

Forest Floor and Soil Nutrients Five Years after Urea Fertilization in a Grand Fir Forest

Abstract

Five years after thinning and fertilization with 350 kg ha⁻¹ of N as urea in an interior Pacific Northwest grand fir (*Abies grandis* (Dougl.) Forbes) forest, we measured concentrations of total carbon (C), nitrogen (N), phosphorus (P), sulfur (S), and potassium (K) in the forest floor and upper 30 cm of soil. Effect of fertilization and thinning treatments on available N, P, S, and K in the soil was determined by bioassay with barley as a test plant in a growth chamber experiment. Field treatment combinations were: control; not thinned, fertilized (NT-F); thinned, not fertilized (T-NF); and thinned, fertilized (T-F). Total N concentration of the forest floor was substantially and significantly greater for the NT-F treatment than the other three treatments. This finding supported results of other studies that the forest floor retained a substantial portion of applied N. We did not detect any differences among thinned and fertilized treatments and the control for concentrations of soil total C, N, P, K, or S. Also, availabilities of N, P, and K in soil from thinned and fertilized treatments were the same as the control. Thus, there was no detectable effect of N fertilization on total or available N after 5 years. The salient feature of the bioassay trial was reduced availability of soil S with the NT-F treatment compared to the control and the T-NF treatment. Availability of S was also lower for the TF treatment compared to T-NF treatment. Application of a large quantity of N at this site with extant low levels of soil S further depressed S availability. Nitrogen fertilization should be supplemented with S in sites where soil S levels are comparable to those we observed (0.008%).

Introduction

Forest fertilization has become an attractive option for forest managers to offset nutrient limitations in soils of forested sites and to maintain or enhance growth of coniferous species (Moore 1988, Chappell et al. 1992, Miller et al. 1992). Periodic annual increment in unthinned Douglas-fir (*Pseudotsuga menziesii* (Mirbel) Franco) stands of western Oregon and Washington responded to nitrogen (N) fertilization with a 2.9 to 6.0 m³ ha⁻¹ yr⁻¹ increase in growth at 224 kg ha⁻¹ of N and 3.8 to 6.2 m³ ha⁻¹ yr⁻¹ increase at 448 kg ha⁻¹ of N (Peterson and Hazard 1990). Enhancement of growth and yield is the most common reason to fertilize forests, but fertilization also shows promise as a means of ameliorating the effects of insects such as the western spruce budworm (*Choristoneura occidentalis* Freeman) on tree vigor and growth (Mason et al. 1992). Wickman et al. (1992) found that fertilization with 350 kg ha⁻¹ N as urea significantly reduced defoliation, increased biomass of shoots, and increased radial growth and height growth of grand fir (*Abies grandis* (Dougl.) Forbes). Height growth of fertilized trees was almost double that for unfertilized. The integrated response was an improvement of 140% in growth efficiency as measured by wood production per

unit of leaf area on thinned and fertilized plots (Waring et al. 1992). By the fifth year after treatment, radial growth of grand fir with fertilized treatments was still significantly greater than the control (Wickman et al. 1992), suggesting protracted enhancement of N availability.

Even though the importance of a balanced supply of nutrients for plant growth is well understood, forest fertilization often involves application of only N. Rates sometimes exceed 300 kg ha⁻¹ of N. Application of a single nutrient such as N has the potential to create limitations of other nutrients and to aggravate existing nutrient limitations (Stalfelt 1972). Even if other nutrients are not limiting, but in marginal supply, the addition of a large amount of a single nutrient such as N may create deficiency (nutrient stress) of one or more of the other nutrients (Klemmedson and Ferguson 1973, Klemmedson and Tiedemann 1995).

