Intermountain Forest Tree Nutrition Cooperative

Supplemental Report No. 4

December 1999

Jay C. Hayek

James A. Moore

John M. Mandzak

Multi-nutrient Fertilizer Response Differs by Rock Type in Central Idaho Forests

Submitted to Soil Science Society of America Journal

MULTI-NUTRIENT FERTILIZER RESPONSE DIFFERS BY ROCK TYPE IN CENTRAL IDAHO FORESTS

By

Jay C. Hayek

Caterpillar Inc.

Forest Products Group

Aurora, IL 60507

James A. Moore*

Department of Forest Resources

University of Idaho

Moscow, ID 83844

and

John M. Mandzak

Boise Cascade Corporation

PO Box 156

125 Mill Road

Horseshoe Bend, ID 83629-0156

Acknowledgments:

This research was supported by Boise Cascade Corporation and the Idaho Department of Lands. The authors thank Intermountain Tree Nutrition Cooperative members as well as Mariann Garrison, Terry Shaw, Peter Mika and Mary Moore. College of Forestry, Wildlife, and Range Experiment Station, University of Idaho.

ABSTRACT

Eight "single tree" multi-nutrient screening trials were established on granite, granodiorite, tonalite, and basalt rock types in central Idaho. Foliar nutrient concentrations, contents, and needle weights of individually fertilized ponderosa and lodgepole pine [*Pinus ponderosa* (Law.) and *Pinus contorta* var. *latifolia* (Engelm.)] trees were examined one year following multi-nutrient fertilization. Diagnosis and interpretation of nutrient status using graphical vector analysis identified that N, S, and B were deficient at every research site. Significant needle weight increases, up to 47%, were observed over the control needle weights from application of N, NKS + micros, or NPKSMg + micros fertilizer treatments. Vector analysis also identified Mg deficiencies on tonalite lithologies, K deficiencies on granodiorite lithologies, and Cu and Zn deficiencies on basalt and tonalite lithologies, respectively. Screening trials proved effective in determining nutrient deficiencies across soil parent materials on similar habitat types within one growing season. Untreated foliar nutrient concentrations were significantly different between rock types and rock mineralogy and soil textural differences combined to explain tree foliar nutrient differences for some elements.

INTRODUCTION

Inland northwest conifer forests are commonly nutrient deficient (Loewenstein and Pitkin 1963, Moore et al 1991). Nitrogen and sometimes potassium, phosphorus, and sulfur have been used in fertilizer blends to increase yield, reduce stand rotation length, and ameliorate site specific nutrient deficiencies (Loewenstein and Pitkin 1963; Cochran 1973, 1977, 1978; Turner and Lambert 1979; Steinbrenner 1981; Shafii et al. 1989; Blake et al. 1990; Mika and Moore 1990; Binkley et al. 1995; Garrison et al. 1999). Multi-nutrient fertilizer blends incorporating micronutrients, though, are relatively new in the science of forest fertilization. Boron. along with copper and zinc, are the primary micronutrients that have been studied regarding deficiency and sufficiency in managed forest stands (Parker 1956; Beaton et al. 1965; Stone 1968; Boardman and McGuire 1990; Carter and Brockley 1990; McLaren et al. 1990; Turvey and Grant 1990; Zasoski et al. 1990; Green and Carter 1993; Brockley and Sherman 1994).

The need for site-specific fertilizer prescriptions is increasingly apparent. However, fertilizer trials involving multi-nutrient blends that include micronutrients are rare. Furthermore, examination, correlation, and explanation of foliage and growth response across multiple parent rock lithologies to multi-nutrient fertilization have not been undertaken. The underlying geology and surfical deposits comprising forest soil parent materials play an essential role in determining mineral nutrition of forests throughout the world (Lutz 1960; Baule and Fricker 1970; Heilman 1979; Pritchett and Fisher 1987; Buol et al. 1989). Few studies, though, have attempted to directly correlate stand mineral nutrition and fertilizer response with the underlying geology of northwest conifer forests. Recently, the Intermountain Forest Tree Nutrition Cooperative (IFTNC) has focused on establishing site specific fertilizer prescriptions assessing and identifying sites on the basis of geographic subregion, habitat type, and soil parent material (Mika and Moore 1990; Mika et al. 1992; Mandzak and Moore 1994; Moore et al. 1994, 1998; Garrison et al 1999; Garrison and Moore 1998). The relationship between site moisture status, as represented by habitat type (Daubenmire and Daubenmire 1968), and parent material and tree/stand response to fertilization based on "good" rocks (high nutrient supplying soil parent materials) and "bad" rocks (low nutrient supplying soil parent materials) underlying northwest conifer forests has been discussed by Mandzak and Moore (1994) and Moore et al. (1998).

1997

Correlating stand and tree level fertilizer response and the underlying soil parent material is not a new concept, although the relationships have not been thoroughly examined. Turner and Lambert (1979) identified sulfur deficiencies in New South Wales Australia that were apparently related to soil parent material. *Pinus radiata* plantations that occurred over basalt, diorite, and weathered granite parent materials were determined to have a greater likelihood of low sulfur concentrations in the foliage of *P. radiata* and subsequently required sulfur in addition to nitrogen in the fertilizer prescriptions. Powers et al. (1988) reported relative volume response to fertilization varied greatly between metasedimentary, granite, and volcanic parent material, with metasediments showing the largest growth increase and granites the least; despite granites having higher site indexes. Mika et al. (1992) showed that growth response and mortality to N fertilization was greatly influenced by soil K status as affected by the underlying parent material. Boron deficiencies have been identified not only with organic matter removal and oxidation, but also the underlying parent material (Stone 1968; Lambert and Turner 1977; Carter et al.

1984; Carter et al. 1986; Carter and Brockley 1990). Soil parent material will likely be an important part of site specific fertilizer prescriptions since knowing the elements contained in the rock and their mineral form greatly affects soil nutrient availability and improves our understanding of tree/site fertilizer interactions.

In our multi-nutrient fertilizer screening trials, preliminary interpretation and diagnoses of tree foliage response to fertilization was identified using graphical vector analysis. This technique was pioneered by Krause (1965) and Heinsdorf (1967) and later modified by Weetman and Fournier (1982), Timmer and Stone (1978) and their respective associates. The graphical vector analysis approach provides a diagnostic technique to identify nutrient interactions in the soil or in the plant itself (Prescott et al. 1992; Munson et al. 1993; Weetman et al. 1993; Joslin and Wolfe 1994; Haase and Rose 1995; Kiefer and Fenn 1996; Haase 1997; Imo and Timmer 1997). Reviews of diagnostic techniques involving forest/tree nutrition further emphasize the use, portability, and effectiveness of vector analysis in fertilizer screening trials, field trials, and nursery experiments (Pritchett and Fisher 1987; Timmer 1991; Carter 1992; Haase and Rose 1995; Meyer et al. 1997). For these reasons we used vector analysis to screen (identify and diagnose) ponderosa and lodgepole pine response to fertilization across different rock lithologies. Thus, the objectives of the central Idaho screening trial study were to: (i) screen multi-nutrient fertilizer treatments across different parent rock lithologies, (ii) correlate foliar nutrient and needle weight responses to different parent rock lithologies, and (iii) diagnose and interpret fertilizer response for various rock types using graphical vector analyses.

