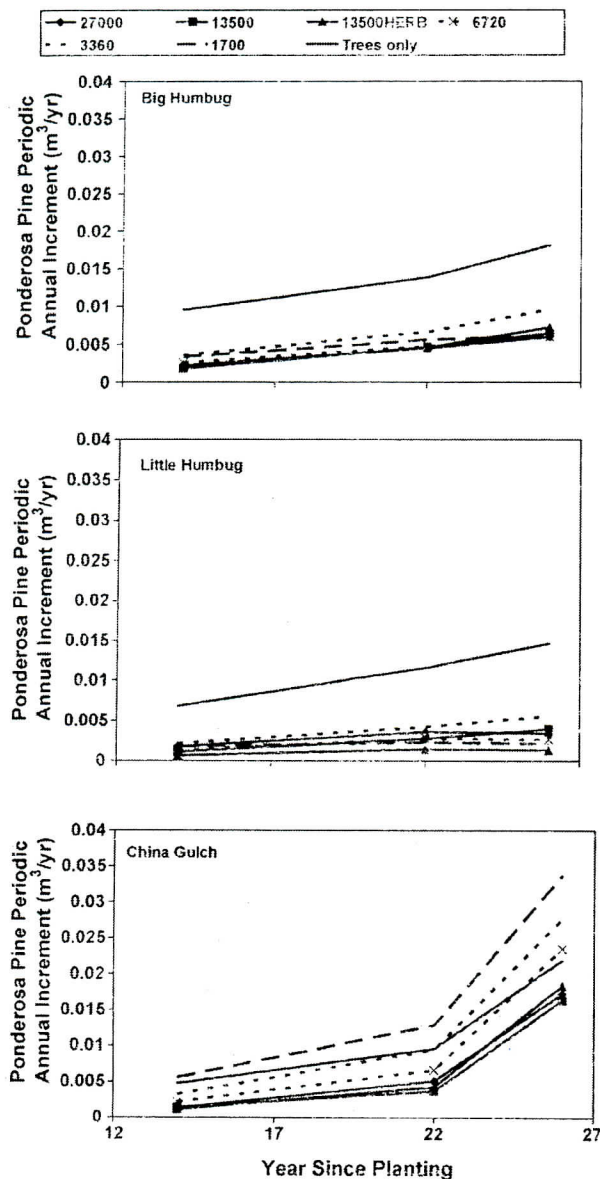


Fig. 9. Ponderosa pine periodic annual volume/tree increment for three sites of the manzanita study. Numbers were calculated from data and not trend lines.

in healthy trees. Harrington and Tappeiner (2004) have observed similar effects of varying densities of tanoak on Douglas-fir in two separate areas of southwestern Oregon, but they also reported the occurrence of the "black stain" disease primarily in plots with near-complete control of non-coniferous cover. In interior British Columbia, Simard and Vyse (2006) observed greater Douglas-fir growth where paper birch (*Betula papyrifera* Marsh.) had been removed, but also reported greater Douglas-fir mortality due to *Armillaria ostoyae* (Romagnesi) Herink where the birch had been manually cut or girdled. Cut stump treatments with glyphosate did not result in an increase in mortality, indicating an apparent relationship among increased Douglas-fir growth, *A. ostoyae*, other saprophytic fungi, and mortality. We have observed some mortality in No-madrone plots, but source is unidentified, and occurrence is sporadic and low.

When we compared the periodic height growth with data listed by King (1966), there was evidence that height curves were of a different shape from King's (1966) as postulated by Hanson (1997)

and Newton and Hanson (1998). These data show that there is logic in developing height curves and measuring site index in stands grown with very low levels of competition, and that positive departure from conventional model growth curves can be expected as the result of reducing competition. Existence of a maturing brushfield or hardwood stand with little or stunted conifer stocking on harsh sites such as our study areas is not necessarily evidence of sites incapable of producing a substantial yield of conifers. Without long-term data, one risks serious over- or underestimates of potential yield.

We also found that plantation growth models were likely to differ markedly from those derived from natural regeneration, especially in uncontrolled competition. The act of planting alone after a land-clearing disturbance provides a different pattern of growth and maintenance of dominance, a phenomenon noted by Cain (1999) in southeastern USA. Shatford et al. (2007) suggested that natural regeneration on sites similar to our Shoestring site after fire was likely to be adequate in numbers, but acknowledged that planting and vegetation control may be desirable if the goal includes achievement of large tree size and perhaps yield at an earlier age. Miller et al. (1993) found that Douglas-fir planted after slash burning on sites in the Cascade Range of western Oregon and Washington reached breast height 3 years sooner than natural regeneration on those sites, despite having been planted an average of 2 years after the burning. Planting alone is apparently an important element in predicting yield. Our analyses of competition control are additive to effects of planting.

The possibility always exists that once a stand of weeded trees fully occupy a site, total stand growth will then plateau similar to unweeded stands. In Maine, Daggett and Wagner (2002) found that vegetation management without pre-commercially thinning naturally regenerated stands of balsam fir (*Abies balsamea* (L.) P. Mill.) and red spruce (*Picea rubens* Sarg.) resulted in stands with similar total merchantable volume to untreated controls, but of different composition. PAI for the Shoestring plots was increasing among all treatments (Fig. 10), with No madrone exhibiting the largest increases. The prolonged presence of hardwood or shrub cover will likely lead to delay in arrival at maximum yield for a given stocking of crop conifers, and reduction in conifer growth as long as the site is shared. The projected "increase" in measured site index resulting from early increased height growth would not be sustained once crop trees start competing with each other, and the weeded and unweeded trajectories would presumably merge at the same plateau as they approach their upper asymptote. The value of modified growth curves would then depend on how long trees are expected to grow until harvest or if thinning of conifers had occurred.

