Management of Ponderosa Pine Nutrition Through Fertilization [1]

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Abstract

The results of a series of replicated fertilization trials established throughout the Inland Northwest were reviewed for information specific to ponderosa pine (*Pinus ponderosa* P. and C. Lawson) nutrition. Ponderosa pine nitrogen (N) status was often better than the N-status of other Inland Northwest species, and therefore growth response to N fertilization was often lower than that of other species. Fertilization of ponderosa pine with N alone sometimes appeared to cause increased tree susceptibility to mortality by insect, disease and perhaps abiotic stresses. Growth and mortality response to N fertilization appeared to be related to foliage potassium (K)/N ratio in some cases. The application of K and micronutrients in combination with N may have protected the trees from N-related mortality while stimulating a growth response. Sulfur fertilization was not found to evoke a growth response in ponderosa pine, and may have increased mortality rates slightly. On certain rock types and vegetation series, ponderosa pine showed high growth response to macronutrient plus micronutrient fertilization as well as herbicide treatment. Ponderosa pine generally did not show a strong growth response to N fertilization, except on 'good' rock types on moist sites. Multinutrient (macro- plus micronutrient) fertilization combined with an herbicide treatment often provided a better response than N alone on moderate to dry sites and/or 'bad' rock types. Other species in mixed-conifer stands, particularly grand fir (*Abies grandis* (Dougl. ex D. Don) Lindl.), often showed a better growth response to fertilization than ponderosa pine. The nutritional ecology of ponderosa pine is unique among Inland forest tree species and should be considered when evaluating nutrient management options.

Introduction

Since its inception in 1980, the Intermountain Forest Tree Nutrition Cooperative (IFTNC) has established numerous studies of forest tree response to various fertilization treatments throughout the inland portion of the northwestern United States (*table 1*). The initial studies, established in Douglas-fir (*Pseudotsuga menziesii* (Mirbel) Franco) and ponderosa pine (*Pinus ponderosa* P. and C. Lawson) stands, tested various rates of nitrogen (N) fertilizer, while subsequent studies incorporated potassium (K). During the establishment of the Forest Health and Nutrition study in the mid-1990's, rock type was implicated in plantation success and stand health, leading to the establishment of a region-wide Seedling Establishment study (Moore and Mika 1997, Garrison and others

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[1] An abbreviated version of this paper was presented at the symposium on Ponderosa Pine: Issues, Trends and Management, October 18-21, 2004, Klamath Falls, Oregon.

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1997, Garrison and Shaw 1998). A series of individual tree screening trials in ponderosa pine and other tree species tested growth response to various combinations of fertilizer and herbicide[4]. More recently, unfertilized foliage nutrient concentrations of four tree species, including ponderosa pine, were compiled to identify suggested sample sizes for nutrient testing, as well as to identify natural ranges of nutrient variability (Moore and others 2004). The objective of this paper is to summarize the implications of these studies for ponderosa pine nutrition. Changes in nutrient concentration and growth rate after fertilization or herbicide application will be addressed in detail.

Tree nutrition may be assessed by comparing foliage nutrient concentrations to published critical levels (*table 2*). Average concentrations of both unfertilized and fertilized ponderosa pine foliage from several IFTNC studies were measured one year after treatment (*table 3*). If the measured foliage concentration was below the critical level for ponderosa pine, the trees were considered deficient in that element, and the element was considered growth limiting. A yield response to fertilization with the deficient element was therefore expected. If a nutrient concentration was at or above the critical level, the trees were considered to have a sufficient quantity of that element for growth, and the element was considered non-limiting; thus, no yield response was expected.

Critical levels are based on traditional yield curves, and therefore provide a direct, species-specific and biologically significant technique for assessing the effects of nutrient amendments on tree growth and yield. A related method of nutrient assessment involves the use of optimum nutrient proportions (nutrient ratios). This technique is based on the hypothesis that for a given amount of one element, usually N, a certain proportion of other elements is required to maintain an optimum nutrient balance within the plant (Powers 1983, Blake and others 1990, Ingestad 1971). The optimum concentration of other elements therefore varies based on the N concentration. Several of the critical levels proposed in *table 2* were derived using optimum ratios in conjunction with the established critical N level for ponderosa pine. Because nutrient ratios are not tied to a yield expectation, they provide a useful assessment of internal plant nutritional balances, and are suited to assessment of forest stands for general nutritional status even in the absence of fertilization. Because one of the primary research directives of the IFTNC is to increase forest yield through improved tree nutrition, the critical level method is more commonly referenced throughout this paper.

Several terms used throughout this paper require some additional explanation. The terms ‘rock type’, ‘underlying geology’ and similar references to the dominant geology underlying forest stands is used intentionally, rather than the more common terms ‘parent material’ or ‘soil type.’ Forested sites are often underlain by several parent materials, including bedrock and one or more surficial deposits. The underlying geologic formation often dominates soil properties, and has been a useful variable in explaining forest nutrition and fertilization response during IFTNC research. Therefore, references to the underlying geologic formation are used as such throughout this paper. The term ‘vegetation series’ refers to a grouping of habitat types or plant associations named after a tree species that is expected to become

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[4] Unpublished data on file, Intermountain Forest Tree Nutrition Cooperative, University of Idaho, Moscow, Idaho

Table 1—*List of selected fertilization and herbicide studies established by the Intermountain Forest Tree Nutrition Cooperative between 1980 and 2000. Regions refer to northeastern Oregon (NE OR), central Washington (C WA), northeastern Washington (NE WA), central Idaho (C ID), northern Idaho (N ID) and western Montana (W MT).*

Trial name	**No. of sites**	**Year(s) established**	**Stand composition**	**Region**	**Treatments and rates[1]**
Douglas-fir trials	90	1980-1982	Douglas-fir	C ID, C WA, NE WA, NE OR, N ID, W MT	control; 224 kg N; 448 kg N
Ponderosa pine	10	1985	Ponderosa pine	NE OR, C WA	control; 224 kg N; 448 kg N
Montana ponderosa pine	6	1987	Ponderosa pine	W MT	control; 224 kg N; 224 kg N + 190 kg K
Umatilla mixed conifer	8	1991	Mixed conifer	NE OR	control; 224 kg N; 224 kg N + 112 kg S
Okanogan mixed conifer	8	1993	Mixed conifer	C WA	control; 224 kg N; 224 kg N + 190 kg K
Forest health and nutrition	31	1994-1996	Mixed conifer	C ID, C WA, NE WA, NE OR, N ID	1994 (12 sites): control; 336 kg N; 190 kg K; 336 kg N + 190 kg K 1995 (12 sites): control; 336 kg N; 190 kg K; 336 kg N + 190 kg K; 336 kg N + 190 kg K + 112 kg S 1996 (7 sites): control; 336 kg N; 190 kg K; 336 kg N + 190 kg K; 336 kg N + 190 kg K + 112 kg S + 5.6 kg B + 11.2 kg Cu +11.2 kg Zn + 0.1 kg Mo All years: Additional N+K combinations ranging from 0 kg N and 0 kg K to 672 kg N and 574 kg K, per experimental design
Seedling establishment	12	1998	Douglas-fir and ponderosa pine	C ID, C WA, NE WA, NE OR, N ID	control; 16 g N; 16 g N + 4.8 g S; 16 g N + 12 g K; 16 g N + 12 g K+ 4.8 g S; 16 g N + 12 g K + 4.8 g S + 4.1 g P + 0.61 g Mg + 0.01 g B + 0.03 g Cu + 0.26 g Fe + 0.04 g Mn + 0.01 g Mo
Screening trials	29	1999-2000	Ponderosa pine	C ID, C WA, NE WA, NE OR	control; 224 kg N; 224 kg N + 190 kg K + 101 kg S + 1.1 kg Mg + 1.1 kg Cu + 3.4 kg B + 1.1 kg Zn + 3.4 kg Fe (multinutrient); 3.4 kg hexazinone; multinutrient + 3.4 g hexazinone

