

RESPONSE OF PONDEROSA PINE AND LODGEPOLE PINE TO FERTILIZATION

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ABSTRACT

Increases in volume growth of up to 75 percent for ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) and up to 100 percent for lodgepole pine (*Pinus contorta* Dougl. ex Loud.) have been obtained on fertilized study plots in thinned, pole-sized stands. Responses are primarily due to nitrogen; but sulfur, phosphorus, and potassium may also be important on some soils. Some pole-size stands of ponderosa pine have not responded to nitrogen fertilization. The responses of seedling and small sapling stands, as well as old sawtimber-size trees, are uncertain. Current costs and economic benefits of fertilization are debatable, even in the highly responsive stands.

INTRODUCTION

Values of lodgepole (*Pinus contorta* Dougl. ex Loud.) and ponderosa pine (*Pinus ponderosa* Dougl. ex Laws.) logs are generally increasing with time. The costs of cultural treatments of stands designed to produce more usable wood are also rising. These constantly changing values and costs point out the need for frequent evaluation of various management practices. These evaluations raise questions concerning the possible benefits of fertilization. Will the stands under consideration respond? How long will the response last? What kinds of fertilizers should be applied? What are the proper levels of application? What time of year should the application take place? What are the costs and benefits? The purpose of this paper is to summarize the information available in the literature, to see what questions can at least be partially answered from ongoing studies, and to suggest some direction for future research.

LITERATURE REVIEW

Vlams et al. (1959) have shown that ponderosa pine seedlings respond to N fertilization on a number of California soils. In a greenhouse study, Youngberg and Dyrness (1965) found marked response to N from ponderosa pine seedlings grown on a Lapine soil along with strong N-P and N-P-S interactions. Tarrant and Silen (1966) conducted an irrigation and

fertilization study with small sapling ponderosa pine and found a definite response to N but an even greater response to irrigation.

Mosher (1960) conducted an irrigation and fertilization experiment in a 90-yr-old ponderosa stand in eastern Washington. Fertilizer was ammonium nitrate (33.3% N) applied at the rate of 67 lb N/acre (74.7 kg/ha). Some plots were not irrigated, some were irrigated once, and others twice during the growing season. The amount of water supplied per irrigation was approximately 6 in. (18 cm). Mosher observed increases in diameter growth over controls, shown in Table 1.

Wagle and Beasley (1968) fertilized thinned ponderosa pine in Arizona with 75 lb N/acre (84 kg/ha; NH_4NO_3), 150 lb P_2O_5 /acre (168 kg/ha; $\text{CaH}_4(\text{PO}_4)_2$), 5 lb Fe/acre (5.6 kg/ha), 2.75 lb Zn/acre (3.1 kg/ha), 2.75 lb Mn/acre (3.1 kg/ha), 1.25 lb Cu/acre (1.40 kg/ha), 2.75 lb B/acre (3.1 kg/ha). Iron, Zn, Mn, and Cu were applied together in a chelated form. At the end of 2 yr, added nutrients appeared to inhibit height growth and stimulate radial growth.

Youngberg (1975) applied five different treatments to thinned and unthinned plots in a 45-yr-old ponderosa pine stand on a Lapine loamy coarse sand. The treatments applied in the fall were: (1) control; (2) magnesium ammonium phosphate (Mag Amp) at a rate equivalent to 96 lb N and 210 lb P/acre (108 and 235 kg/ha), respectively; (3) ammonium sulfate at rates of 100 lb N and 114 lb S/acre (112 and 128 kg/ha), respectively; (4) ammonium sulfate plus treble superphosphate at rates of 109 lb N, 114 lb S, and 190 lb P/acre (122, 128, and 213 kg P/ha), respectively; and (5) ammonium sulfate and treble superphosphate at the above rates plus murate of potash (240 lb K/acre [269 kg/ha]).

Table 1. Increase in diameter growth over controls for 2-yr period (Mosher 1960).

