Two-Year Foliar and Basal Area Response to Multi-Nutrient Fertilization in South-Central Washington (Windy)

Terry M. Shaw

James A. Moore

Intermountain Forest Tree Nutrition Cooperative
University of Idaho

March, 2000

SUMMARY

Significant foliar nutrient response due to fertilization was seen for N, S, B and Cu for Douglas-fir and N, K, S and Cu for ponderosa pine. Nutrient concentration response was generally higher two growing seasons after fertilization than it was after one growing season. The low N application rate (90#/ac) did not significantly increase N concentrations above controls. Those plots receiving the 300#/ac N application rate showed imbalanced K/N and N/S ratios after treatment. Different application rates of K did not appear to significantly change K concentrations following treatments.

Foliar analysis also showed deficiencies before treatment as well as treatment induced deficiencies for all the nutrients applied in this study. According to published nutrient critical levels; N, S and B were deficient for Douglas-fir, while S, B, Cu and Zn were deficient for ponderosa pine. Phosphorus, Ca, Mg, Zn and Mo concentrations were lower on all the fertilized treatments compared to the control. In addition, vector analysis diagnoses of foliar response revealed S, Cu and Mo deficiencies for Douglas-fir and N, K and Mo deficiencies for ponderosa pine. Nutrient dilution vectors occurred for all nutrients relative to the N-Alone treatment.

The fertilizer treatments were successful in significantly ($p \leq 0.10$) increasing foliar needle weights above that of the control for all treatments having micro-nutrients in the fertilizer mix. Similar to foliar nutrient response, needle weight response tended to be higher two growing seasons after fertilization than it was after one growing season. Importantly, only treatments that included micro-nutrients produced significant ($p \leq 0.10$) needle weight increases in 1998 for both Douglas-fir and ponderosa pine. Delayed foliar nutrient and needle weight responses may be due to spring fertilization, where the effects of fertilizer treatments may not have been established early or long enough in 1997 for the trees to show a strong response at the end of one growing season.

Two-year net and gross average basal area response was highest on the K-Alone and N-Alone treatments with 29% and 16% increases over the control, respectively. Basal area response was unsignificant ($p \leq 0.10$) and less than 10% on those treatments having micro-nutrients in the fertilizer mix. Low two-year basal area response on the micro-nutrient treatments may be attributed to delayed foliar nutrient and needle weight responses due to spring fertilization. Forthcoming results that include both diameter and height response measurements may provide better information.

STUDY AREA

In the spring of 1998 twelve fertilization research plots were established on Boise Cascade ownership in the "Butler Creek Block" of south-central Washington. The site was planted with Douglas-fir and ponderosa pine stock in the early to mid 1980's. Site characteristics include grand fir climax vegetation type and Wanapum basalt parent material. The stand exhibits *Phellinus weirii* root rot infestation. Stump and root extraction techniques were used after harvesting and before planting in an effort to remove *Phellinus weirii* inoculum from the site.

METHODS

Plot Establishment

The study area consists of twelve square 0.2 acre plots with a 20 ft. buffer strip around each plot. Inside the 0.2 acre plot, a nested 0.1 acre plot was established to serve as growth monitoring plot. Plot trees are monumented with a blue (0.2 acre) or yellow (0.1 acre) number and paint line at breast height. Trees in the 0.1 acre plots were numbered separately from the 0.2 acre plots. Plots were established to be as similar as possible based on plot tree density, species composition and site characteristics. Plots were monumented with blue (0.2 acre corners) and yellow (0.1 acre corners) painted PVC tubing installed at plot corners and plot center. A red forest fertilization study sign is attached to the plot center stake. Trees too small for suitable paint identification were tagged with an aluminum tag at the base of the tree. Forest fertilization study signs are posted along adjacent roads to identify the stand as a study area.

Treatments

Seven different fertilizer treatments were applied on twelve research plots. Table 1 shows the treatments, elemental rates and sources of the fertilizers by plot number.

Measurements

Initial measurements were made in the spring of 1998. All live trees taller than 4.5 feet in height were measured for heights, diameters and defect at the time of treatment. Diameters are re-measured every two years on all trees and incidence of damage or mortality along with probable cause will be noted. Heights will be re-measured every four years after treatment on all trees. Tree volumes are estimated using regional species-specific volume equations (Wykoff et al. 1982). Site characteristics and plot summaries are given in Appendix A.