[1] *Rates in kg ha^{-1} as broadcast application, except for seedling establishment study for which the rate is g seedling^{-1} as a subsurface (dibble) application.*

dominant under late successional conditions (Cooper and others 1991, Lillybridge and others 1995).Vegetation series are used as a proxy for site moisture regimes by the IFTNC, with the more common series in the IFTNC study region ranging from dry to moist in the order of ponderosa pine, Douglas-fir, grand fir, western red cedar (*Thuja plicata* Donn ex. D. Don) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.). The habitat types or plant associations comprising each vegetation series are based on understory vegetation and also show a gradual progression from dry to moist. The term 'plant association' is more commonly used in Oregon and Washington, while the term 'habitat type' is more commonly used in Idaho and Montana. Both terms are used on occasion in this paper to refer to relative moisture regimes within a vegetation series.

Results from eight replicated studies were reviewed for this paper. Analysis of variance was used to detect treatment effects, and results were considered significant at or below a level of p=0.10.

Table 2—*Critical nutrient concentrations for current, upper-crown ponderosa pine foliage in the northwestern United States.*

Nutrient	Concentration[1]
Nitrogen (N; pct)	1.10[3]
Phosphorus (P; pct)	0.08[3]
Potassium (K; pct)	0.48[2]
Sulfur (S; pct)	0.08
Calcium (Ca; pct)	0.05[2]
Magnesium (Mg; pct)	0.05[2]
Manganese (Mn; ppm)	60[3]
Iron (Fe; ppm)	50[3]
Zinc (Zn; ppm)	30[3]
Copper (Cu; ppm)	3[3]
Boron (B; ppm)	20[3]

[1] Value for N from Powers and others (1985), values for P, K, Ca and Mg from Powers (1983) and Powers and others (1985). Critical S value derived for this paper using an N/S ratio of 14.7 with the critical N value (Turner and Lambert 1979, Blake and others 1990). Micronutrients from Boyer (1984, personal communication).

[2] Derived by cited author(s) using optimal proportions

[3] Derived by cited author(s) experimentally

Nutrition of mature, second-growth stands

Nitrogen and potassium

Nitrogen is probably the most common fertilizer element utilized in forest management applications in the western United States (Moore and others 1991, Mitchell and others 1996, Peterson and others 1984, Shumway and Chappell 1995, Tiedemann and others 1998, Chappell and others 1999, Carter and others 1998). In the Inland Northwest, N has traditionally been applied towards the end of the rotation, when the cost of application can be recouped through increased growth during the final few years. Fertilization with N typically results in increased foliage N concentrations the first year after fertilization (*table 3*), with concentrations in ponderosa pine foliage collected one year after fertilization typically well-correlated with N application rate. For example, increasing rate of N fertilization during the Forest Health and Nutrition Study resulted in an almost linear increase in foliage N concentrations of about 60 percent over the unfertilized control trees at 600 lb ac^{-1} N, with the K fertilizer having no notable effect on the foliage N response (*fig. 1*).

Table 3*—Average nutrient concentrations of current-year, upper-crown ponderosa pine foliage measured one year after application of various fertilization treatments for several Intermountain Forest Tree Nutrition Cooperative studies.*

Average foliage N concentrations (pct)

Treatment Study	Control	N[1]	N+K	N+S	N+K+S	Multi-nutrient[2]
Montana ponderosa pine	1.24	1.46	1.48			
Umatilla/Okanogan mixed conifer	1.27	1.63	1.56	1.44		
Forest health and nutrition	1.15	1.57	1.71		1.65	1.66
Seedling establishment	1.44	1.65		1.61	1.71	1.73

Average foliage K concentrations (pct)

Treatment Study	Control	N[1]	N+K	N+S	N+K+S	Multi-nutrient[2]
Montana ponderosa pine	0.75	0.72	0.79			
Umatilla/Okanogan mixed conifer	0.81	0.74	0.79	0.81		
Forest health and nutrition	0.89	0.90	0.89		0.99	0.92
Seedling establishment	0.65	0.56		0.64	0.62	0.64

Average foliage S concentrations (pct)

Treatment Study	Control	N[1]	N+K	N+S	N+K+S	Multi-nutrient[2]
Umatilla/Okanogan mixed conifer	0.06	0.06		0.06		
Forest health and nutrition	0.09	0.07	0.07		0.08	0.08
Seedling establishment	0.10	0.10		0.12	0.12	0.12

[1] *For treatment rates see table 1*

[2] *Multinutrient fertilization consisted of some combination of macronutrient and micronutrient fertilization and varied depending on the study (table 1).*

Nitrogen leads to increased tree growth by building tree foliage, which in turns leads to increased rates of photosynthesis and growth response (Miller 1981, Cole and Gessel 1992, Ballard and Carter 1985). An increase in ponderosa pine needle weight typically accompanies increased N-application rate. For example, needle weights in the same study also increased with increasing N fertilization rates, leveling off at around 400 lb N ac^{-1} with an increase of over 2 g 100 needles^{-1} over the unfertilized needles (*fig. 2*). Potassium fertilization resulted in somewhat decreased needle sizes at application rates greater than 200 lb K ac^{-1} when applied in the absence of N fertilizer.

While IFTNC studies have shown that foliage N concentrations increase after N fertilization in ponderosa pine, these studies have also shown that (1) ponderosa pine generally has higher foliage N concentrations than other common Inland Northwest forest species, and (2) other species are more often N-deficient and generally show greater increases in N concentration and needle weight following N fertilization. The

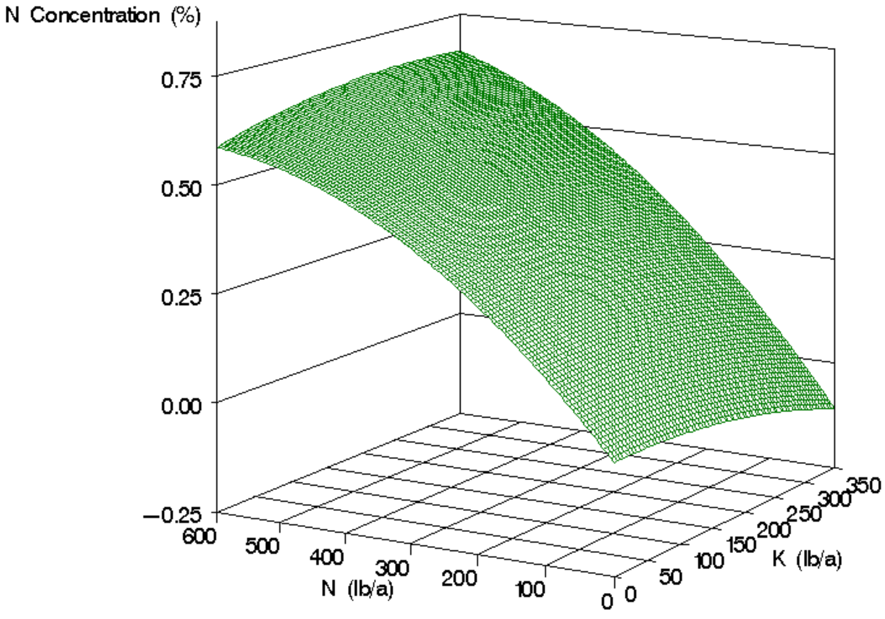

Figure 1—Percent difference between fertilized and unfertilized ponderosa pine foliage nitrogen (N) concentration one year after application of nitrogen (N) and potassium (K) fertilizer during the Forest Health and Nutrition study, for all rock types and vegetation series combined.

