THE GARDEN OF EDEN EXPERIMENT: FOUR YEAR GROWTH OF PONDEROSA PINE PLANTATIONS

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ABSTRACT

Soil moisture and nutrient availability, along with possible damage from feeding insects, are the primary factors controlling the performance of young plantations of ponderosa pine in California. Early findings from a comprehensive, three-factor field experiment conducted on eight sites indicate that plantation growth can be increased from one-half to more than seven times by the regular application of herbicides and fertilizers. The strongest single effect of this is to reduce demand from competing vegetation for soil moisture and nutrients. Repeated application of herbicides increased growth nearly threefold in the first 4 years. Most plantations responded to fertilization, but only if competing vegetation was controlled as well. Insect damage was nil on all field sites, and and insecticide treatments did not improve growth. Six year results from the oldest plantation suggest that differences between treatments will widen until stands reach crown closure.

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INTRODUCTION

Pacific ponderosa pine (*Pinus ponderosa* Dougl. ex Laws. var. *ponderosa*) is the most widely planted tree in California. Despite recent reductions in clearcutting on federal lands and trends toward more reliance on natural regeneration, ponderosa pine will continue to be planted extensively following wildfires, brushfield conversions, and in forest harvest operations where natural regeneration is unreliable. On private lands, it will continue to be planted extensively. Thus, plantation silviculture will remain an important aspect of ponderosa pine management in California. Because plantations will serve an increasingly important role in California's wood production, there is an acute need to understand how interacting factors affect plantation productivity and sustainability. This paper reports 4-year growth response results of an interdisciplinary experiment designed to address this need.

Limiting Factors

Keys to success in establishing ponderosa pine plantations are well known, and include effective site preparation, appropriate planting stock, and proper lifting and planting procedures (Oliver *et al.*, 1983). However, subsequent growth can be disappointing. California's Mediterranean climate ensures that summers will be warm and dry in the ponderosa pine region west of the crest of the Cascades and Sierra Nevada. This, coupled with shallow, gravelly, or infertile soils on many westside sites and the agressive nature of well-adapted native shrubs such as manzanita (*Arctostaphylos* sp. Adans.), ceanothus (*Ceanothus* sp. L.), and bearclover (*Chamaebatia foliolosa* Benth.), as well as bracken (*Pteridium aquilinum* L.) and various species of forbs and grasses, means that stress can be severe in planted trees during the growing season. In turn, stressed trees are less able to resist attacks from such common forest insects as the pine reproduction weevil (*Cylindrocopturus eatoni* Buchanan), ponderosa pine tip moth (*Rhyacionia zozana* [Kearfott] Stevens), gouty pitch midge (*Cecidomyia piniinopis* Osten Sacken [Eaton and Yuill]), and the California fivespined ips (*Ips paraconfusus* Lanier).

Woody shrubs generally are regarded as pine's strongest competitors for scarce site resources. Shainsky and Radosevich (1986) showed that ponderosa pine growth was reduced substantially by as little as 25 percent ground cover of manzanita. Oliver (1984) found that regardless of site quality, woody shrubs exerted nearly their full competitive effect at coverages as low as 30 percent. Competition exists even after trees have overtopped their competition. Trees four-times taller than surrounding woody shrubs still responded strongly to weeding (Powers 1984). Even on excellent sites, pine plantation volumes can be twice as great after 20 years where shrubs have been excluded (Oliver 1990). Fiske (1982) concluded that plantations undergoing average competition from manzanita ultimately would fail to meet either stocking or productivity objectives.

Herbaceous competition has not drawn as much research attention as woody shrubs. Many foresters consider them to be less serious competitors once seedlings are established. Roots of herbaceous species do not penetrate the soil as deeply as shrub roots, although they can extract soil moisture as deeply as 0.9 m (White and Newton 1989). Thus, they probably are incapable of drying the full soil profile on very deep soils (Tappeiner *et al.* 1992). Because of this, McDonald (1986) suggested that a grass cover established 3 to 5 years after trees are planted might reduce shrub competition and benefit tree growth on deep soils. Baron (1962) reported that ponderosa pine survival was not affected by grass cover if they were established simultaneously. Yet, in southwestern Oregon, stem volumes of 5-year-old ponderosa pine growing in association with manzanita were 53-percent greater where herbs had been excluded (White and Newton 1989). For interior "eastside" forests of ponderosa pine in California (Gordon 1962) and Oregon (Barrett 1965), removing grasses and herbs from established, natural stands increased pine growth significantly.

Nutrient deficiency, particularly nitrogen (N), is common in ponderosa pine forests of California and Oregon. Deficiencies seem most severe on soils derived from metasedimentary rocks and least severe of soils derived from granitics (Powers *et al.* 1988). On the average, a single application of N at 200 kg/ha increases 5-year volume growth by 23 percent in plantations with significant competition from shrubs, but response is twice as great if weed competition is low (Powers *et al.* 1988). Heavy competition from shrubs can preclude fertilization response entirely, even on sites with severe N deficiencies (Powers and Jackson 1978, Powers 1983). Combining weeding with fertilization produces an effect that often is synergistic on poor sites, and additive on better.

The identity and biology of many insects feeding on young ponderosa pine is well understood (Furniss and Carolin 1977). However, we know much less about the effect of insects on the performance of young plantations under varying degrees of management. Terminal feeders such as the ponderosa pine tip moth and the western pine shoot borer (*Eucosma sonomana* Kearfott) often attack young plantations between 5 and 10 years of age. Such insects may not be lethal, but cumulative effects can be significant. *Eucosma* can reduce volumes of young stands of interior ponderosa pine by 25 percent, and height growth can be reduced even more (Stoszek 1973). The pine reproduction weevil kills many young pine trees. Infestations have been most serious in plantations on dry, thin soils and in the presence of severe brush competition. Oliver (1984) found that top deformities in planted ponderosa pine caused by the gouty pitch midge were more than twice as common for trees growing in competition with manzanita as for trees in shrub-free plots. Rapidly growing trees may resist attacks from some species of insects, but they may be more susceptible to attacks from others. Powers and Sundahl (1973) found that the Sequoia pitch moth (*Vespamima sequoiae* Hy. Edwards) was most successful in pine growing free from brush competition, at lower stand densities, and of better than average vigor. But on a poorer site, no correlation was found between pitch moth attack and shrub competition (Oliver 1984).