The importance of adequate soil sulfur (S) for tree nutrition and growth has been documented in studies by Cochran (1978), Edmonds and Hsiang (1987) and Blake et al. (1990)). In the interior Pacific northwest, with some soils already shown to be deficient in S (Klock et al. 1971, Tiedemann and Berndt 1972, Tiedemann and Klock 1977),

fertilization with N has the potential to aggravate extant S deficiencies. Potassium (K) availability may also be adversely influenced by N fertilization (Mika et al. 1992).

The study site established by Mason et al. (1992), Waring et al. (1992) and Wickman et al. (1992) provided us an opportunity to examine effects of thinning and fertilization with 350 kg ha⁻¹ of N as urea on concentrations of soil and forest floor nutrients five years after fertilization. We also wanted to determine if N fertilization at this rate influenced availabilities of phosphorus (P), S, or K after five years.

Methods

Description of the Study Area

A detailed description of the study area and rationale for treatments are found in Mason et al. (1992). Briefly, the study was conducted in a mixed conifer forest dominated by grand fir with scattered ponderosa pine (*Pinus ponderosa* Laws.) and Douglas-fir on the Malheur National Forest near Burns, Oregon. Elevation is approximately 1850 m. Annual precipitation is approximately 50 cm with most occurring as snowfall during the winter (Tiedemann and Higgins 1989). Soils are of the clayey, mixed, frigid family of Andic Xerochrepts and loamy-skeletal, mixed, frigid family of Lithic Argixerolls (Carlson 1974). These two soil types are intermixed throughout the study area. For both soil types, surface soils are gravelly or silt loams with pH from 5.6 to 6.5 that vary in depth from 15 to 30 cm with flat and angular rock fragments comprising 10 to 30%. Subsoils are gravelly or cobbly clay loam with pH 5.6 to 6.5, varying from 15 to 60 cm in thickness. Bedrock is hard basalt and andesite with tuffaceous interflow material (Carlson 1974). Understory vegetation in unthinned stands consisted mainly of small herbs of the Ericaceae and Orchidaceae families (Personal communication, Dr. Richard Waring, Professor, Forest Science, Oregon State University, Corvallis). Stand openings promoted development of bromegrass (*Bromus vulgaris* (Hook.) Shear) and shrubs such as rose (*Rosa gymnocarpa* Nutt.), pachistima (*Pachistima myrsinites* (Pursh) Raf.) and currant (*Ribes lacustre* (Pers.) Poir). Elk sedge (*Carex geyeri* Boott) and pinegrass (*Calamagrostis rubescens* Buckl.) were also common in both dis-

turbed and undisturbed stands. Canadian and bull thistle (*Cirsium* spp.) were abundant in thinned stands.

Experimental Design and Treatments

Four square blocks, each 2.6 ha in size, were established on the study site. In summer 1984, a random one-half of each block was thinned to average tree spacing of 5.5 m, with emphasis on removal of trees smaller than 12.7 cm dbh for grand fir and 17.8 cm dbh for ponderosa pine. Trees were felled and left in place. In the fall of 1984, a random half of each thinned and unthinned plot was fertilized with 350 kg ha⁻¹ of N as urea. This resulted in the following array of treatments on each of the four blocks:

1. Control (not thinned, not fertilized)
2. Not thinned, fertilized (NT-F)
3. Thinned, not fertilized (T-NF)
4. Thinned, fertilized (T-F)

Field Sampling

In late fall 1989, we collected forest floor and soil samples at 3 random locations on each plot of each block. Samples were collected at specified distances on a diagonal line across the plot from a random start with the plot corner as the random choice for starting point. At each location, forest floor samples were collected to mineral soil in a 400 cm² frame. No attempt was made to separate the forest floor into organic layers. Soils were collected at depths from 0-10 cm, 10-20 cm, and 20-30 cm with a bucket auger. No volume/weight measurements were taken. Samples were oven-dried to constant weight at 70°C. At each sample location, a bulk soil sample to 20 cm was collected for bioassay determination of nutrient availability. These samples were air-dried to constant weight in a well-ventilated greenhouse.