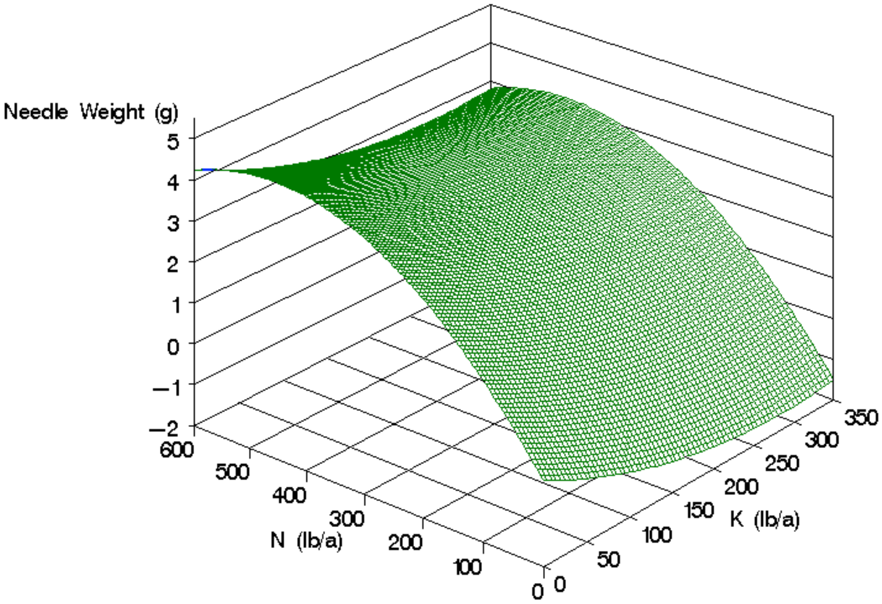

Figure 2—Difference between fertilized and unfertilized ponderosa pine needle weight (g 100 fascicles^{-1}) one year after application of nitrogen (N) and potassium (K) fertilizer during the Intermountain Forest Tree Nutrition Cooperative's Forest Health and Nutrition study, for all rock types and vegetation series combined.

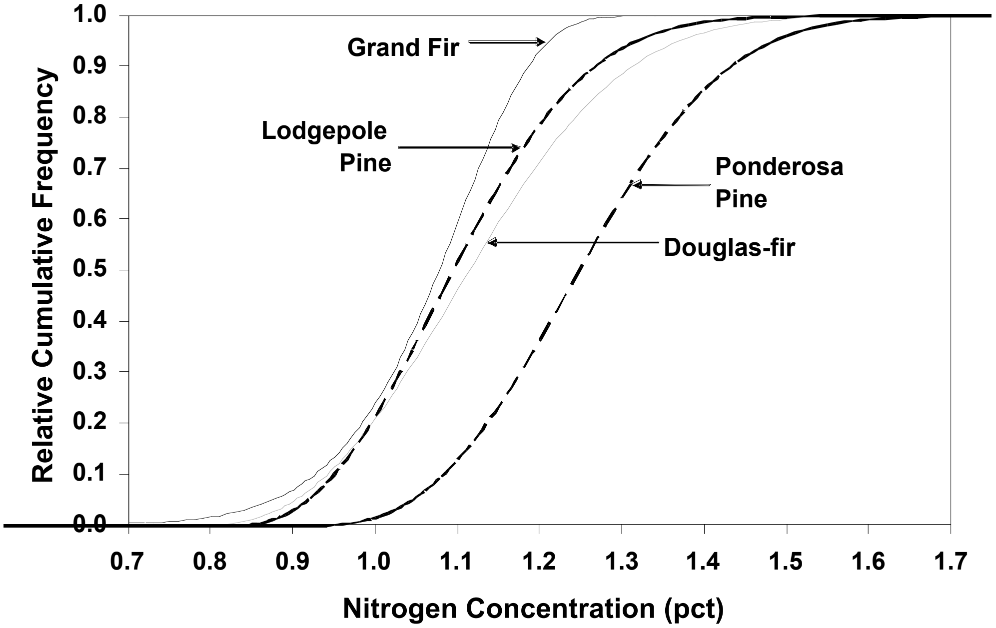

Figure 3—Cumulative frequency distribution of nitrogen (N) concentrations in unfertilized ponderosa pine, lodgepole pine, Douglas-fir and grand fir trees in the Inland Northwest. From Moore and others (2004).

first point was illustrated graphically in frequency distributions of foliage N in unfertilized ponderosa pine trees from 37 sites, Douglas-fir from 130 sites, grand fir (*Abies grandis* (Dougl. ex D. Don) Lindl.) from 14 sites and lodgepole pine (*Pinus contorta* Dougl. ex. Loud.) from nine sites across the Inland Northwest (*fig. 3*) (Moore and others 2004). The vertical axis of this graph is the proportion of all sites with foliage concentrations less than or equal to a particular value on the horizontal axis. Ponderosa pine foliage N concentrations were significantly higher than the other three species, which were all similar to each other. Critical nutrient concentrations were also evaluated using this distribution. For example, trees on about 97 percent of the Douglas-fir sites were below the critical foliage N concentration of 1.40 percent.

Most of the lodgepole and grand fir trees were also below their respective critical levels (1.20 and 1.15 percent, respectively). However, only about 15 percent of ponderosa pine N concentrations were below the critical level of 1.10 percent (*table 2*). Furthermore, foliage N response of ponderosa pine was usually of lower magnitude and showed more variation than Douglas-fir, grand fir or lodgepole pine on the same or similar sites. Correspondingly, volume growth response to N fertilization was typically lower for ponderosa pine than other species (Garrison and others 2000, Moore and others 1998). These results suggest that the critical level of 1.10 percent for N in ponderosa pine foliage may be somewhat low. A foliage N concentration of 1.20 percent (approximately the 35th percentile in the foliage N distribution) may be a more reasonable critical level for Inland Northwest ponderosa pine, based on positive four-year growth responses to 224 kg ha^{-1} N fertilization of ponderosa pine with N concentrations ranging from 1.18 to 1.24 percent (IFTNC 1992a, IFTNC 1992b). Positive growth responses of ponderosa pine to 448 kg ha^{-1} N fertilizer have been obtained with foliage N concentrations as high as 1.47 percent.

