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Foliar Nitrogen Content and Tree Growth After Prescribed Fire in Ponderosa Pine

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Abstract

This initial study of prescribed burning in ponderosa pine *(Pinus ponderosa* Dougl. ex Laws.) stands in central Oregon showed that all periodic annual growth increments were reduced for trees alive four growing seasons later. Height growth was reduced 8 percent in areas burned by fires with moderate fuel consumption and 18 percent in areas with high fuel consumption. Basal area growth was reduced 16 percent in the moderate fuel consumption areas and 28 percent in the high fuel consumption areas; volume growth declined 23 percent at both levels of fuel consumption.

Foliar nitrogen (N) concentration was not affected by the prescribed fires; however, total foliar N content was reduced immediately after burning, and it remained depressed four growing seasons later after the burned areas had recovered from crown scorch. Foliar N content was significantly correlated with the observed reductions in periodic annual increments. Prescribed fire needs additional evaluation for a longer period and in additional ponderosa pine communities to determine long-term effects.

Keywords: Prescribed burning, fire effects, foliar analysis, increment (height), increment (basal area), increment (volume), ponderosa pine, *Pinus ponderosa*.

Introduction

The use of prescribed fire as a silvicultural tool has been questioned because of the potential loss of volatile nutrients from the site, especially nitrogen (N), and the subsequent effect of lower N content—less tree growth. A linear relationship between foliar N concentration and growth in forest-grown trees has been demonstrated (Leyton 1954, Leyton and Armson 1955, Wright 1959).

Research shows that the N content of the duff layer of a soil in western Washington was reduced to 33 percent of the original value by a severe fire (Isaac and Hopkins 1937). Laboratory experiments by Knight (1966) indicated a 25- to 64-percent loss of N from the forest floor at temperatures of 575 to 1300 °F. A loss of 10 to 30 percent of the N in the forest floor was produced by light surface burning in central Oregon ponderosa pine *(Pinus ponderosa* Dougl. ex Laws.) (Nissley 1978). DeBell and Ralston (1970) found that 62 percent

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of the N contained in pine litter and leaf materials was released by burning, and a major portion was volatilized as N_2 gas. Fire, which volatilizes N, has the short-term effect of increasing N stress in fire-dominated ecosystems (Raison 1979, Vitousek and others 1982). These losses of N through fire could be expected to reduce tree growth.

Second-growth ponderosa pine covers a large area of central Oregon. These stands were established after railroad logging of the area in the 1920's, and they have developed during a period of fire exclusion. Prescribed fire is now being implemented as a silvicultural option for reducing fuel and fire hazard, stimulating nutrient release, increasing forage production, and improving wildlife habitat. Questions remain concerning the effect of prescribed fire on tree stem growth in ponderosa pine.

Objectives

This study investigated the effects of prescribed fire on foliar N concentration and content and on tree growth in central Oregon ponderosa pine. Prescribed fires at two levels of fuel consumption and a no-burn control were established. Specific objectives were to determine changes in fuel load, duff depth, foliar N concentration and content, and stem growth with treatment.

Methods

Research Location

The study site is representative of natural regeneration, second-growth ponderosa pine stands found over large areas of central Oregon. The community type is ponderosa pine/bitterbrush/needlegrass *(P. ponderosa/Purshia tridentata* (Pursh) Oc./*Stipa occidentalis* Thurb. ex Wats.). Community type designation is CP-S2-12 (Volland 1982).

The site is 10 miles south of Bend near Lava Butte in the Fort Rock District of the Deschutes National Forest. The research area covers 42 acres at an elevation of 4,750 feet and has less than 2 percent slope to the north and west. The area receives about 20 inches of precipitation annually, mainly as snow; summers are normally hot and dry.

The stand is on a Typic Cryorthent (Shanahan- and Klawhop-like series) soil developing on Mazama pumice and ash. A sandy loam A1 horizon 2 inches thick and a sandy loam AC horizon 22 inches thick overlie older buried material. The stand was precommercially thinned in 1961, and the thinning slash was not treated before burning. Average dead and down woody fuel load ranged from 12.2 to 17.8 tons per acre and the duff layer from 2.5 to 4.6 inches in depth.[1]

Site index of the area is 108 feet (100-year basis) (Barrett 1978). When the study was installed in the spring of 1979, the stand had a basal area of 124 square feet per acre on 240 stems. The quadratic mean diameter (diameter of tree of average basal area) was 9.7 inches, and the stand age at breast height was 45 years. The average height was 54 feet, and the average live crown ratio was 0.68.

[1]In this paper dead and down woody fuel refers to the stems, branches, and twigs lying above the continuous duff layers (organic horizons 01 and 02).