One and two growing seasons after treatment, dormant season foliage samples were obtained from the two most abundant tree species represented within the installation. Two dominant or co-dominant trees on each plot were selected per species for foliage collection. Foliage was collected from the third whorl from the top of each tree. Foliar N concentrations were determined using standard micro-Kjeldahl procedure while all other nutrients were determined by ICP emission. Nutrient chemical analysis for 1997 was performed by Scotts Testing Laboratory, Allentown, PA, while 1998 nutrient chemical analysis was performed by Harris Agronomic Services, Lincoln, Nebraska. Nutrient chemical analysis was not conducted for Mo in 1998. Critical foliar nutrient concentrations and the sources for these estimates are given in Appendix B. Foliar nutrient contents were calculated for all nutrients present in the fertilizer mix using the following formula: nutrient concentration x weight of thirty needles. Nutrient content is considered an index of treatment response. Nutrient content was not calculated for phosphorus (P), calcium (C) and magnesium (Mg) because they were not present in the fertilizer mix.

Data Analysis

General linear contrasts and differences between means by treatment for the basal area growth and foliar nutrient responses were determined by using the least-squares routine of the general linear models procedure (PROC GLM) of the Statistical Analysis System (SAS Institute Inc. 1985). No mortality was recorded for the two-year re-measurement, therefore gross basal area growth is the same as net.

Net basal area growth was calculated using the following formula:

$$\text{Net Basal Area Growth} = BA_2 - BA_0$$

where: BA_0 = Basal Area (initial)
BA_2 = Basal Area (2-year)

Contrasts between basal area means are considered average growth responses to the treatments. Installation growth responses are smoothed estimates which are adjusted to a common initial basal area of 8.6 ft^2/acre. Response for this study is defined as the growth difference between the control plots and the treated plots. Conclusions based on absolute and relative basal area response were similar, therefore, only absolute response is presented in this report.

Vector Analysis

Vector analysis was used to compare plant growth, nutrient concentrations and nutrient content. Current year dormant season needle nutrient concentration, nutrient content, and dry weight is used in a graphical vector analysis approach (Timmer and Stone 1978; Weetman and Fournier 1982). Each point on the vector analysis represents the magnitude and directional shift of each nutrient from the control. Distance from the control represents the responsiveness of the treatment for the nutrient being analyzed. Figure 10 shows a schematic of the approach for added nutrients. A detailed description

of vector analysis can be found in Weetman and Fournier (1986) and Hasse and Rose (1995).

RESULTS

Foliar Nutrient Response

Nitrogen

Foliar N response varied by treatment, year and species. Those Douglas-fir receiving the 300#N/ac. treatments showed significantly ($p \leq 0.10$) higher foliar N concentrations and contents than the controls for both sampling years (Tables 2 and 4). However, when the N treatment was low (70#N/ac.), no significant foliar N response was shown for either sampling year (Tables 2 and 4). Douglas-fir foliar N concentrations below 1.4% are considered to be deficient and N concentrations for treatments that did not include N in the fertilizer blend were at or below 1.4% (Figure 1a). Vector analysis showed classical N deficiencies, a "C-shift", for those Douglas-fir receiving N treatments, relative to the control (Figures 11a and 11c). Notably, the magnitude of vector shift was smaller for those Douglas-fir receiving the Low N+S+Micro treatment (Figures 11a and 11c).

Ponderosa pine foliar N concentrations and contents were higher on those treatments that included 300#N/ac compared to the control, K-Alone or low N treatments (Tables 3 and 5). Significant ($p \leq 0.10$) content responses were shown on the N-Alone and N+Low K+S+Micro treatments in 1997 and the N+S+Micro treatment in 1998 (Table 5). Nitrogen concentrations were above the reported 1.2% critical level (Moore et al, In progress), for all treatments (Figure 1b). Vector analysis revealed small to

moderate deficiency “C-shifts”, relative to the control, on those treatments receiving the 300#N/ac treatments in both 1997 and 1998 (Figures 11b and 11d).

Phosphorus

Phosphorus was not included in the fertilizer mix but was examined for nutrient deficiencies. Phosphorus concentrations were found to be above the recommended 0.12% and 0.08% critical levels on all treatments, including the control, for Douglas-fir and ponderosa pine, respectively (Tables 2 and 3). Both species showed significantly lower phosphorus concentrations on those plots receiving the fertilizer treatments than that of the control plot (Tables 2 and 3), suggesting dilution effects from the fertilizer treatments.