We did not measure forest floor depth or mass because this was beyond the scope of the experiment.

Chemical Analyses

Forest floor and soil samples for the three sample locations were composited by plot for each depth and analyzed for concentrations of total carbon (C), N, P, S, and K. Compositing samples enabled us to reduce costs for analyses. Compared

to single samples on each plot, compositing enabled us to incorporate point-to-point variability and, thus, to provide greater precision in estimate of plot means (Binkley and Vitousek 1989). Chemical analyses for forest floor and soils were as follows: total C by dry combustion using a high-frequency induction furnace (Nelson and Sommers 1982); total N by the Kjeldahl procedure (Bremner and Mulvaney 1982); total P on forest floor samples by magnesium nitrate dry ashing followed by vanadate-molybdate yellow color development (Chapman and Pratt 1961); total P for soils by hydrofluoric acid digest followed by ammonium molybdate-ascorbic acid color development (Bowman, 1988); total S was by dry combustion in a high-frequency induction furnace (Tiedemann and Anderson 1971); and total K by perchloric acid digestion followed by ICP spectroscopy (Barnes 1977).

Assessment of Nutrient Availability

A bioassay technique described by Jenny et al. (1950) was used to determine availabilities of N, P, S, and K using soil from each field treatment. 'Mica' barley (*Hordeum vulgare* L.) grown from certified seed was used as the test plant. The 3 field samples collected from each plot served as growth chamber replications. Soils were air-dried and sieved to pass a 2 mm screen. Each pot contained 400 g of soil. The following nutrient treatments were applied to the pots:

1. Check—no added nutrients
2. N₀—no nitrogen (P, K, and S added)
3. P₀—no phosphorus (N, K, and S added)
4. S₀—no sulfur (N, P, and K added)
5. K₀—no potassium (N, P, and S added)
6. Full—N, P, S, and K added

Nitrogen was added as ammonium nitrate (NH₄NO₃) at a rate equivalent to 300 kg ha⁻¹ of N; phosphorus as calcium ortho-phosphate (Ca(H₂PO₄)₂·H₂O) at 200 kg ha⁻¹ of P; sulfur as calcium sulfate (CaSO₄·2H₂O) at 100 kg ha⁻¹ of S and potassium as potassium chloride (KCl) at 100 kg ha⁻¹ of K. Barley was grown for 16 weeks at alternating day-night temperatures of 24/18°C with a 12-hour day length. Lighting was provided by full spectrum fluorescent bulbs with wavelength emission comparable to that of sunlight. At the end of the trial, plants were harvested at the soil

surface, oven-dried at 70°C to constant mass, and weighed.

We elected to use the bioassay test for nutrient availability, rather than chemical extraction, because we feel that it more accurately portrays availability of nutrients than does chemical extraction. Bioassay trials were originally developed by Mitscherlich, an early pioneer in soils research, before chemical testing was available. This type of test was refined by Jenny et al. (1950) and is an established means of assessing nutrient availability (Binkley and Vitousek 1989, Harrison and Helliwell 1979). Barley is not intended as a surrogate to indicate availability of nutrients to native tree species on the site—rather, it is a tool to assess availability of individual nutrients in the soil. We used barley as a test plant because of genetic uniformity and rapid growth rate whereby the entire soil mass is explored by plant roots during the 6 weeks of the test.

Statistical Analyses

The field design for the study was a split-plot analysis of variance in which thinning treatments were the major plots while fertilization treatments were the sub-plots. Differences among thinned and fertilized treatments for soil nutrient concentrations were analyzed using a split-split plot design with depths as the second split. Design for the forest floor statistical analysis was the same except there was no split for depth. A similar design was used for the bioassay trial except that the 3 field collection locations that served as growth chamber replicates were considered to be subsamples and growth chamber bioassay treatments were treated as another split in the analysis. Mean comparisons were made with the LSD test (Carmer and Swanson 1971). Unless otherwise indicated, significance level is P<0.05 for main effects and interactions in the ANOVA and for LSD means comparisons.