Study Objectives

We lack a comprehensive understanding of how plantation performance is constrained by natural limiting factors and what we can do about them silviculturally. Much of our current knowledge rests on study results of limited scope, and more complex studies often are anecdotal. To address this, we began a multi-factor field experiment in 1985 that has come to be known popularly as "The Garden of Eden Study." Our objectives were to:

1. Determine the growth potential of planted ponderosa pine in California as constrained by (A) moisture availability, (B) nutrient availability, (C) insects, and (D) their interactions.

2. Investigate how these factors affect tree physiology, pest resistance, nutrient and water use, plant succession, and other site processes.

3. Develop a flexible model to predict the effects of herbicide, fertilizer, and insecticide treatments over a broad array of forest sites.

METHODS

Site Selection

Our interest centered on the region of California known popularly as the "westside ponderosa pine type," which includes the most productive ponderosa pine forests in North America (Oliver *et al.* 1983). Potential study sites were examined between 1985 and 1987. Our aim was to span the full range of commercial site qualities within this forest type. All prospective sites were on industrial forest lands of southern and eastern slopes of the Klamath Mountains and western slopes of the Cascades and Sierra Nevada. To be selected, sites had to meet the following standards:

1. Apparent site index (Powers and Oliver 1978) could not vary more than 6 m about the mean for an area of 1.5 to 2.0 ha.

2. Slope variability could not exceed 20 percent and aspects could not vary by more than 45°.

3. Soil variability could not exceed that at the Family level, and soil series had to be typical soils of the commercial forest zone.

4. There could be no evidence of soil diseases that might affect plantation growth.

5. Insect species known to attack young ponderosa pine had to be present in adjacent areas to provide a source of infestation.

The first two sites were selected in 1985. Our intent was to chose two to four sites per year, and nine had been identified by 1987 (Fig. 1). Six sites supported naturally regenerated, young sawtimber stands of ponderosa pine or lower elevation mixed conifers. Three sites (Elkhorn Ridge, Pondosa, and Whitmore) supported mature brushfields dominated by one or more species of manzanita. One site, Elkhorn Ridge, supported a poorly stocked, brush-choked ponderosa pine plantation. Where possible, site index was estimated from dominant ponderosa pine in the surrounding area. Where wildfire or past cutting practices had eliminated suitable measurement trees, professional judgement was used to arrive at a relative measure of site quality. Soils were tentatively classified to the series level from local soil maps and from inspection of soil profiles. General characteristics of the nine study sites are shown in Table 1.

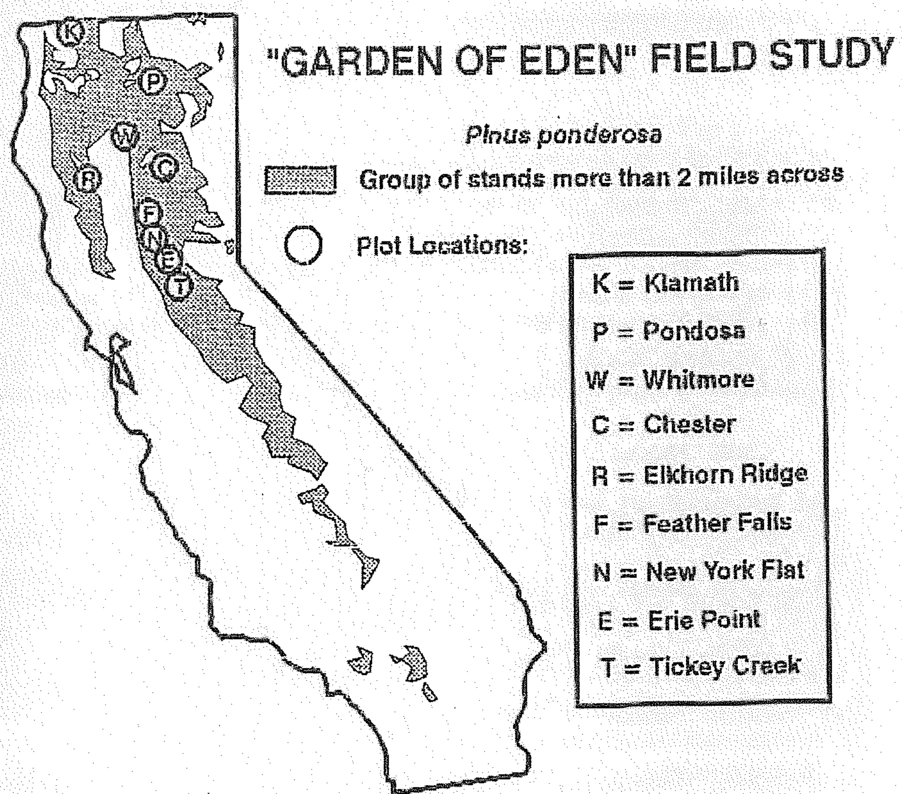

Figure 1.–Location of Garden of Eden plantations relative to the natural range of ponderosa pine in California. Fertilizer and insecticide treatments were discontinued at New York Flat after the second year.

