THE "GARDEN OF EDEN" STUDY REVISITED. FINDINGS AT EIGHT YEARS.

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ABSTRACT

What is the capacity of a pine plantation for growing wood? How is this influenced by vegetation management? By fertilization? How serious are insect pests? The Garden of Eden experiment was launched to answer these and other questions for ponderosa pine across a broad span of site qualities in California. Findings from the first 8 years show that plantation growth potential is several times greater than previously realized. Stand volumes from combined treatments averaged more than 3-times those for untreated controls. The poorest sites were limited mainly by soil drought and fertilization offered no advantage over weed control, alone. Why is this so? Droughty sites often are infertile, and moisture stress aggravates the problem. Weeds are particularly strong competitors for both moisture and nutrients. On the drier sites, repeated vegetation control more than tripled volume growth and increased foliar nutrient concentrations in pine. Fertilization without weed control simply boosted weed growth. But weed control had much less effect on sites receiving more than 1500 mm of precipitation annually.

Plantations on the best sites responded positively to both herbicides and fertilizers, and combining these treatments increased growth substantially. Despite an extreme range of site and plant stress conditions, insects had little influence on plantation development. High foliar nutrient concentrations had no effect on pine susceptibility to insects. Thus, insecticides had no effect on tree growth. Weed control seems essential for plantation development on poor sites under California's climatic conditions, but it is not essential on better sites. Fertilization responses should be short-lived on poor sites, but should persist on better.

Keywords: plant competition; weed management; fertilization; herbicides; insecticides; *Pinus ponderosa*.

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 operations where natural regeneration is unreliable. On private lands it continues to be planted extensively. Thus, plantation silviculture will remain an important aspect of ponderosa pine management. Because plantations will serve an increasingly important role in California's wood production, we must understand how management can influence plantation productivity and sustainability.

Woody shrubs adapted to California's summer-dry climate seem to be pine's strongest competitor. Foremost are manzanita (*Arctostaphylos* sp. L.), an evergreen genus, and ceanothus (*Ceanothus* sp. L.), a genus that includes both evergreen and deciduous species. Following disturbance, these aggressive shrubs can form dense thickets that compete with trees for site resources. But densities do not have to be high to have an effect. Oliver (1984), Shainsky and Radosevich (1986), and White and Newton (1989) showed that pine growth was reduced substantially by as little as 20% to 30% ground cover of manzanita—a relationship that seems independent of site quality (Oliver 1984). On the better sites and wider tree spacings, competition from woody shrubs can depress plantation growth for nearly two decades (Oliver 1990). Fiske (1982) concluded that many pine plantations undergoing average competition from manzanita ultimately will fail.

Moisture availability generally is seen as the main factor limiting plant growth in our state and in other regions of Mediterranean climate. Thus, competition for soil moisture is considered the main means by which shrubs and ponderosa pine compete. McDonald and Fiddler (1990) found that predawn plant water potentials in August were 0.7 MPa higher in ponderosa pine plantations kept shrub-free with herbicides. Minimum potentials for pine in untreated plots occurred by midmorning, but stress was delayed another 5 hours where vegetation was controlled. Photosynthesis requires open stomates for CO_2 to move from the atmosphere to the chloroplasts of leaf mesophyll cells. But open stomates mean transpirational losses of plant water. As an adaptation to drought, ponderosa pine closes its stomates when plant water potentials fall below -1.2 MPa (Lopushinsky 1969), which can happen a few hours after sunrise during our dry summer. Thus, trees free of weed competition may extend their photosynthetic period beyond the morning hours during summer months. In contrast, summer daily water potentials in manzanita are far lower than ponderosa pine because it seems to lack stomatal regulation (Powers and Reynolds, unpublished). However, manzanita maintains turgor and does not wilt. Manzanita has many fine feeder roots near the soil surface, but other roots extend very deeply. Thus, it is capable of drying the soil profile to considerable depth during the summer (Anderson 1990). Herbaceous species have not drawn as much research attention as woody shrubs because they are not as deeply rooted. However, White and Newton (1989) have shown that herbs and grasses are strong competitors in young plantations and can extract moisture as deeply as 0.9 m.

Despite the great significance of summer drought, many ponderosa pine plantations also are stressed nutritionally and respond well to fertilization (Powers et al. 1988). Throughout the region, a single application of N at 200 kg ha^{-1} increases 5-year volume growth by an average of nearly one-quarter where shrubs are not controlled, but response is doubled if shrub competition is low. Weeds are adapted to dry summers and are extremely effective competitors for nutrients. Their presence can preclude fertilization response entirely—even when trees are severely deficient in N (Powers and Jackson 1978). When combined, weeding and fertilization treatments seem to interact additively on better sites ($1 + 1 = 2$) and synergistically on poorer ($1 + 1 > 2$) (Powers 1983). Research on nutrients other than N has been limited, but the growth responses which have been described have not been impressive (Cochran et al. 1981, Powers et al. 1988).

The identity and biology of many insects feeding on young ponderosa pine is well understood (Furniss and Carolin 1977). However, much of what is known is based on *ex post facto* observations of trees already under conditions of unusual stress where causes can only be surmised. Consequently, the attention directed to severe but unusual cases may mistakenly be seen as the norm. We know much less about how insects affect the performance of young plantations under varying degrees of management. Terminal feeders such as the ponderosa pine tip moth (*Rhyacionia zozana* [Kearfott] Stevens) and the western shoot borer (*Eucosma sonomana* Kearfott) often attack young plantations and, while they may not be lethal, they can suppress height growth to the point that trees are less competitive with weeds (Stevens 1966, Stoszek 1973).

As plant competition increases, tree vigor may be lowered to the point that trees are less attractive to shoot-feeding insects. Zutter et al. (1986) found in the southern U.S. that pine tip moth infestations decreased with increasing levels of vegetative competition. Ross et al. (1990) noted that *Rhyacionia* infestation can be high in herbicide-treated plots, but that high growth rates allowed trees to recover quickly. Infestation rates of trees on moisture-stressed and nutrient poor sites may be lower than better sites, but weakened trees also are less tolerant of damage (Meeker and Kulhavy 1992). In California, Oliver (1984) found that top deformities in ponderosa pine plantations caused by the gouty pitch midge (*Cecidomyia piniinopis* Osten Sacken [Eaton and Yuill]) were more than twice as common for trees growing in competition with manzanita as for trees in shrub-free plots. Bedard et al. (1989) showed that height growth can be reduced where both competition and midge injury are severe.