	Increase (%)
Fertilized only	29
Irrigated only once	76
Irrigated once and fertilized	127
Irrigated twice	139
Irrigated twice and fertilized	94

One growing season later, an additional 100 lb N/acre (112 kg/ha) were applied to the fertilized treatments as ammonium nitrate. The thinning occurred three growing seasons previous to treatment, and leave trees were spaced at about 11.5 ft (3.5 m).

Five growing seasons after initial application, fertilization resulted in significant increases in basal area for thinned plots. For the unthinned plots all fertilizers except Map Amp significantly increased basal area growth (Table 2). Foliar N concentration in the current year's foliage at the end of the first growing season following fertilization was 1.04% for the control and 1.08%, 1.25%, 1.20%, and 1.14% for the Mag Amp, N, NP, and NPK treatments, respectively. These results suggest that in dense stands, soil water is more limiting than N; but as water becomes more available through thinning, N becomes the primary limiting factor.

Agee and Biswell (1970) applied a total of 4439 lb/acre (4 988 kg/ha) ammonium sulfate (934 lb N/acre and 1068 lb S/acre [1 047 kg N/ha and 1 197 kg S/ha]) in nine equal applications over a 3-yr period to thinned and unthinned ponderosa pine stands in northern California. For the 12-yr period following initial fertilization, percent increases in basal area were: unfertilized unthinned, 8.2; fertilized unthinned, 45.9; unfertilized thinned, 82.8; fertilized thinned, 134.1.

Barrett and Youngberg (1970) reported that 5.3 oz (323 g) of Mag Amp fertilizer placed in the planting hole increased leader growth of ponderosa pine in central Oregon; however, the increase in leader growth over the controls (10 in. [25.4 cm] in 7 yr) was not large.

Cochran (1973) applied N fertilizer in the form of urea at rates of 200 and 400 lb N/acre (224 and 448 kg/ha), during November to 0.1-acre (0.04-ha) plots in thinned pole-size ponderosa pine on a loam soil in northeastern Oregon. The fertilization produced greater height, basal area, and volume growth for the dominant or codominant test trees in the center of these plots than the control treatment during the first four growing seasons. Differences between the 200 and 400 lb N/acre (224 and 448 kg/ha) rates were not significant. In a related study in central Oregon, Cochran (1973) fertilized 0.1-acre (0.04-ha) plots around ponderosa pine test trees in thinned stands in three different plant communities reflecting low,

medium, and high amounts of available soil water. The three treatments were: (1) control; (2) 200 lb N/acre, 100 lb P/acre, 30 lb S/acre, and 1.9 lb B/acre (224, 112, 33.6, and 2.11 kg/ha), respectively; and (3) double the amounts of treatment (2).

After four growing seasons, height growth of the test trees was increased by fertilization only on the site with the highest available water. Fertilization increased basal area growth of the test trees on all areas and volume growth on the two highest sites. The higher rate of fertilization did not produce a significant increase in growth over the lower application rate in any area. For the fifth through eighth growing seasons after fertilizer application, height growth was not increased in any of the four areas; but basal area and volume growth continued to respond on every site except the site with the most available water in central Oregon (Cochran 1977). Even at this site, the fertilized trees on the average had more rapid growth but variation within treatments was great.

Cochran (1975) applied the unusually high rates of 600, 300, and 90 lb/acre (673, 336, and 101 kg/ha) of N, P, and S, respectively, in the fall to thinned, pole-size lodgepole pine on a Lapine soil. These high rates of application did not increase height growth during the first four growing seasons after application. During the second 4-yr period after initial application, however, annual height growth was increased from an average of 6 in. (0.18 m) for the control treatments to 1.2 in. (0.3 m) for the fertilized treatments (Cochran 1979a). The percentage of increases over the control treatment for volume, basal area, and bole area due to initial application are shown in Table 3.

While these percentages are high, the actual amount of wood produced was not. The base figures are the amount of wood produced by the control plots at a basal area of 40 ft²/acre (9.2 m²/ha). At this basal area, the control plots produced only 37.2 ft³/acre (2.6 m³/ha) for the 1971-1974 period and only 48.6 ft³/acre (3.4 m³/ha) for the 1975-1978 period. Grass production in the understory was also increased for both periods by fertilization, and the response of grass declined for the second 4-yr period as did the wood volume growth.