METHODS

Eight "single tree" fertilizer trials consisting of 20 trees per site were established in May of 1998. The study sites were located in the vicinity of McCall and Cascade, Idaho on Boise Cascade Corporation lands. Seven of the eight sites were established within young ponderosa pine stands. Stand age across all sites ranged from 10-15 yr. total age. A naturally regenerated, managed lodgepole pine stand of similar age was also included in the study. Site and initial stand characteristics for the eight study sites are summarized in Table 1. Young, vigorous, even-aged, managed stands that had uniform site characteristics were selected for screening. All stands had regenerated after logging and all planted trees were from a local seed source.

Parent rock lithology and vegetation type were the site selection criteria for this study. Soils were developed in place from the underlying bedrock. Elevation, slope, aspect, and stand density were kept common or uniform within a stand. By design, we sampled four parent material classes and one vegetation series. Soil parent lithologies selected originated from either the Idaho batholith or Columbia River basalt flows and included the following rock types: granodiorite, granite, tonalite, and basalt. All study sites were located on grand fir (*Abies grandis*) vegetation types. A factorial design was used with four treatments and five replications for each treatment applied at each site. Fertilizer treatments are described in Table 2 and are identical for all study sites except for the two Lardo sites (basalt parent materials), in which potassium was omitted from the fertilizer blends. Past research by the IFTNC demonstrated little response to K fertilization on basalt parent materials (Moore et al. 1998). All treatments were applied in the spring of 1998.

Transect Layout and Single Tree Selection

A single tree screening trial approach was used to rapidly test individual tree response to multiple fertilizer amendments (Timmer and Stone 1978; Weetman and Fournier 1982). A total of 140 ponderosa pine and 20 lodgepole pine trees were sampled in the study. Five dominant trees were selected for measurement, fertilization, and foliar sampling per treatment (20 trees per site). Trees sampled were void of visual defect, in good health and vigor, and were representative of the stand. All installations were still in the juvenile stage of stand development and had not yet achieved canopy closure (Miller et al. 1981).

Transect lines were randomly placed throughout each site and trees that fell on or within arms-reach of our transect line and also fit the requirements described above were recorded and randomly selected for fertilization. Each tree was marked with paint and coded according to the randomly assigned treatment it received. Measurements of tree diameter at breast height (DBH) and total tree height to the base of current year's terminal leader were taken at the time of initial installation, preceding bud flush. Diameter breast height and final height measurements were taken again at time of dormant season foliage collection (October). Distance between adjacent trees on common transects and crown drip-line radius measurements were also recorded for each selected tree. A minimum buffer zone of 6 m was provided between adjacent treatment areas so as not to confound fertilizer treatment effects. Treatment area for selected trees was defined as:

$$\text{[Eq. 1]} \qquad \text{Treatment Area} = (\text{Crown drip-line radius} + 3.3\text{ m})^2 \times 3.14$$

Where: Crown drip-line radius is equal to line distance perpendicular from the center of the stem to the edge of the live crown.

Fertilizer was broadcast in a circular plot around each individual tree using hand-operated spreaders based on the elemental rate and treatment area for each selected tree. Initial volatilization losses due to warm air temperature, wind, and moisture were presumably very low since urea was applied in May and there was subsequent substantial precipitation. Additionally, the volatilization rates of potassium chloride and other fertilizer amendments that were also applied are very low (Ouyang et al. 1998).

Soil and Rock Sampling and Geochemical Analysis

Twenty core soil samples were randomly collected at site establishment prior to treatment from the upper 25 cm of mineral soil were taken and composited for chemical analysis of each installation. Surface organic material was not included in the soil samples and care was taken to avoid sampling trees growing in or near decaying logs, stumps or other irregularities such as burned slash piles. Fresh rock samples were also collected to verify the parent lithology from published geology maps. Rock and soil samples were analyzed to identify and quantify elemental, mineral, and nutrient content. Analyses of rock samples included geochemical analysis to determine the overall chemical composition of the rocks and petrographic analysis to identify and verify their mineral composition. Soil pH, NO_3^--N, available P, Mn, Cu, Zn, Fe and exchangeable K, Ca, and Mg were analyzed. Soil pH was measured 1:1 in H_2O. Nitrate was extracted with calcium oxide and then determined using automated colorimetry. Exchangeable K, Ca, and Mg (1 N ammonium acetate, pH 3.0) were estimated by inductively coupled plasma (ICP) spectrometry. Available P was determined on a 2-g sub-sample of soil extracted with 12 ml of Bray's solution (Bray and Kurtz 1945). Available Mn, Zn, Cu, and Fe were analyzed by atomic absorption. Washington State University's GeoAnalytical Lab performed geochemical analyses, and their procedures are described in Johnson et al (1999). Spectrum Petrographics Inc. performed petrographic analyses and Nesse (1991). outlined their procedures.

Foliage Collection and Analysis

Foliage samples were collected after the onset of dormancy at the end of the first growing season following fertilizer application. Current year's primary lateral shoot growth was collected from the third whorl from the top of each tree using telescoping tree-pruners. Foliage samples were immediately placed in zip-lock storage bags and placed in an ice chest for storage and transport.

In the laboratory, current year's needles were separated from the stems and oven-dried at 70° centigrade for 24 hours. The dried needle samples for each tree were counted and weighed (3 separate samples of 30 needle fascicles) for needle weight comparisons. Needle weights were the average of the 3 samples of 30 needle fascicles. After weighing, needle samples within the same site and treatment were composited and ground in a coffee grinder and sent to Scotts Laboratories in Allentown, PA for chemical tissue analysis. Tissue nutrient concentrations analyzed were: N, P, K, S, Ca, Mg, Zn, Cu, B, Fe, Mn, Mo, Al, and Na. Foliar N was determined using a standard micro-Kjeldahl procedure. Phosphorus, K, Mg, Fe, Cu, and Zn were determined by ICP emission with digested plant tissue.

Statistical and Vector Analyses

All statistical analyses were conducted as analysis of variance (ANOVA) procedures in the general linear models module of SAS (SAS Institute Inc. 1985). Means were compared for each rock type, treatment, and the interaction of rock type and treatment. Statistical analyses of treatment effects were conducted on both nutrient contents and concentrations, though content is believed to be a truer index of treatment response (Timmer and Morrow 1984; Weetman and Fournier 1986). Comparisons of means were made using the least squares means (LS means) test (SAS Institute Inc. 1985). Unless otherwise indicated, the significance level is 0.1 for main effects and interactions in the LS means comparisons. The granodiorite/lodgepole pine site was not included in statistical comparisons between rock types for foliar content and concentration due to potential confounding species differences between lodgepole and ponderosa pine. Interpretation and preliminary diagnosis of tree/site mineral nutrition was performed on current year dormant season needle nutrient concentration, nutrient content, and dry fascicle weight using a graphical vector analysis approach (Weetman and Fournier 1982; Timmer and Stone 1978). A general explanatory schematic of the approach for added nutrients is provided in Figure 1. and a detailed description of vector analysis can be found in Weetman and Fournier (1986) and Haase and Rose (1995).

RESULTS

Nitrogen

Geochemical analysis for N was not undertaken because primary mineral weathering of N is typically negligible within most soil parent materials; however, soil N levels were analyzed. Plant available NO_3-N and NH_4-N were determined for all eight trials (Table 3). Ammonium-nitrogen levels were highest for the RVW and LB sites and lowest for PF I. Nitrate-nitrogen soil levels were highest for LB and FC I, and were low for all other installations.