Treatments

This research was designed to test the effect of prescribed fire at two levels of fuel consumption on foliar N concentration and content and on growth of tree stems. The three treatments were: (1) a prescribed burn with high fuel consumption, (2) a prescribed burn with moderate fuel consumption, and (3) a no-burn control. Each treatment was applied twice. The moderate fuel consumption burns were prescribed to remove 80 percent of the dead and down woody fuel less than or equal to 1 inch in diameter and to leave 50 percent of the duff and woody fuel greater than or equal to 3 inches in diameter. The high fuel consumption burns were prescribed to remove 85 percent of all dead and down woody fuel and duff. Before each prescribed fire, a small test area was burned to assure that consumption was within the limits of the objectives.

The 42-acre area was divided into six units of 4.0 to 11.9 acres each. Each treatment was randomly assigned to two units. Each unit contained four to six 1/5-acre plots surrounded by a half-chain buffer strip. The plots were selected to be representative of the area and to provide a treatment response for each unit.

Statistical Design

The statistical design was completely randomized with the successive dates of foliage sampling treated as a split plot in time and crown position treated as a split plot in space. Periodic annual basal area and volume growth were analyzed by analysis of variance for unequal sample size (Steel and Torrie 1960a). Analysis of covariance for basal area and volume growth was rejected because of a lack of correlation between initial basal area and subsequent increments. Height growth, foliar N concentration and content, and crown biomass were also analyzed by analysis of variance. The whole plot experimental errors in these analyses have only a few degrees of freedom; therefore, differences in means must be substantial to be significantly different. Tukey's w-procedure was used to isolate differences among treatment means (Steel and Torrie 1960b). The level of significance is 5 percent unless otherwise given.

Measurement

The diameter of all trees was measured to the nearest 0.1 inch. On each 1/5-acre plot, 12 to 15 trees were measured with optical dendrometers so a volume table could be constructed for that plot. These trees encompassed the range of size on each plot but were selected to sample a higher proportion of the larger trees since larger trees have the most volume. Height of the remaining trees was measured to the nearest 0.5 foot.

Volumes (V) for trees not measured with a dendrometer were calculated by use of diameters (d) and heights (h) from equations of the form,

$$\ln V = a + b (\ln d) + c (\ln h);$$

where ln is the symbol for natural logarithms. The constant a and coefficients b and c were determined separately for each plot by fitting a stepwise regression to the values for the trees measured with a dendrometer. Measurements were made before the start of the first growing season. Four growing seasons later, the same trees were remeasured with optical dendrometers. All remaining trees were measured for diameter and height, and volumes were calculated from new volume equations for each plot by the above procedure. Periodic annual height, basal area, and volume growth were determined from differences in height, basal area, and volume based on trees that were alive when the second measurements were made.

Dead and down woody fuel loads were measured by size class with the planar intersect technique (Brown 1974). Before and after burning, the duff depth at 12 points and four 49-foot planar intersect lines were measured on each plot.

During the burns, samples for moisture content were collected hourly from the dead and down fuel classes at locations within the treatment areas. These samples were sealed in metal cans and weighed immediately after transport to the laboratory. Samples were then dried to constant weight at 160 °F, and moisture levels were calculated as percent dry weight. Average moisture for the duff layers is given in table 1.

Flame characteristics were observed at 5- to 10-minute intervals, and weather conditions were recorded every 30 minutes during the burning period (table 2).

Table 1—Average duff moisture and standard deviation during prescribed burns in ponderosa pine in central Oregon

Treatment	Date	Upper duff	Lower duff
		Percent	
Moderate fuel consumption:			
1st burn	May 15, 1979	23.5 ± 21.6	63.8 ± 46.9
2d burn	May 16, 1979	13.0 ± 6.8	20.3 ± 2.1
High fuel consumption:			
1st burn	June 12, 1979	8.6 ± 2.6	11.4 ± 2.7
2d burn	June 12, 1979	11.3 ± 1.9	9.4 ± 1.2

Table 2—Weather and fire behavior during prescribed burns in ponderosa pine in central Oregon

Treatment	Temperature	Relative humidity	Wind-speed[1]	Flame length	Flame height	Rate of spread
	°F	*Percent*	*Miles per hour*	*Inches*	*Inches*	*Feet per minute*
Moderate fuel consumption:						
1st burn	72-47	33-74	0-7	12	9	2.0
2d burn	59-45	38-67	0-8	22	18	4.6
High fuel consumption:						
1st burn	51-46	53-67	2-7	24	16	2.0
2d burn	40-36	50-84	0-3	41	31	1.0

[1]Measured 4.5 feet above the ground.