Results and Discussion

Concentrations of total C, N, and S from the control plots were higher in the forest floor than in soil (Table 1). Differences among soil depths were significant (P<0.001) for total C, N, and P. The soil depth X fertilizer/thinning treatment interaction was not significant for any constituent. Thus, depth relationships for soil nutrient data presented for the control plots are comparable to those for

TABLE 1. Concentrations (percent by weight) of total nutrients in forest floor and soil from the control treatment.

Constituent	Forest floor	Soil 0-10 cm	Soil 10-20 cm	Soil 20-30 cm
Total C	31.4 ¹	1.94 ^{a2}	1.03 ^b	0.79 ^b
Total N	0.71	0.09 ^a	0.06 ^b	0.05 ^b
Total P	0.08	0.11 ^a	0.09 ^{ab}	0.06 ^b
Total S	0.07	0.008 ^a	0.008 ^a	0.008 ^a
Total K	0.20	0.27 ^a	0.28 ^a	0.27 ^a

¹ Forest floor values were not compared statistically to soil values.

² Values for soil depths within an individual nutrient with the same lowercase letter are not significantly different at $P < 0.05$.

the treated plots. Total C in soils from the control plots declined from 1.94 % in the surface 0 to 10 cm to 0.79% in the 20 to 30 cm depth (Table 1). Total N and total P followed this same trend. Our values for total N are near the lower end of the range reported by Geist and Strickler (1978) for volcanic ash soils with mixed conifer vegetation and the depth relationships are similar. Total N and S values are also comparable to those of Tiedemann and Klock (1977) for a grand fir forest developed on recent volcanic ash. In those

studies, it was concluded that soil N and S were deficient to the point that they would likely limit plant growth. That conclusion was reinforced by bioassay studies by Klock et al. (1971). It is likely, therefore, that N and S are both limiting at the present study site.

Forest Floor Nutrient Responses

Effects of thinning in the ANOVA were not significant for any measured nutrient constituent in the forest floor. This corresponds with results of Edmonds and Hsiang (1987) who compared N concentrations in forest floor of 35 thinned sites with that in 85 unthinned sites and found no significant difference.

Total N concentration of the forest floor was the only nutrient constituent influenced by fertilization, and the thinning X fertilization interaction was significant. Significantly higher N concentration in the NT-F treatment (0.92%) than in the other 3 treatments (0.71 to 0.77%) was responsible for the significant thinning X fertilization interaction (Table 2). Several interacting factors could account for higher N concentration in the forest floor of the NT-F treatment. Foliar N and litter N concentrations have both been shown to increase after fertilization (Turner 1977, Binkley and Reid 1985). Post-fertilization needle-fall

TABLE 2. Comparison of forest floor and soil nutrient concentrations (percent by weight) among thinned and fertilized treatments and the control. Soil nutrient values are the average of 0-10, 10-20, and 20-30 cm depths.

Constituent	Control	Not thinned, fertilized (NT-F)	Thinned, not fertilized (T-NF)	Thinned, fertilized (T-F)
forest floor				
Total C	31.4 ¹	34.7	32.1	33.1
Total N	0.71 ^{a2}	0.92 ^b	0.76 ^a	0.77 ^a
Total P	0.08	0.08	0.07	0.07
Total S	0.07	0.08	0.07	0.06
Total K	0.20	0.15	0.16	0.17
soil				
Total C	1.26	1.56	1.40	1.47
Total N	0.07	0.07	0.08	0.08
Total P	0.09	0.08	0.08	0.08
Total S	0.008	0.008	0.008	0.008
Total K	0.27	0.27	0.34	0.30

¹ No comparison among means was made where the analysis of variance indicated that the main effect for thinning and fertilization treatments was not significant.