Plant stresses stemming from competition for water and nutrients can be worsened by insect pests but much depends on physiological adaptations. Findings often seem contradictory because of small plot size and lack of understanding of moisture and nutritional relationships. Unfortunately, the significance of interactions between each of these factors on plantation performance in North America is unknown.

Recently, Powers et al. (1992) described an unusual experiment of factorial combinations of herbicide, fertilization, and insecticide treatments applied repetitively to plantations of ponderosa pine spanning a wide array of California sites. Findings after 4 years showed the overwhelming significance of early weed control, particularly on the poorest sites. On average, tree volumes were doubled when weeds were controlled with herbicides, and nearly quadrupled when herbicides were combined with fertilization and insecticide treatments. Insect damage was nil on all sites. But on the best sites, tree growth seemed depressed by annual applications of insecticides. Indications were that treatment differences would continue to widen. To our knowledge, only one other study combining weed, soil fertility and insect control has been reported—that for *Eucalyptus grandis* Hill ex Maiden in New South Wales (Birk and Turner 1992). There, plantation biomass more than doubled when herbicides, fertilizers and insecticides were applied repetitively for the first 6 years. However, the presence of an *Acacia* understory severely reduced N uptake in *Eucalyptus* and largely blocked its response to fertilization.

Study Objectives

Scientists and forest managers have a weak understanding of how plantation performance is constrained by natural limiting factors and what can be done silviculturally. Current knowledge rests on studies of single factors. Findings often are anecdotal and all are of limited scope. We tackled this problem by beginning a multi-factor field experiment in 1985 that has come to be known popularly as "The Garden of Eden Study" (Powers et al. 1992). Our long-range objectives were to

1. Determine the growth potential of planted ponderosa pine in California as constrained or enhanced 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 estimate the effects of herbicides, fertilizer, and insecticide treatments over a broad array of forest sites.

This paper reports 8-year findings from the plantations described previously (Powers et al. 1992). The period covered in our previous paper only encompassed fertilization at planting and again at age 2 years. Fertilization after years 4 and 6 added 15-times the amounts of nutrients applied previously. Beside growth response, we emphasize nutritional changes in the trees as affected by weed competition and fertilization and the mechanisms causing them. Finally, we make growth predictions through the next decade using the growth simulator SYSTUM-1 (Powers et al. 1989, Ritchie and Powers 1994).

METHODS

Study Area

We focused on California's westside ponderosa pine forest, a temperate region of warm, dry summers and comparatively mild, wet winters. The drier portion falls within the eastern rain shadow of the low Coast Ranges and Klamath mountains, while the wetter portion covers the western flanks of the Sierra Nevada. Seldom does snow amount to more than a third to half of annual precipitation. The region encompasses a broad range of sites including the most productive ponderosa pine forests in North America (Oliver et al. 1983). Our study examines the full sweep of site qualities typically under plantation management. We wished to control vegetation with herbicides, which was administratively difficult to accomplish on federal lands. Therefore, we sought and obtained the enthusiastic cooperation of forest industry for this experiment. Site selection criteria were described by Powers et al. (1992).

Eight sites covering six ownerships were found in three geomorphic provinces in northern California (Table 1). Four were timbered, three were in brushfields which developed from wildfires, and one was in a brush-choked, sparsely-stocked pine plantation. Elevations were determined from topographic maps and annual precipitation was estimated from isohytal maps of long-term averages for the state. Where possible, site index (Powers and Oliver 1978) was estimated from dominant trees bordering the site. Otherwise, it was estimated with less confidence from soil type and general climate. Soils were identified to the series level through reference to maps or through on-site profile descriptions. General characteristics of the eight sites appear in Table 1.

Table 1—Characteristics of eight Garden of Eden plantations in California.

Plantation	Ownership	Site index (m)	Elev. (m)	Annual precip. (mm)	Geomorphic province	Geologic material	Soil series (tenative)	Year planted
Elkhorn (P)*	Crane Mills	17	1490	1015	Klamath	Metasediment	Sheetiron	1988
Pondosa (B)	Roseburg	20**	1175	760	Cascade	Volcanic	Whitlow	1988
Chester (B)	Roseburg	20	1465	890	Cascade	Volcanic	Red River	1987
Whitmore (B)	Beaty & Assoc.	23	730	1140	Cascade	Volcanic	Aiken	1986
Jaws (N)	Fruit Growers	23**	1005	1035	Klamath	Metasediment	Seiad	1988
Erie (N)	Sierra Pacific	24	1370	1700	Sierra	Metasediment	Hurlbut	1987
Tickey (N)	Sierra Pacific	28	1280	1525	Sierra	Volcanic	Cohasset	1987
Feather (N)	Louisiana Pacific	30**	1220	1780	Sierra	Volcanic	Cohasset	1988

*Previous vegetation was a plantation (P), brushfield (B), or natural stand (N).

**Site index (base age 50 years) estimated. No suitable site trees present.

Site Preparation and Plantation Establishment

Timbered sites were harvested and merchantable trees were skidded by tractor to landings beyond the study area. Logging residues and brushfields were cleared by tractor and brush rake using normal operational practices during summer when soils were dry and less likely to compact. Care was taken to remove as little topsoil as possible. With the exception of the Jaws plantation, residues were piled off the study site. At Jaws, the nature of landforms made off-site disposal impractical, so residues were concentrated into piles and burned.

Following site preparation, 24 contiguous, rectangular plots, each measuring 0.04 ha, were established by transit and tape in four columns and six rows. Planting spots were flagged at a square spacing of 2.4 m. In spring when soil temperatures had warmed to 6°C, bare root seedlings were planted in holes augered to enhance survival. Except for the first plantation (Whitmore), seedlings were chosen from seed lots judged by the Forest Service Regional Geneticist to be superior performers for the elevation and seed zone of each specific plantation. Whitmore seedlings were from seeds collected from superior phenotypes in neighboring stands. Except for the first plantation (Whitmore), seedlings were raised at the Institute of Forest Genetics at Placerville and lifted as 1-0 stock. Plantations were established between 1986 and 1988 (Table 1)

Treatments

Insecticide, herbicide and fertilizer treatments, each at two levels, were assigned randomly to the 24 plots, producing three replications of eight factorial treatment combinations per plantation in a completely randomized design. Treatments were selected to create extreme "all-or-nothing" combinations of insect, weed, and soil fertility control applied repeatedly to at least the point of crown closure. Our aim was to create a series of growing conditions from minimal to maximal stress within the constraints of local climate. Main effect treatments and methods of application were:

1 Insect control using systemic insecticides (I): acephate or dimethoate applied directly to trees each spring when new needles had broken their bundle sheaths. Formulations were based on manufacturer's recommendations for the insects likely to be present and were applied by backpack sprayer to the point that crowns began to drip. Levels: annual application vs. no application.