Samples for foliar N analysis were obtained from one dominant or codominant tree on each plot. Foliage was sampled from the upper, middle, and lower crowns. A composite sample across all needle ages was obtained from each crown section to access changes within the entire crown. Samples were taken at about 3-week intervals during the first and second growing seasons and once at the end of the fourth growing season after burning. Foliar N concentration was determined in duplicate on 1979 and 1980 foliage by semimicro Kjeldahl procedure (American Society of Agronomy 1965) on air-dry samples ground in a Wiley mill to pass through a 40-mesh sieve.[2] The Kjeldahl procedure was not modified to include nitrate or nitrite because these forms were not found in measurable amounts in these samples. The 1982 samples were analyzed by a lithium sulfate-hydrogen peroxide-sulfuric acid digestion procedure (Parkinson and Allen 1975), followed by segmented flow colorimetry on a Technicon AutoAnalyzer II (1978).

Needle mass and N content of the foliage were calculated for the first growing season after the fire (Landsberg and Cochran 1980). Those calculations were repeated at the end of the fourth growing season with new measurements for height, diameter, height to live crown, and foliar N concentration.

Results and Discussion

Woody Fuel Consumption

Dead and down woody fuel was significantly reduced in both burn treatments (table 3). Reductions in woody fuel averaged 34 and 37 percent for the two moderate fuel consumption units; a mean fuel load of 7.9 tons/acre remained after the fire. The high fuel consumption units had much greater fuel reductions; 68 and 70 percent of all dead and down woody fuel was consumed, leaving an average fuel load of 4.7 tons/acre.

Table 3—Woody fuel load, depth of duff, and standard deviation before prescribed burning and average reduction after burning in ponderosa pine in central Oregon

Treatment	Woody fuel load: Before burning	Woody fuel load: Reduction after burning	Depth of duff: Before burning	Depth of duff: Reduction after burning
	Tons per acre	*Percent*	*Inches*	*Percent*
Control	17.8 ± 3.7	—	4.6 ± 0.9	—
Moderate fuel consumption	12.2 ± 7.0	35	2.5 ± .7	49
High fuel consumption	15.0 ± 5.8	69	3.9 ± 1.6	88

[2]Mention of trade names does not imply endorsement by the U.S. Department of Agriculture.

Duff Consumption

Duff consumption ranged from 28 to 68 percent in the moderate fuel consumption burns, and from 76 to 93 percent in the high fuel consumption burns. Duff depths after burning were 0.6 to 1.7 inches for the moderate fuel consumption units and 0.3 to 0.8 inch for the high fuel consumption units. These reductions and depths were significantly different ($P \leq 0.01$).

Moisture content of lower duff on the moderate fuel consumption plots was 20 to 68 percent, and the reductions we obtained were similar to the 42-percent reduction in surface and ground fuels obtained by Sackett (1980) while burning in ponderosa pine stands at night with a duff moisture of 28 percent. In contrast, lower duff moisture content on the high fuel consumption units averaged 9 and 11 percent, and reductions were comparable to those obtained in other studies. Sackett (1980) obtained a reduction of 63 percent in surface and ground fuels when ground fuels averaged 10 to 19 percent moisture. Harrington (1981) obtained needle and humus reductions of 33 to 77 percent in open and closed ponderosa pine canopies with lower duff moistures of 21 to 88 percent.

Reductions of all dead and down fuels, including duff, were close to the objectives set forth in the study plan.

Foliar Nitrogen Concentration

There were no differences in foliar N concentration among the control, the moderate fuel consumption areas, and the high fuel consumption areas during the study period. If there had been changes in the amount or availability of N to the trees, changes would be expected in foliar N levels (van den Driessche 1974). Generally, foliar N concentrations were low, falling to 0.8 percent during needle elongation and rising to 1.2 percent at the end of the growing seasons. These concentrations of foliar N during needle elongation are below the critical level of 0.9 percent (Powers 1980), but they are uniform throughout the treatment areas. If the different needle ages had been analyzed separately, subtle differences might have been detected. For this research, however, composite sampling of all needle ages was used to access changes within the entire crown.

Significant differences were found in foliar N concentration for both crown position and date of sampling (table 4). Generally, lower crown foliage was expected to have lower concentrations of N. This was true in 1979 ($P \leq 0.01$). In 1980, however, the N concentration in each position was significantly different from that in every other crown position ($P \leq 0.01$); the midcrown foliage had the lowest concentration. In 1982, there were no significant differences in foliar N concentration with crown position.

A composite curve and its equation giving foliar N concentration in the midcrown on the sampling date were developed earlier (Landsberg and Cochran 1980). That curve and a curve developed from 1980 midcrown samples are shown in figure 1. Because there was no significant difference with treatment, all treatments were pooled; however, there could be differences that are not apparent because of the limited number of degrees of freedom. The curves are similar in form, and they show the rapid decline in foliar N concentrations that occurs concurrently with bud burst and needle elongation, and an increase in N toward the end of the growing season.