Conventional wisdom has generally held that growth response of ponderosa pine and other forest species will increase linearly with increased rates of N application. Studies by the IFTNC have shown that under ideal growth conditions, this is often the case (Mika and VanderPloeg 1991, Moore and others 1994). However, growth response of ponderosa pine to N fertilization appears to depend on several factors, including moisture regime, underlying rock type, and the availability of other nutrients on the site. These relationships were first illustrated during the initial ponderosa pine study established by the IFTNC in 1985, comprised of a series of N rate trials located in ten ponderosa pine stands in northeastern Oregon and central Washington. The stands were predominantly mature, second-growth, managed stands, and N was applied at the rate of 0, 224 and 448 kg ha^{-1} as urea. Growth response was measured as the difference between treated and control plots at each site, and results were adjusted to a common initial basal area. Growth response was expected to increase proportionately with increased N rate. However, the six-year results of this study showed that gross basal area response after adding 448 kg ha^{-1} was not different than after adding 224 kg ha^{-1}. Both responses were greater than the untreated controls (IFTNC 1992a, IFTNC 1992b). Net basal area response for the same time period was insignificant for both fertilization treatments. The difference between the gross and net results was due to mortality. Mortality was greater on N-fertilized plots than on the control plots during the first four years, particularly for the 448 kg treatment on the northeast Oregon sites, though mortality diminished during subsequent measurement periods (IFTNC 1992b). Growth and mortality were related to vegetation series, with lower growth and higher mortality occurring on the relatively drier Douglas-fir series compared to the grand fir series. Growth and mortality were also related to parent material, with lower growth and higher mortality occurring on basaltic sites, and higher growth response with less mortality occurring on sandstones. Also of interest during this study was the finding that, based on two-year periodic response analysis during the first six years, growth rates were the same for all three two-year periods, suggesting that response to fertilization was not declining and continued to be positive six years after fertilization.

Potassium was implicated in tree mortality following the 1985 ponderosa pine trials and an earlier series of Douglas-fir trials testing the same N treatments. Potassium status on all sites was assessed using a foliage K/N ratio (Ingestad 1971). Foliage K/N ratio of 0.50 is considered critical, and a ratio of 0.65 or higher is considered sufficient. The nutrient ratio method is a useful means of assessing K status, as K does not typically show a significant change in foliage concentration following fertilizer application (*table 3*). Foliage K/N ratios were examined in unfertilized trees on the IFTNC ponderosa pine and Douglas-fir trial sites. Those sites with unfertilized foliage K/N ratios greater than 0.65 appeared to have less mortality and greater growth response to the 448 kg ha^{-1} N treatment. In contrast, those sites with unfertilized foliage K/N ratios less than 0.50 experienced high mortality, particularly in response to the 448 kg N treatment. Thus, as foliage K status appeared likely related to mortality rates after N fertilization, K was incorporated into most subsequent IFTNC studies. An N+K combination treatment was first included in a study established in six ponderosa pine stands in western Montana in 1987. On these sites, the 448 kg treatment was dropped, and a treatment consisting of 224 kg ha^{-1} N plus 190 kg ha^{-1} K was substituted. This same series of treatments (unfertilized control, 224 kg N and 224 kg N+190 kg K ha^{-1}) was applied in eight mixed conifer stands on the Okanogan National Forest in 1993. A series of N+K treatments in a response surface design was also applied to 31 mixed conifer stands during the Forest Health and Nutrition study in the mid-1990's (*table 1*).

Foliage K concentrations in treated plots one year after fertilization did not show significant differences from control plots during any of these studies (*table 3*).

Potassium concentrations occasionally decreased slightly following N-only fertilization, due to an effect known as nutrient dilution. Nutrient dilution refers to a decrease in nutrient concentration due to an increase in foliage biomass that is not matched by accelerated uptake of a nutrient (Jarrel and Beverly 1981). In most cases, the combined N+K treatment restored foliage K concentrations to unfertilized levels, suggesting uptake of applied K.

Interestingly, foliage K levels occasionally appeared to increase as a result of S fertilization, as shown during a study established in 1991 in mixed conifer stands on the Umatilla National Forest (*tables 1 and 3*). This study did not include K fertilization, but did include an N+S combination, with the S and some N applied as ammonium sulfate, and the remainder of the N as urea. Foliage K concentrations were above critical levels for all treatments, with no significant differences among the controls and any treatment. Examination of total K content (K concentration multiplied by foliage biomass of 100 fascicles) indicated that the N+S treatment produced greater total K content than the controls (Garrison and others 2000). This K response to N+S fertilization may be explained in part by the chemical properties of ammonium sulfate, particularly when applied to soils high in clay such as those derived from basalts. The influx of NH_4^+ ions from ammonium-based fertilizers has been shown to compete with K^+ ions for sites on the soil exchange complex (Liu and others 1997, Chen and Mackenzie 1992). In our study, this appears to have resulted in an increase in exchangeable K available for plant uptake.

The 10-year results from the Montana ponderosa pine study supported the hypothesis that N+K application would decrease tree mortality compared to N-only fertilization (IFTNC 1998). While neither fertilization treatment increased net basal area growth over control plot growth, the N+K treatment did increase gross basal area growth. The difference between gross and net responses was due to mortality, with the N+K treatment showing positive growth response (10.4 percent gross basal area response) and low mortality (3.1 percent of gross basal area), and the N treatment showing low growth response (1.9 percent gross basal area response) and high mortality (7.2 percent of gross basal area) compared to the control plots (1.1 percent mortality; *fig. 4*). In other words, N+K fertilization appeared to protect the trees from mortality while allowing them to respond to N fertilization. Notably, most of the mortality during this study was caused by mountain pine beetle. The IFTNC hypothesized that beetles were responding to some physiological or chemical differences in the trees that were fertilized with N alone (Mika and others 1993). Alternatively, K provided in the N+K treatment may have enabled some protective mechanisms in those trees, allowing them to withstand beetle attack. Similar results occurred during the Douglas-fir trials established in the early 1980's, though the mortality agents were different (Mika and Moore 1991).

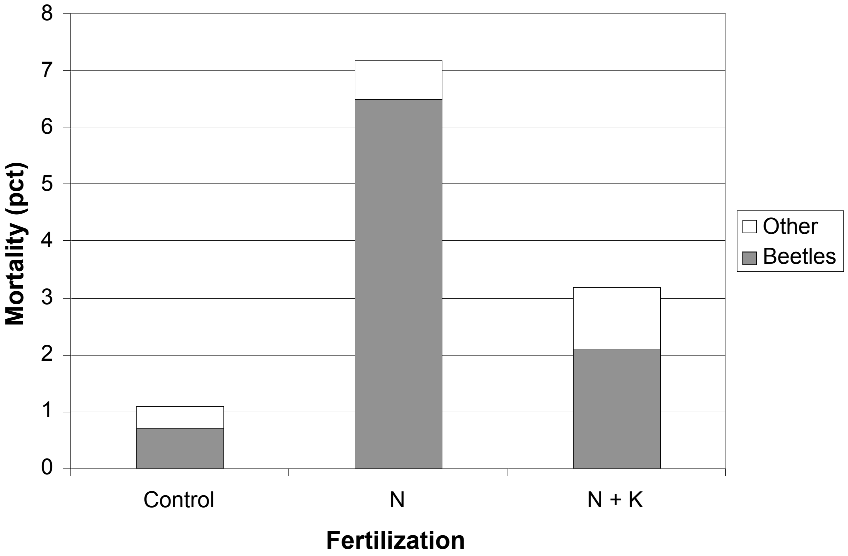

Figure 4— Mortality response and cause of mortality of ponderosa pine ten years after 224 kg ha^{-1} nitrogen (N) and 224 kg ha^{-1} nitrogen plus 190 kg ha^{-1} potassium (N+K) fertilization during the Intermountain Forest Tree Nutrition Cooperative's Montana ponderosa pine fertilization trials.