Potassium

Foliar K concentrations were not significantly ($p \leq 0.10$) higher on those treatments with K in the fertilizer mix compared to the controls for both species and both sampling years (Tables 2 and 3). However, significant content increases over the control were seen for Douglas-fir on the N-Alone treatment in 1997 and for ponderosa pine on the Low N+S+Micro treatment in 1998 (Tables 4 and 5). Douglas-fir and ponderosa pine foliar K concentrations were well above recommended critical levels for all treatments, including the control, for both sampling years (Figures 2a and 2b). Vector analysis showed a synergistic shift, a “C-shift”, on the N-Alone treatment for Douglas-fir, demonstrating a significant ($p \leq 0.10$) K content increase on a treatment with no K applied (Figure 12a). Ponderosa pine vector analysis showed little K effect in 1997, however, deficiency “C-Shifts” were shown in 1998 relative to the control and N-Alone treatment for all treatments that included K, as well as synergistic shifts for the other treatments that did not include K in the blend. Significantly ($p \leq 0.10$) lower K/N ratios

were shown for Douglas-fir on those plots receiving N treatments compared to the control or K-Alone treatment (Table 2). Even though significantly lower Douglas-fir ratios were shown, all K/N ratios were above the 0.50 critical level suggested for conifers by Ingestad (1979), suggesting balanced K to N (Figure 8). Ponderosa pine K/N ratio for the N-Alone treatment was significantly ($p \leq 0.10$) lower than that of the control in 1997. In addition, ponderosa pine K/N ratios were below the suggested 0.50 critical ratio for all treatments except the low N treatment in 1998 (Figure 8b).

Sulfur

Foliar S concentrations on plots receiving S in the fertilizer blends did not significantly ($p \leq 0.10$) increase over the controls for both species (Tables 2 and 3). Significant ($p \leq 0.10$) positive response, measured as foliar content, was seen in 1998 for Douglas-fir on the N+Low K+S+Micro treatment and for ponderosa pine on the N+S+Micro treatment (Tables 4 and 5). When N was applied alone, both Douglas-fir and ponderosa pine S concentrations significantly ($p \leq 0.10$) decreased from the controls and (Figures 3a –3d) declined below published critical levels for sulfur. Generally, 1997 vector analysis showed no significant ($p \leq 0.10$) S "C-Shift" deficiency for either tree species, relative to the control. However, ponderosa pine did show strong S dilution effects or "A-Shifts" for all treatments in 1997 (Figures 13a and 13b). Similar "A-Shifts" relative to the controls were shown for both species in 1998 as well as classical deficiency "C-Shifts" for all treatments that included S in the blend when compared to the N-Alone treatment, demonstrating positive S response when N was also added (Figures 13c and 13d). Douglas-fir and ponderosa pine showed 1997 and 1998 N/S ratios above the 14.7 critical ratio suggested by Blake et al (1990) on all treatments receiving the 300#N/ac rate, suggesting N to S imbalances (Tables 2 and 3).

Calcium

Similar to phosphorus, calcium foliar concentrations were significantly ($p \leq 0.10$) lower than the control treatment on all fertilizer treatments (Tables 2 and 3), again suggesting dilution effects of Ca due to fertilization. With the exception of the K-Alone treatment for Douglas-fir in 1997, Ca concentrations were all above the recommended 0.15% critical level for Douglas-fir and the 0.05% critical level for ponderosa pine (Tables 2 and 3).

Magnesium

Magnesium concentrations were lower on all fertilizer treatments compared to the controls (Tables 2 and 3), similar to the dilution effects on P and Ca concentrations caused by all fertilizer treatments. Douglas-fir showed significantly ($p \leq 0.10$) lower Mg concentrations on all the treatments in 1998 while ponderosa pine showed significantly lower Mg concentrations on the Low N+S+Micro treatment in 1997, as well as on the N+Low K+S+Micro treatment in 1998. Foliar Mg concentrations were at or above current critical levels for Douglas-fir (0.08%) and ponderosa pine (0.05%) (Tables 2 and 3).