In an attempt to test the importance of S and P in addition to N, Cochran (1979) used five treatments with fall application to thinned pole-size ponderosa pine on a Shanahan soil. The Shanahan soil is developing on Mazama pumice and ash but generally at a greater distance from the source of the parent

Table 2. Increases in basal area for thinned and unthinned plots after fertilization.

Treatment		Increase (%)	
		unthinned	thinned
(1)	Control	18.9	35.4
(2)	Mag Amp	18.4	46.3
(3)	N	25.3	51.4
(4)	NP	22.8	48.9
(5)	NPK	26.8	47.2

Table 3. Increases (in percent) due to initial fertilization over control treatment for volume, basal area, and bole area.

	1971-1974	1975-1978
Volume	100	62
Basal area	100	60
Bole area	77	43

material than the Lapine soil. Therefore, the pumice particle sizes are smaller in the Shanahan soil. The five treatments were: (1) control, (2) 200 lb N/acre (224 kg/ha), (3) 200 lb N and 100 lb P/acre (224 kg and 112 kg/ha), (4) 200 lb N and 40 lb S/acre (224 and 33.6 kg/ha), (5) 200 lb N, 100 lb P, and 40 lb S/acre (224, 112, and 33.6 kg/ha).

Adjusted means from the covariance analysis showed that the control treatments produced 55.7 ft³/acre (3.9 m³/ha) per year volume, 2.6 ft²/acre (0.6 m²/ha) per year basal area, and 318.4 ft²/acre (73.1 m²/ha) per year bole area over the 4-yr study period. Fertilizer application caused the increases in adjusted means over the 4-yr period shown in Table 4.

All treatments were significantly greater than the control, but the only significant difference among fertilizer treatments was the production of more basal area by the NPS combination. Height growth averaged 1 ft (0.3 m) per year and was not increased by fertilization.

Will and Youngberg (1978) used a 2 + 2 + 2 NPS factorial arrangement of treatments in each of four blocks within a thinned, pole-size stand of ponderosa pine on a Shanahan soil. This experiment attempted to assess the importance of S and P in combination with N. Rates of application were 200 lb N/acre (224 kg/ha) as ammonium nitrate, 50 lb P/acre (57 kg/ha) as treble superphosphate, and 100 lb S/acre (112 kg/ha) as gypsum. Basal area increases for the first and second 5-yr periods after application as well as for the total 10-yr period are given in Table 5.

Table 4. Percentage of increases in adjusted means over the 4-yr period, caused by fertilization.

Treatment	Volume growth	Basal area growth	Bole area growth
N	34	23	20
NP	38	25	36
NS	56	38	44
NPS	56	58	51

Table 5. Basal area increases for first and second 5-yr periods after fertilization and for total 10-yr period (in percent).

Treatment	First 5-yr	Second 5-yr	10-yr total
Control	23.4	15.2	42.1
P	25.2	14.6	43.4
S	26.0	16.4	46.7
PS	26.2	14.7	44.5
N	33.7	17.8	57.4
NP	28.2	15.4	48.1
NS	39.5	15.7	61.0
NPS	34.3	18.5	58.6

The data for the PS and S treatments possibly indicate a slight S effect, while the NPS treatment showed the best response during the second 5-yr period, indicating a possible N-P-S interaction during this period.

In connection with this field study, Will and Youngberg (1978) also conducted a greenhouse pot trial with 22 soil layers from several locations in south-central Oregon. Monterey pine (*Pinus radiata* D. Don) were used as test plants in a randomized block design to see if S, when combined with N and P, increased growth over NP alone. Sulfur definitely caused an increase in growth for 18 of these 22 soils.

Cochran (1979b) established twenty-four 0.2-acre (0.08-ha) plots in a pole-size ponderosa pine stand thinned to an average spacing of about 17 ft (5.2 m). Twelve of the 24 plots were randomly chosen for fertilization in the fall with 200 lb N/acre (224 kg/ha), 100 lb P/acre (112 kg/ha), and 33 lb S/acre (37 kg/ha). Fertilizer significantly increased growth of volume, basal area, bole area, and height. Adjusted means from analysis of covariance of average annual growth rates for the control and fertilized treatments are shown in Table 6.

