Intensive Management of Ponderosa Pine Plantations: Sustainable Productivity for the 21st Century

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INTRODUCTION

Natural forest reserves and type conversions are shifting the burden of growing wood at superior levels to plantations. This causes two questions to arise: can plantations produce more, and can higher productivity be sustained? Managers often see productivity as a compromise between a site potential conditioned by climate and soil, and a current yield constrained by genetic potential, tree stocking and age, weed competition, forest pests, and economics. But site potential also is malleable. It can be lowered or raised by practices that alter the soil resource (Nambiar, 1996; Powers et al., 1997). The "Garden of Eden" experiment was established in 1986 to see how both current and potential productivity of planted ponderosa pine (*Pinus ponderosa* var.

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ponderosa) can be altered silviculturally in a Mediterranean climate. First-decade findings are summarized here.

METHODS

Insecticides, herbicides, and fertilizers were applied repeatedly to eight plantations across a broad gradient of site qualities in California (Table 1). Each plantation contained 3 replications of 8 treatments assigned randomly to 24-0.04-ha plots. Treatments were full factorial combinations of acephate or dimethoate and glyphosate or hexazinone applied annually at manufacturers' recommended rates, and a 9-nutrient mix (applied biennially at an exponential rate) delivering from 36 kg boron ha^{-1} to 1,074 kg nitrogen (N) ha^{-1} over 6 years. Trees of superior families were planted at 2.4 m spacing. Site and treatment details are those described by Powers and Ferrell (1997). Dimensions and foliar chemistry of the innermost 20 trees per plot were measured in staggered years, and soil chemistry was measured between years 8 and 10. Soil fauna (Moldenke, 1992), plant water relations and net assimilation (Reynolds and Powers, 2000) were assessed less regularly. Data were examined by analysis of variance ($\alpha = 0.05$) with mean separations by Tukey's test or Fisher's LSD. Yield projections were made to age 50 using the growth simulator SYSTUM-1 (Ritchie and Powers, 1993).

RESULTS

Through the First 10 Years

Neither repeated fertilization nor insecticide treatment had an overall effect on volume growth. Despite the broad range of physiological

TABLE 1. Physical characteristics of eight Garden of Eden plantations in California.

Location	Site index	Yr. planted	Elevation	Annual ppt.	Geology	Soil texture
Chester	20	1987	1465	890	Volcanic ash	Cindery
Elkhorn	17	1988	1490	1015	Schist	Loamy skeletal
Erie Point	24	1987	1370	1700	Schist	Loamy skeletal
Feather	30	1988	1220	1780	Basalt	Loam
Jaws	23	1988	1005	1035	Schist	Loam
Pondosa	20	1988	1175	760	Volcanic ash	Sandy loam
Tickey	28	1987	1280	1525	Basalt	Clay loam
Whitmore	23	1986	730	1140	Basalt	Clayey

stress conditions created by site quality and treatment, insect activity was negligible and will not, therefore, insecticide effects be discussed further. Herbicides, with or without fertilization, had a major impact, however, usually tripling volume growth across all sites. Leaf water potentials were raised significantly by weed control–particularly on drier sites such as Whitmore, where summer leaf water potential (ψ) averaged 0.1 MPa greater in weed-free plots (Reynolds and Powers, 2000). However, effects dissipated as trees approached crown closure. Weed control also improved tree nutrition as early as the first year (Powers and Ferrell, 1996), with effects lasting through year 9 on average and poorer sites (Table 2). The effect was particularly strong at Whitmore, the lowest and droughtiest plantation. Without weed control on drier sites, foliar concentrations of N (sometimes phosphorus [P]) declined steadily to deficiency levels by year 5 (Powers and Ferrell, 1996).