Site Clearing and Plantation Establishment

The first two sites were prepared in 1985. New York Flat was clearcut and Whitmore was cleared of brush and scatterd trees. Residues were removed by crawler tractors equipped with brush rakes. Care was taken to remove as little topsoil as possible during piling operations, and soils were dry enough to preclude substantial compaction. At each plantation, treatment plot boundaries were established by transit and tape on a 19.5 m by 22 m grid to produce 24 0.04-ha plots arranged in four columns and six rows. Within each plot, tree planting locations were marked at a square spacing of 2.4 m. Eight treatments were assigned randomly at each site, producing three replications of each treatment (actual treatments were withheld until the trees had been planted).

Trees were planted in spring 1986 when soil temperatures at 10 cm had warmed to 6°C and were showing a warming trend (Jenkinson 1980). To favor survival, planting holes were dug with a gasoline powered soil auger. Planting stock was 2-0 bare root ponderosa pine raised in commercial nurseries from seed collected near each site from superior phenotypes. Thereafter, seed was chosen from families judged by progeny tests to be superior performers. Treatment plots were planted with 72 trees each to form an inner measurement plot of four rows of five trees surrounded by two outer rows of buffer trees. Using this same protocol, three more plantations were established in 1987, and another four in 1988. All seedlings were raised at the Forest Service Institute of Forest Genetics in Placerville and planted as 1-0 stock. Each plot at a given plantation received equal numbers of 10 superior families appropriate for that seed zone and elevation.

Table 1.–Characteristics of nine Garden of Eden plantations in California.

Plantation (and symbol code)	SI[1]	Elev. (m)	Geomorphic province	Geologic material	Tentative soil series	Year planted	Ownership
New York Flat (N)[2]	VH	762	Sierras	Metavolcanic	Sites	1986	Soper-Wheeler
Tickey Creek (T)	28	1,280	Sierras	Volcanic	Cohasset	1987	Michigan-California
Feather Falls (F)	H	1,220	Sierras	Volcanic	Cohasset	1988	Sierra-Pacific
Whitmore (W)	23	730	Cascades	Volcanic	Aiken	1986	Beaty & Associates
Erie Point (E)	23	1,370	Sierras	Metasediment	Hurlbut	1987	Sierra-Pacific
Pondosa (P)	M	1,175	Cascades	Volcanic	McCarthy	1988	Roseburg
Chester (C)	20	1,465	Cascades	Volcanic	Windy	1987	Roseburg
Klamath (K)	M/L	1,005	Klamaths	Metasediment	Seiad	1988	Fruit Growers Supply
Elkhorn Ridge (R)	17	1,490	Klamaths	Metasediment	Sheetiron	1988	Crane Mills

[1] Site index (SI) is height in meters of dominant trees at 50 years total age. Relative rankings of very high (VH), high (H), medium (M), and low (L) are for plantations where suitable measurement trees were absent. Plantations are ranked in descending order of site quality.
[2] Fertilization and insecticide treatments were not continued at New York Flat beyond the second year. However, herbicjde treatments were continued by Soper-Wheeler.

Treatments

Our experiment involved three factors designed to affect water and nutrient availability and insect herbivory. Each factor was at two levels (applied or not applied), producing eight combinations of treatments. The three factors and methods of treatment were:

1. Vegetation Control with Herbicides (H): annual spring applications of commercial formulations of glyphosate, hexazinone, or tryclopyr according to manufacturers' recommendations for the vegetation present. Herbicides were applied by backpack sprayer directly to all vegetation other than planted trees.

2. Nutrient Control with Fertilizers (F): biennial applications of dry salts of N, phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), boron (B), copper (Cu), and zinc (Zn) before growth began. Premixed fertilizers were poured into holes dug to a depth of about 15 cm at four points around individual trees at a distance from the tree equal to about two-thirds of its height. Fertilization followed a ramp schedule, with each seedling receiving 9, 27, 123, and 471 g of N at planting age 0, 2, 4, and 6 years, respectively. Setting N equal to 100, each nutrient was applied in the following relative proportions: P (50), K (50), Ca (33), Mg (33), S (10), Zn (7), Cu (3) and B (3). Formulation and rate were based upon projected average rates of nutrient demand for optimal nutrition, and on sorption and leaching properties assumed for average soils.

3. Insect Control with Insecticides (I): Acephate or dimethoate applied annually (or more often if needed) as a commercial formulation at manufacturers' recommended rates for insects likely to be present. Using a backpack sprayer, tree crowns were sprayed directly to the point of drip. Trees were sprayed each spring once new needles had broken their needle sheaths.

Our aim of repetitive treatments was to ensure that treated trees remained under minimal stress for a given limiting factor. Seedlings at New York Flat suffered herbicide damage during the second year of growth. Consequently, fertilization and insecticide treatments and growth measurements were not continued after 1987 and this plantation was excluded from analyses in this report. Despite this, herbicide treatments were continued by the cooperator, and the site has been sampled by Moldenke and McColl (these proceedings) in their investigations of fundamental soil processes.

Measurements and Analysis

Measurements were taken every second year on all measurement plots. Variables measured for all trees included height, stem diameter at 20 cm from the ground, width and length of the live crown, and average weight and nutrient content of current-year and 1-year old needles. Competing vegetation was measured on four parallel 10-m line transects in each measurement plot. Vegetation coverage was estimated for each species from the proportion of the line intercepted by plant crowns. Height was measured for each species at transect intervals.

Data were summed for each plot and averaged to provide mean estimates. A proxy for tree volume was determined by squaring the diameter of each tree and multiplying it by tree height. The sum of the products divided by the number of trees on each plot produced a cylindrical measure of tree volume per plot that is directly proportional to actual tree volume.

Analyses of variance were conducted on all data. If overall treatment effects were found significant at a Type I error probability of 0.05, comparisons were made of individual treatment means using Fisher's protected least significant difference test. Data expressed as percentages, such as survival, were analyzed following arcsin transformation. Findings reported here are confined to survival, height, and volume dynamics for trees, and percent cover and composition for other vegetation.