Relative volume growth response (four-year volume growth on fertilized plots relative to unfertilized plots) for ponderosa pine in the Okanogan and Umatilla mixed conifer studies was marginally greater for the N+K treatment compared to the controls (Garrison and others 2000). None of the other treatments applied during those studies (N or N+S) differed from each other or from the controls. These results were similar to those of the Montana ponderosa pine study. However, six-year basal area growth response during the Forest Health and Nutrition study confirmed the expected growth increase with increasing N rate[5]. Basal area increased by as much as 30 percent at the higher rates of N application and decreased somewhat with increasing K application to a low of almost 20 percent lower lasal area growth on the fertilized compared to control trees at the 0 lb N ac^{-1} rate (*fig. 5*). As suggested by the results of the earlier fertilization trials, variation in N response was likely related to moisture regime and perhaps rock type. The Montana and Okanogan studies were installed on relatively dry sites supporting Douglas-fir series and some drier habitat types and plant associations within the grand fir series. In contrast, the Forest Health and Nutrition study incorporated moister habitat types and plant associations within the grand fir series, as well as sites in the western red cedar and western hemlock series. While several of the Montana sites were on nutritionally poor metasedimentary rocks, the Okanogan and many of the Forest Health and Nutrition sites were on nutritionally better granitic and basaltic rock types. These factors likely interact, with higher response by ponderosa pine to N fertilization occurring on moister sites and better rock types. This pattern also holds true for Douglas-fir and grand fir, although these species performed better on the drier sites compared to ponderosa pine. On the relatively drier Okanogan and Umatilla study sites, Douglas-fir showed a strong growth response to N fertilization, while ponderosa pine

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[5] Unpublished data on file, Intermountain Forest Tree Nutrition Cooperative, University of Idaho, Moscow, Idaho

did not. During the Forest Health and Nutrition study, both species responded at about the same rates due to inclusion of moister sites.

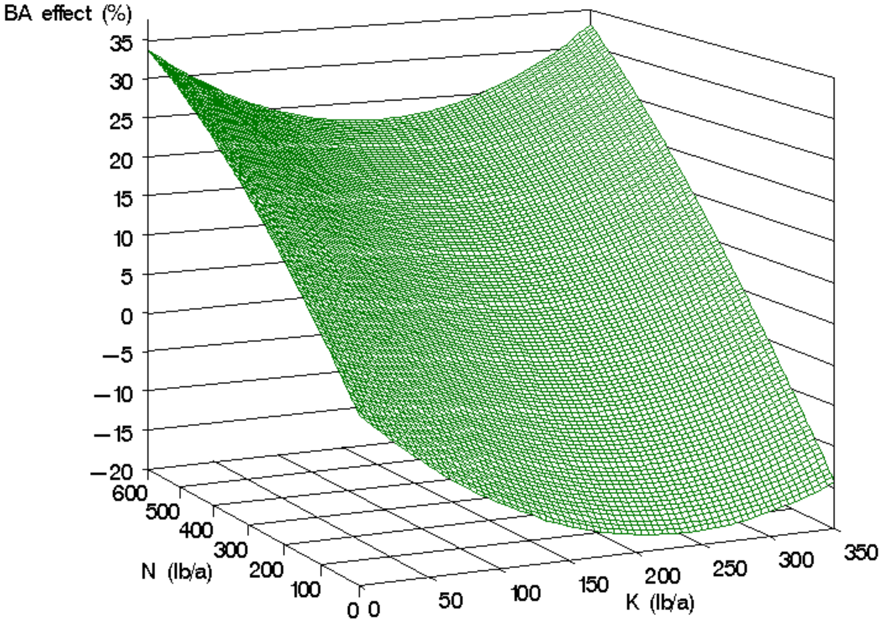

Figure 5—Relative basal area (BA) response of ponderosa pine on fertilized plots relative to unfertilized plots six years after application of nitrogen (N) and potassium (K) fertilizer during the Intermountain Forest Tree Nutrition Cooperative's Forest Health and Nutrition study, for all rock types and vegetation series combined.

Table 4—*Cumulative frequency distributions of foliage weight and nutrient concentrations for unfertilized ponderosa pine from 37 sites across the Inland Northwestern United States. Modified from Moore and others (2004).*

Percentile	Weight[1] (g)	N (pct)	P (pct)	K (pct)	S (pct)	Ca (pct)	Mg (pct)	B (ppm)	Cu (ppm)
5	10.2	1.045	0.135	0.534	0.037	0.052	0.068	12.8	1.64
10	12.5	1.083	0.148	0.572	0.046	0.061	0.072	14.7	1.88
20	15.4	1.135	0.165	0.624	0.056	0.073	0.077	16.8	2.21
30	17.5	1.176	0.176	0.663	0.064	0.083	0.081	18.4	2.48
40	19.4	1.213	0.186	0.699	0.071	0.092	0.085	19.6	2.72
50	21.1	1.248	0.194	0.733	0.078	0.101	0.088	20.7	2.96
60	22.8	1.283	0.202	0.767	0.084	0.110	0.092	21.8	3.20
70	24.6	1.322	0.210	0.804	0.091	0.120	0.096	23.0	3.47
80	26.7	1.368	0.220	0.848	0.099	0.132	0.101	24.2	3.78
90	29.5	1.432	0.232	0.908	0.109	0.149	0.108	25.9	4.23
95	31.8	1.484	0.241	0.958	0.118	0.164	0.114	27.2	4.60

[1] Foliage weight for 100 needle fascicles and sheaths.

The cumulative frequency distribution of unfertilized plots by foliar K (*table 4*) suggests that the critical K level of 0.48 percent for ponderosa pine (*table 2*) may be reasonable, particularly given the generally low growth response (gross and net responses by both basal area and cubic foot volume) to K fertilization demonstrated in the various studies. Specifically, K availability in the Okanogan, Umatilla and Forest Health and Nutrition studies seemed adequate based on both initial K concentrations (all greater than 0.48 percent) and the low response of foliage K to fertilization. In the Forest Health and Nutrition study, while mortality of ponderosa pine appeared to increase with increasing N rate to almost 2 percent 6 years after fertilization at the highest N application rates, mortality decreased with increasing K rate to less than 1 percent at the highest K rates in the absence of N fertilization (*fig. 6*). Thus, K fertilization alone did not increase growth rates in this study (and may have slightly decreased growth rates), but appeared to decrease mortality rates. Results of this study were consistent with those of the Montana study, underscoring the importance of K in eliciting an N response by decreasing mortality. As with growth response, effects of N and K fertilization on mortality appeared related to rock type and moisture regime, with higher mortality rates occurring on drier sites and nutritionally poorer rock types following N-only fertilization, and lower mortality rates on moister sites and nutritionally better rock types. Potassium fertilization may mitigate mortality acceleration of N fertilization, as demonstrated in the Montana ponderosa pine study and the region-wide Forest Health and Nutrition study. However, it is important to note that K fertilization does not always have this effect, and that rock type (which affects soil characteristics), moisture regime and K fertilization all interact to determine growth and mortality response to N fertilization.