Nitrogen response was extremely positive, indicating a chronic deficiency of this nutrient across the majority of rock types. Foliar N concentration across rock type showed no real difference for the control trees (Table 5). Nitrogen additions alone or in combination with other nutrients substantially increased N concentration on all rock types and N content on basalt, granite and tonalites (Tables 4 and 6). Vector analysis displayed changes in N concentration, content, and needle weight from the N additions relative to control treatments that were characteristic of N deficiency i.e., a "C-shift" (Figure 2).

Tonalite rock types, after receiving each fertilizer treatment had significantly higher foliar N concentrations than all other rock types (Table 5). Application of 330 kg N ha^{-1} alone or in a multi-nutrient blend greatly increased foliar N concentrations compared to the control treatments for all rock types (Table 4). This increase occurred despite all foliar N concentrations across the ponderosa pine sites being well above the published critical level, 1.10% (Powers et al. 1988). Tonalite lithologies had significantly greater foliar N contents following application of the NKS + micros and NPKSMg + micros treatments compared to granite and basalt lithologies (Table 7).

Phosphorus

Geochemical analysis of mineral P revealed that volcanic rocks typically had greater amounts of P_2O_5 compared to plutonic rocks, with the exception of the Paddy Flat trials (Figure 3). Soil P levels, however, did not correlate well with rock mineral P_2O_5 content.

Tonalite lithologies with P applied were significantly higher in foliar P content and concentration compared to the other rock types (Tables 5 and 7). Application of 330N alone increased foliar P concentrations for all rock types (Table 4), apparently reflecting a synergistic effect (when a non-added nutrient concentration increases from the addition of a different nutrient). Phosphorus/nitrogen concentration ratios for all fertilizer treatments were between the critical and optimal ratio range of 8-15% (Ingestad 1979).

No significant increase in foliar P concentration was observed following P application on granite lithologies (Table 4, and Figure 4a), although we see a synergistic effect, a "C-shift" from the application of only N, reflecting a significant increase in foliar P content. On the granodiorite lithology, both NKS + micros and NPKSMg + micros treatments significantly increased foliar P concentrations above that of the control treatments (Figure 4b). Ballard and Carter (1986) reported a P critical level of 0.12% for lodgepole pine; therefore a moderate deficiency of P may have existed for the lodgepole pine study site on the granodiorite lithology.

Tonalite lithologies did not show significant increases in foliar P concentrations from inclusion of P in the fertilizer (Table 4). However, relative to control treatments, vector analysis showed that PF II displayed a moderate P deficiency, a "C-shift", from P fertilizer additions and also displayed a moderate synergistic shift, a "C-shift", from the NKS + micros treatment (Figure 4c), reflecting a significant increase in P content, despite control foliar P concentrations that were substantially higher than the critical level of 0.08%.

No significant increase in foliar P concentration was observed following addition of P fertilizer on basalt lithologies (Table 4). However, relative to the N only treatment, vector analysis for LRD I displayed a "C" deficiency shift from P fertilizer additions (Figure 4d) due to the significant P content increase. LRD I also showed a moderate to large synergistic shift, also a "C-shift", from the NS + micros treatment.

Tonalite lithologies had significantly greater control foliar P concentrations and contents compared to controls on all other lithologies (Table 5). Additionally, tonalite lithologies had significantly greater foliar P concentrations following all fertilizer treatments compared to all other lithologies. Application of 110 kg P ha^{-1} did not increase foliar P concentrations for the majority of the ponderosa pine study sites, especially for the granite and basalt lithologies, but P content increased significantly on all rock types (Tables 4 and 6).

Potassium

Vector analysis of foliar K, relative to control values, showed an apparent dilution effect for most fertilizer treatments across the majority of rock types. No significant increase in foliar K concentration was observed from the addition of KCl fertilizer on granite lithologies (Table 4). Minimal K uptake was associated with high control foliar K concentrations, ranging from 0.554 to 0.813% for the granite installations, well above the proposed critical level of 0.48% (Powers 1983).

The granodiorite-lodgepole pine installation showed no significant increase in foliar K concentration from the addition of KCl compared to control foliar K concentrations. However, relative to N only values, this site appeared to have a positive "C-shift" response to K additions, indicative of K deficiency (Table 4 and Figure 5b).

Tonalite lithologies, generally, did not show significant increases in foliar K concentrations above that of the controls from application of K fertilizer (Table 4). However, vector analysis showed that both PF I and PF II displayed moderate K deficiency shifts, "C-shifts", relative to the N only treatment from application of K fertilizers (Figure 5c). Despite diluted foliar K concentration following N additions and apparent deficiency vector shifts from added K (relative to the N treatment), foliar K concentrations remained above critical on tonalite lithologies. Vector analysis showed that compared to the control, N alone fertilizer applications reduced foliar K concentrations on basalt lithologies (Figure 5d).

Application of 187 kg K ha $^{-1}$ generally did not significantly increase foliar K concentrations across rock types; however, dilution effects of added N influenced these results (Table 4). Foliar K/N ratios were below the published critical level of 50% (Ingestad 1979) for half of the study sites on the control treatments, showing no distinct pattern by rock types. Application of N with or without K decreased K/N ratios below the critical ratio for all treatments across all rock types.

Tonalite rock types had significantly higher concentrations of foliar K in control trees than all other lithologies (Table 5). Control foliar K concentrations on basalt rocks were significantly lower compared to granite, and tonalite parent materials, despite having the highest plant available K levels in the upper 25 cm of mineral soil (Table 3). Potassium concentrations from additions of 187 kg ha $^{-1}$ did not differ significantly from control foliar K concentrations. Based on agricultural standards, soil K levels for all screening trials contained adequate amounts of plant available K.

Sulfur

Sulfur was deficient and not significantly different across all rock types (Table 5). Response to S was extremely positive and uptake behaved as expected if S was deficient. Vector analysis showed large magnitude vector shifts characteristic of deficiency, a "C-shift" (Figure 6). The same diagram also depicts a classic dilution "A-shift" of S after fertilization with N only. The 330N treatment diluted S in the foliage as demonstrated in other studies (Turner and Lambert 1979). Control treatments for all rock types had N/S ratios at or below 14.7, indicating N/S balance, however, following fertilizer additions of both N and S, foliar N/S ratios were typically above the critical ratio of 14.7, implying an imbalance between the two elements (Turner and Lambert 1979). Application of 99 kg S ha^{-1} was sufficient to increase foliar S levels, but did not bring the ratio back into balance. Application of S significantly raised foliar S levels above that of their corresponding control values for all rock types (Table 4). Tonalite lithologies, after receiving the NPKSMg + micros treatment were significantly higher in sulfur concentration than all other rock types (Table 5).

Magnesium

Basalt rocks had significantly higher MgO contents compared to plutonic rocks (Figure 3). The basalts at LRD I and LRD II had MgO contents of 4.13 and 5.64%, respectively compared to 0.23 and 1.86% for the plutonic rocks at LB and PF. Olivine is the principal mineral containing Mg in these basalt lithologies.

Tonalite rock types and two of the three granite rock types (LB and FC I) showed increased foliar Mg concentrations after Mg application. Tonalite rock types had significantly higher foliar Mg concentrations and contents following treatments with Mg than all other rock types suggesting potential Mg deficiency (Tables 5 and 7). Application of N alone depressed Mg foliar levels indicated by 5 out of 8 installations having lower Mg concentrations after N treatment compared to their controls (Figure 7). Foliar Mg concentrations were well above published critical levels (0.05%) for all sites and treatments (Powers 1983) and Mg/N ratios were within the critical to optimal range of 5-10% for all control treatments. However, the N alone or NKS + micros treatments often decreased foliar Mg/N ratios below critical (Ingestad 1979). Magnesium application in the more complete blend alleviated sub-critical Mg/N ratios for only half of the study sites.