EARLY RESULTS

Vegetative Cover

Without vegetation control, rates of change in plant cover varied widely between plantations (Fig. 2). Total plant cover increased linearly with time, provided that coverage was less than 50 percent. For the two plantations achieving greater than 50 percent plant cover, values tended to stabilize as coverage approached 100 percent. By year 4, coverage on control plots varied from 8 percent at Tickey Creek (mainly manzanita) to 100 percent at Klamath (mainly grasses and forbs). Coverage was unrelated to site quality. Plantations at the two site index extremes (Feather Falls and Elkhorn Ridge) had similar amounts of vegetation. Plants tended to be grasses, forbs, and thistles on the poorer site qualities and perennial woody shrubs on the better (Table 2).

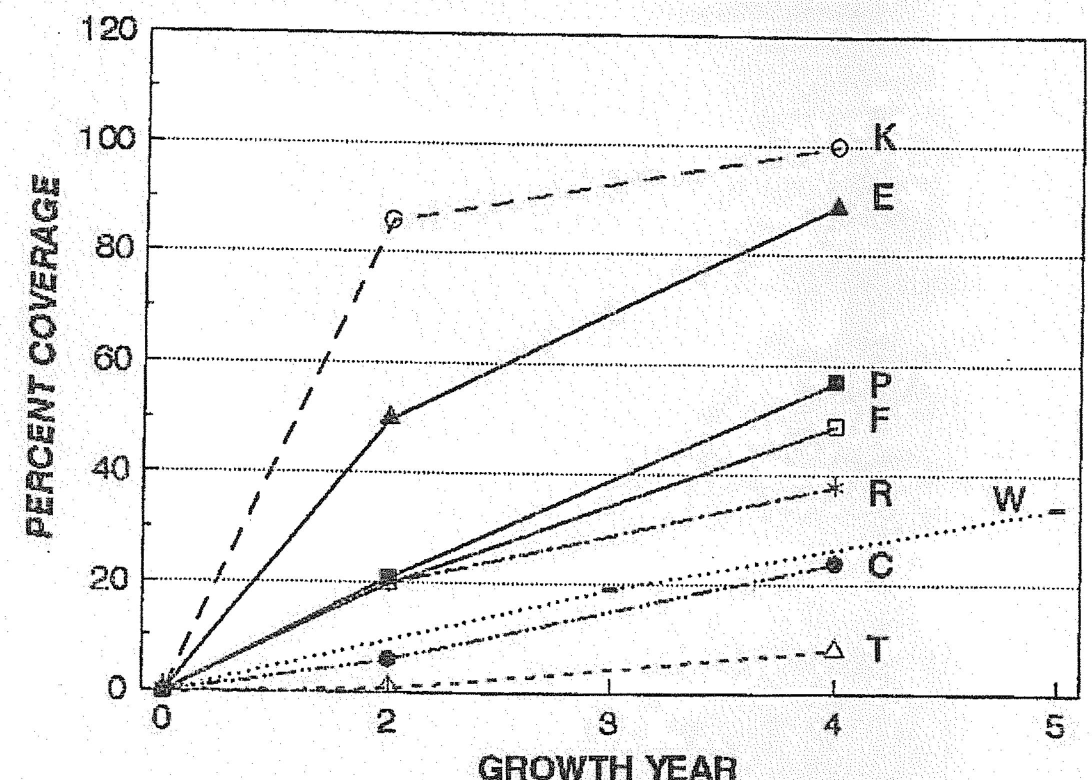

Figure 2.–Changes in percent ground cover of all vegetation in control plots of eight Garden of Eden plantations. Plantation symbols are identified in Fig. 1.

For the most part, herbicide treatment controlled competing vegetation. Plant coverage averaged only 13 percent through the fourth year for plots treated with herbicides (Table 2). At Erie Point, however, herbicides did not control all species. Although woody plants were excluded, grasses and forbs covered 62 percent of the ground surface after 4 years. Fertilization had no consistent effect on vegetative cover.

Table 2.–Treatment effect on percentage plant cover and composition after 4 years.

Plantation	Plant cover (and main composition[1]) when treatment was–		
	Herbicide only	Control	Fertilization
	- - - - - - - - - - - - - -	percent	- - - - - - - - - - - - - -
Tickey Creek	10 (manz.)	8 (manz.)	14 (manz.)
Feather Falls	7 (forbs/cean.)	49 (cean./bracken)	39 (cean./bracken)
Whitmore	2 (thistle)	34 (manz./cean.)	53 (manz./cean.)
Erie Point	62 (grass/forbs)	89 (grass/bearclov.)	73 (grass/bearclover)
Pondosa	4 (grass/forbs)	56 (grass)	68 (grass)
Chester	1 (grass)	24 (grass/thistle)	38 (grass/thistle)
Klamath	7 (forbs/grass)	100 (grass)	103 (grass)
Elkhorn Ridge	11 (forbs/grass)	41 (forbs/grass)	38 (forbs/grass)
Average	13	50	53

[1] Main composition refers to species comprising at least 25 percent of ground cover.

Survival

Tree mortality was greatest in the first 2 years following establishment and had stabilized in most plantations by the fourth growing season (Fig. 3). Survival was greatest for plantations on volcanic soils (86 to 100 percent) and least for those on metasedimentaries (64 to 74 percent). Erie Point fared poorly. Survival there was lowest for the insecticide treatment (Table 3), although differences were not statistically significant. Mortality also was high at Elkhorn Ridge and Klamath, where fertilized plots had significantly poorer survival than other plots. Even at Whitmore where overall survival was high (95 percent), survival was lower on fertilized plots. No treatment seemed superior except at Klamath, where survival was significantly higher on herbicide-treated plots.