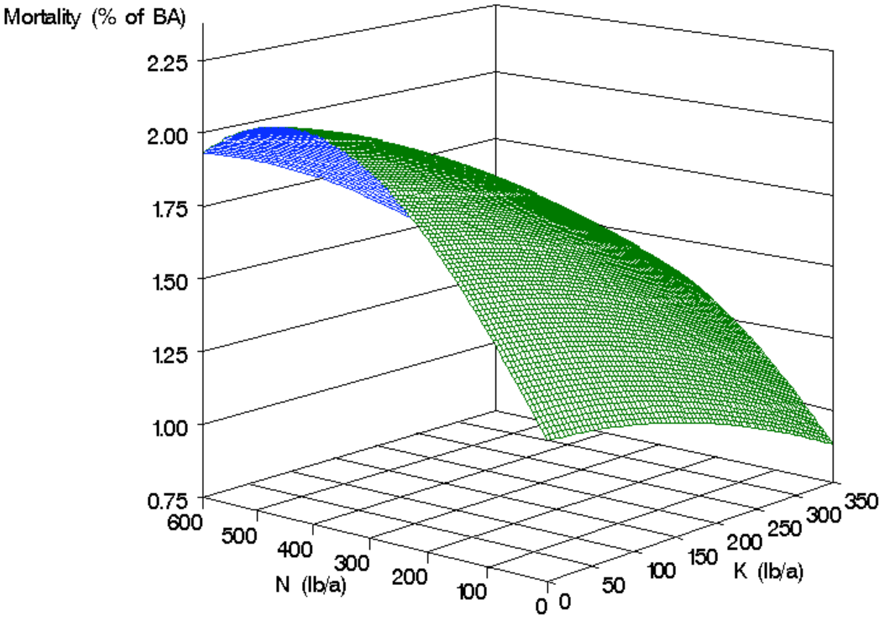

Figure 6—Ponderosa pine mortality as percent of gross basal area (BA) six years after application of nitrogen (N) and potassium (K) fertilizer during the Intermountain Tree Nutrition Cooperative's Forest Health and Nutrition study, for all rock types and vegetation series combined.

Sulfur and micronutrients

Sulfur (S) was first tested by the IFTNC in 1991 during the Umatilla study (Garrison and others 2000), and again as a treatment applied to several sites during the Forest Health and Nutrition study in 1995 and 1996[6]. In both studies, foliage S concentrations for ponderosa pine were deficient on most of the control plots, and were above critical level following N+S fertilization. Grand fir and Douglas-fir in both studies were also S-deficient on unfertilized plots. While grand fir S concentrations increased to above-critical levels on most plots following S fertilization, most Douglas-fir S concentrations remained deficient. Thus, ponderosa pine behaved more like grand fir in terms of foliage response. Examination of ponderosa pine total foliage S content (S concentration times foliage biomass of 100 fascicles) in the Umatilla study showed that S contents (g 100 fascicles^{-1}) increased on the N+S treatments, providing evidence for S uptake by ponderosa pine. However, in neither study did S appreciably stimulate volume growth for ponderosa pine. Grand fir growing in the same stands with ponderosa pine in the Forest Health and Nutrition study showed positive responses to S fertilization, as did Douglas-fir to a lesser extent. During the Umatilla study, neither grand fir nor Douglas-fir responded particularly strongly to S fertilization, though Douglas-fir showed a marginally positive response, and both species responded better than ponderosa pine.

The cumulative frequency distribution of foliage S concentrations of ponderosa pine across the Inland Northwest (*table 4*) suggests that about half of the ponderosa pine stands in the Inland Northwest are S-deficient (critical S level = 0.08 percent, *table 2*). However the lack of growth response to S fertilization during various IFTNC studies suggests that this may not be the case. Reasons for the lack of growth response to S fertilization in ponderosa pine, particularly on apparently S-limited sites, are not entirely clear. A slight decrease in foliage weight for N+K+S treatment compared to N+K did occur during the Forest Health and Nutrition study, and when viewed together with the increase in foliage S concentration, might suggest S toxicity. A more reasonable hypothesis, however, was that some other element besides S might be limiting growth response on those sites.

The inclusion of several micronutrients in a multinutrient fertilization treatment during the 1996 Forest Health and Nutrition trials provided one of the first opportunities to test growth response to those elements in mature, second-growth mixed conifer stands in the Inland Northwest[7]. The multinutrient treatment included N, K, S, boron (B), copper (Cu), zinc (Zn) and molybdenum (Mo). Foliage nutrient characteristics measured one year after fertilization showed that ponderosa pine B concentrations increased from 16 to 39 ppm following micronutrient fertilization, raising foliage B levels from deficient (below critical level) to adequate (above critical level). While B concentrations also increased for Douglas-fir and grand fir, neither species was B-deficient in unfertilized trees. Ponderosa pine foliage Cu concentrations increased slightly from 2.6 to 2.9 ppm following fertilization, but remained below the critical level of 3.0 ppm. Grand fir and Douglas-fir Cu concentrations were both adequate following Cu fertilization. Ponderosa pine Zn concentrations increased from 28 to 60 ppm following micronutrient fertilization, raising Zn concentrations to adequate. Douglas-fir and grand fir Zn concentrations were adequate in unfertilized trees, and did not change following fertilization. Molybdenum concentrations increased from 0.3 to 0.5 ppm in ponderosa pine. Neither Douglas-fir nor grand fir showed foliage Mo responses to Mo

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[6,7] Unpublished data on file, Intermountain Forest Tree Nutrition Cooperative, University of Idaho, Moscow, Idaho

fertilization. Ponderosa pine needle weights increased from 27 g 100 needles^{-1} following N+K+S fertilization to 33 g 100 needles^{-1} following N+K+S+micronutrient fertilization, an increase attributable to the micronutrients. Grand fir and Douglas-fir needle weights did not differ between the same two treatments.

The increases in ponderosa pine foliage nutrient concentrations and needle weights following fertilization with N+K+S+micronutrients suggest that a growth response to that treatment might be expected. In fact, six-year gross basal area growth was 41 percent greater on those plots than the controls. Comparison of that response to the N+K+S response indicated that 8 percent of the growth response was due to Cu, Zn, Mo and B fertilization, demonstrating the potential importance of these less-studied elements. The rest of the growth response was due to N, but not to K or S. Because the micronutrient elements were applied in combination, it was not possible to determine which particular element(s) caused the growth response, but this finding did provide evidence that ponderosa pine may respond to micronutrient fertilization. In the same study, Douglas-fir and grand fir growing in mixed conifer stands did not show positive growth responses to micronutrient fertilization, though they did respond to S fertilization (though only marginally so for Douglas-fir). Sulfur fertilization increased six-year mortality in ponderosa pine and Douglas-fir, while S led to decreased mortality in grand fir. In contrast, micronutrients led to decreased mortality in ponderosa pine and Douglas-fir, but did not affect grand fir mortality. Disease, insect and weather-related death were the leading causes of mortality in all species.

Growth and mortality responses indicated that in mixed conifer stands, grand fir responded best to S fertilization but not to micronutrients. Douglas-fir responded marginally in growth to S and showed a slight decrease in mortality (but no change in growth) due to micronutrients. Ponderosa pine did not respond to S fertilization, but did respond in both increased growth and decreased mortality to micronutrients. Thus, stands dominated by grand fir might respond better to N, K and S fertilization, while those dominated by ponderosa pine might respond better to a combination of N, K and micronutrients. Douglas-fir should respond well to N and perhaps N+K fertilization (where site K limitations exist), but may respond only marginally to S fertilization, and not at all to micronutrient application.

Notably, these results at least partially disproved the previous hypothesis that another element might be limiting growth response to S fertilization in ponderosa pine. Even in the presence of positive foliage and growth responses to four important micronutrients, no S response was observed in ponderosa pine. Some additional experimentation with other elements may be warranted; however, possible S-toxicity suggested by foliage analysis also merits further consideration.