2 Vegetation control using herbicides (H): annual spring applications of glyphosate, hexazinone or triclopyr based on manufacturer's recommendations for the soil type and vegetation present. Herbicides were applied by backpack sprayer directly to all vegetation other than planted trees (which were shielded from spray through the first several years). Levels: annual application vs. no application.

3 Nutrient control using fertilizers (F): dry, commercial salts of N, P, K, Ca, Mg, S, B, Cu and Zn applied during the dormant season. Application followed a ramp schedule in which nutrient supply increases with demand (Axelsson 1983). Formulations and rates were based on estimated needs for optimal nutrition on an average site during the exponential phase of growth (Table 2). The first three applications (springs of years 1, 3 and 5) were poured from pre-weighed bags to holes at four positions around each seedling at a distance of about two-thirds seedling height. The last application was so massive that it was applied to the surface in parallel bands between rows of trees in the autumn of the 6th year so that it would solubilize and move into the soil by the start of growth year 7. Levels: biennial application vs. no application.

Table 2--Quantity of nutrients applied as dry salts at 2-year intervals.

	Amount applied (kg ha^{-1})				
Nutrient applied	At planting	End of year 2	End of year 4	End of year 6	Sum for 6 years
Nitrogen	15.6	46.6	213.7	798.7	1,074.4
Phosphorus	7.9	23.2	103.4	395.2	529.7
Potassium	7.7	23.2	109.6	399.4	539.9
Calcium	10.1	23.6	118.6	264.0	416.3
Magnesium	5.5	16.8	61.7	137.2	221.2
Sulfur	5.2	28.3	16.0	62.4	111.9
Zinc	1.1	3.2	14.0	55.1	73.4
Copper	0.5	1.6	6.8	26.9	35.8
Boron	0.5	1.6	6.8	26.8	35.7

Measurements and Analysis

Measurement plots were established inward from the third row of trees of each treatment plot, creating a 2-tree buffer surrounding 20 measurement trees. Soil samples were taken at 10 random locations in each plot during the year of establishment. Samples from the 0-10 and 10-20 cm depth were air-dried, sieved to 2 mm, and analyzed chemically by standard methods (Page et al. 1982). Plots were visited every year with mensurational data collected after growth completion in years 2, 4, 6 and 8 and foliar collections made in the autumns of years 1, 3, 5 and 7. Tree measurements included height, stem diameter at 20 cm above the ground or at breast height, and live crown length and width as measured at two right angles. Competing vegetation was measured on four parallel strips, each 10-m long and centered between tree rows. Plot coverage was determined for each species by the proportion of the 40-m transects intercepted by plant crowns and measured by tape to the nearest cm. Heights also were recorded by species for each intercept. Volumes of tree stems were estimated by conic formula for trees shorter than breast height, and by the regression function developed by Oliver and Powers (1978) for larger trees. Crown volumes were estimated from conic formula.

Inadvertently, cooperators thinned the Erie and Tickey planations at the end of year 7. To salvage what we could, we measured both standing and felled trees. Eight-year standing volumes were estimated for Erie and Tickey from reconstructed 7-year volumes and a 1-year projection based on recent growth trends. Samples of fully expanded current- and 1-year-old needles were composited by age class from 8 to 10 trees per measurement plot. Collections came from two or three branches in the second or third branch whorl from the top. Foliage was oven-dried at 65°C, weighed to determine average fascicle mass, ground, and analyzed chemically using procedures described previously (Powers et al. 1992).

The nearness of the Whitmore plantation allowed more frequent measurements. From summer 1991 through summer 1992 (years 6 and 7), monthly readings were made of soil temperature and water potential using soil cells buried at 20 and 50 cm, and of leaf water potential by pressure bomb. Leaf water potentials were made at predawn and midday on five trees and five manzanita shrubs per plot. Stomatal conductance also was measured at midday on the same plants using diffusion porometry. Trees and shrubs were chosen subjectively to span the range in height classes present. Understory vegetation was harvested at Whitmore in autumn 1992 from four 1.0 m^2 subplots per treatment plot for biomass analysis before deciduous leaves had fallen. Manzanita, the dominant species, was separated into wood and leaf components. Leaf areas were determined on fresh subsamples of manzanita foliage by scanning photometer. All samples were oven-dried, weighed, and analyzed chemically.

Treatment effects were examined by analysis of variance (ANOVA). Percentage or binomial data were transformed by arcsin. Logarithmic transformations were used for data with variance proportional to the mean. Where treatment effects were judged significant at $\alpha = 0.10$ or less, pairwise comparisons were made using Fisher's least significant difference (LSD) or t-tests for simple comparisons of grouped data.

RESULTS AND DISCUSSION

General Effects

Climatically, the study period 1986 through 1995 was not unusual. Using Nevada City as an index, precipitation averaged 1452 mm, which is only 31 mm above the 30-year average. As is typical for California, precipitation varied greatly from year to year, ranging from a high of 2264 mm in 1995 to a low of 1033 mm in 1990. The years 1987-1992 marked a 6-year period of less than average precipitation, while 1986 and 1995 were unusually high.

As described previously (Powers et al. 1992), tree survival averaged 85% overall with most of the mortality occurring in the first 2 years. Survival varied from a low of 64% at Elkhorn (the poorest site) to 100% at Feather (the most productive site). As a group, plantations on metasedimentary soils (Elkhorn, Jaws and Erie) showed greater mortality than plantations on volcanics (71% survival vs. 93%). Tree mortality on metasediments was associated mainly with fertilization at planting. Presumably, root systems already stressed by drought on dry, gravelly soils were injured further by fertilizer salts placed in the immediate rooting zone. Survival on volcanics was unrelated to treatment.

The overall effect of treatment on standing volume at 8 years is shown in Figure 1. On the average, insecticide and fertilizer treatments alone or combined had little impact on growth and variance among plantations was low. The big effect came with herbicide control of weeds. With repetitive herbicide treatment, volume growth increased threefold, but response varied considerably among plantations. On average, growth was not improved further by combining herbicides with other treatments. However, variance among plantations also was high, suggesting that some plantations responded differently than others. In other words, herbicide treatment was important, but response to herbicides and other treatments depended on certain site factors.