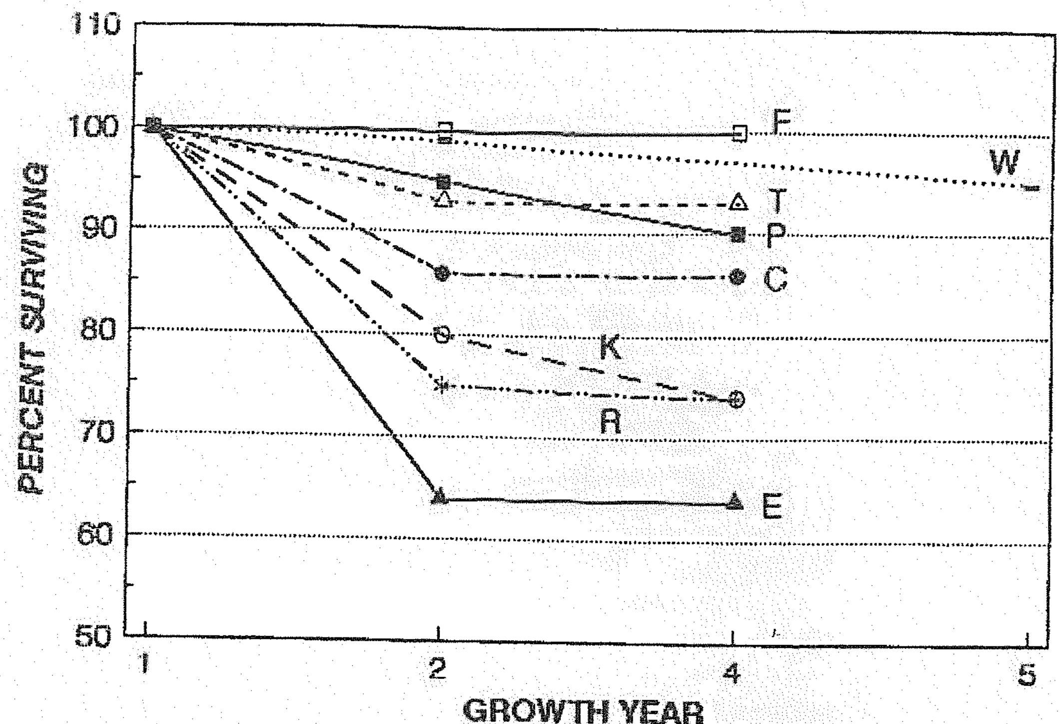

Figure 3.–Changes in survival of planted trees in eight Garden of Eden plantations for all treatments combined. Plantation symbols are identified in Fig. 1.

Growth

After 4 years, average tree heights varied threefold between Garden of Eden plantations (Fig. 4). Heights ranged from a low of 40 cm at Elkhorn Ridge to a high of nearly 125 cm at both Tickey Creek and Feather Falls. Generally, plantations grew at rates corresponding to their site index rankings in Table 1. The Whitmore plantation was an exception, growing less than expected for its site index (the same site index as at Erie Point). Variance analysis of 4-year data indicates that height growth was significantly improved by the complete (HFI) treatment at all plantations except Tickey Creek and Erie Point. At Whitmore, Pondosa, and Klamath, HFI response was due mainly to herbicide treatment. Herbicides were effective at Feather Falls, Pondosa, and Chester when combined with fertilizer.

How was volume growth affected by treatment? Comparing treatment responses for plantations spanning such a broad spectrum of site qualities is not simple, because growth rates are products of both treatment effects and inherent site differences for each plantation. One way of making such comparisons is to convert absolute growth for each plantation to a common, relative basis–in this case, the percentage difference between volumes of trees on treated and control plots (Table 4). While all treatments significantly affected growth to some degree, herbicides either with or without fertilizer or insecticide had the most consistent effect. Herbicides alone increased volume growth by an average of 176 percent, ranging between 6 percent (Tickey Creek) and 755 percent (Klamath). Neither fertilization alone nor insecticide alone promoted growth significantly. And at two plantations (Tickey Creek and Klamath), volume growth was significantly less on plots treated with insecticides. The highest growth rates were associated with the complete treatment.