² Values with the same lowercase letter are not significantly different at $P < 0.05$.

would, thus, be expected to elevate litter (L or O_1) and, consequently, forest floor N concentrations. If this was a major factor responsible for greater N in the forest floor of NT-F treatment, we would have expected higher N concentrations with the T-F treatment as well. However, N concentrations with this treatment were the same as the control and the T-NF treatments. A more plausible explanation may be that the forest floor acts as a sink for applied nutrients as suggested by Fenn et al. (1991) where C/N ratios are large ($C/N = 44$ in the forest floor of our study). Up to 50% of applied N may be retained by the forest floor (Axellson 1985, Nason and Myrold 1992). Disturbance during thinning the T-F treatment may have reduced the effectiveness of the forest floor to retain fertilizer N and may explain the difference in total N concentration between this treatment and the NT-F treatment. Unfortunately, because we did not measure forest floor depth or mass, we cannot confirm this speculation.

Soil Nutrient Responses

There were no significant differences among thinned and fertilized treatments and the control (average of 3 soil depths) for soil total C, N, P, S, or K five years after fertilization (Table 2). Soil depths were averaged because the soil depth X fertilization/thinning treatment interaction was not significant for any nutrient.

Analysis of variance for bioassay of nutrient availability showed that differences among bioassay nutrient treatments and the interaction of bioassay nutrient treatments X fertilization/thinning treatments were highly significant ($P < 0.001$ and $P < 0.007$, respectively).

For thinning and fertilization treatments averaged, barley yields from the check treatment were significantly ($P < 0.01$) less than the full nutrient treatment, indicating a deficiency of one or more nutrients (Table 3). Yields for N_0 , S_0 , and K_0 bioassay nutrient treatments were all significantly less ($P < 0.01$) than yields of the full nutrient treatment indicating a possible deficiency of each of these nutrients (Table 3). There were no significant differences between the full nutrient treatment and P_0 , indicating that P supply was sufficient. The severity of deficiency of N, S, and K can be evaluated using the "relative yield" concept of Jenny et al. (1950). Percent relative yield (RY) was determined by dividing the yield for

TABLE 3. Barley yields (grams) and relative yields (percent) for 6 bioassay treatments averaged among thinning and fertilizer treatments.

Check	Bioassay treatment				
	N_0	P_0	S_0	K_0	Full
0.774 ^{a1}	0.836 ^a	4.117 ^d	1.601 ^b	3.641 ^c	4.300 ^d
	Relative yield (RY)				
	19 ²	96	37	85	

¹ Values with the same lowercase letter are not significantly different at $P < 0.01$.

² Relative Yield (RY) = $\frac{\text{Yield for the } X_i \text{ Treatment}}{\text{Yield for the Full Treatment}} \times 100$

individual treatments (i.e., N_0) by the yield from the full nutrient treatment and multiplying by 100. Relative yield for N (19%) was considerably below the level (30%) that Jenny et al. (1950) indicate will yield a measurable response in the field to addition of N fertilizer (Table 3). The relative yield for S was also low (37%) but probably not at a level that a field response to fertilization would occur (Jenny et al. 1950). Even though K_0 yields were significantly less than the full nutrient treatment, relative yield of 85% suggests that availability of this nutrient was not limited.

There were no significant differences in actual barley yields among field treatments for N_0 , P_0 , or K_0 (Table 4). Thus, it appears that high levels of urea-N fertilization did not have any effect on availabilities of those nutrients after 5 years. The decline of available N in soil from fertilized treatments to the same level as the control in 5 years supports results of Johnson et al. (1980). They found that within 161 days after urea fertilization at 200 kg ha⁻¹, soil mineral N levels (mostly ammonium-N) declined from 200 ppm to <10 ppm. Binkley (1986) also indicates that most soil N fertilization effects are short-lived. However, our results present a contrast to those of Binkley and Reid (1985) where N availability was twice as great in fertilized plots than unfertilized 18 years after application of ammonium nitrate.