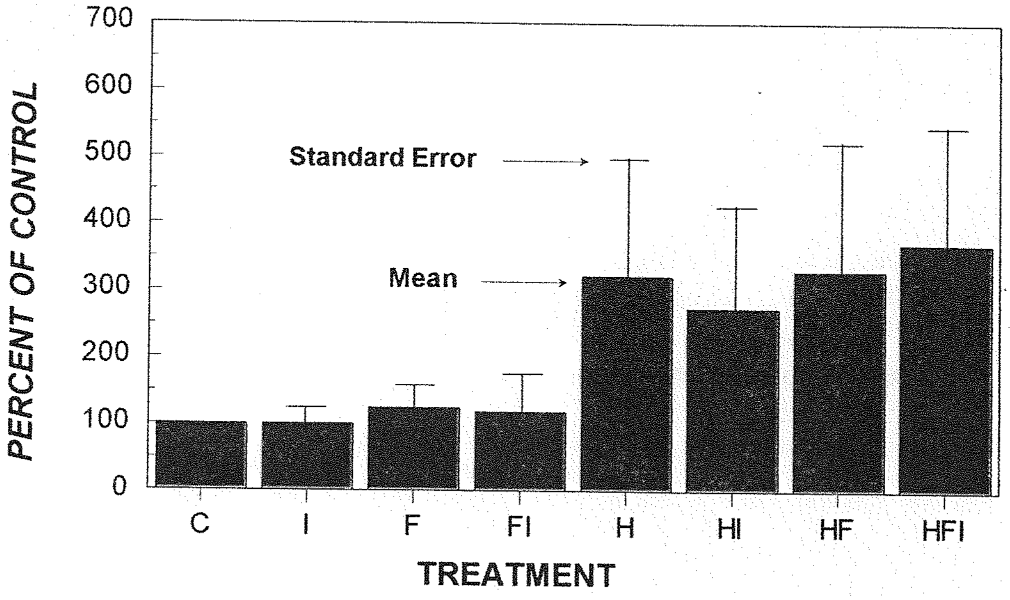

Figure 1—Average volume at 8 years for all Garden of Eden plantations relative to volume in the control treatments. Means and standard errors for eight plantations. Treatments are control (C), and repetitive applications of insecticide (I), fertilizer (F), and herbicide (H).

We hypothesized that treatment responses varied by site quality. But because some of the site indices were only estimated (Table 1), we grouped our planations into low, medium and high site classes corresponding to site indices less than 23, 23 to 24, and greater than 24, respectively. We then subjected 8-year volumes to a 3-factor, 2-level, split plot ANOVA with 3-way interactions. Herbicide and fertilizer main effects were found to be highly significant statistically, as were site quality and its interactions with herbicide and with fertilizer treatments. This means that while there was a general response to both weed control and fertilization, the response varied with site quality. Therefore, we proceeded to a more detailed examination of responses by individual plantation.

Variance analysis of volume growth for individual plantations showed significant treatment effects at $\alpha = 0.05$ or less for all plantations except Erie where differences were significant only at $\alpha = 0.10$ (Table 3). Poor survival at Erie coupled with the thinning at age 7 created variability, making interpretations of volume growth per unit area somewhat speculative. Insecticide seemed to have no effect or one that was slightly negative. Although all plantations responded positively to herbicide treatment, response on the best sites seemed relatively weak. Tree growth was not improved by fertilization at most plantations unless weeds were controlled with herbicides. However, fertilization without herbicides increased volume growth by over 50% on the two best sites (Tickey and Feather), which was comparable to the gain from herbicide treatment alone.

Table 3--Average stem volume per hectare at 8 years for control (C), insecticide (I), fertilizer (F) and herbicide (H) treatments in each plantation.

	Volume at 8 years ($m^3 ha^{-1}$) when treatment was---								LSD*at---	
Plantation	C	I	F	FI	H	HI	HF	HFI	0.05	0.10
Elkhorn	0.72	1.19	0.63	0.41	1.74	1.87	2.03	1.52	1.17	0.97
Pondosa	0.75	0.85	0.98	0.82	3.28	2.81	3.66	3.94	1.10	0.91
Erie**	1.97	0.86	2.95	2.34	4.05	1.72	3.31	4.92	3.57	2.94
Whitmore	2.00	1.72	2.88	3.49	10.46	9.42	14.33	15.54	3.53	2.90
Chester	5.30	7.27	6.49	6.57	13.28	12.88	13.41	14.54	2.63	2.17
Jaws	2.28	1.68	1.08	0.75	14.06	10.74	7.93	11.63	3.34	2.75
Tickey**	10.24	8.44	15.95	12.80	13.42	12.72	18.02	16.79	3.92	3.23
Feather	14.52	14.26	22.32	29.23	23.82	22.56	29.20	37.03	8.06	6.64

*Least significant difference at $\alpha = 0.05$ and 0.10 by Fisher's LSD.

**Trees thinned at Erie and Tickey at 7 years. Volumes estimated for year 8.

Our overall ANOVA indicated that growth response to our main effect treatments depended very much on site quality ($\alpha = 0.001$). The simplest way of examining this graphically is to plot the volume growth response to treatment against estimated site index as shown in Table 1. To simplify it further, we divided 8-year standing volumes for herbicide, fertilizer, insecticide and combined treatments by the standing volumes on control plots as shown in Table 3. Thus, Elkhorn's volume growth response to herbicide treatment is "2.42" (1.74/0.72) at site index 17, or a 142% increase in volume over the control treatment.

Figure 2 indicates a very pronounced response to herbicide treatment for plantations with site indices of 24 or less, but a much lower relative response for those with site indices of 28 or more. Fertilization produced negligible response in plantations rated site index 24 or less, while responses were positive on sites rated 28 and higher. Insecticide treatment had no significant effect on growth in any plantation (Table 3), and the growth decline with increasing site quality noted in year 4 (Powers et al. 1992) seems to have dissipated. Combining all main effect treatments produced a positive growth increase on all sites, regardless of apparent site quality. However, the strongest proportional increases occurred on the medium quality sites.