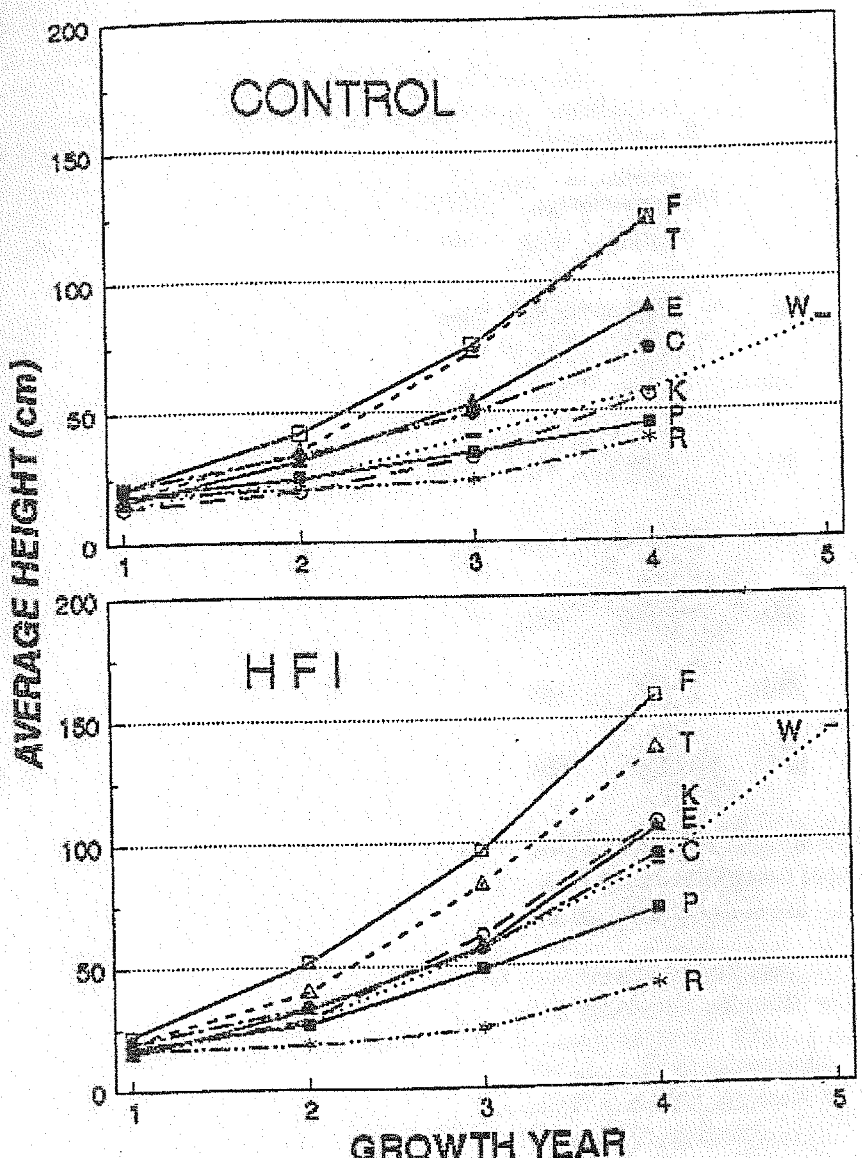

Figure 4.–Trends in average heights for trees in control and HFI (complete) treatments. Plantation symbols are identified in Fig. 1.

Relative volume response (Table 4) seems unrelated to site index as determined from trees in adjacent natural stands (Table 1). Plantations at site index extremes (Tickey Creek and Elkhorn Ridge) had nearly the same relative response to the complete treatment (volume increases of 35 and 47 percent, respectively). Yet, relative responses differed greatly between plantations of similar site quality (Tickey Creek and Feather Falls). Site index estimated from adjacent, natural stands seems a poor indicator of how well plantation trees respond to treatment.

Table 3.–Treatment effect on percentage tree survival through 4 years.

Plantation	Survival when treatment[1] was–							
	Control	H	F	I	HF	HI	FI	HFI
	percent							
Tickey Creek	87a[2]	92a	87a	90a	97a	93a	98a	100a
Feather Falls	100a	100a	100a	98a	100a	98a	100a	100a
Whitmore	95ab	100a	82c	95ab	98ab	100a	92bc	98ab
Erie Point	65a	78a	77a	50a	63a	55a	73a	53a
Pondosa	73a	90a	87a	87a	97a	95a	82a	97a
Chester	88a	83a	80a	87a	87a	87a	90a	85a
Klamath	80ab	95c	52a	85bc	67ab	92c	53a	87bc
Elkhorn Ridge	85a	82a	63ab	92a	78a	90a	37b	63ab

[1] Treatments are herbicide (H), fertilizer (F), and insecticide (I).
[2] Row means not sharing a common letter differ significantly at $p = 0.05$.

Although relative growth response to treatment does help standardize differences between sites, it can be deceiving. For example, doubling a small amount of growth may seem impressive–but it still amounts to only a small absolute increase. Also, site index can vary between plantations and adjacent, older, natural stands because of differences in tree genetics, soil impacts during timber harvest or site preparation, climatic differences during the life of the natural stand and the plantation, and possibly other factors. To adjust for this, absolute volumes of trees in treated plots were compared with tree volumes in control plots for all plantations. Volume at a particular age is a definitive measure of productivity within each plantation, and is a much more direct measure of site quality in young plantations than is site index estimated from adjoining natural stands.

Figure 5 shows the individual effects of insecticide, herbicide, fertilizer, and complete treatments on absolute volume growth response. Insecticide applied alone seemed to decrease volume growth on the more productive sites (Fig. 5). However, differences were significant only at Tickey Creek. In five of the plantations, response was less where insecticides and herbicides were combined than where herbicides were applied alone. For the herbicide treatment, volume response was unrelated to site quality, and was significantly greater at four plantations. For the fertilizer treatment, response increased linearly with plantation productivity. However, Type I errors all were greater than 0.05

for the three most productive sites–Erie Point, Feather Falls, and Tickey Creek. When herbicide and fertilizer treatments were combined, i.e. "HF" (not shown), responses at Feather Falls, Pondosa, and Chester significantly exceeded those from herbicide treatment, alone. The complete treatment increased volume growth significantly in all plantations except the poorest site, Elkhorn Ridge. For the remaining plantations, growth response was similar across the range of site qualities.

Table 4.–Relative effect of treatment (percentage difference between treated and untreated trees) on average tree volume after 4 growing seasons.

Plantation	Difference in volume when treatment[1] was–						
	H	F	I	HF	HI	FI	HFI
	- - - - - - - - -	- - -	- - -	percent	- - -	- - -	- - -
Tickey Creek	6	31	-29*[2]	42*	-8	9	35
Feather Falls	21	25	-8	97**	21	78*	127**
Whitmore	249**	38	6	354**	201**	44	422**
Erie Point	66	33	-34	40	2	23	110*
Pondosa	165**	43	7	258**	123*	11	284**
Chester	86**	27	44	100**	110**	27	131**
Klamath	755**	-12	-58	550**	477**	-67	630**
Elkhorn Ridge	62	-18	5	112	89	-23	47
Average	176	21	-8	194	127	13	223

[1] Treatments are herbicide (H), fertilizer (F), and insecticide (I).
[2] Means followed by * or ** differ significantly from the control at $p = 0.10$ and 0.05, respectively.