The positive foliar response of tonalite sites to added Mg was associated with very low soil extractable Mg levels on this rock type (Table 3). However, tonalite rocks had the highest magnesium (MgO) content (Figure 3). Granite lithologies had significantly lower control Mg concentrations compared to basalts. Only the granite and tonalite rock types significantly increased in Mg concentrations following Mg treatments compared to the controls.

The granodiorite lithology did not show significant uptake of Mg, relative to the control, from Mg fertilizer application (Table 4). However, the NKS + micros treatment produced a synergism effect, a "C-shift", on foliar Mg concentrations relative to the N only treatment (Figure 7b). A Mg deficiency shift was observed following the NPKSMg +

micros treatment; however, it was smaller than the shift from the NKS + micros treatment, suggesting that Mg is non-limiting on this site.

Tonalite lithologies showed significant increases in foliar Mg concentrations following application of Mg fertilizer (Table 4). Vector analysis revealed significant deficiency shifts, "C-shifts", relative to the control to further support the idea of Mg deficiency (Figure 7c); despite foliar Mg levels above critical levels for control trees.

Basalt rocks generally did not show an increase in foliar Mg concentrations above those of the control from application of Mg. LRD I showed increased foliar Mg levels from Mg application relative to N only fertilizer additions, but not compared to the control (Figure 7d). Nitrogen only additions diluted foliar Mg concentrations within the Lardo screening trials. Furthermore on LRD I, application of the NS + micros treatment produced a synergistic effect on foliar Mg concentrations relative to both the N only and control treatments.

Boron

Foliar B concentrations for controls showed no significant differences by rock type (Table 5), but like S and N, B was deficient across all rock types. Control foliar concentrations of B were below the published critical level of 20 ppm further suggesting that a positive response should occur following B additions. Applications of B greatly increased foliar B levels in all eight screening trials as expected for a deficient nutrient. Vector analysis showed large magnitude vector shifts characteristic of deficiency, a "C-shift" (Figure 8). Vector analysis showed dilution tendencies for foliar B concentrations following N alone treatments. The largest deficiency vector response was seen on the granodiorite, lodgepole pine site. Application of N alone reduced B concentrations below control foliar levels in seven of the eight installations. Including 5.5 kg B ha^{-1} in the blend was sufficient to raise foliar B concentrations above the critical level within one year of treatment.

Geochemical analysis for B was not conducted, although soil B analysis was completed. Soil B levels were highest for volcanic parent materials and lowest for tonalite rock types (Table 3). Boron soil levels, based on agricultural standards, were deficient for all plutonic rock types and marginally deficient for the volcanic lithologies.

Copper

Geochemical analysis showed that all plutonic rock types were virtually devoid of any mineral Cu^{2+} (Figure 3). Volcanic rocks, however, were quite abundant in mineral Cu^{2+}, though foliar chemical analysis did not substantiate this difference between these major rock groups. Basalt rocks had lower control foliar Cu concentrations compared to tonalite rock types. Copper foliar concentrations for all rock types were below the critical level, (3 ppm), for ponderosa pine (Boyer 1984, unpublished). The N alone treatment caused decreased foliar Cu levels in seven of the eight installations (Figure 9). Additions of Cu, however, did not alleviate the apparent Cu deficiency within the first growing season following fertilization since foliar Cu concentrations did not increase above the controls for any rock type, but did produce foliar Cu levels above the depressed concentrations for the N only treatments for basalt, granodiorite, and tonalite lithologies.

No significant increase in foliar Cu concentrations was observed from the application of Cu on granite lithologies (Table 4). Application of N only significantly diluted foliar Cu concentration relative to controls in two of the three granite trials (Figure 9a). Since Cu was not readily taken up within one year after application, it seems not to be limiting on this rock type despite marginally deficient foliar concentrations.

Granodiorite lithologies showed no significant increase in foliar Cu concentrations following Cu fertilization; however, foliar Cu for the N only treatment was significantly diluted following the 330N treatment. Vector analysis showed that application of Cu in the NKS + micros and NPKSMg + micros treatments significantly raised foliar Cu concentrations relative to the N only treatment, but not relative to the control (Figure 9b). Lodgepole pine foliar Cu critical level is 2.7 ppm, thus this site should be marginally deficient, but the lack of significant Cu uptake compared to the control makes this assessment questionable.

On tonalite lithologies, no significant increase in foliar Cu concentration was observed from the addition of Cu fertilizer compared to the controls (Table 4). The 330N treatment significantly diluted foliar Cu concentrations relative to untreated foliage and the NKS + micros and NPKSMg + micros treatments significantly increased foliar Cu concentration and content relative to the 330N treatment (Figure 9c) suggesting Cu limitations.

Basalt lithologies showed a significant increase in foliar Cu concentration from the NS + micros fertilizer treatment, but not to the NPSMg + micros treatment (Table 4). Relative to both the control and 330 N treatment, vector analysis showed deficiency, a "C-shift", from added Cu at the LRD 1 site, suggesting Cu deficiency (Figure 9d).

Zinc

Basalt rocks contained the largest amount of Zn^{2+} while the plutonic rocks were lower than basalts (Figure 3); however, Zn^{2+} was present in greater amounts than Cu. Tonalite rock types generally had higher amounts of Zn than did the granite rocks. We did not conduct soil analyses for Zn. Granites were significantly lower in foliar control Zn compared to tonalites and basalts. Application of N alone also increased foliar Zn levels above the control values for six of the eight sites, indicative of potential synergism (Figure 10). However, relative to the N only treatment, vector analysis identified PF II and LRD I as displaying weak graphical indications of Zn deficiency. Foliar Zn concentrations, though, were above the critical level of 30ppm (Boyer 1984, unpublished) for all treatments. The NPKSMg + micros treatment produced a significant foliar Zn increase over the controls only for basalt and granite lithologies (Table 4). Zinc additions increased foliar Zn concentrations only at the LRD I and PF II research sites, thus suggesting a Zn limitation.

A small but significant increase in foliar Zn concentration was observed after Zn fertilization on granite lithologies (Table 4). However, a larger significant increase was observed from the N only treatment (Figure 10a), indicative of synergism, a "C-shift" for a non-added nutrient. The small vector shift of added Zn on the granite lithologies and the adequate amounts of foliar Zn in the control foliage suggests that Zn is not limiting on the granite lithologies.

On the granodiorite rock type, no significant increase in foliar Zn concentration was observed from Zn fertilizer applications over that of the untreated foliage. The 330N, treatment significantly diluted foliar Zn concentrations compared to the control (Figure

10b), and there was a significant increase in foliar Zn concentration from application of Zn compared to the N only treatment (Table 4). Foliar Zn concentration for untreated foliage was below the published critical level of 52 ppm for lodgepole pine (Ballard and Carter 1986), thereby suggesting marginal deficiencies at this site. Although the vector shift of added Zn did not fall into the deficiency zone as outlined by Timmer and Ray (1988), the direction and magnitude of the vector with added Zn, relative to the 330N treatment, was significant suggesting Zn deficiency following N only fertilization.