Boron

Application of B significantly ($p \leq 0.10$) increased Douglas-fir foliar B concentrations above the controls, K-Alone and N-Alone treatments. In addition, 1997 Douglas-fir B concentrations on treatments that included B were above the recommended 20 ppm (Moore et al, In progress) critical level. Similar Douglas-fir response was seen in 1998 but results also differed such that all foliar B concentrations were above the critical level for all treatments (Figure 4a). This result may reflect differences in the two

laboratories that conducted the analyses in the two years. Ponderosa pine foliar B response was not significant ($p \leq 0.10$) for any treatment and all B concentrations for both years were below the 20 ppm critical level (Figure 4b). Notably, B concentrations decreased for both species in 1997 following the N-Alone treatment, significantly ($p \leq 0.10$) so for ponderosa pine (Tables 2 and 3). Douglas-fir B content significantly ($p \leq 0.10$) increased for all treatments that included B in the blend for both years, while ponderosa pine B foliar content did not significantly change compared to the control (Tables 4 and 5). Vector analysis showed deficiency "C-Shifts" relative to the control and N-Alone treatments for Douglas-fir in both years for all treatments that included B in the blend (Figures 14a and 14c). Douglas-fir showed a B dilution "A-Shift" following the N-Alone treatment in 1997 (Figure 14a), however, the dilution was not apparent in 1998 because no increase in needle weight resulted from the N alone treatment in 1998 (Figure 14c). Boron dilution, a "A-shift", following the N-Alone treatment was also evident for ponderosa pine, however, unlike Douglas-fir, the dilution lasted both sampling years because needle weight increase continued for the N-Alone treatment in 1998 for ponderosa pine. Additionally, ponderosa pine expressed deficiency "C-Shifts" both sampling years on all treatments containing B in the fertilizer mix relative to the N-Alone treatment (Figures 14b and 14d).

Copper

Except for the N+Low K+S+Micro treatment for Douglas-fir in 1997, application of Cu in the fertilizer mix did not significantly ($p \leq 0.10$) increase foliar Cu concentrations above that of the controls for both species in both sampling years. The N-Alone treatment for ponderosa pine in 1997 produced significantly ($p \leq 0.10$) lower foliar Cu concentration than the controls (Table 3). With the exception of the N-Alone treatment for ponderosa pine in 1997, Cu concentrations were at or above critical levels

for Douglas-fir and ponderosa pine (Figures 5a and 5b). Significant ($p \leq 0.10$) increases in foliar Cu contents resulted from the N-Alone and N+Low K+S+Micro treatments for Douglas-fir in 1997 and the Low N+S+Micro treatment for ponderosa pine in 1998 (Tables 4 and 5). Vector analysis showed Cu deficiency "C-Shifts" on the N+Low K+S+Micro and N+S+K+Micro treatments for Douglas-fir in 1997. However, no strong response vectors occurred following Cu applications for Douglas-fir in 1998. Ponderosa pine showed Cu dilution "A-Shifts" following the N-Alone treatment for both sampling years. Additionally, moderate to strong deficiency "C-shifts" were seen for ponderosa pine relative to the N-Alone treatment (Figures 15b and 15d).

Zinc

Similar to P, Ca, and Mg concentrations, Zn concentrations were lower on all the fertilizer treatments compared to the controls, and several were significantly ($p \leq 0.10$) lower (Tables 2 and 3). However, despite decreasing Zn concentrations on the treated plots, Zn was generally above reported critical levels for both species in both sampling years, except for ponderosa pine on the N-Alone treatment in 1997 where Zn concentrations fell below the recommended 30 ppm critical level (Figures 6a and 6b). Foliar Zn content decreased significantly ($p \leq 0.10$) for three of the four treatments containing Zn in the fertilizer blend, as well as for the K-Alone treatment for Douglas-fir in 1997 (Tables 4 and 5). Vector analysis showed an overall Zn dilution "A-Shift" for all treatments for both species, relative to the control (Figure 16). Ponderosa pine and Douglas-fir expressed Zn deficiency "C-Shifts' relative to the N-Alone treatment in 1997 and 1998, indicating a positive foliar response to Zn in the micro-nutrient mix.