Treatment responses evident by year 5 should persist and even increase with time. Measurements made after the sixth year at Whitmore–the oldest plantation on a relatively average site–indicates that treatment differences apparent at year 4 had widened by year 6 (Fig. 6).

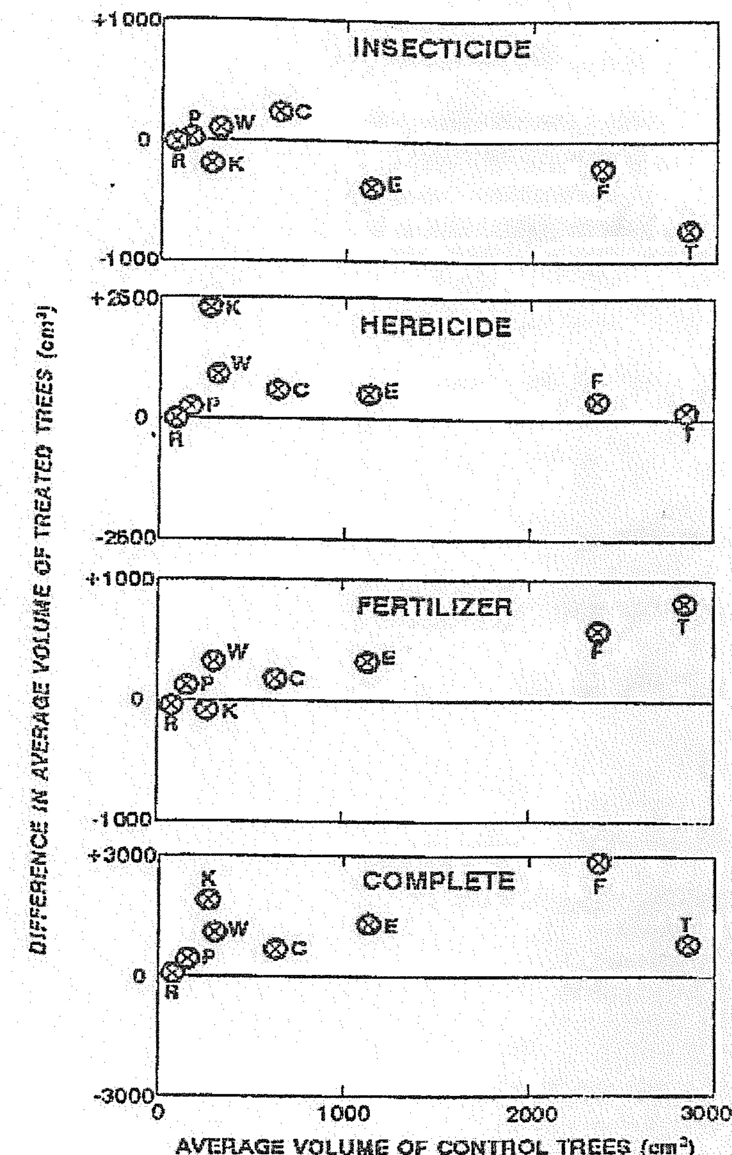

Figure 5.–Average volume difference between treated and control trees after 4 years. Positive increment indicates that treated trees grew more than control trees. Negative increment indicates less growth. Shown are the individual effects of insecticide, herbicide, and fertilization treatments, and the combined effect of all three. Plantation symbols are identified in Fig. 1.

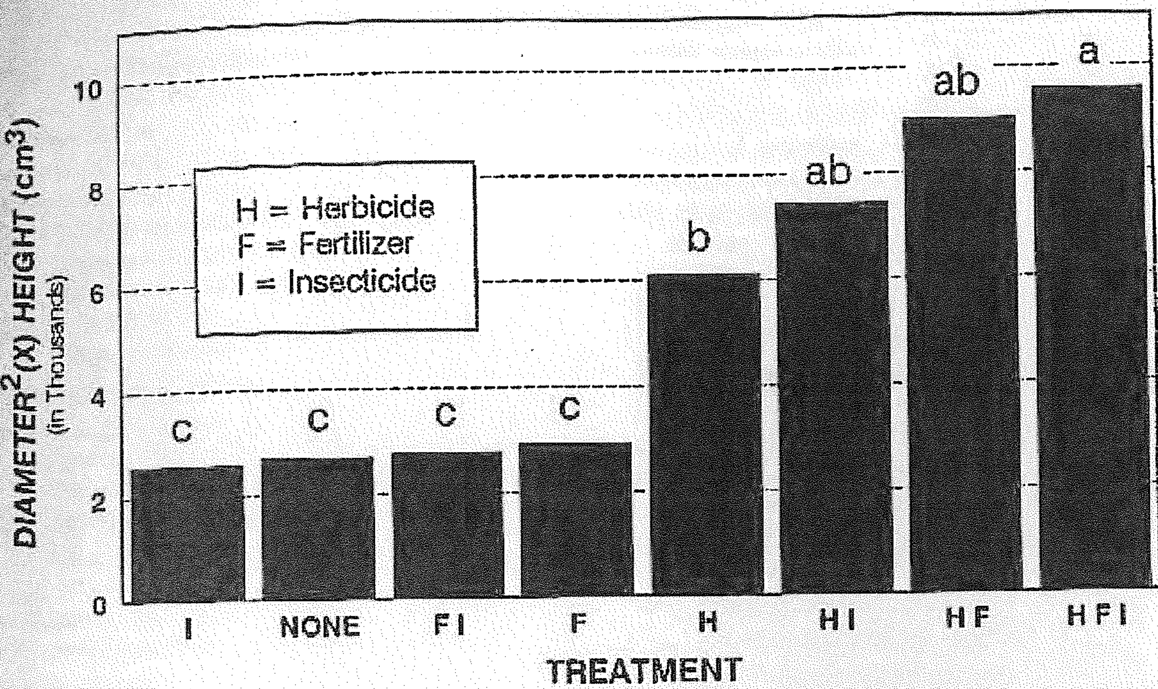

Figure 6.–Average tree volumes by treatment at Whitmore after 6 years. Treatment bars not sharing common letters differ significantly at a 0.05 probability of Type I error.