Relative growth responses to treatment shown in Figure 2 are a little misleading. For example, the greatest relative volume increase to herbicide treatment—517%—occurred at Jaws (site index 23), which translates to an absolute gain of 11.9 m^3 ha^{-1} (Table 3). At Feather (site index 30), relative volume increase was a modest 64%, but this translates to an absolute gain of 9.3 m^3 ha^{-1}. And while the best sites had positive but proportionally low responses to fertilizers (Fig. 2), absolute gains in growth were substantial—net gains of 5.7 and 7.8 m^3 ha^{-1} at Tickey and Feather, respectively (Table 3).

But Figure 2 raises other questions. For example, if poor sites tend to be droughty, why did two of the poorest sites—Elkhorn and Chester—respond relatively weakly to herbicides, compared with other sites? And if nutrient deficiencies are common on many California sites (Powers 1983), particularly pine plantations (Powers et al. 1988), why did plantations of poor to average site quality not respond more to fertilization?

Other Site Effects

Plantations on the five poorest sites also were the droughtiest. Precipitation averaged less than 1150 mm annually (Table 1). Three plantations in this group (Elkhorn, Chester and Jaws) have high gravel contents in their soils, and the Pondosa plantation is underlain at less than a meter by a duripan that restricts water storage and rooting. Whitmore receives the most precipitation and has the deepest soil of this group, but it also is lowest in elevation (730 m) and undoubtedly is the warmest (summer air temperature maxima routinely exceed 40°C and humidity is low). The soil is a deeply weathered Aiken clay with low available water retention.

In contrast, the three plantations receiving more than 1500 mm of precipitation annually showed lesser response to herbicides. Two of these (Tickey and Feather) grow on deep Cohasset loams

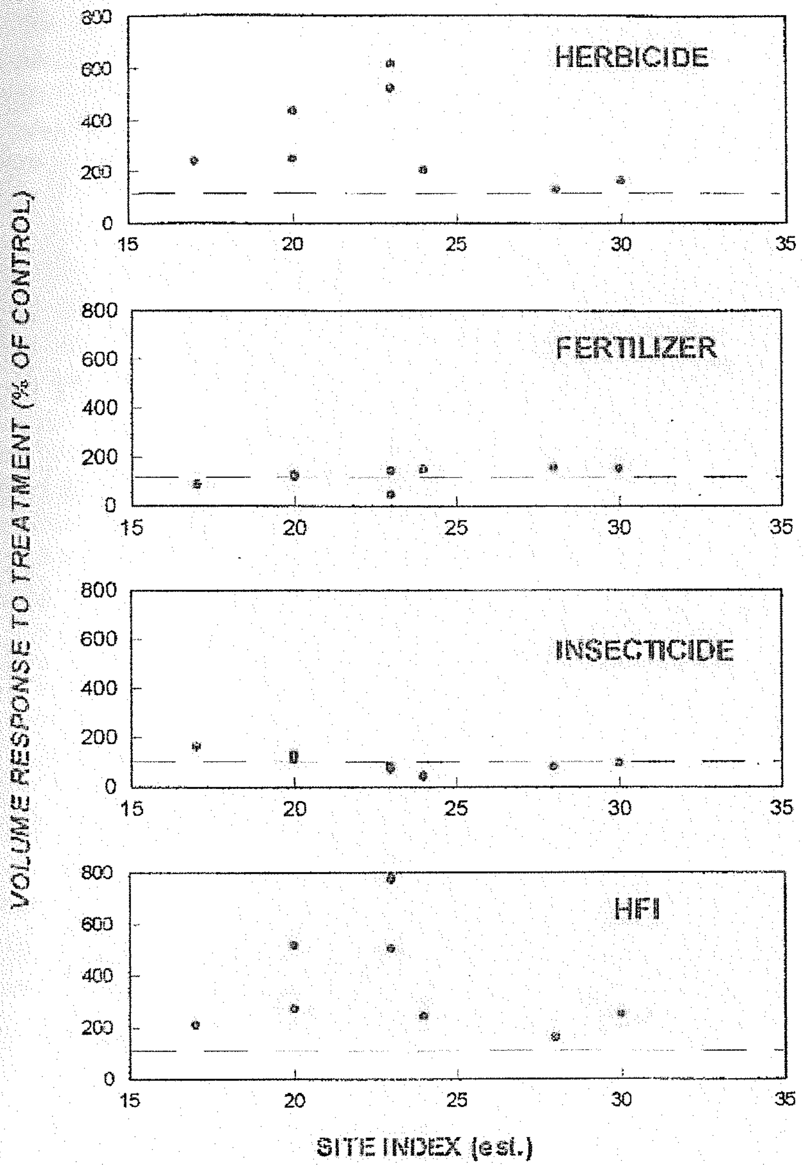

Figure 2– Volume response of all plantations at 8 years to main effect and combined treatments in respect to estimated site index.

with relatively high available water holding capacities. Soil of the Erie plantation is a gravelly loam of the Hurlbut series. However, soil moisture availability probably is greater than expected for a gravelly soil. The Hurlbut series is formed from vertically tipped, fractured, weathered schist which permits fairly deep water and root penetration. Thus, treatment response differences associated with site index probably actually reflect differences in soil resource availability.

Weed Control Effects

Obviously, weed control influences soil moisture availability. Regular measurements made through years 6 and 7 at Whitmore (Powers and Reynolds, unpublished) show that soil moisture on control plots was dried to -1.5 MPa ("wilting point") to a depth of 50 cm by mid April in 1992, whereas moisture was extended another 5 weeks by herbicide treatment. Less soil water depletion spells better plant recharge at night when stomates are closed. Throughout the summer at Whitmore, predawn plant water potentials averaged several hundred kPa higher in pine on weed-free plots than on untreated controls.

Table 4—Approximate soil moisture contents of surface and subsurface soils as influenced by vegetation control (June 7-9, 1995).

Competing vegetation	Soil depth (cm)	Soil moisture content at-- Chester	Whitmore	Feather
		----------(%)----------		
Present	20	26	12	16
Absent	20	50	11	22
Present	50	31	13	27
Absent	50	28	14	20

However, the biological impact of weed control depends on other site factors. For example, Table 4 shows approximate soil moisture contents at Chester (high elevation, low precipitation), Whitmore (low elevation, moderate precipitation), and Feather (middle elevation, high precipitation). In early June, a period when growth rates are near their peak, soil moisture at Chester was higher than either of the other plantations. Largely, this is due to cooler air temperatures and slower growth rates (less transpiring crown surface). Together, these work to reduce evapotranspiration so that water deficits remain relatively low. Consequently, relative growth response to herbicide treatment was only half that at Whitmore. At Whitmore, trees responded very strongly to herbicide treatment. However, large trees freed of weed competition use soil moisture as effectively as do shrubs. By June, soil at Whitmore was extremely dry to 50 cm, regardless of treatment Therefore, water availability alone cannot account for Whitmore's strong response to herbicide treatment. At Feather, higher elevation and higher precipitation should reduce evapotranspiration deficits, meaning that water stress should be less than at Whitmore—despite the fact that trees are larger at Feather (Table 3). However, larger trees at Feather will have greater water demands than at Chester. Consequently, soil moisture at Feather remains higher than at Whitmore (but lower than at Chester) and response to herbicide treatment was relatively modest.