Table 4—Foliar nitrogen concentration by date and crown position[1] in ponderosa pine in central Oregon

Date	Upper crown	Midcrown	Lower crown
		Weight percent	
1979:			
May 7	1.04 a	1.01 a	0.89 b
June 5	—	.83 a	.95 b
June 20	.89 a	.92 a	.84 b
July 5	—	.86 a	.97 b
July 27	.98 a	1.02 a	.87 b
August 10	.97 a	1.02 a	.84 b
September 20	—	1.15 a	1.11 b
1980:			
May 20	1.05 c	.97 d	.99 e
June 19	.99 c	.89 d	.94 e
July 23	1.06 c	.92 d	.97 e
August 14	1.05 c	.94 d	1.01 e
September 17	1.04 c	.99 d	1.01 e
1982:			
October 6	1.09 f	1.08 f	1.06 f

[1]Crown positions with different letters are significantly different ($P \leq 0.01$) from other crown positions within that year.

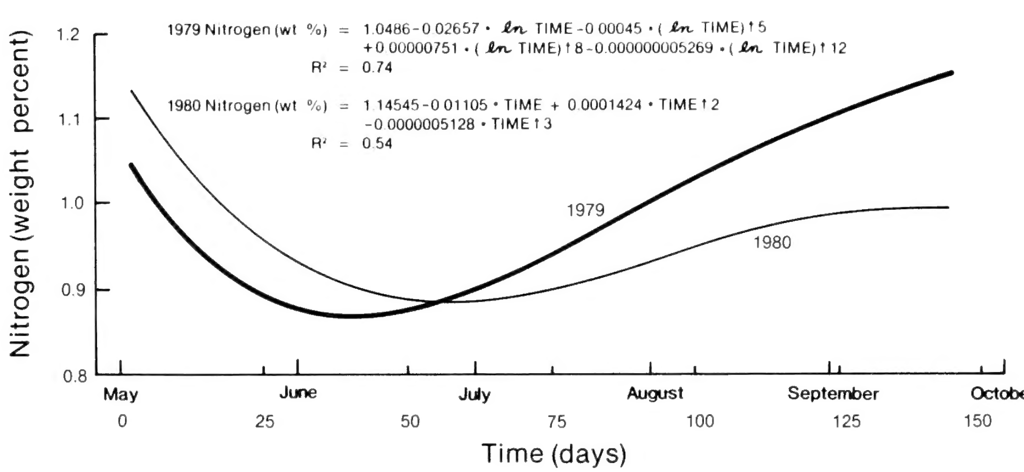

Figure 1.—Midcrown foliar nitrogen concentrations in 1979 and 1980.

Foliar Nitrogen Content

Landsberg and Cochran (1980) reported 4- and 20-percent reductions in crown needle mass in the moderate fuel consumption and high fuel consumption areas, respectively, because of crown scorch. This reduction in lower crown would be similar to that caused by pruning. Dahms (1954), Gordon (1959), and Barrett (1968) found no effect of pruning in ponderosa pine when less than 25 percent of the live crown was removed. Therefore, this reduction in lower crown caused by scorching probably would not affect tree growth to any great extent.

At the end of the fourth growing season, however, there was still significantly less needle mass in the burned areas (table 5). A small part of this may be a residual effect of crown scorch in the high fuel consumption units, but height growth in the moderate fuel consumption units would have increased the crown ratio to the preburn value. This loss of needle mass produced a concomitant reduction in foliar N content. Foliar N content was reduced 14 percent in the moderate fuel consumption area and 33 percent in the high fuel consumption area. Foliar needle mass and foliar N content four growing seasons after burning both correlate with post-burn reductions in duff depth (fig. 2).

Table 5—Needle mass and nitrogen content of ponderosa pine foliage at end of 1st and 4th growing seasons after prescribed burning, central Oregon

	Needle mass		Foliar nitrogen	
Treatment	First growing season	Fourth growing season	First growing season	Fourth growing season
	Pounds per acre			
Control	8,800	9,600	96	105
Moderate fuel consumption	8,500	8,600	94	90
High fuel consumption	7,100	6,500	79	70