DISCUSSION AND CONCLUSIONS

Vegetative composition on control plots was related loosely to site quality, with forbs and grasses dominating the poorest sites (which tended to be droughty) and woody, perennial shrubs dominating the more mesic and productive sites (Table 2). Rates of vegetative regrowth were unrelated to site quality. The poorest regrowth rates were on one of the best sites–Tickey Creek. However, Tickey Creek was unique in that the entire area was broadcast sprayed with hexazinone in fall 1986 following site preparation. Four years later, regrowth covered only 8 percent of the ground in control plots. Repeated herbicide treatments excluded competing vegetation very effectively in all plantations except Erie Point. There, spring applications of glyphosate excluded woody vegetation, but grasses and forbs covered more than half of the ground surface of this droughty site after four years.

Tree survival was best on volcanic soils and poorest on soils formed on metasedimentary rocks. Plantations with the poorest overall survival–Elkhorn Ridge and Erie Point–have soils which are quite gravelly. We believe that mortality there was due largely to low soil water holding capacities and the relative planting difficulty of establishing a good soil/root contact in gravelly soils. No treatment consistently improved survival. On some sites, fertilization alone or with insecticide reduced survival significantly, and survival was never improved by fertilization. We conclude that adding fertilizer salts at the time of planting may be detrimental to root growth or water uptake on low elevation, warm sites like Whitmore or sites with shallow, skeletal soils like Elkhorn Ridge. This may be due to root damage from direct contact with high salt concentrations, or to reduced soil water potential from elevated osmotic concentrations. This does not appear to be a problem on deeper soils with better moisture and temperature characteristics.

Clearly, herbicide treatment was the most effective means for increasing growth through the first 4 years from planting (Table 4, Fig. 5). On the average, tree volumes nearly tripled on herbicide treated plots. Four plantations did not respond significantly, but lack of response at both Tickey Creek and Erie Point can be explained by the fact that vegetative cover on control and herbicide-treated plots did not differ greatly at either plantation (Table 2). As stated previously, vegetative cover at Tickey Creek was low on control plots because of the carryover effect of hexazinone applied after site preparation. At Erie Point, volume on herbicide-treated plots was 66 percent greater than on controls (presumably, from the exclusion of bearclover). However, there was a 26-percent liklihood that this difference was due merely to chance. Herbicide treated plots at Erie Point had been captured by grasses and forbs. Such plants have a strong, competitive effect on tree growth. For example, grass control at Klamath increased tree volumes more than eightfold.

Generally, foresters assume that the main mode of plant competition in summer dry California is for soil water. Undoubtedly, water is the main factor limiting plant growth in regions of summer drought. But water stress from plant competition always is accompanied by some degree of nutrient stress (Nambiar and Sands, in press). Six-year findings at Whitmore show that uptake of N, P, K, Mg, and S all were increased in ponderosa pine foliage merely by eliminating vegetative competition (Powers *et al.*, in review). Thus, reducing weed competition not only improves soil moisture availability, but nutrient availability, as well. This is accomplished in two ways. First, reducing root competition increases the accessibility of fixed resources (soil nutrients) to the remaining vegetation (in this case, ponderosa pine). Second, reducing root competition increases soil moisture availability in spring and early summer. This stimulates microbial decomposition of soil organic matter, thus releasing organically-bound nutrients and increasing the rate at which mineral nutrients are supplied for uptake by roots.

For these reasons, mineral nutrition undoubtedly was improved for trees by vegetation control. However, growth usually improved even more when fertilizer was included with herbicide, indicating that many sites still were low in nutrients. The fact that fertilization alone did not improve growth significantly drives home the message that soil moisture is the primary factor limiting growth in the westside ponderosa pine region of California, even on sites of low fertility (Powers 1983, Powers *et al.* 1988). Therefore, soil moisture competition must be adequate in order for fertilization to work.

Despite a serious pine reproduction weevil investation near Pondosa, insect damage was nil in any plantation. Apparently, if cleared sites are prepared and planted well, twig, tip, and leaf insects do not pose a problem for westside plantations of ponderosa pine during the first 4 years of growth. However, insecticide treated trees were smaller than control trees in over half of the plantations. Sprayed trees had no outward appearance of injury, and reasons for depressed growth are not at all clear. Trends seen in Table 4 and Fig. 5, although consistent, may simply reflect chance variation or something more fundamental. In any case, this phenomenon merits further study.

Effects of individual factors tended to be additive or slightly synergistic. Growth improvements of 400 to 600 percent in this experiment indicate the effect of repeated, combined treatments on the growth potential of ponderosa pine. This potential is much higher than shown in earlier, simpler studies, and differences between treatments should widen until crown closure when trees will have fully captured the site and inter-tree competition will be strong. Developing means for predicting potential response on a site-specific basis is a high priority. Preliminary analyses suggest that absolute volume growth response to the combined treatment is related linearly to tree height in control plots (Fig. 4). If further work shows this to be correct, there is a strong liklihood that SYSTUM-1 (Powers *et al.* 1989) can be programed to predict tree and stand response to a variety of silvicultural treatments.

Another priority is to understand the pathway and fate of applied chemicals in the plantation ecosystem. We also must evaluate the effect of treatment on such non-target organisms as soil fauna that may play a vital, if largely unseen, role in sustaining site productivity. To this end we have invited other scientists to work with us in addressing these subjects (see McColl and Moldenke, these proceedings).

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This paper neither advocates the use of any specific pesticides reported, nor implies that the pesticides have been registered by appropriate governmental agencies.

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