Tonalite lithologies overall did not show significant foliar Zn concentration increases following the Zn applications (Table4). However, vector analysis showed that PF II displayed a deficiency "C-shift" from application of Zn fertilizer (Figure 10c).

Basalt rock types showed significant foliar Zn concentration increases following the Zn treatment (Table 4). For the LRD II site, vector analysis revealed a large magnitude vector shift indicating deficiency when the Zn treatment was compared to both control and N only treatments. Additionally, application of the NS + micros treatment at LRD II produced a large magnitude shift towards synergism, a "C-shift" (Figure 10d). However, foliar Zn concentrations for the control treatments were above the deficiency concentration on this rock type. Furthermore, based on LRD II site vector analysis, Zn seems not to be limiting due to the synergistic effect on foliar Zn levels from adding other nutrients.

Iron

Iron, except on calcareous soils, has generally received little research attention in northwest conifer forests. Iron was not examined through vector analysis because it was not an added nutrient in these screening trials. However, foliar Fe levels were found to be quite low, ranging from 18.7 to 31 ppm, well below the critical level of 50 ppm suggested by Boyer (1984, unpublished). Iron should be examined in future screening trials on central Idaho parent materials.

Needle Weight Response

Comparing across rock types, needle weights for the controls showed no significant difference between ponderosa pine sites (Table 7). Needle weight response ranged between -11 to 45% for all fertilizer treatments compared to the controls (Table 8). Needle weight response to the N only treatment ranged from -11 to 24%, whereas needle response to NKS and NPKSMg + micros ranged from 10 to 45% and from 3 to 43 %, respectively. The granodiorite lithology site (RVW) and the PF II site were the only installations that did not show significant needle weight response compared to the control resulting from the N only fertilizer treatment. Only the granodiorite lithology did not show significant needle weight response to the multi-nutrient fertilizer blends (Table 6). Additionally, only the tonalite lithology responded significantly to NPKSMg + micros over that of the NKS + micros treatment, suggesting that P, Mg, or Zn further increased needle weight response and that one of these elements may limit growth for this rock type.

DISCUSSION

Nitrogen

Nitrogen was deficient or marginally deficient for the majority of the screening trials. Nitrogen applied at 330 kg ha^{-1} was sufficient to elevate foliar N concentrations significantly above untreated foliar N levels across all rock types sampled. Nitrogen fertilization increased needle weights up to 24% over untreated foliage (Table 8). Graphical vector analysis (Figure 2) also showed deficiency shifts from N additions for almost all screening trials.

Despite N foliar concentration increases from the application of 330N at the RVW-granodiorite trial, needle weight increases were not observed suggesting that another nutrient also limited needle weight response for this site and potentially this rock type even though control foliar N concentrations were in the range of moderate deficiency (Swan 1972). The lack of needle weight N response for RVW may be related to relatively high rates of soil available NH_4-N, which was the highest of all central Idaho screening trials at 5.7 μg/g (Table 3).

The published ponderosa pine N concentration critical level is 1.10%, however, N additions significantly increased concentrations and typically increased needle weights over corresponding control treatments. Therefore, the stated critical level for ponderosa pine may be too low.

The literature suggests that N is the most common limiting nutrient in Northwest conifer forests. Growth responses to N additions are well documented and response to N fertilization has been demonstrated across a variety of parent materials (Loewenstein and Pitkin 1963; Agee and Biswell 1970; Cochran 1978; Mika and VanderPloeg 1991; Moore et al. 1991; Weetman and Fournier 1982; Powers et al. 1988; Weetman et al. 1988; Shafii et al. 1989; Blake et al. 1990; Brockley 1990, 1995; Binkley et al. 1995; Garrison et al. 1999). Our screening trial results support the premise of general N deficiencies in Northwest conifer forests.

Phosphorus

Phosphorus was found to be adequate for all eight screening trials. Phosphorus applied at a rate of 187 kg ha^{-1} did not significantly raise foliar P concentrations above untreated foliar P levels for any rock type (Table 4). Application of just urea caused synergistic uptake of non-added P on seven of the eight screening trials. Vector analysis revealed no P deficiencies across the central Idaho trials. Lack of P response following the application of P fertilizer reflected the high control foliar P concentrations that were well above the critical level of 0.08% (Powers 1983) and, coupled with the apparent synergistic effect from the NS + micros treatment for the Lardo trials, suggests that P was not limiting.

Binkley et al (1995) reported P deficiencies for mature lodgepole pine in SE Wyoming and that applications of P fertilizers assisted in correcting those deficiencies. Timmer and Stone (1978) suggested that additional N uptake with no further increase in needle weight in a screening trial was seen as potential late season storage of a non-limiting nutrient. Similar luxury consumption patterns for P in our study may have occurred. Rock content of P_2O_5 ranged from 0.072 to 0.390% across all study sites, with basalts containing the largest amount. In the plutonic rocks, mainly the Flat Creek and Paddy Flat sites, P was primarily contained in the mineral apatite with a typical composition of $Ca_5(PO_4)_3(F, Cl, OH)$. Waring and Running (1998) reported that 80 to 90% of an ecosystem's long-term P supply is derived from mineral weathering. However, Clayton et al. (1979) emphasized that mineralization and release of P from organic matter and Ca, Al, and Fe complexes is likely to be a much greater source of tree available P in the short term compared to weathering inputs of P bearing minerals, which were found to be quite low in a SW Idaho batholith (quartz monzonite) watershed study (Clayton and Kennedy 1985). Thus rock differences in P content may not be apparent in tree tissue analysis over the short term such as in our study.

Potassium

Generally, K applied at an elemental rate of 187 kg ha^{-1}, did not significantly raise foliar K concentrations above untreated foliar K levels across all rock types, thus indicating that K was not deficient at most sites. Potassium was found to be marginally deficient on only the RVW-granodiorite trial. Vector analysis also showed a dilution effect of K following the N only fertilizer treatment. Other research indicates that urea hydrolysis following fertilization may complicate K uptake by plants (Ouyang et al. 1998). They reported that NH_4^+ and K^+ compete for similar sites on the soil exchange complex and that rapid hydrolysis of urea may potentially inundate the exchange complex with NH_4^+, thereby interfering with plant K uptake and potentially fixing the K into interlayer positions of silicate clays (Webster and Dobkowski 1983, Liu et al. 1997; Foth and Ellis 1997). However, Chen and Mackenzie (1992) found application of urea with KCl resulted in increased N and K availability through reduced fixation on fine textured agriculture soils. Apparently the application of K fertilizer on our granodiorite lithologies helped minimize the potential K-fixation effect of urea on the soil/plant available K. The functionality and versatility of the vector analysis approach used in our study was evident in that previously undetected deficiencies could be seen if quadrant zones on the diagram were ignored and interpretation was based on vector direction and magnitude, regardless of whether the treatment shift occurred in the dilution zone relative to the control. Based on this interpretation of the vectors, differences between dilution effects and true deficiency or sufficiency symptoms caused from N only fertilizer additions may be discerned. A good example of this interpretation is provided in Figure 5b and the vectors between the N only and multi-nutrient treatments containing K in the blend.