Height curves in weed-free studies differ from those currently used site curves (King, 1966) for Douglas-fir; the analogies in loblolly pine (Miller et al., 2003) and white spruce (*Picea glauca* (Moench) Voss) (Cole et al., 2003) suggest that each commercial species warrants mensurational data relevant to deliberate management for conifer yield. Establishment of long-term growth plots around each region would offer an opportunity to calibrate local site estimation with corrections for existing competition (Newton and Hanson, 1998), extended to current planting stock and competition levels normally used in production forests.

The futures of these experiments will show changes of unknown import. These studies are old enough so that the dominant woody species have clearly had an effect on understory shrubs and herbs. In the pine study, herbs have now been suppressed almost out of existence at all densities of manzanita, and the herb effect has been supplanted by that of shrubs. Manzanita is deteriorating beneath pine plantations to the extent that future divergence in pine yield warrants continued observa-

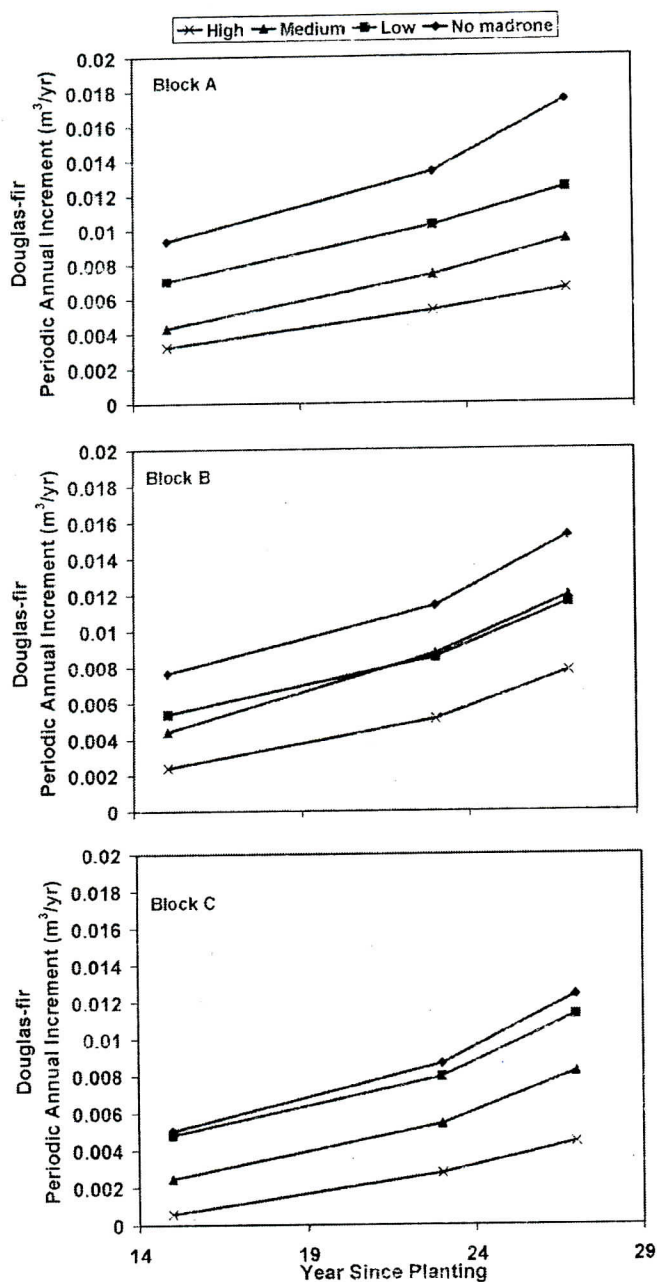


Fig. 10. Douglas-fir periodic annual volume/tree increment for three blocks at Shoestring. Numbers were calculated from data and not trend lines.

tion. Madrone remains co-dominant with Douglas-fir except where it was removed completely 25 years ago, but Douglas-fir is growing in height more rapidly now than is madrone. Madrone is a persistent species and its shade tolerance suggests it will continue to compete. One may postulate that the four levels of madrone density may reveal whether degree of continued divergence is contingent on the abundance of residual co-dominant hardwoods.

## 5. Conclusions

Despite being different species, and on sites with different competitors, terrain, soils, and rainfall, these experiments show conceptually similar responses of planted conifers to controlled

densities of competitors in two studies and locations. The difference between conifer-only plots and the lowest levels of competition provided the largest increase in volume of conifers much of the time. These studies extend the general picture of reduced conifer growth across a spectrum of regions and sites ranging to the poorest commercially viable sites. Their striking similarity to related studies with different competitors accentuates the conceptual nature of the role of competition. Patterns of growth differed substantially from one replication to another and one site to another, but removal of nearly all large woody competitors increased growth and yield substantially. Among madrone competitors, planting alone will succeed in providing some dominant conifers after 27 years although with far less volume than where competitors are rare or absent. Planted trees facing competition will be taller than naturally regenerated trees. Estimates of conifer site productivity may be lower where site trees have grown in mixture with competing hardwoods or evergreen shrubs, and where natural regeneration provides the basis for site evaluation.

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