Powers and Jackson (1978) investigated the response of ponderosa pine plantations to brush removal and fertilization on two contrasting soils in California. One soil (the Mariposa series) is a gravelly silt loam less than 3.3 ft (1 m) deep over fractured schist. The other soil (the Cohasset series) is a loam/clay loam greater than 3.3 ft (1 m) deep. Each soil has slightly more than 4461 lb N/acre (5 000 kg/ha) in the profile; and like many soils, most of the N is in the organic form, unavailable to higher plants.

Important differences in mineralization rates also exist between the soils. Fertilization treatments (0, 200, and 400 lb N/acre; 0, 224, and 448 kg/ha) combined with removal or non-removal of competing brush were established in both soil series. Fertilizer was applied in November. One season after treatment, fertilization plus brush removal produced a significant increase in height and diameter growth on the Mariposa soil with 200 lb N/acre (224 kg/ha) producing the primary response. Height and diameter growth on the Cohasset soil, where N mineralization rates are higher, was unaffected by

Table 6. Adjusted means from analysis of covariance of annual growth rates for control and fertilized treatments.

	Volume growth (m ³ ·ha ⁻¹ ·yr ⁻¹)	Basal area growth (m ² ·ha ⁻¹ ·yr ⁻¹)	Bole area growth (m ² ·ha ⁻¹ ·yr ⁻¹)	Height (m/yr)
Control	3.20	0.60	60.40	0.23
Fertilized	5.6	0.9	98.7	0.35
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Increase due to fertilization (%)	75	50	63	52

treatment. Foliar analyses of the trees on the two soils show that trees on the Mariposa soil were critically low in N for this area of California (<0.85%).

CURRENT STUDIES

Several pertinent studies with results not yet reported need to be considered. Two ponderosa pine fertilization studies are being conducted by Weyerhaeuser Company scientists in south-central Oregon. The first study is a randomized complete block design with two replications at each of nine different locations. Stands in this study were thinned to spacings of about 10 × 10 ft (3 + 3 m). Average diameters of the leave trees on the 0.1-acre (0.04-ha) study plots varied at the start of the study from a low of 4 in. (10 cm) on seven of the installations to 9.8 in. (25 cm) on two installations.

The soils, parent materials, and treatments along with preliminary responses are summarized in Table 7. In this study, fertilization significantly increased growth ($P = 0.5$) when all sites were considered collectively. Periodic annual increments produced by the N 400 PKS treatment were significantly greater than those produced by the N 200 spring and N 400 fall treatments (Table 8).

Even though the percent responses in volume production are high in some instances (Table 7), the actual amount of wood produced by fertilization is low because thinning reduced the growing stock level to the point where the average rate of growth for the control treatments was 44.3 ft³/acre (3.1 m³/ha) per year.

In the second Weyerhaeuser Company study in progress,

Table 7. Response of volume growth to fertilizer for thinned, sapling-size ponderosa pine in south-central Oregon. Responses are for a 5-yr period unless otherwise noted.

Soil series	Soil parent material	Treatment			
		N 200 Spring	N 400 Spring	N 400 Fall	N 400 PKS ^a Spring
<i>Percent increase in volume growth over control</i>					
Ward	Basalt	39	57	28	75
Lapine	Pumice	24	61	48	50 ^b
Shanahan	Ash	27	39	33	64
Pokegma	Basalt	30	12	18	16 ^c
Shanahan	Ash	26	36	51	44 ^c
Ze-eks	Ash	27	40	14	65
Pokegma	Basalt	11	42	39	64
Ze-eks	Ash	30	28	-2	21
Klipple	Ash	0	22	-8	38

^aNitrogen in kg/ha applied as urea; P, K, and S applied at 56 kg/ha as triple superphosphate, potassium chloride, and gypsum, respectively.
^b6-yr response period. ^c4-yr response period.

seven treatments (control, N, NP, NK, NS, NPS, and NPKS with levels of 400, 100, 100, and 50 lb/acre [448, 112, 112, and 56 kg/ha] for N, P, K, and S, respectively) were installed using 0.05-acre (0.02-ha) plots on three different soils. The experimental design is a randomized complete block with two replications on each soil. The ponderosa pine stands on the three soils were thinned prior to treatment producing the characteristics shown in Table 9.