Differences between rock K_2O content are evident between the lithologies examined in this study and seem to be reflected in the varied rates of K uptake following fertilizer K additions. Potassium contents for volcanic lithologies were the lowest of all rocks sampled, ranging from 1.09% for LRD II to 1.49% for LRD I. Despite volcanic lithologies having lower K_2O content than the plutonic lithologies (which ranged from 2.05% for Paddy Flat to 5.23% for Little Bogus), volcanic rocks weathered into finer textured soils with significantly higher exchangeable soil K^+. However, sites on volcanic rocks did not always behave the same after treatment. Dilution effects were evident at LRD II but not LRD I probably due to mineralogical differences between the basalt rocks at these sites. The basalt at LRD I contained approximately 80% glass compared to 25% glass for LRD II. Higher glass content would contribute to decreased porosity and may account for LRD I's decreased mineral weathering rate for K in this example.

Of the plutonic rocks sampled in this study granodiorite and tonalite had the lowest K_2O contents, 2.94 and 2.05% respectively. Vector analysis confirmed different K deficiency diagnoses within the plutonic rock group since addition of K fertilizer produced moderate to large deficiency shifts relative to N only fertilizer treatments on granodiorite and tonalite lithologies. When comparing K weathering rates among plutonic rocks, where soils are typically coarse textured, close examination of rock mineralogy is needed to better understand nutrient availability and response to fertilization. The Little Bogus site had the highest K_2O content of all plutonic rocks, 5.23%, followed by both Flat Creek installations with 3.35% K_2O. These two installations did not respond significantly to K fertilization. Little Bogus and Flat Creek both had high amounts of K-feldspar (an intermediate weathering, K-bearing mineral), 35 and 33% respectively, compared to the other plutonic parent materials (Table 3). Based on work with a quartz monzonite rock in the SW Idaho batholith, Clayton and Kennedy (1985) determined the main source of K for the forested watershed in their study was from weathering of orthoclase (a K-feldspar). However, it has been asserted that because K-feldspars have slower weathering rates compared to the mineral biotite little correlation would be evident between weathering rates of K-feldspar and "amount of soil K and amount of K adsorbed by plants" (Foth and Ellis 1997). The tonalite rocks in our study, containing high amounts of biotite, should have high K weathering rates that should therefore be associated with higher foliar K levels for trees growing on this rock type. Paddy Flat, our tonalite site, did show the highest untreated foliar K concentrations compared to all other rock types confirming the observation of Foth and Ellis (1997).

Sulfur

Sulfur was found to be deficient in all eight of the screening trials. Sulfur applied at a rate of 99 kg ha^{-1} was sufficient to raise foliar S concentrations significantly above untreated foliar S levels across all lithologies in central Idaho (Table 4). Deficiency of S was further demonstrated across the screening trials based on the directional shifts and magnitude of vectors using graphical vector analysis. Additionally, vector analysis identified the dilution effect of foliar S concentrations following the application of N alone.

Turner and Lambert (1979) studied S nutrition in radiata pine and Douglas-fir (*Pseudotsuga menziesii* var. *menziesii*) and found S deficiencies to occur more commonly on basalt, diorite, and highly weathered granite lithologies as compared to sedimentary and glacial parent materials. Furthermore, they found that low SO_4-S in the foliage correlated with low growth responses to N and that an adequate reserve of SO_4-S is important for the physiological utilization of added N from fertilization.

Growth response to S fertilization has been positive in the northwest, further suggesting a regional deficiency of this nutrient. Since primary weathering of S is typically low (Clayton and Kennedy 1985) and atmospheric inputs of S are relatively low, supplementation is commonly needed, especially when N is added as a fertilizer to Northwest conifer forests. Powers et al. (1988) reported ponderosa pine growth response in Oregon was probably due to additions of S on metasedimentary, volcanic, and granitic lithologies. Brockley and Sherman (1994) reported N+S additions significantly increased lodgepole pine first year fascicle weight in the interior British Columbia on mesic to submesic glacial parent materials. Additional fertilization studies on a variety of lithologies have also found foliar S concentrations to be low in Northwest conifers (Carter et al. 1984; Moore and Mika 1997; Garrison et al. 1999).

Magnesium

Magnesium was found to be deficient on only the tonalite lithologies. Magnesium is contained in biotite minerals of plutonic rocks thus explaining why the biotite-rich PF site had the highest MgO content of any plutonic rock, and why tonalite lithologies had significantly greater Mg concentrations in untreated foliage compared to granite lithologies (Table 5). However, Mg applied at 11 kg ha $^{-1}$ as magnesium sulfate significantly raised foliar Mg concentrations on only the tonalite and granite lithologies (Table 4). Vector analysis further identified the tonalite lithologies as Mg deficient; additionally, uptake of Mg by the trees on the tonalite lithology was associated with low soil exchangeable Mg (Table 3).

Demonstrated Mg deficiencies in the northwest are relatively rare in the literature. Carter et al. (1984) found foliar Mg levels on glacial till of acid igneous origin in 30-year old Douglas-fir to be quite low. Additionally, Green and Carter (1993) found that B+Mg treatment improved Douglas-fir height growth on soils derived from granitic rock.

Boron

Boron was deficient for all eight of the central Idaho screening trials. Boron applied at 5.5 kg ha $^{-1}$ was sufficient to raise foliar B concentrations significantly above untreated foliar B levels across all rock types (Table 4). Based on the directional shifts and magnitude of vectors using graphical vector analysis, deficiency of B was further substantiated across all lithologies. Additionally, vector analysis identified dilution of foliar B concentrations from application of N alone across all lithologies.

Recognition of B deficiencies is more common in the northwest and in forests throughout the world. Turner and Lambert (1979) found B deficiencies to be correlated with S deficiencies, which further may be related to soil parent material. Carter et al. (1986) also found B concentrations were correlated with foliar S concentrations. Both

Carter et al. (1986) and Carter and Brockley (1990) found B deficiencies to be associated with coarse-textured soils derived from acid igneous parent materials. Green and Carter (1993) found B additions significantly increased annual height growth in Douglas-fir on granite soil parent material. Additionally, Brockley (1990) found N + B significantly increased growth over N alone on glaciofluvial parent material on young lodgepole pine in the interior of British Columbia. Shaw (1998) found N alone to significantly reduce foliar B concentrations in the foliage of ponderosa pine and Douglas-fir growing on basalt parent material in central Washington. Lambert and Turner (1977) also found N fertilization to depress foliar B concentrations below critical levels.

Copper

Generally, Cu applied at 11 kg ha^{-1} was insufficient to significantly raise Cu concentrations above untreated foliar Cu levels across all lithologies within one year of broadcast application; except for the NS + micros treatment on the basalt lithologies (Table 4). Vector analysis showed deficiency shifts for added Cu on the LRD I basalt trial (Figure 9). The N only fertilizer treatment diluted foliar Cu concentrations on all plutonic rocks.

According to Foth and Ellis (1997) nearly 99% of soil solution Cu is complexed by the soil organic material. Bloomfield and Sanders (1977) reported 79% of Cu in solution was complexed by colloidal lucerne material at pH 6.5 compared to 35% of Cu in solution being complexed at pH 4.5. We observed that N applied as urea reduced foliar Cu levels. McLaren et al (1990) suggested that young plantations might be subject to Cu deficiencies due to minimal biogeochemical cycling during the pre-canopy closure stage of stand development.