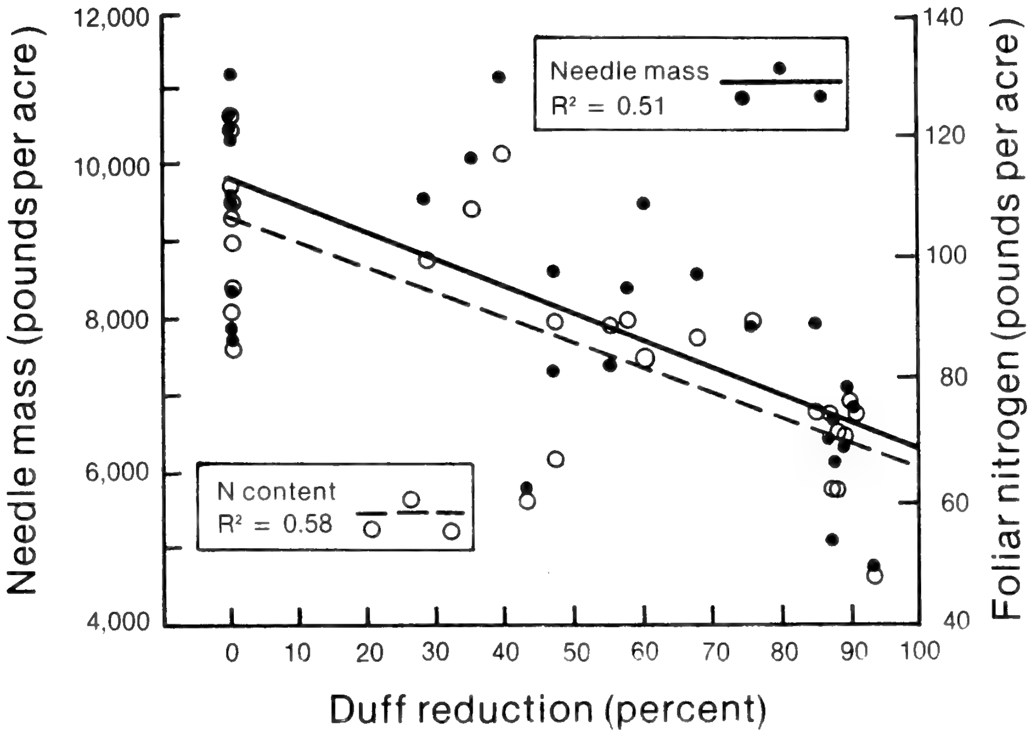

Figure 2 —Foliar needle mass and foliar nitrogen content four growing seasons after burning correlate with duff reduction

Growth and Yield

A significant ($P \leq 0.10$) reduction was found in all periodic annual growth increments: height, basal area, and volume (table 6). Height growth was depressed 8 percent in the moderate fuel consumption area and 18 percent in the high fuel consumption area for trees alive four growing seasons after burning. Basal area growth was reduced by 16 percent in the moderate fuel consumption area and 28 percent in the high fuel consumption area, and volume growth was reduced by

Table 6—Periodic annual increments for ponderosa pine over 4 growing seasons, central Oregon

Treatment	Height growth	Basal area growth per acre	Volume growth per acre
	Feet	*Square feet*	*Cubic feet*
Control	1.2	3.2	117
Moderate fuel consumption	1.1	2.7	91
High fuel consumption	1.0	2.3	91

23 percent in both areas. Periodic annual increments are significantly correlated with reductions in duff depth (fig. 3) and with reductions in foliar N content (fig. 4). As duff depth was reduced, periodic annual increments declined; and as foliar N content declined, periodic annual increments were reduced. Reduction of duff depth and the concomitant reduction of foliar N content play a part in the reduction of periodic annual increments. The volume growth reduction in the moderate fuel consumption area is the same as that in the high fuel consumption area.