Fertility Effects

Weed Competition.

While increased soil moisture availability generally is thought to be the primary effect of vegetation control on drier sites, a companion effect of at least equal significance is improved nutrition (Nambiar and Sands 1993, Messier 1993). In our study, vegetation control had a strong effect on soil nutrient availability and nutrient uptake by trees, but the effect depended on site quality.

Table 5--Effect of competing vegetation on crown volume per tree, fascicle mass and elemental concentration in ponderosa pine needles at age 7 years. Average crown volume and fascicle mass determined at 8 years.

Plantation (and site index)	Competing vegetation	Crown volume tree^{-1} (m^3)	Mass per fascicle (mg)	Foliar concentration of----				
				N	P	K	S	Al
				------------(g kg^{-1})--------			(mg kg^{-1})	
Elkhorn (17)	Present	0.31a*	139a	8.77a	1.02a	6.70a	574a	159a
	Absent	0.88b	148a	10.17a**	1.24b	8.71b	659b	155a
Whitmore (23)	Present	0.56a	208a	9.54a	0.72a	4.45a	594a	161a
	Absent	1.46b	211a**	12.80b	0.75a	5.60b	748b	162a
Feather (30)	Present	2.34a	186a	11.28a	1.01a	6.36a	767a	176a
	Absent	3.32b	196a	11.85a	1.00a	6.52a	773a	178a

*Column means for a site quality class followed by the same letter do not differ significantly at α = 0.05.

**Significant at α = 0.10.

Table 5 illustrates this for Elkhorn, Whitmore, and Feather—low, medium and high quality sites, respectively. At Elkhorn, seventh-year foliar concentrations of N, P, K and S were increased significantly by weed control. At Whitmore, foliar concentrations of N, K and S concentrations were increased, but P was not. And at Feather—the best site—foliar nutrient concentrations were unaffected by weed control.

The significance of this may be profound. Without vegetation control, trees at Elkhorn and Whitmore were under severe nutrient stress. By age 7, foliar N concentrations were below the critical level of 10.5 g N kg^{-1} foliage (Powers 1983, Powers et al. 1988), and stress was reversed by weed control. Phosphorus deficiency also was apparent at Whitmore where foliar P was below the critical level of 0.8 g kg^{-1} (Powers 1983). Although P concentrations seemed to be slightly higher following weed control, they remained below critical level by age 7 years. Given the notorious ability of the Aiken soil series to fix P into insoluble forms (Ulrich et al. 1947), this outcome is as expected.

Although mean mass of individual fascicles was not affected much by weed control, crown volumes were increased substantially. Greater crown volumes comprised of fascicles of higher nutrient content indicates that vegetation control increased soil nutrient availability and nutrient uptake by trees. On the most productive site (Feather), vegetation control neither raised nor lowered foliar nutrient concentration. However, 42% greater crown volume at Feather accompanied by stable foliar nutrient concentrations means that nutrient uptake increased at the same rate as crown growth. Interestingly, increasing nutrient availability through weed control did not accelerate the uptake of a non-nutrient, Al. Aluminum concentrations in needles were not affected by vegetation control, regardless of site quality (Table 5).

Fertilization.

On the five poorest and droughtiest sites, weed competition was severe enough to preclude response to fertilization. And in some cases, growth on fertilized or fertilizer plus insecticide plots averaged less than on the controls (Table 3). A major reason for this is the positive response of weed species to fertilization. For example, by the seventh year at Whitmore woody shrubs on fertilized plots had more than doubled in mass and leaf area compared with shrubs on controls (Table 6). Increased leaf area spells more soil moisture depletion through transpiration. Total vegetative cover was increased slightly by fertilization on all but the poorest sites where low soil moisture restricted response to improved nutrition. However, as shown in Table 6, small increases in percent vegetative cover can understate the increases occurring in understory biomass and area of transpiring leaf surface. Such increases of understory species spell large increases in water use, nutrient uptake and nutrient immobilization. At Whitmore, assuming a mean concentration of 4 g N kg^{-1} wood, N immobilization in woody shrubs could account for about 7% (70 kg ha^{-1}) of the N applied in fertilizer by year seven (1,074 kg N ha^{-1}, Table 2).

Table 6--Characteristics of competing vegetation after 7 years at Whitmore as affected by fertilization. Mass, leaf N and LAI are for manzanita, only.

	Treatment				
Characteristic	C	F	H	HF	LSD
Coverage (%)	55a*	65a	4b	4b	27
Volume ($m^3 m^{-2}$)	0.19a	0.24a	0.01b	0.01b	0.15
Total mass ($Mg\ ha^{-1}$)	6.29a	16.40b	0	0	9.57
Leaf mass ($Mg\ ha^{-1}$)	3.23a	7.84b	0	0	3.70
Leaf N ($kg\ Mg^{-1}$)	7.86a	9.37b	0	0	0.37
LAI ($m^2 m^{-2}$)	1.07a	2.44b	0	0	1.34

*Means within a row followed by the same letter do not differ significantly at $\alpha = 0.10$. Fisher's LSD for control (C) and fertilizer (F) contrasts, only. Analyses for coverage based on arcsin transformations.

The two extreme sites, Elkhorn and Feather, illustrate how fertilization response is influenced by soil fertility. Soil tests made at plantation establishment show that Elkhorn soil had appreciably less organic C and N than Feather, but much greater levels of soluble P (Table 7). And while the Sheetiron soil series at Elkhorn had a higher proportion of its cation exchange sites saturated with K, Ca, Mg and Na, its exchange capacity was only half that of that for the Cohasset soil series at Feather. In essence, all that the soil at Elkhorn really had going for it was a higher level of soluble P. The capacity of the Cohasset soil series to fix soil phosphate into sparingly soluble forms is approximately 7-times that of Sheetiron (Powers et al. 1975).