Zinc

Zinc applied at 11 kg ha^{-1} generally did not raise foliar Zn concentrations significantly above untreated foliar Zn levels across the screening trials. Zinc availability is positively correlated with soil organic matter levels, therefore harvesting and site preparation activities can adversely affect soil Zn reserves. Zinc deficiencies were apparent based on the directional shifts and magnitude of vectors using vector analysis for PF II –tonalite and RVW-granodiorite, although the Zn deficiency on the RVW site is more difficult to discern due to the dilution effect of the N only fertilizer treatment. Deficiencies of Zn are not common in the literature. Carter et al. (1986) reported Zn deficiencies in young coastal Douglas-fir, silver fir, and hemlock stands in British Columbia. They found low Zn levels commonly occurred on glacial soil parent materials. Furthermore, the authors concluded, "deficiencies of…Zn may be acute rather than chronic, with the appearance of periodic acute deficiencies being influenced by growing season and moisture supply." Zasoski et al (1990) suggested that Zn availability is additionally related to soil parent material and potentially to soil texture.

Our fertilizer screening trial results were likely influenced by past harvesting and site preparation activities and consequent organic matter removal, top-soil displacement (Jurgensen et al. 1997) and soil compaction (Froehlich et al. 1985; Page-Dumroese et al. 1998) that further affected soil moisture (Geist and Strickler 1978) and mycorrhizal activity (Amaranthus et al. 1996) thus masking some inherent rock type differences. Past management practices probably contributed to the universal S and B deficiencies we observed.

CONCLUSIONS

Our results show that N, S, and B are deficient at all study sites including Idaho batholith granite, granodiorite, and tonalite and Columbia River Grande Ronde basalt lithologies. These screening trials results and those from additional fertilizer trials in the region, add to the growing evidence that inland Northwest conifer forests are regionally deficient in N, S, and B. Potassium deficiencies were identified on granodiorite and Mg deficiencies on tonalite lithologies. Furthermore, vector analysis identified site specific deficiencies, with PF II and LRD I exhibiting moderate deficiencies of Zn and Cu, respectively.

Untreated foliar nutrient concentrations were significantly different between central Idaho lithologies. Potassium control concentrations were higher on the biotite-rich tonalite lithologies. Phosphorus concentrations were also higher on the tonalite lithologies, probably due to the greater amounts of mineral apatite. Magnesium control foliar levels were highest on granodiorite lithologies, however no discernable rock mineralogical attribute was associated with this result.

The use of screening trials and vector analysis greatly enhanced the diagnosis and interpretation of multi-nutrient fertilization response on the different rock types. The combined use of nutrient concentration, content, and needle weight on a relative scale in a graphical format facilitated the analysis of fertilizer response compared to individual examination of the same variables in a non-graphical format.

Our results contribute to a better understanding of the mineral nutrition of forests growing on common rock types in the inland Northwest. Our study also provides information to develop site specific fertilizer blends to be used in future research designed to test the screening trial results.

LITERATURE CITED

Agee, J.K. and H.H. Biswell. 1970. Some effects of thinning and fertilization on ponderosa pine and understory vegetation. J. For. **68(11)**: 709-711.

Amaranthus, M.P., D.S. Page-Dumroese, A.E. Harvey, E. Cazares, L.F. Bednar. 1996. Soil compaction and organic matter removal affect conifer seedling nonmycorrhizal and ectomycorrhizal root tip abundance and diversity. Res. Pap. PNW-RP-494. Portland, OR: USDA. For. Serv. Pacific Northwest Research Station. 12p.

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.

Baule, H. and C. Fricker. 1970. The fertilizer treatment of forest trees. *Transl.* C.L. Whittles. BLV Verlag. mbH. Munchen. 259p.

Beaton, J.D., G. Brown, R.C. Speer, I. MacRae, W.P.T. McGhee, A. Moss, and R. Kosick. 1965. Concentration of micronutrients in foliage of three coniferous tree species in British Columbia. Soil Sci. Soc. Am. J. **29**: 299-302.

Binkley, D., F.W. Smith, and Y. Son. 1995. Nutrient supply and declines in leaf area and production in lodgepole pine. Can. J. For. Res. **25**: 621-628.

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.

Bloomfield, C. and J.R. Sanders. 1977. The complexing of copper by humified organic matter from laboratory preparations, soil and peat. J. Soil. Sci. **28**:435-444.

Boardman, R. and D.O. McGuire. 1990. The role of zinc in forestry. I. Zinc in forest environments, ecosystems and tree nutrition. For. Ecol. Manage. **37**: 167-205.

Brockley, R.P. 1990. Response of thinned, immature lodgepole pine to nitrogen and boron fertilization. Can. J. For. Res. **20**: 579-585.

Brockley, R.P. 1995. Effects of nitrogen source and season of application on the nutrition and growth of lodgepole pine. Can. J. For. Res. **25**: 516-526.

Brockley, R.P. and F.J. Sherman. 1994. Foliar nutrient status and fascicle weight of lodgepole pine after nitrogen and sulphur fertilization in the interior of British Columbia. Can. J. For. Res. **24**: 792-803.

Buol, S.W., F.D. Hole, and R.J. McCracken. 1989. Soil genesis and classification. 3rd edition. Iowa State University Press, Ames. 446p.

Carter, R.E. 1992. Diagnosis and interpretation of forest stand nutrient status. *In*: Forest fertilization: Sustaining and improving nutrition and growth of western forests, 12-14 Feb. 1991, Seattle, WA. Edited by H.N. Chappell, G.F. Weetman, and R.E. Miller. Inst. of For. Res., Univ. of Washington, Seattle. Contrib. 73. p.90-97.

Carter, R.E. J. Otchere-Boateng. and K. Klinka. 1984. Dieback of a 30-year-old Douglas-fir plantation in the Brittain River Valley, British Columbia: symptoms and diagnosis. For. Ecol. Manage. 7:249-263.

Carter, R.E., A.M Scagel, and K. Klinka. 1986. Nutritional aspects of distorted growth in immature forest stands of southwestern coastal British Columbia. Can. J. For. Res. 16:36-41.

Carter. R.E. and R.P. Brockley. 1990. Boron deficiencies in British Columbia: diagnosis and treatment evaluation. For. Ecol. Manage. 37:83-94.

Chen. J.S. and A.F. Mackenzie. 1992. Fixed ammonium and potassium as affected by added nitrogen and potassium in three Quebec soils. Can. J. For. Res. 9:19-26.

Clayton. J.L., W.F. Megahan. and D. Hampton. 1979. Soil and bedrock properties: Weathering and alteration products and processes in the Idaho batholith. USDA For. Serv. Res. Note INT-237, Intermountain For. Range Exp. Stn., Ogden, UT.

Clayton, J.L. and D.A. Kennedy. 1985. Nutrient losses from timber harvest in the Idaho batholith. Soil Sci. Soc. Am. J. 49:1041-1049.

Cochran, P.H. 1973. Response of individual ponderosa pine trees to fertilization. USDA For. Serv. Note PNW-206. 15p. USDA Forest Service, Portland, OR.

Cochran, P.H. 1977. Response of ponderosa pine 8 years after fertilization. USDA For. Serv. Note PNW-301. 7p. USDA Forest Service, Portland, OR.

Cochran, P.H. 1978. Response of pole-size ponderosa pine stand to nitrogen, phosphorus, and sulfur. USDA For. Serv. Note PNW-319. 8p. USDA Forest Service, Portland, OR.

Daubenmire, R. and J.B. Daubenmire. 1968. Forest vegetation of eastern Washington and northern Idaho. Wash. Agr. Exp. Sta. Tech. Bul. 60. 104p.

Foth, H.D. and B.G. Ellis. 1997. Soil Fertility (2nd ed.). CRC Press Inc., Boca Raton, FL, 290p.