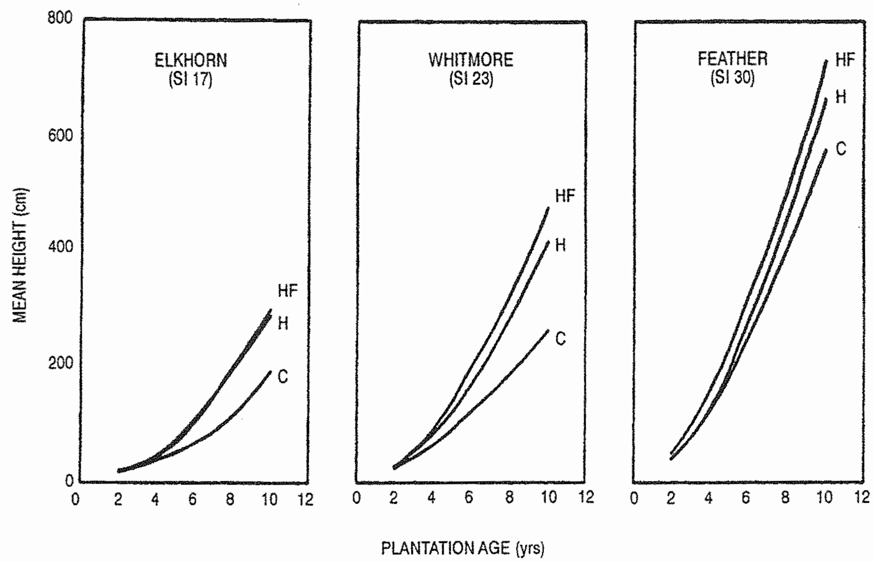
Fertilization improved nutrient uptake by pines the first year but weed growth also increased, generally masking early nutritional benefits to pines by year 5 (Powers and Ferrell, 1996). But with the massive fertilizer increment in year 6, both uptake (particularly of N, Table 2) and growth (Figure 1) surged again in trees on average and better sites. Combined with herbicides, fertilization improved tree

TABLE 2. Nutrient concentration in current-year foliage of 9-year-old ponderosa pine relative to site index and silvicultural treatment. Annual precipitation at Elkhorn, Whitmore, and Feather averages 1015, 1140, and 1780 mm, respectively.

Location Site Index	Treatment	Foliar concentration of– N	P	K	Ca	Mg	S	Cu	Fe	Zn	B
		g kg^{-1}					mg kg^{-1}				
Elkhorn	Control	8.8a*	1.11a	8.9a	1.15a	0.99a	552a	3.28a	38.5a	26.2	28.3a
(17 m)	Fertilizer	12.4b	1.24a	9.5ab	1.25ab	1.02a	628ab	3.12a	36.3a	26.3	59.3b
	Herbicide	9.8a	1.37b	11.4c	1.30ab	1.17a	611ab	3.38a	38.0a	28.3	35.3a
	Herb. + Fert.	12.6b	1.44b	10.4bc	1.47b	1.11a	709b	3.55a	36.7a	29.8	72.3b
Whitmore	Control	8.5a	0.78a	4.6a	1.02a	0.80a	524a	2.47a	36.3a	176.3ab	20.3a
(23 m)	Fertilizer	10.7b	0.89ab	4.9a	1.04ab	0.75a	605b	3.17b	34.0a	197.0b	19.7a
	Herbicide	11.8c	0.83a	6.8b	1.06b	0.97b	710c	3.45b	35.2a	156.2a	25.3a
	Herb. + Fert.	12.5d	0.98b	6.8b	1.32c	0.94b	752c	3.38b	57.2a	204.0b	23.5a
Feather	Control	11.0a	1.11a	7.7a	1.48a	1.25a	720a	3.95a	42.3a	175.7	23.5a
(30 m)	Fertilizer	12.8b	1.15a	8.9a	1.81b	1.15b	781b	3.83a	32.8a	137.8	24.2a
	Herbicide	10.7a	1.14a	7.8a	1.65ab	1.34a	756ab	3.88a	35.0a	185.5	23.2a
	Herb. + Fert.	12.5b	1.09a	8.8a	1.69ab	1.15b	791b	4.08a	34.3a	131.2	22.2a

*Plantation means followed by differing letters within a column differ significantly at $\alpha = 0.05$.

FIGURE 1. Cumulative height growth for control (C), herbicide, (H), and herbicide + fertilizer (HF) treatments through the first 10 years at three Garden of Eden plantations of site indices 17, 23, and 30 m at 50 years (adapted from Powers and Ferrell, 1996).



growth and uptake of most nutrients on all sites. Although trees receiving combined treatments grew faster, their leaf ψ was not affected until late summer, when ψ was 0.2 MPa lower at Whitmore (which is droughty) and 0.2 Mpa higher at Feather (which is more mesic).

Soil organic carbon and N were not affected by repeated vegetation control, contrasting with Busse et al.'s (1996) longer-term findings in eastern Oregon. Soil arthropods in 5- and 6-year-old plantations were fewer and less diverse than in adjacent natural stands (Moldenke, 1992). Other than a lack of litter-dwelling arthropods (a continuous litter layer had not yet formed by year 6), functional guilds (arthropods grouped by their roles in ecosystem processes) were not eliminated by treatment.