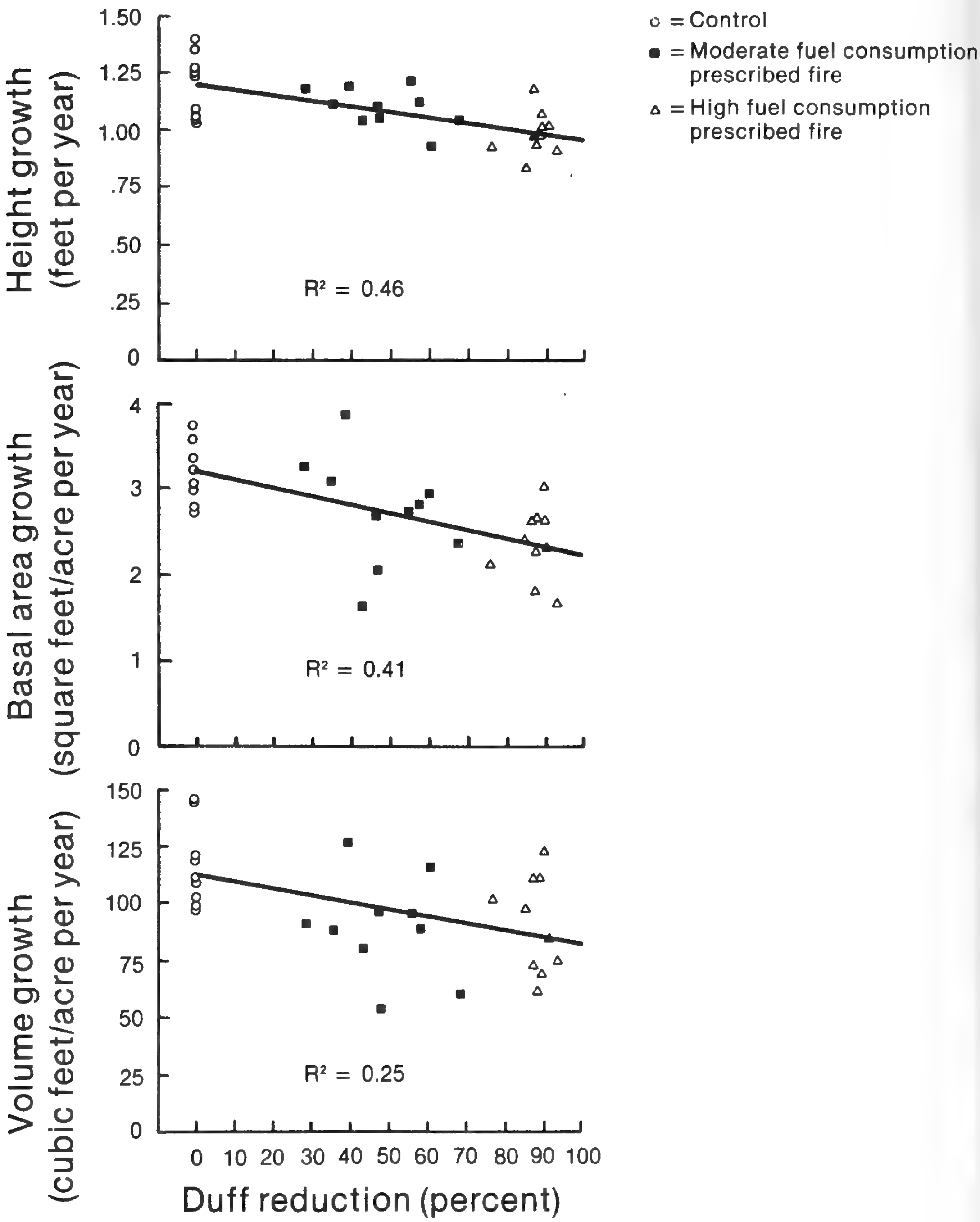

Figure 3.—Periodic annual growth in height, basal area, and volume were reduced four growing seasons after burning as duff reduction increased.