Molybdenum

Mo concentrations were lower on all fertilizer treatments compared to the controls, thus Mo fertilization did not increase foliar Mo concentrations (Tables 2 and 3). Significantly ($p \leq 0.10$) lower Mo concentrations were produced by the N-Alone and K-Alone treatments for Douglas-fir as well as the N-Alone treatment for ponderosa pine, suggesting a dilution effect (Tables 2 and 3). Unpublished literature suggests that the Mo critical level should be 0.01 ppm. Molybdenum concentrations were well above 0.01 ppm for both species and all treatments, including the control. No significant ($p \leq 0.10$) foliar Mo content response was shown for those treatments containing Mo in the fertilizer mix (Tables 4 and 5). Vector analysis showed Mo dilution effects, an "A-Shift", on the N-Alone treatment for both species (Figures 17a and 17b). Deficiency "C-Shifts" were also produced by all treatments containing Mo in the fertilizer mix, relative to the N-Alone treatment (Figures 12a and 12b).

Foliar Growth Response

Overall, needles collected from the upper crown were larger on those treatments receiving N than those trees receiving no N in the fertilizer mix (Tables 6 and 7). The greatest 1997 Douglas-fir needle weight response was on the N-Alone treatment with a 31.8% increase but this treatment did not produce larger needles in 1998. The greatest response in 1998 was produced by the N+Low K+S+Micro treatment with a 52.4% increase over the controls. Ponderosa pine needle weight response was lower than Douglas-fir. No treatment produced significantly larger ponderosa pine needles in 1997 (Table 7). The largest 1998 needle weight response for ponderosa pine was 45.8% on the N+S+Micro treatment. Importantly, only treatments that included micro-nutrients produced significant ($p \leq 0.10$) needle weight increases in 1998 for both Douglas-fir and ponderosa pine.

Basal Area Response

Two-year net basal area response was significantly ($p \leq 0.10$) higher on the plots receiving the K-Alone and N-Alone treatments compared to the control plots (Table 8). Average basal area growth response for the K-Alone treatment was 3.2 ft^2/ac (28.6%) while response on the N-Alone was 1.8 ft^2/ac (16.1%) (Table 8). Negative net basal area response was seen on the Low N+S+Micro treatment (Table 8). Basal area response on those plots receiving micro-nutrients was insignificant ($p \leq 0.10$).

DISCUSSION

Foliar Nutrient Response

Nitrogen

The fertilizer treatments increased foliar N concentrations for both Douglas-fir and ponderosa pine. Foliar N response was much higher on those treatments receiving the 300#N/ac rate than the treatment that received 90#N/ac rate. Furthermore, the low N (90#N/ac) treatment showed no N foliar response. Nitrogen response was highest on the N-Alone treatment with a two-year average increase of 56% for Douglas-fir and 12% for ponderosa pine, over that of the control. Nitrogen foliar concentrations followed similar response patterns by treatments for both sampling years.

Nitrogen was strongly deficient for Douglas-fir while only moderately so for ponderosa pine. Douglas-fir showed strong to moderate foliar response with significant increases of N concentrations and strong magnitude vector shifts on those treatments receiving 300#N/ac, relative to the control or treatments receiving low or no N. Additionally, Douglas-fir N concentrations were below published critical levels on the control but increased above the critical level on those treatments where N was applied at

the 300#N/ac level. Ponderosa pine foliage did respond to N fertilization but not significantly ($p \leq 0.10$) so and not to the magnitude of Douglas-fir response. Ponderosa pine N concentrations were above the published critical levels for all treatments, including the control. Apparently, good ponderosa pine N status lowered N response to N fertilization. Other IFTNC studies support this result, where ponderosa pine usually has better N status, response is more variable and of lower magnitude than other conifers on the same sites (Moore et al 1998 and Garrison et al 1998).

Potassium

According to published critical levels, K was not deficient for either Douglas-fir or ponderosa pine in this study (Figures 2a and 2b). In addition, K applied at the 80#K/ac or 170#K/ac rate did not significantly ($p \leq 0.10$) increase foliar K concentrations over controls. However, vector analysis did discern increased K demand and response through synergistic (foliar nutrient increase of non-added nutrient) and deficient "C-Shifts", relative to the N-Alone treatment (Figures 12a, 12c and 12d). Perhaps the effect of the N treatment increased K demands and foliar response. Hayek et al (1999) showed similar foliar K results for ponderosa pine on basalt parent material types. In their study, vector analysis showed diluted foliar K concentrations on a N alone treatment plus K deficiency response on treatments containing N and K. In addition, the "Windy" installation showed imbalanced K/N ratios for both species on those plots receiving the N alone application (Figures 8a and 8b).