Foliar analyses made through the first 7 years show that trees responded very quickly to fertilizers placed in the soil at planting (Fig. 3). The less fertile the site, the greater the rise in foliar nutrient concentration. Foliar N concentrations in control trees were relatively low at Elkhorn by the end of the first growing season. Concentrations dropped steadily with time—probably reaching critical level by year 4. Herbicide treatment raised nutrient concentrations for several years. But because soil fertility had not been fundamentally altered, foliar N concentrations inevitably fell to critical level by year 7. In contrast, N concentrations in fertilized trees averaged about one-third greater than in controls ($\alpha = 0.01$) regardless of weed control, and the upward trend suggests that N stress will not occur at Elkhorn.

Table 7--Chemical characteristics of surface soils on the least and most productive sites at the start of the Garden of Eden experiment.

Plantation (site index)	Soil depth (cm)	pH	C	N	P	CEC*	BS**
			----(g kg^{-1})---		($mg\ kg^{-1}$)		
Elkhorn (17)	0-10	5.9	22.6	0.97	14.1	13.4	84
Feather (30)	0-10	5.4	50.4	1.17	1.4	22.2	38
Elkhorn (17)	10-20	5.7	13.6	0.78	9.8	11.1	84
Feather (30)	10-20	5.4	46.3	1.65	1.1	21.2	38

*Cation exchange capacity in cmol(+)kg^{-1}.
**Percent of CEC occupied by bases (K, Ca, Mg, Na).

First-year foliar P concentrations at Elkhorn were high and well-above deficiency levels for all treatments (Fig. 3), reflecting the greater native solubility of soil P (Table 7). Initially, foliar P concentrations were lower on fertilized plots ($\alpha = 0.01$), reflecting the dilution of non-limiting nutrients that occurs when growth is increased by a limiting nutrient (N, in this case). By the third through seventh years, foliar P concentrations at Elkhorn did not differ significantly between fertilized and unfertilized trees. Phosphorus was sustained at adequate levels.

At Feather, foliar concentrations of both N and P were high in all treatments at the end of the first year (Fig. 3), reflecting the higher soil N fertility of the Cohasset soil series and perhaps some genetic differences of the recommended seed lots. As usually happens when nutrients are at luxury levels and trees begin their rapid phase of growth, uptake does not keep pace with growth gain as trees began to tax the site. Therefore, concentrations drop. By year 3, concentrations in all treatments approached or reached critical levels, then rose again to adequate levels by year 5.

There is a second reason for the very low foliar N (and particularly P) concentrations occurring in year 3 (1990). This was the driest year of the entire study period. As soils dry, ion diffusion follows an increasingly tortuous pathway along water films lining soil pores. Therefore, uptake declines (Barber 1974). Further, the P sorption capacity of the Cohasset soil series is very high (Powers et al. 1975). Together, drought and soil P sorption capacity largely account for the fact that foliar P fell to critical level by year 3 at Feather. Phosphorus stress may have lessened uptake of other nutrients as well. By year 7, N concentrations were falling to stress levels in unfertilized plots, but were increasing on fertilized plots and both N and P were at luxury consumption.

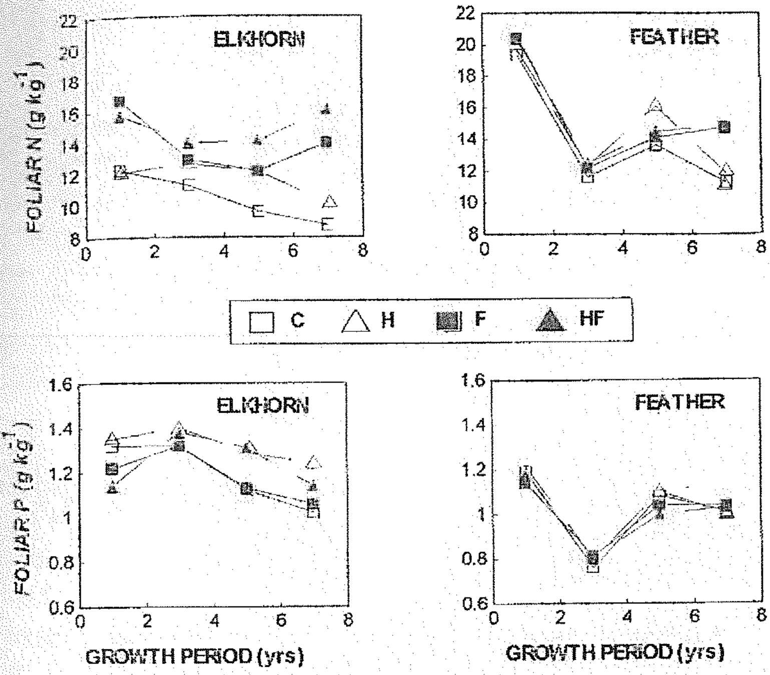

Figure 3–Concentrations of N and P in current-year needles of ponderosa pine on low productivity (Elkhorn) and high productivity (Feather) sites. Treatments are control (C), herbicide (H), fertilizer (F), and herbicide plus fertilizer (HF). Dark symbols denote fertilized, light symbols denote not fertilized. Each mean is the average of six treatment plots.

DISCUSSION

Annual fall surveys show that overall incidence of injury from pine-feeding insects was very low in all plantations and unrelated to treatment. Occasionally, terminal or lateral shoots were killed or stunted by the western shoot borer (*Eucosma sonomana*) or the ponderosa pine tip moth (*Rhyacionia zozana*). But incidence was low, rarely exceeding one or two shoots in 10% of the trees. Injured terminals sometimes caused forking. But with the usual resumption of dominance by a single terminal shoot, long-term effects on tree growth are expected to be minimal.

At least half of our study period coincided with several years of consecutive drought which might have influenced insect-host relationships. However, this seemed a normal period relative to insect activity in plantations throughout the region (Anonymous 1986-1993). Perhaps early control of competition through effective site preparation reduced problems to the point of insignificance.

On poorer, droughtier sites, weed control improves both moisture and nutrient availability and early growth is accelerated. However, accelerated growth quickly depletes available soil nutrients and trees become stressed within a few years. Nutrient stress can be eliminated through fertilization, but trees on droughty sites eventually will reach a growth ceiling set by soil moisture. Therefore, we doubt that fertilization will have a prolonged effect on droughty sites. On average and better sites, growth clearly is improved when fertilizers are combined with weed control. And, judging from foliar nutrient trends (Fig. 3), differences seem to be widening. Because trees on better sites are less impacted by water deficits, we expect that forest fertilization will have a positive effect for many years.