Parent materials are basalt/ash, ash/basalt/andesite, and pumice for the Ward, Ze-eks, and Lapine soils, respectively. Fertilizers were urea, treble superphosphate, murate of potash, and gypsum. No statistically significant response was obtained on the Ward soil (Table 10). The only fertilization treatments

Table 8. Average periodic annual increment for all locations (in cubic meters per hectare per year).

Treatment	Increment
Control	3.1
N 200 spring	3.9
N 400 spring	4.3
N 400 fall	3.8
N 400 PKS	4.4

Table 9. Results of thinning and fertilization of ponderosa pine stands on three soils.

Soil	Trees/ha	Basal area (m ² /ha)	Average height (m)	Volume (m ³ /ha)
Ward	565	10.5	7.4	27.5
Ze-eks	371	8.6	8.8	24.5
Lapine	520	13.9	9.3	40.0

Table 10. Five-year gross periodic annual growth (m³·ha⁻¹·yr⁻¹) of thinned, sapling-size ponderosa pine in south-central Oregon following fertilization with various nutrients.^a

Treatment	Soils		
	Ward	Ze-eks	Lapine
Check	2.9	2.0	3.1 ^a
N	4.3	2.4	3.1 ^a
NP	3.7	2.2 ^a	3.6 ^a
NK	3.6	2.0 ^a	4.2
NS	4.4	3.0	4.7
NPS	3.4	2.2 ^a	4.9
NPKS	2.9	2.2 ^a	5.2

^aValues with differing subscript letters are significantly different at the 0.05 level of probability according to Duncan's new multiple range test (Steel and Torry 1960).

that produced increases in volume for the Ze-eks soil were the N and NP treatments, where P with N outproduced N alone. All fertilizer treatment except N alone resulted in increased volume production on the Lapine soil. Sulfur added with P and N produced more wood than P plus N without S for this pumice soil.

Weyerhaeuser scientists are also conducting investigations of the response of lodgepole pine on Lapine and Shanahan soils in south-central Oregon. A randomized complete block design with two replications on two soils is employed with 0.1-acre (0.04-ha) plots as experimental units. Treatments, periodic annual increments for a 3-yr period, and percentage of increases over the control are given in Table 11. In this study, there were from 2501 to 2684 trees/acre (1012–1086 ha) for each treatment. Basal area ranged from 68.8 to 102.8 ft²/acre (15.7–23.6 m²/ha), and heights ranged from 44.3 to 50.5 ft (13.5–15.4). Fertilization significantly increased volume production of lodgepole pine on the Lapine soil. Additions of P, K, and S with N increased response over N alone on the Lapine soil, and there was no difference in the two levels of N. Much within-treatment variation occurred on the Shanahan soil, and the increases produced by fertilization were not statistically significant.

In contrast to the above study, fertilization of smaller lodgepole pine seedlings on a Lapine soil with N, P, and S produced no increase in growth during the first three growing seasons in an ongoing Forest Service study. This study design is completely randomized with five replications of the control and fertilizer treatments. The experimental units are 0.1-acre (0.04-ha) plots. Fertilization rate was 182 lb N/acre (204 kg/ha) combined with 74 lb P/acre (83 kg/ha) and 120 lb S/acre (135 kg/ha). Seedlings averaged (1 m) tall at the start of the study and grew an average of 17.3 in. (0.44 m) per year for the first three growing seasons after treatment.

Youngberg fertilized a 110-yr-old ponderosa pine stand on a

Table 11. Treatments and corresponding periodic annual volume increments for a 3-yr period in Lapine and Shanahan soils.