Sulfur

Sulfur fertilization did not significantly ($p \leq 0.10$) increase foliar S concentrations over the controls. However, relative to the to the N-Alone treatment, S concentrations were highly deficient. Vector analysis showed classic dilution "A-Shift" for S after

fertilization with N only for both species (Figure 13a and 13b). In addition, large magnitude deficiency "C-Shifts" were demonstrated indicating good S response relative to the N-Alone treatment. Foliar S dilution following N treatments has been demonstrated in other studies (Turner and Lambert 1979 and Hayek et al. 1999). Sulfur concentration fell below recommended critical levels for both species when N was applied alone, however, if S was in the fertilizer mix, S concentrations were generally above the critical level for foliar S, except on the N+S+Micro treatment for Douglas-fir. In addition, ponderosa pine showed N/S ratio imbalances for all treatments, including the control (Figure 3b). These results suggest N to S imbalances with or without the addition of N to augment S dilution on this site. Turner and Lambert (1979) also found S deficiencies were more common on basalt parent materials, as demonstrated in this study.

Boron

Boron concentrations were highly deficient for both Douglas-fir and ponderosa pine. Control, K-Alone and N-Alone treatments were below established B critical levels for both species (Figure 4a and 4b). Additionally, all treatments, including the control, showed B concentrations below published critical levels (Figure 4a). Similar to S foliar concentrations, the addition of N alone decreased or diluted B concentrations. Douglas-fir and ponderosa pine B response was highly positive for those treatments having B in the fertilizer mix when compared to that of the N-Alone treatment (Figures 4a and 4b). Mika et al (1998) and Hayek et al. (1999) also reported foliar B following B fertilization. Vector analysis diagnosed N induced B dilution, a "A-Shift", and a large magnitude "C-Shift" response with the addition of B to the fertilizer mix (Figures 14a, 14b and 14c). Interestingly, the effects of the N-alone treatment on Douglas-fir B dilution ceased in 1998 (Figure 14c) because no foliar weight increase occurred in 1998.

Copper

Application of Cu at the 10#Cu/ac rate was generally insufficient to significantly ($p \leq 0.10$) raise Cu concentrations above untreated plots for both species during both sampling years, except for the N+Low K+S+Micro treatment for Douglas-fir in 1997 (Table 2). Ponderosa pine foliar Cu concentration on the N-Alone treatment was significantly ($p \leq 0.10$) lower than that of the control and was below the recommended Cu critical level (Figure 5b). Vector analysis showed dilution "A-Shifts" on the N-Alone treatment for ponderosa pine. Deficiency, "C-Shifts" were also shown on all treatments containing Cu in the fertilizer mix relative to the N-Alone treatment, suggesting Cu deficiencies.

Zinc

Application of the fertilizer treatments significantly ($p \leq 0.10$) decreased Zn concentrations and content below controls for both species (Tables 2, 3, 4 and 5). The Low N+S+Micro treatment was the only treatment that did not significantly ($p \leq 0.10$) reduce Zn concentrations (Tables 2 and 3). Vector analysis clearly revealed dilution "A-Shifts" relative to the control and deficiency "C-Shifts" relative to the N-Alone treatment for both species. Generally Zn concentrations were not below recommended Zn critical levels, however, when K was applied alone Zn concentrations fell near or below this critical level for both species (Figures 6a and 6b). Although Zn deficiencies are not common, Hayek et al. (1999) also found Zn deficiencies on basalt rock types in central Idaho. Zinc levels are highly correlated to soil organic matter levels. High disturbance and removal of organic matter on this site may have contributed to reduced Zn levels.

Molybdenum

Similar to Zn concentrations, Mo concentrations were lower on those plots receiving the fertilizer treatments than on the control, for both species. Molybdenum concentrations significantly ($p \leq 0.10$) fell below the control on the K-Alone treatment for Douglas-fir and N-Alone treatment for both Douglas-fir and ponderosa pine. In addition, Mo concentrations tended to be higher on those treatments receiving Mo in the fertilizer mix, although not higher than the control treatment. Vector analysis also showed large magnitude Mo dilution "A-Shifts" and deficiency "C-Shifts relative to the N-Alone treatment. However, according to unpublished critical levels, Mo concentrations were well above the 0.01ppm critical level for both species (Tables 2 and 3). The application of Mo at the 1#/Mo/ac rate may not be sufficient to maintain or increase Mo concentration above that of the control. Further investigations are needed to better understand Mo mineral nutrition.