How can these early findings guide management? What are the implications for commercial yields? Obviously, we'll know with the passage of time. But in the interim, we used SYSTUM-1 (Ritchie and Powers 1994) to project our early findings to age 50 years for high, medium and low productivity sites as typified by the Feather, Whitmore and Elkhorn plantations. Using starting values at age 4 for each plantation and calibrating SYSTUM-1 for trends through year 8, we developed cumulative volume growth projections for control, herbicide, fertilizer, and herbicide plus fertilizer repetitive treatments. We assumed that fertilization would have no influence on site quality on the poorest sites because of water limitations, but that there would be improvements of a few percent on medium and better sites. We based this on conservative estimates of site index changes from recent height growth measurements in herbicide only and herbicide plus fertilizer treatments. We believe that the massive amounts of nutrients added in fertilizers will have a long-lasting impact on medium and better quality sites through retention and recycling.

Figure 4 indicates that average sites such as at Whitmore will give the greatest payoff for management investments. Combining herbicide with fertilization leads to a predicted volume increase of 86%, equivalent to 177 m^3 of added wood growth per hectare at plantation age 50. The direct effect of weed control largely ceases by 25 years when crowns close on control plots and competing vegetation is shaded out. Fertilization without early weed control has no positive influence on future yields. Based on our early findings, this projection seems logical.

On the poorest sites as represented by Elkhorn, failure to control competing vegetation leads to stagnation—the failure predicted by Fiske (1982). As our early findings indicate, fertilization has no benefit because site productivity ultimately is limited by moisture availability. We believe that this scenario is likely.

On the best sites as represented by the Feather plantation, fertilization and herbicide treatment—either separately or combined—show growth gains to year 50. However, the volume increase between the control and the best treatment is only 16% (67 m^3 ha^{-1}). Based on better moisture availability on the best sites, we believe this projection is conservative.

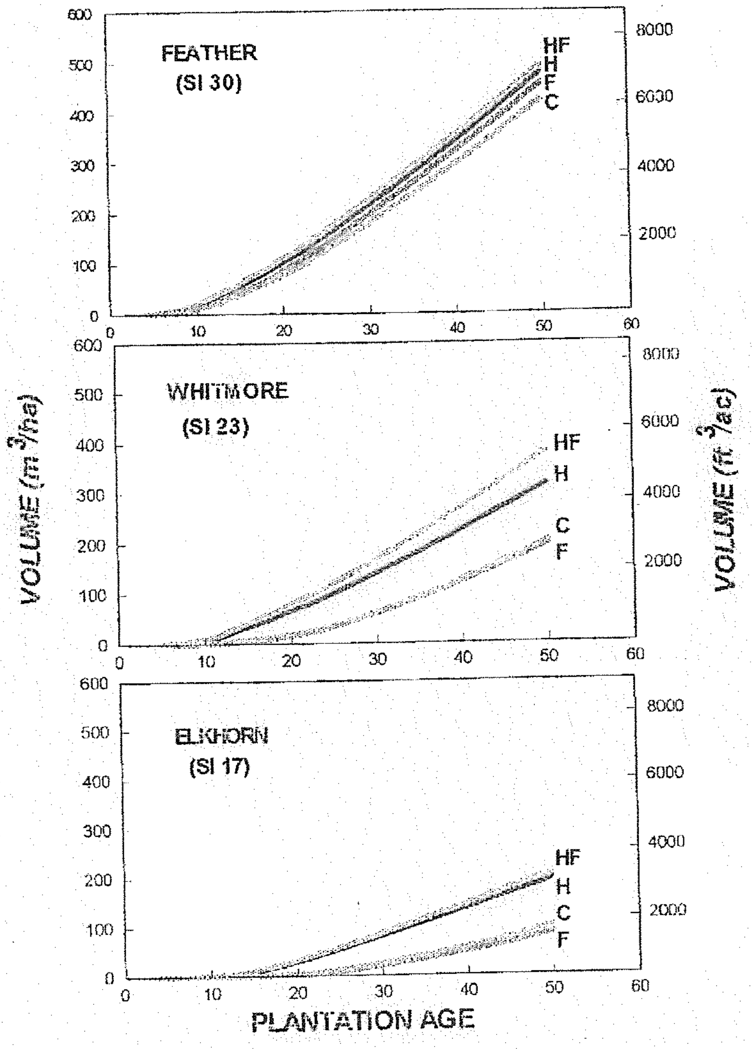

Figure 4--SYSTUM-1 projections of cumulative yields for Feather, Whitmore and Elkhorn plantations to age 50 years. Treatments are control (C), and repetitive applications of fertilizer (F), herbicide (H), and herbicide plus fertilizer (HF).

Finally, we caution that these projections are subject to limitations and assumptions of all growth models, including SYSTUM-1 (Powers et al. 1989). Values should not be used in an absolute sense.

CONCLUSIONS

1. On average, growth rates in ponderosa pine plantations were tripled through 8 years by appropriate combinations of weed and nutrient control treatments applied repetitively.

2. Insects, sometimes seen as pest problems in young plantations, had no influence on tree growth across the extreme range of physiological stresses and enhancements encompassed by the Garden of Eden experiment. Thus, assumptions about pest problems in young, westside plantations must be reassessed.

3. Weed control seems essential for satisfactory plantation performance on poor, droughty sites. Soil moisture is such an overriding factor that weed control plus fertilizer offers no further advantage beyond weed control alone. Furthermore, the presence of weeds essentially blocks uptake of fertilizer nutrients by pine.

4. Positive effects from weeding were not due simply to improved soil moisture. Droughty sites often are nutrient deficient, and effective weeding enhances soil nutrient availability as well as soil moisture supply. Uptake rates increase for nutrients but not for non-nutrient cations such as Al.

5. Pine on sites averaging more than 1500 mm annual precipitation responded positively to weeding and fertilization alone or in combination. Weed control had relatively less effect on growth response or nutrient uptake than for poorer, drier sites. Put simply, drought is less of a limiting factor on better sites.

6. Contrary to popular belief, fertilization response roughly increased with site quality. Survival was decreased by fertilization on the poorest sites, but not on better.

7. In general, tree growth responses to fertilizer and herbicide treatments are additive. Growth and foliar nutrient trends indicate that fertilization will have a long-lasting effect on sites of average and better quality.

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