Nutrition of outplanted seedlings

While the various IFTNC studies provided new information on the growth and nutrition of ponderosa pine following various fertilization treatments, an additional factor affecting forest health became apparent during the site selection process for the Forest Health and Nutrition study. The study design included three sites each in a four by three sampling matrix based on four rock types (metasedimentary, granitic, basaltic and mixed) and three moisture regimes (Douglas-fir, grand fir and western red cedar/western hemlock vegetation series). Despite extensive review of numerous candidate sites, no suitable stands were found on metasedimentary rock types in the Douglas-fir series. Furthermore, only two sites were found on this rock type in the grand fir series, one of which was subsequently found to overlay granitics on about half the plots. The importance of rock type had been evident in previous studies; however, the difficulty of finding stands on metasedimentary rocks in the Forest Health and Nutrition study design further implicated underlying geology as an important component of stand health. Therefore, the Seedling Establishment study was designed with to compare establishment of seedlings on ‘good’ and ‘bad’ rocks.

The overall intent of this study was to determine whether fertilization could mitigate the perceived rock type effect detected during the Forest Health and Nutrition study. The study design called for selecting pairs of sites on differing rock types, with all other site characteristics being matched as closely as possible (IFTNC 1997). Six paired sites were selected throughout Idaho, Oregon and Washington. The rocks underlying the sites in each pair were rated as ‘good’ or ‘bad’ relative to each other (*table 5*). At each site, four blocks of six plots each were established. In the spring of 1998, two blocks each were planted with Douglas-fir and ponderosa pine, with species randomly assigned to the four blocks. Immediately after planting, fertilizer was applied as a subsurface treatment next to each seedling (*table 1*). The six fertilization treatments were randomly assigned to the six plots within each block. In 1999, a second fertilization was applied to the seedlings, using the same fertilizer treatments as previously applied on each plot, but doubling the rate and applying the treatment as a spot broadcast rather than subsurface. In 2000 a third fertilization was applied to a subset of sites. This consisted of a block-wide broadcast application of multiple nutrients plus hexazinone herbicide to one of the two blocks per species per site.

Table 5—*Relative rating of rock types as ‘good’ or ‘bad’ for paired study established at six locations in five regions during the Intermountain Forest Tree Nutrition Cooperative’s Seedling Establishment study.*

Region	‘Good’ rock	‘Bad’ rock
Northeastern Washington	Quartz monzonite	Sericite schist
Central Washington	Teanaway pyroclastic	Roslyn formation sandstone
Central Washington	Basalt of Camas Prairie	Andesite of Laurel
North Idaho	Basalt of Onaway	Striped Peak quartzite
Central Idaho	Columbia River basalt	Quartz diorite gneiss
Northeastern Oregon	Ferro-basaltic andesite	Andesite

Seedling caliper and height were measured every year following establishment. Three-year volume growth was heavily affected by rock type. For ponderosa pine, those sites associated with ‘good’ rocks showed higher growth response and somewhat lower mortality than those associated with ‘bad’ rocks. Furthermore, only the multinutrient plus hexazinone treatment on good rocks produced positive growth increases over the controls. As in the Forest Health and Nutrition study, micronutrients seemed key for eliciting a ponderosa pine growth response, this time for seedlings. Furthermore, the importance of herbicide as a tool to reduce competition and increase availability of resources for seedlings was underscored. While Douglas-fir showed stronger growth responses than ponderosa pine, the pattern of better response on ‘good’ rocks was similar.

Treatments that included N increased Douglas-fir mortality on ‘bad’ rocks relative to the same treatments on ‘good’ rocks. For ponderosa pine, similar trends were evident, though not all treatments with N increased mortality. Moisture deficit patterns were examined for all sites during these three years, to determine whether moisture deficit, rather than rock type, might have affected the results. Patterns were similar for all three years, with about half the regions showing higher moisture deficit on the good rocks, and half showing higher moisture deficit on the bad rocks. Moisture deficit patterns therefore did not vary consistently with respect to 'good' or 'bad' rock, and did not explain the growth response results. In contrast, response did appear to be affected by rock type.

Foliage nutrient concentrations the first year after planting were affected by the nutrient-loading that occurred at the nursery. Some nursery effect was still present after the second fertilization treatment, though during both years effects of field fertilization were also evident in the foliage chemistry. The most significant finding of foliage analysis was a notable B deficiency. Boron concentrations on all plots following the first two treatments, and on the control plots following the third treatment, were at or below the recommended minimum of 20 ppm for both species. However, with application of the third multinutrient treatment, which included a higher B rate than the previous two fertilization treatments, B concentrations were well above critical levels, and notably higher than previous foliage B levels. The results suggested that B application rates applied in previous treatments were below levels required for Douglas-fir and ponderosa pine response.

The seedling establishment study has been followed on only four of the original 12 sites, largely because mortality due to vegetative competition and browsing resulted in too few live trees to continue the study with statistical reliability. However, initial results of growth response (caliper and volume) on all 12 sites as well as the continued growth response on the four remaining sites suggest that (1) a significant rock type effect exists and (2) boron was initially deficient in these seedlings and remained deficient after the first two fertilization treatments, likely hindering growth response to other applied elements. Mitigation of rock type effects through fertilization remains inconclusive, in part because of the apparent growth-limiting effect of B on seedling fertilization response during this study.

Nutrition of young plantations

A series of individual tree screening trials were established to test the effects of herbicide and various nutrients on tree growth. Screening trials provide a means of assessing a variety of fertilization and herbicide treatments within a relatively small area and short time frame. Treatments that provide the greatest short-term response are then selected for long-term plot-based trials. Between 1999 and 2000, 29 ponderosa pine screening trials were established in young (15 to 30 year-old) plantations (*table 1*), all of which contained ponderosa pine as a significant component. Each screening trial included up to nine treatments incorporating various combinations of fertilizer and herbicide. Five treatments common to all sites were an unfertilized control, N only, a multinutrient blend, herbicide only, and herbicide plus the multinutrient blend. The multinutrient blend included N, K, S, magnesium (Mg), Cu, B, Zn and iron (Fe) (*table 1*). The trials were located on sites with three moisture regimes, classified by Douglas-fir, grand fir and western red cedar series; and four rock types, classified as metasedimentary, mixed (principally glacial deposits), granitic and basaltic. While sites did not occur on all combinations of rock type and vegetation series, several comparisons of response across rock types and vegetation series were possible.

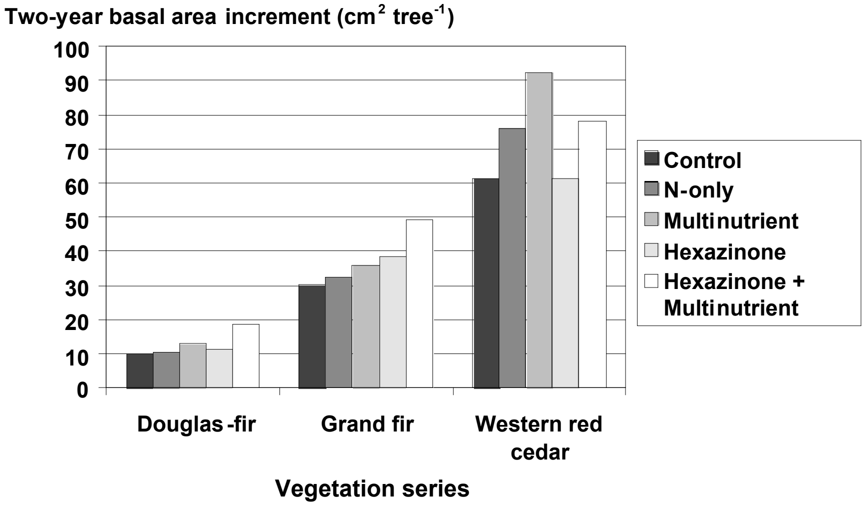

Figure 7—Two-year basal area increment of ponderosa pine trees from three vegetation series on granitic substrates following five fertilization and herbicide treatments during the Screening Trial study.