Foliar Growth Response

Overall, needle weight response was generally positive for all treatments and both species (Tables 4 and 5). The N-Alone treatment produced the greatest needle weight responses for Douglas-fir in 1997, however there was no needle weight response for Douglas-fir for this treatment in 1998. The largest ponderosa pine needle weight response was for the N+S+Micro treatment in 1998 with a 45.8% increase over the controls. Except for the N-Alone and Low N+S+Micro treatments, Douglas-fir needle weight response was greater in 1998 than 1997 and significantly ($p \leq 0.10$) so on three of the four treatments having micro-nutrients in the fertilizer mix (Tables 4 and 5). Similarly, ponderosa pine 1998 needle weight response was more than twice the 1997 response on three of the four micro-nutrient treatments (Table 7). The general tendency

of delayed needle weight response may in part be due to spring fertilization. The effect of spring application may not have manifested itself in time to show a strong needle growth response in 1997. Douglas-fir needle weight response was good on the low N (90#N/ac) treatment with 22.7% and 14.3 % increases over the controls in 1997 and 1998, respectively. In contrast, ponderosa pine needle weight responses on the low N treatment by year were -1.5% and 33.2%, for 1997 and 1998 respectively. No significant ($p \leq 0.10$) needle weight response was shown on the K-Alone treatment for either species.

Basal Area Response

Generally, the fertilizer treatments increased basal area growth over the controls. Except for the Low N+S+Micro (90#N/ac) treatment, basal area response due to fertilization was positive, with growth response ranging from 2.7% on the N+Low K+S+Micro treatment to 28.6% on the K-Alone treatment. High growth response from K alone fertilization is unusual. Results from other IFTNC studies have not shown any significant growth effect from K alone treatments (Moore et al 1993 and Mika 1999). Furthermore, foliar nutrient and weight response did not show a significant ($p \leq 0.10$) response to the K-Alone treatment. However, although K may not have a direct affect on growth (McDonald, 1991) the good growth on the K-Alone treatment could be attributed to indirect K influences. Potassium affects many plant processes (water relations, production of defensive compounds or carbohydrate transport) other than photosynthesis. Notably, the Low N+S+Micro treatment showed the only negative response relative to the controls. Given delayed foliar response to the spring fertilizer treatments, two-year basal area response may not fully express the effects of the fertilizer treatments. Particularly on those micro-nutrient treatments where significant foliar response was not shown until the second growing season after fertilization. Four-year response, which

includes both diameter and height response, should show the full effects of the fertilizer treatments.

CONCLUSIONS

Through the use of several foliar analysis techniques, results from this study show foliar nutrient deficiencies or induced deficiencies for N, K, S, B, Cu, Zn and Mo. In part, these nutrient deficiencies were induced through the dilution effects of large needle weight increases caused by N alone fertilization. Nutrient dilution following N fertilization was seen in this study for S, B, Cu, Zn and Mo. Generally, those nutrients that expressed N induced dilution deficiencies responded well when that nutrient was added to the fertilizer mix. Foliar growth response tended to be greater two growing seasons after fertilization than it was after one growing season, for both species. Delayed foliar growth response may have been caused by spring fertilization where the fertilization effect may not have completely manifested itself in a strong foliar growth response in 1997. Delayed foliar growth response was especially evident in ponderosa pine where no significant ($p \leq 0.10$) foliar growth was shown in 1997 but was evident in 1998. Notably, significant ($p \leq 0.10$) foliar weight response did not occur on the micro-nutrient treatments for both species until two growing seasons (1998) after fertilization. In addition, delayed foliar response may also have delayed or decreased basal area response in this study, particularly on the micro-nutrient treatments. Future results should provide a clearer picture in explaining growth response. The nutrient deficiencies encountered on this site might be explained through past management practices (ie.- organic matter removal and surface soil disturbance). Furthermore, the Wanapum basalt parent material present on this site may be a factor influencing foliar nutrition and growth response. Other IFTNC studies have shown poor fertilizer response on Wanapum basalt parent materials (IFTNC 1989, Shaw and Moore 2000). Significant basal area growth

response from the K-Alone treatment in this study is unusual. In contrast, foliar growth response was not significant for the K-Alone treatment for both species. Perhaps two-year basal area response did not capture the full effects of the fertilization treatments, due to the late spring application. Future results may help in explaining the observed basal area growth results.