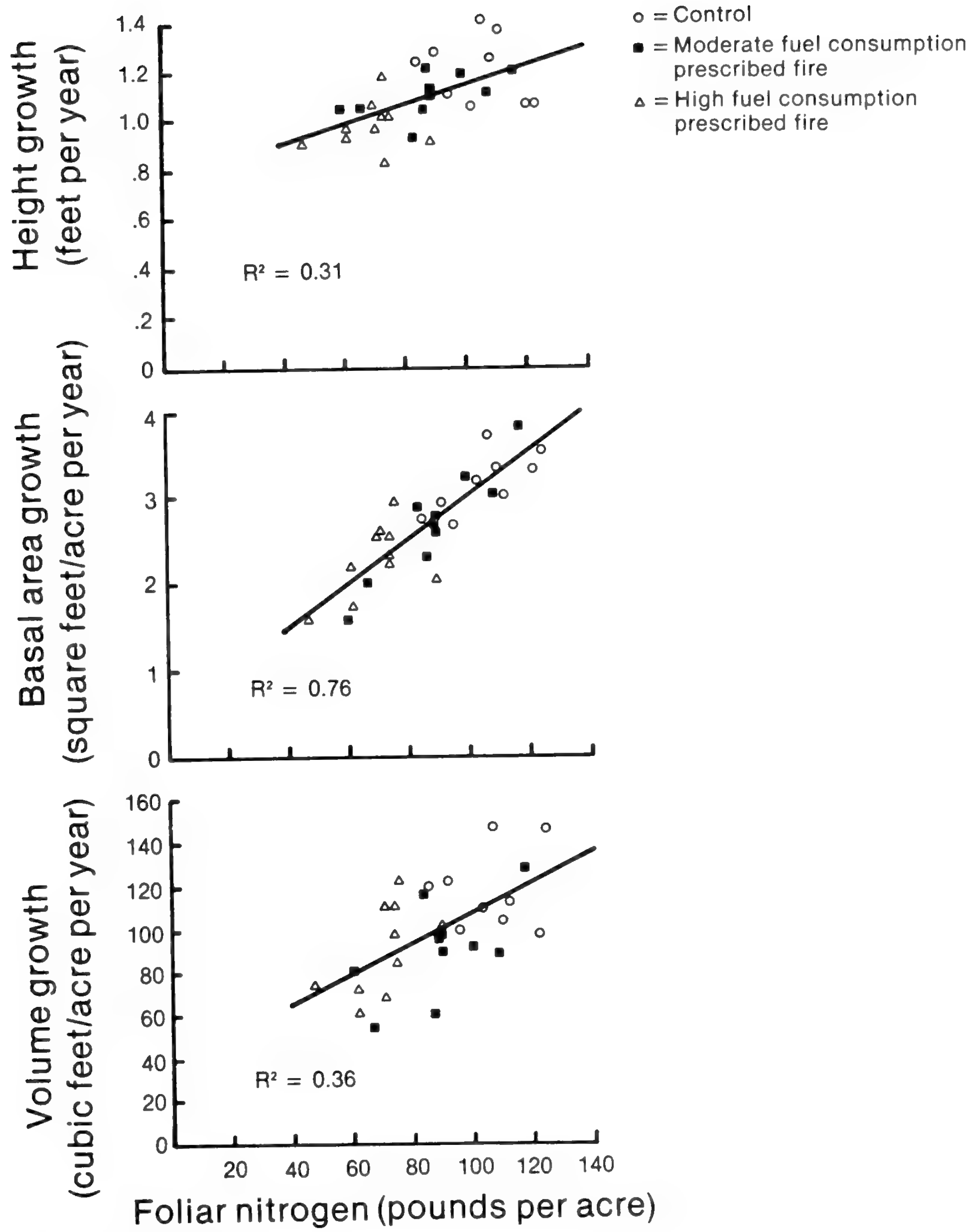

Figure 4.—Periodic annual growth in height, basal area, and volume correlates with foliar nitrogen content four growing seasons after burning

Other research on the effects of prescribed fire on growth of ponderosa pine has produced conflicting results. Some researchers have reported increases in growth with burning; others have found reductions as we did. Lynch (1959) found reductions in diameter growth of 30 to 50 percent in trees that had 50 percent crown scorch after burning, but height growth was not affected.

In contrast, increases in both height and diameter growth were found in northeast Washington ponderosa pine six growing seasons after burning that produced 46 percent crown scorch (Morris and Mowat 1958). The diameter growth of trees on burned areas exceeded that on unburned areas by 36 percent after six growing seasons when results were adjusted to initial diameter through analysis of covariance, whereas the height growth on burned areas exceeded that on unburned areas by 7 percent.

The results of Morris and Mowat (1958) seem to contradict our results, but the differences may be due to the drastic reduction in competition resulting from their prescribed fires. Their work was done in a ponderosa pine thicket with 2,550 stems/acre before burning and 830 stems/acre six growing seasons later, and the numbers of stems in the unburned areas dropped from 3,260 stems/acre to 2,900 over the 6-year period. Our research area had 240 stems/acre.

Mortality

Mortality at the end of the fourth growing season was 1.1 and 3.7 percent of the initial basal area in the moderate fuel consumption and the high fuel consumption units, respectively. Mortality was a result of burning and was confined to the smaller trees. The area was overstocked so some mortality was acceptable. No mortality occurred on the control plots. Some of the cambium on one side of some trees in the burn units, principally the high fuel consumption units, died. This may produce additional mortality or a reduction in volume in the future.

Conclusions

Two distinct levels of fuel consumption were obtained by prescribed fire. Burning with appropriate fuel moisture conditions produced an average reduction of 35 percent in woody fuel and an average reduction of 49 percent in duff depth in the moderate fuel consumption units, whereas in the high fuel consumption burns the woody fuel load was reduced 69 percent and the duff depth 88 percent.

No differences were found in foliar N concentrations after burning.

Crown needle mass and foliar N content were significantly reduced by the fires and declined to even lower levels four growing seasons later.

Periodic annual growth in height, basal area, and volume was significantly reduced by the prescribed fires.

Prescribed burning needs further evaluation in larger studies conducted over a longer time in a variety of ponderosa pine communities to determine long-term effects on tree growth.

Metric Conversion Factors

°F = (°C × 9/5) + 32
1 mile = 1.61 kilometers
1 acre = 0.405 hectare
1 foot = 0.3048 meter
1 inch = 2.54 centimeters
1 ton/acre = 0.445 tonne/hectare
1 square foot/acre = 0.229568 square meter/hectare
1 cubic foot/acre = 0.069972 cubic meter/hectare
1 chain = 20.1168 meters

Literature Cited

American Society of Agronomy, Inc. Semimicro-Kjeldahl method. in. Black, C. A., ed. Methods of soil analysis, part 2, chemical and microbiological properties. Madison, WI; **1965:** 1171-1175.