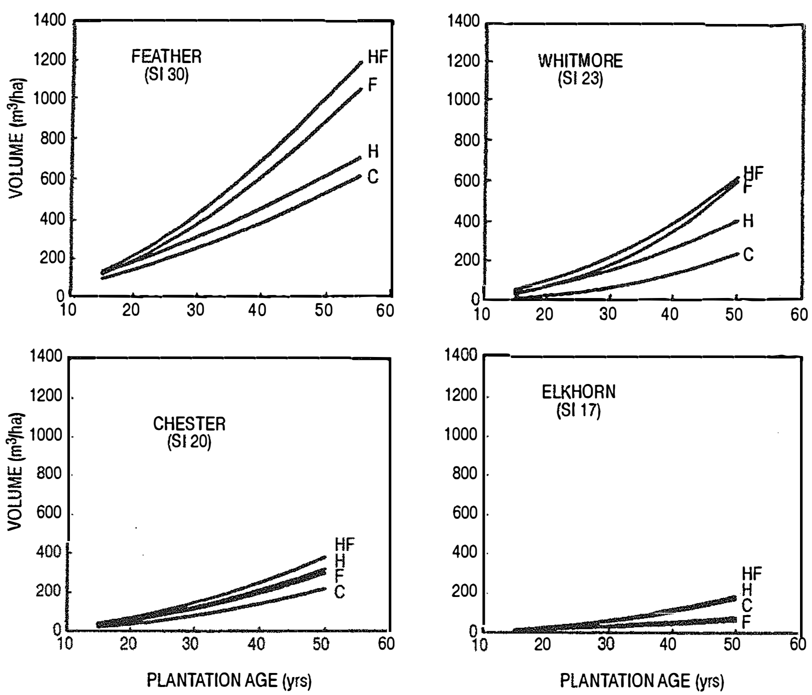
Projections to Age 50

Stand growth projected to 50 years suggests a sizable gain from weed control that persists on poorer sites and diminishes on better sites. On the best site (Feather), effects dissipated quickly, accounting for only a 12% yield gain by age 50. In contrast, fertilization leads to notable gains on average and better sites, appearing progressively sooner as site quality improves (Figure 2). On poorer sites, early weed control projects to a doubling of volume growth by age 50 but fertilization offers no further advantage.

DISCUSSION

Weed control with herbicides was the most effective early treatment across all site qualities, but response was variable. Weed competition for water and nutrients was greatest on the poorer sites–a key fact where drought dominates site quality. There, weed control spells the difference between plantation success and failure. Responses to herbi-

FIGURE 2. SYSTUM-1 projections of cumulative yields for several Garden of Eden plantations. Treatment codes follow those in Figure 1, as well as fertilization (F). Site indices (SI) are in meters at 50 years.



cides were less striking on better sites where deeper soils and lower vapor pressure deficits (Reynolds and Powers, 2000) buffer them against midsummer drought. Weed control improved soil moisture and nutrient availability on poor sites, but stresses returned as stands approached crown closure and moisture again became the primary limit-ing factor.

Nutrient uptake–particularly N–was increased substantially by fertilization on all sites through year 9 (Table 2), but growth was increased only where site quality was average or better (Figure 1). Growth response is limited where drought dominates production. Stands on sites with more mesic moisture regimes usually develop incipient nutrient deficiencies, especially N and P, as they approach crown closure, making them prime candidates for prolonged fertilization response if rates are balanced in quality and quantity.

CONCLUSIONS

Massive incremental loadings of nine nutrients coupled with low rates of nutrient leaching common to summer-dry climates (Frazer et al., 1990; McColl and Powers, 1984; Powers, 1992), point to nutrient retention and to fundamental increases in site potential on average and better sites. Because functional guilds of soil arthropods were resilient to treatment and because litter processors should return once a forest floor develops, biotic regulation of detrital processing, nutrient cy-cling, and soil physical maintenance should not be impaired. There-fore, the long-term projections of treatment responses shown in Fig-ure 2 seem realistic if severe water stress is avoided by timely thinnings. Ponderosa pine plantations are capable of productivity lev-els much greater than currently realized. Such levels should be sus-tainable if soil organic matter and structure are maintained.

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