Trials on all three vegetation series on granitic rocks showed the positive effect of increased moisture on response to fertilization and/or herbicide (*fig. 7*). In the absence of fertilizer or herbicide, two-year basal area growth of ponderosa pine was significantly greater on western red cedar series than on Douglas-fir series, with grand fir series intermediate between the two. In the absence of herbicide, basal area growth was greater following both the N-only and multinutrient treatments on western red cedar series compared to Douglas-fir or grand fir. When herbicide was applied, alone or in combination with fertilizer, two year basal area growth on the grand fir series was greater than on the Douglas-fir series, but was not different from the western red cedar series. In other words, the addition of fertilizer alone increased the growth response on the moister sites compared to the moderate or drier sites, while the addition of herbicide, alone or in combination with fertilizer, increased the growth response on moderate sites over that of drier sites. Thus, management recommendations for enhanced basal area growth on granitic sites might include fertilizer alone on moist sites, herbicide plus fertilizer on moderate sites, and no fertilizer or herbicide on dry sites

Ponderosa pine response was compared between mixed, granitic and basaltic rock types within the grand fir series, and between metasedimentary, mixed and granitic rock types within the western red cedar series. Across the grand fir series, rock type did not have a great effect on basal area growth (*fig. 8*). Herbicide plus multinutrient fertilizer did produce a positive growth response on mixed rocks, but no other treatments showed growth responses. In contrast, rock type did seem to affect ponderosa pine growth on the western red cedar series (*fig. 9*). This finding in itself was interesting because it suggested that as moisture became less limiting, the rock type effect became more apparent. Of those sites on the red cedar series, unfertilized trees on metasedimentary rock types had lower absolute two-year basal area growth than unfertilized trees on granitic rocks, while unfertilized trees on mixed rocks were intermediate between the two. Application of fertilizer alone, whether N-only or multinutrient, resulted in greater absolute two-year basal area growth on granitic rocks compared to mixed rocks and metasedimentary rocks. However, herbicide applied with or without fertilizer resulted in greater absolute two-year basal area growth on mixed and metasedimentary rocks compared to granitic rocks. Thus, the lower growth rates on metasedimentary and mixed rocks appeared to be mitigated by the application of herbicide, whereas fertilizer alone produced the best response on the granitic sites. These findings suggested that while ponderosa pine growing on 'good' rock types and high moisture regime sites may benefit from multinutrient fertilization alone, ponderosa pine on most rock types and moisture regimes should benefit from the application of herbicide in combination with multinutrient fertilization.

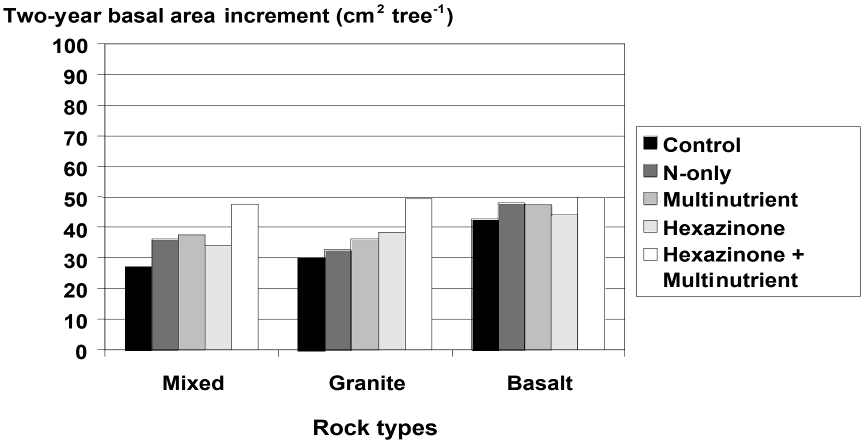

Figure 8—Two-year basal area (BA) increment of ponderosa pine trees on three rock types on grand fir series following five fertilization and herbicide treatments during the Screening Trial study.

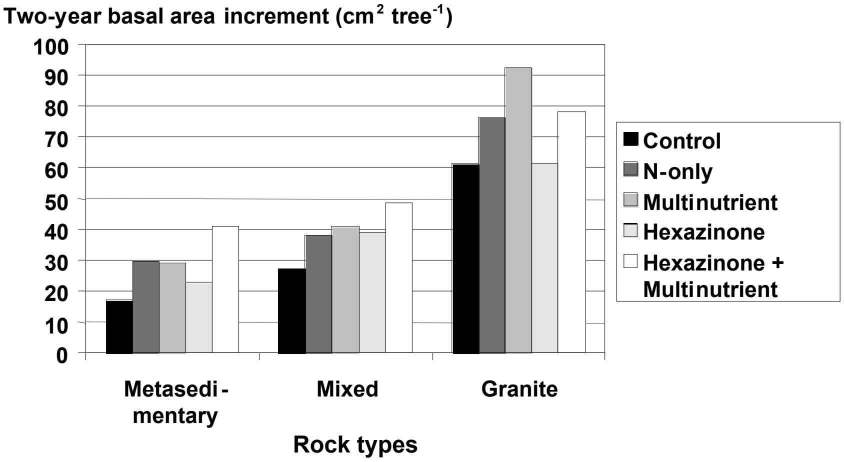

Figure 9—Two-year basal area (BA) increment of ponderosa pine trees on three rock types on western red cedar series following five fertilization and herbicide treatments during the Screening Trial study.

Conclusions

Nitrogen nutrition of unfertilized ponderosa pine in the Inland Northwest is generally better than that of its close associates, even when growing with those other species in mixed-conifer stands. Consequently, growth response to N fertilizer is somewhat lower for ponderosa pine compared to other species. While K fertilization does not usually elicit either a foliage K response or a growth response in any of these species, some evidence does exist that K fertilization can lead to decreased mortality in ponderosa pine. Sulfur fertilization has not been overly successful in increasing growth rates in ponderosa pine, and is probably not a cost-effective addition to operational fertilization regimes, unless other more responsive species such as grand fir are present. The most promising results for ponderosa pine growth response have occurred following fertilization with a combination of N, K and micronutrients, particularly B, Cu, Zn and Mo. Additional research into micronutrient and perhaps additional macronutrient fertilization of ponderosa pine is warranted. Also promising are results related to herbicide application, particularly on drier sites where competition for available moisture may be significant. Rock type appears to interact with moisture in determining tree growth response to herbicide application, such that tree growth on moist sites with 'bad' rock substrates may also benefit from herbicide plus multinutrient fertilization.

Ponderosa pine responds differently to fertilization than grand fir, and somewhat differently than Douglas-fir. Because ponderosa pine and Douglas-fir commonly occur together in stands, the two species could be considered for similar fertilization regimes. Fertilization blends containing N, micronutrients and perhaps K (on K-limited sites) should suffice for these species. For stands containing grand fir, the addition of S to the fertilization regime may elicit a growth response in that species and in Douglas-fir, but not ponderosa pine. Average fertilizer response is greater on moister sites such as the western red cedar series, western hemlock series and moister habitat types and plant associations within the grand fir series, compared to drier sites such as the Douglas-fir series and drier habitat types and plant associations within the grand fir series.

Acknowledgements

The authors acknowledge and thank all current and past members of the Intermountain Forest Tree Nutrition Cooperative, whose collective direction and support during the last 24 years have contributed tremendously to the current state of knowledge regarding Inland Northwest forest tree nutrition. Thanks also to the two technical reviewers of this manuscript, whose comments and suggestions greatly improved the clarity and content of this paper.

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