Barrett, James W. Pruning of ponderosa pine..effect on growth. Res. Pap. PNW-68. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1968.** 9 p.

Barrett, James W. Height growth and site index curves for managed, even-aged stands of ponderosa pine in the Pacific Northwest. Res. Pap. PNW-232. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station; **1978.** 14 p.

Brown, James K. Handbook for inventorying downed woody material. Gen. Tech. Rep. INT-16. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; **1974.** 24 p.

Dahms, Walter G. Growth of pruned ponderosa pine. Journal of Forestry. 52(6): 444-445; **1954.**

DeBell, D. S.; Ralston, C. W. Release of nitrogen by burning light forest fuels. Soil Science Society of America Proceedings. 34: 936-938; **1970.**

Gordon, Donald T. Ten-year observations on pruned ponderosa and Jeffrey pine. Res. Note 153. Berkeley, CA: U.S. Department of Agriculture, Forest Service, Pacific Southwest Forest and Range Experiment Station; **1959.** 4 p.

Harrington, Michael G. Preliminary burning prescriptions for ponderosa pine fuel reductions in southeastern Arizona. Res. Note RM-402. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; **1981.** 7 p.

Isaac, Leo A.; Hopkins, Howard G. The forest soil of the Douglas fir region, and changes wrought upon it by logging and slash burning. Ecology. 18(2): 264-279; **1937.**

Knight, H. Loss of nitrogen from the forest floor by burning. Forestry Chronicle. 42(2): 149-152; **1966.**

Landsberg, J. D.; Cochran, P. H. Prescribed burning effects on foliar nitrogen content in ponderosa pine. In: Proceedings, 6th conference on fire and forest meteorology; 1980 April 22 to 24; Seattle, WA. Washington, DC.: Society of American Foresters; **1980:** 209-213.

Leyton, L. The growth and mineral nutrition of spruce and pine in heathland plantations. Inst. Pap. 31. Oxford, England: Oxford University Imperial Forestry Institute; **1954.** 109 p.

Leyton, L.; Armson, K. A. Mineral composition of the foliage in relation to the growth of Scots pine. Forest Science. 1(3): 210-218; **1955.**

Lynch, Donald W. Effects of a wildfire on mortality and growth of young ponderosa pine trees. Res. Note 66. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Forest and Range Experiment Station; **1959.** 8 p.

Morris, William G.; Mowat, Edwin L. Some effects of thinning a ponderosa pine thicket with a prescribed fire. Journal of Forestry. 56(3): 203-209; **1958.**

Nissley, Steven Daniel. Nutrient changes after prescribed surface burning of Oregon ponderosa pine stands. Seattle, WA: University of Washington; **1978.** 85 p. M.S. thesis.

Parkinson, J. A.; Allen, S. E. A wet oxidation procedure suitable for the determination of nitrogen and mineral nutrients in biological material. Communications in Soil Science and Plant Analysis. 6(1): 1-11; **1975.**

Powers, Robert Field. Nutritional ecology of ponderosa pine *(Pinus ponderosa* Laws.) and associated species. Berkeley: University of California; **1980.** 234 p. Ph. D. dissertation.

Raison, R. J. Modification of the soil environment by vegetation fires, with particular reference to nitrogen transformations: a review. Plant and Soil. 51: 73-108; **1979.**

Sackett, Stephen S. Reducing natural ponderosa pine fuels using prescribed fire: two case studies. Res. Note RM-392. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station; **1980.** 6 p.

Steel, Robert G. D.; Torrie, James H. Analysis of variance V: Unequal subclass numbers. In: Principles and procedures of statistics. New York: McGraw-Hill Book Co., Inc.; **1960a:** 252-265.

Steel, Robert G. D.; Torrie, James H. Tukey's *w*-procedure. In: Principles and procedures of statistics. New York: McGraw-Hill Book Co., Inc.; **1960b:** 109-110.

Technicon AutoAnalyzer II. Individual/simultaneous determination of nitrogen and/or phosphorus in BD acid digests. Industrial Method 329-74W/B. Tarrytown, NY: Technicon Industrial Systems; **1978.** 9 p.

van den Driessche, R. Prediction of mineral nutrient status of trees by foliar analysis. Botanical Review. 40(3): 347-394; **1974.**

Vitousek, Peter M.; Gosz, James R.; Grier, Charles C. [and others]. A comparative analysis of potential nitrification and nitrate mobility in forest ecosystems. Ecological Monographs. 52(2): 155-177; **1982.**

Volland, Leonard A. Plant associations of the central Oregon pumice zone. R6-ECOL-104-1982. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Region; **1982.** p. 60-b.

Wright, T. W. Forest soils of Scotland. Empire Forestry Review. 38: 45-53; **1959.**

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