Availability of S was influenced by N fertilization. Differences in S_0 yields among thinning and fertilization treatments were responsible for the bioassay treatment X field treatment interaction. Yield for S_0 from the NT-F field treatment was significantly less than yield for control and

TABLE 4. Barley yields (grams) for 6 bioassay treatments and 4 thinning and fertilizer field experiment treatments.

Field Experiment Treatment	Bioassay Treatment					
	Check	N ₀	P ₀	S ₀	K ₀	Full
Control	0.597 ^{a1}	0.718 ^a	4.104 ³	1.842 ^{2b}	3.756 ³	4.058 ⁴
NT-F	0.708 ^a	0.712 ^a	4.255 ³	1.233 ²	3.494 ³	4.265 ³
T-NF	0.913 ^a	0.928 ^a	4.039 ³	1.900 ³	3.444 ³	4.202 ³
T-F	0.876 ^a	0.985 ^a	4.074 ³	1.430 ^{2c}	3.874 ³	4.673 ^b

Statistical comparisons are for differences among field experiment treatments for individual bioassay treatments. Values within a column with the same lowercase letter are not significantly different at $P < 0.05$.

T-NF treatments (Table 4). Barley yield from the S₀ bioassay treatment for the field T-F treatment was significantly less than yield for the T-NF treatment, but not significantly different from control or NT-F treatments. Tiedemann and Furniss (1985) observed a similar reduction in soil S availability under defoliated curlleaf cercocarpus (*Cercocarpus ledifolius* Nutt.) trees compared to undefoliated or lightly defoliated trees. In that study, they speculated that increased N and P in the litter layer resulting from deposition of insect frass increased demand for soil S by microbial populations, thereby reducing soil S availability.

Conclusions

Higher concentrations of total N in the forest floor of the NT-F treatment compared to the control leads us to conclude that there was a longer-term effect of fertilization on the forest floor. These differences suggest that the forest floor served as a sink for applied N. Results of Heilman et al. (1982), Axellson (1985) and Nason and Myrold (1992) support this conclusion.

There were no detectable differences in soil total N or available N between thinned and fertilized treatments and the control treatment. During the first year after fertilization at this same study site, Waring et al. (1992) measured substantially elevated levels of extractable ammonium-N and nitrate-N in the upper 15 cm of soil. Plots of the NT-F and T-F treatments had 69 and 184 mg l⁻¹ of extractable N compared to 1.1 mg l⁻¹ for the control treatment. Early growth responses of grand fir to fertilization were attributed to direct effects of increased soil N availability on numbers of primordia of overwintering buds and production of new needles (Waring et al. 1992). But, since N availability in fertilized treatments

was the same as in the control treatment after 5 years, how do we account for increased radial growth of grand fir through the 5th year after fertilization measured by Wickman et al. (1992) on this same study area? Even longer-term tree growth responses (up to 15 years) have been observed in other studies (Miller and Tarrant 1983, Barclay and Brix 1985, Binkley 1986, Shoulders and Tiarks 1990). According to Brix (1983), longer-term growth response to fertilization is a result of improved growth efficiency (increased stem growth per unit leaf area) and increased leaf area. Turner (1977) observed increased foliage mass after fertilization of Douglas-fir in western Washington. On our study site, Wickman et al. (1992) measured increased foliage mass of new growth on trees from fertilized plots during the second through fifth years after fertilization. This likely accounts for the protracted radial growth response.

Although soil P and K availabilities were not affected by N fertilization, results clearly indicate a depression in soil S availability for the NT-F treatment when compared to control and T-NF treatments and for the T-F treatment compared to the T-NF treatment. The high level of N applied in the urea fertilization treatment apparently led to a deficiency of available S. Low inherent availability of soil S (RY = 37%) was probably a factor that contributed to the significant decline in bioassay yields that we observed. Results indicate that both N and S should be used in future fertilization efforts for sites where soil S concentrations are similar to those we observed (0.008%).

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