LITERATURE CITED

Ballard, T.M. and R.E. Carter. 1986. Evaluating forest stand nutrient status. B.C. Min. For. Land Management Report No. 20, Queen's Printer Publications, Victoria, B.C., 60p.

Blake, J.I., H.N. Chappell, W.S. Bennett, S.R. Webster, and S.P. Gessel. 1990. Douglas-fir growth and foliar nutrient responses to nitrogen and sulfur fertilization. Soil Sci. Soc. Am. J. **54**: 257-262.

Garrison, M.T., J.A. Moore, T.M. Shaw, and P.G. Mika. 1998. Foliar nutrient and growth response of mixed-conifer stands on the Okanogan and Umatilla National Forests to three fertilization treatments. FWR, Univ. of Idaho, Moscow, 36p.

Hasse, D.L. and Rose, R., 1995. Vector analysis and its use for interpreting plant nutrient shifts in response to silvicultural treatments. For Sci. 41:54-66.

Hayek, J.C., J.A. Moore and J.M. Mandzak. 1999. Multi-nutrient Fertilization Responses Differs by Rock Type in Central Idaho Forests. IFTNC Supplemental Report No. 4. University of Idaho, Moscow.

Ingestad, T. 1979. Nitrogen stress in birch seedlings II: N, K, P, Ca and Mg nutrition. Physiol. Plant **45**:149-157.

McDonald, A.J., T. Ericsson, and T. Ingestad. 1991. Growth and Nutrition of Tree Seedlings. **In:** A.S. Raghavendra. (ed.) Physiology of Trees. Chap 9. Wiley Interscience. New York. 509 p.

Mika, P.G. 1998. Foliar Response to Fertilization on IFTNC Forest Health Sites in the Inland Northwest. 1998 IFTNC Annual Meeting. University of Idaho.

Mika, P.G. 1999. Growth Response to Fertilization on IFTNC Forest Health Sites in the Inland Northwest. 1999 IFTNC Annual Meeting. University of Idaho.

Moore, J.A., P.G. Mika, T.M. Shaw and M.T. Garrison. In progress. IFTNC Supplemental Document. Nutrient Characteristics of Four Conifer Species in the Inland Northwest. University of Idaho, Moscow.

Powers, R.F. 1983. Forest fertilization research in California. p. 388-397 *In*: Ballard, R. and S.P. Gessel (eds.) IUFRO symposium on forest site and continuous productivity. USDA For. Serv. Gen. Tech. Rep. PNW-163.

SAS Institute. 1985. SAS user's guide: statistics. 5th ed. SAS Inst., Cary, NC.

Timmer, V.R. and E.L. Stone. 1978. Comparative foliar analysis of young balsam fir fertilized with nitrogen, phosphorus, potassium, and lime. Soil Sci. Soc. Am. J. **42**: 125-130.

Turner, J. and M.J. Lambert. 1979. Sulfur nutrition of conifers in relation to response to fertilizer nitrogen, to fungal infections and to soil parent materials. *In*: Forest soils

and land use. Proc. of the Fifth North American forest soils conference. Aug. 1978. C.T. Youngberg, ed. Colorado State Univ., Ft. Collins, CO. p. 546-564.

Webster, S.R. and A. Dobkowski. 1983. Concentrations of foliar nutrients for trees and the dosage frequency of fertilizer trials. Weyerhaeuser Research Report No. 1, Project 050-3920/3 25p.

Weetman, G.F., and R.M. Fournier, 1982. Graphical diagnoses of lodgepole pine response to fertilization. Soil Sci. Soc. Am. J. **46**:1280-1289.

Weetman, G.F. and R.M Fournier 1986. Construction and interpretation of foliar graphical diagnostic technique. P. 55-76. *In*: Interior forest fertilization workshop, 1986. Kamloops, British Columbia.

Wykoff, W.R., N.L. Crookston and A.R. Stage, 1982. Users guide to the Stand Prognosis Model. Gen. Tech. Rep. INT-133. Ogden UT: USDA Forest Service, Intermountain Forest ans Range Exp. Sta., pp 81-84.