Treatment	Annual volume growth (m ³ /ha)		Increase control over (%)	
	Lapine	Shanahan	Lapine	Shanahan
Control	4.6 ^a	7.0		
N 207 ^b	6.4 ^b	9.8	39	40
N 414 ^c	6.7 ^b	9.8	46	40
NPKS ^d	8.6 ^c	10.2	87	46

^aValues with differing subscript letters are significantly different at the 0.05 level of probability to Duncan's new multiple-range test (Steel and Torry 1960). ^b207 kg N/ha in form of urea. ^c414 kg N/ha in form of urea. ^d414 kg N/ha in form of urea, 90 kg P/ha as triple superphosphate, K at 98 kg/ha as KCl, S at 78 kg/ha as gypsum.

Shanahan soil with three treatments (control, NP, and NPK) applied to 0.1-acre (0.04-ha) plots. The tree treatments were replicated three times in a randomized complete block design. Rates of N, P, and K used were 200, 171, and 200 lb/acre (224, 196, and 223 kg/ha), respectively. Table 12 shows average diameter growth and percent basal area increases at the end of five growing seasons. Fertilization did not significantly increase growth. Response was much less than would be expected for a younger stand on this soil.

In a USDA Forest Service study conducted on the Warm Springs Indian Reservation in north-central Oregon, thinned sapling and pole-size ponderosa pine stands with and without scattered overstory were fertilized with 200 lb N/acre (224 kg/ha). In this completely randomized design, a total of twenty 0.2-acre (0.08-ha) plots were used. Five plots each with and without overstory were randomly chosen for fertilization. Fertilization of these low sites on soils high in clay content resulted in no significant response, indicating other limiting factors are present.

ECONOMIC CONSIDERATIONS

The economics of fertilizing pine stands are discussed in a paper by Randall (this volume). Briefly, even though the percentage of increase in growth of thinned stands by fertilization is high on several soils, the increased wood produced on even the most responsive sites merely pay back the cost of fertilization. Costs would not be covered if discounted over the period of time between applying the fertilizer and harvesting the stand without an increase in stumpage values. Future changes in stumpage prices, availability of wood, and milling costs all affect the real returns from fertilization and could change the economic picture.

DISCUSSION AND CONCLUSIONS

Data available at present indicate that large sapling and pole-size stands of lodgepole and ponderosa pine will respond to N fertilization on many, but not all soils. There appears to be additional responses to S and perhaps P in addition to N on soils that are strongly influenced by pumice and volcanic ash. No data on the response of very old, large sawtimber stands are available.

Table 12. Average diameter growth and basal area increases after three treatments of a 110-yr-old ponderosa pine stand.

Treatment	Diameter growth (cm)	Basal area increase (%)
Control	0.9	5.0
NP	1.5	7.3
NPK	1.4	7.6

With the data available, correlations between soil test values and response are impossible to make. Although there must be a correlation between the available amount of a deficient nutrient in the rooting zone and response to that nutrient, this kind of information is not available. Total amounts of N to a certain depth or of P extractable with a certain extracting solution are available for some studies, for example; but they do not appear to be related to response, even in a general way. Other complications include the mycorrhizal relationships of tree roots and proliferation of these roots through differing soil layers.

Better diagnostic tests will probably be built on the rates of availability in the soil (Geist 1977, Powers 1977, Powers et al. 1978, Shumway and Atkinson 1978) or on foliar analysis of current or older needles just at the end of the growing season before mobile nutrients move from older to new foliage (Powers et al. 1978, Powers this volume). Scientists now could begin investigations of foliar nutrient contents and rates of mineralization at existing study locations. Techniques for N are available, but techniques for P and particularly S need to be worked out.

For now, we can state that 200 lb N/acre (224 kg/ha) plus 30 lb S/acre (34 kg/ha) appears to be a reasonable general application rate in the Pacific Northwest for soils influenced by pumice and ash. Time of application should be in late fall or before end of spring precipitation. Thinned stands of large saplings or poles with foliar N concentrations below 0.85% just at the end of the growing season appear most likely to give responses. Grass production in the understory will improve with N and S fertilization (Geist 1976). Responses in wood production can be expected to last at least 4 and possibly 10 yr or more. Still, the land manager should carefully consider the economics (Randall this volume) before initiating a large fertilization project.

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