Froehlich, H.A., D.W.R. Miles, and R.W. Robbins. 1985. Soil bulk density recovery on compacted skid trails in Central Idaho. Soil Sci. Soc. Am. J. 49:1015-1017.

Garrison, M.T. and J.A. Moore. 1998. Nutrient Management: A summary and review. Supplemental Report 98-5, FWR, Univ. of Idaho, Moscow, 50p.

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.

Geist, J.M., and G.S. Strickler. 1978. Physical and chemical properties of some Blue Mountain soils in northeast Oregon. USDA For. Serv. Res. Pap. PNW-236, 19p., illus. Pacific Northwest Forest and Range Experiment Station, Portland, OR.

Green, R.N. and R.E. Carter. 1993. Boron and magnesium fertilization of a coastal Douglas-fir plantation. West. J. Appl. For. 8(2):48-53.

Haase, D.L. 1997. NTC: Current seedling nutrition research. P. 133-140. *In*: Haase, D.L. and Rose, R. (eds.) Symposium proceedings: forest seedling nutrition from the nursery to the field. Corvallis, OR, October 28-29, 1997. Nursery Tech. Coop, Dept. For. Sci., Oregon State University, Corvallis.

Haase, 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.

Heilman, P.E. 1979. Minerals, chemical properties and fertility of forest soils. *In*: P. E. Heilman. H.W. Anderson, and D. M. Baumgartner (eds.), Forest soils of the Douglas-fir region. Washington State Univ., Pullman, WA, pp.121-136.

Heinsdorf, D. 1967. Untersuchungen uber die wirkung mineralischer dungung auf das wachstum und den ernaharungzust und von kiefernkulturen auf sandboden in nordostdeutchen Tiefland. Arch Forstw. **15**:1165-1193.

Imo. M. And V.R. Timmer. 1997. Vector diagnosis of nutrient dynamics in mesquite seedlings. For. Sci. **43(2)**:268-273.

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

Johnson. D.M.. P.R. Hooper and R.M. Conrey. 1999. XRF analysis of rocks and minerals for major and trace elements on a single low dilution Li-tetraborate fused bead. *Advances in X-Ray Analysis* 41:843-867.

Joslin. J.D. and M.H. Wolfe. 1994. Foliar deficiencies of mature southern Appalachian red spruce determined from fertilizer trials. Soil Sci. Soc. Am. J. **58**:1572-1579.

Jurgensen, M.F., A.E. Harvey, R.T. Graham, D.S. Page-Dumroese, J.R. Tonn, M.J. Larsen, and T.B. Jain. 1997. Impacts of timber harvesting on soil organic matter, nitrogen, productivity, and health of inland northwest forests. For. Sci. **43(2)**:234-251.

Kiefer, J.W. and M.E. Fenn. 1997. Using vector analysis to assess nitrogen status of ponderosa and Jeffrey pine along deposition gradients in forests of southern California. For. Ecol. Manage. **94**:47-59.

Krause, H.H. 1965. Untersuchungenuber die Melioration degradierter Sandboden im nordostdeutschen Tiefland. Arch. Forstwes. **14**:499-532.

Lambert, M.J. and J. Turner. 1977. Dieback in high site quality Pinus radiata stands – the role of sulphur and boron deficiencies. N.Z.J. For. Sci. **7**:333-348.

Liu, Y.J., D.A Laird, and P. Barak. 1997. Release and fixation of ammonium and potassium under long-term fertility management. Soil Sci. Soc. Am. J. **61**:310-314.

Loewenstein, H. and F.H. Pitkin. 1963. Response of grand fir and western white pine to fertilizer applications. Northwest Science **37**:23-30.

Lutz, H.J. 1960. Geology and soil in relation to forest vegetation. *In*: Proc. North American forest soils conference. T.D. Stevens and R.L. Cook (eds.). Michigan St. Univ. p. 75-85.

Mandzak, J.M. and J.A. Moore. 1994. The role of nutrition in the health of inland western forests. J. Sust. For. **2**:191-210.

McLaren, R.G., D.S. Hogg, and R.S. Swift. 1990. Some factors affecting the availability of native and applied soil copper in New Zealand soils. For. Ecol. Manage. **37**:131-142.

Meyer, W.L., F.W. Bell, P.J. Bastarache and C. Bowling. 1997. Concepts of tree mineral nutrition related to fertilizer use in northern Ontario forests. Ont. Min. Natur. Resour., NW Reg. Sci. & Technol., Thunder Bay, Ontario. NWST Tech. Rep. TR-114. 34p.

Miller, H.G., J.D. Miller, and J.M. Cooper. 1981. Optimum foliar nitrogen concentration in pine and its changes with stand age. Can. J. For. Res. **11**:563-572.

Mika, P.G. and J.A. Moore. 1990. Foliar potassium status explains Douglas-fir response to nitrogen fertilization in the Inland Northwest, USA. Water, Air, and Soil Pollution. **54**:477-491.

Mika, P.G. J.A. Moore, R.P. Brockley, and R.F. Powers. 1992. Fertilization response by interior forests: when, where, and how much? *In*: Forest fertilization: Sustaining and improving nutrition and growth of western forests, 12-14 Feb. 1991, Seattle, WA. Edited by H.N. Chappell, G.F. Weetman, and R.E. Miller. Inst. of For. Res., Univ. of Washington, Seattle. Contrib. 73. pp. 127-142.

Mika. P.G. and J. VanderPloeg. 1991. Six year fertilizer response of managed second-growth Douglas-fir stands in the Intermountain Northwest. p. 293-301 *In*: Baumgartner, D.M. and J. E. Lotan, eds. Proc. Interior Douglas-fir: The species and its management, 1990. Washington State University. Cooperative Extension, Pullman.

Moore, J.A., D.F. Hanley, H.N. Chappell, J.S. Shumway, and J.M. Mandzak. 1998. Fertilizing eastern Washington coniferous forests: a guide for nonindustrial private forest landowners. WSU Cooperative Extension. Bulletin EB1874. 18p. WSU, Pullman.

Moore, J.A. and P.G. Mika. 1997. Influence of soil parent material on the nutrition and health of established conifer stands in the inland northwest. p. 112-117 *In*: Haase, D.L. and Rose, R. (eds.) Symposium proceedings: forest seedling nutrition from the nursery to the field. Corvallis, OR, October 28-29. 1997. Nursery Tech. Coop, Dept. For. Sci., Oregon State University, Corvallis.

Moore. J.A., P.G. Mika. J.W. Schwandt and T.M. Shaw. 1994. Nutrition and forest health. p.173-176 *In*: D.M. Baumgartner (ed.). Proc. Interior cedar-hemlock-white pine forests: ecology and management. Spokane. WA. March 2-4. 1993. Dept. Res. Sci., Washington State University. Pullman.

Moore, J.A., P.G. Mika. and J.L. VanderPloeg. 1991. Nitrogen fertilizer response of Rocky Mountain Douglas-fir by geographic area across the Inland Northwest. West. J. Appl. For. 6(4):94-98.

Munson, A.D., H.A. Margolis, and D.G. Brand. 1993. Intensive silvicultural treatment: impacts on soil fertility and planted conifer response. Soil Sci. Soc. Am. J. 57:246-255.

Nesse, W.D., 1991. Introduction to Optical Mineralogy (2nd ed.). Oxford University Press, New York, 335p.

Ouyang, D.S., A.F. Mackenzie, and M.X. Fan. 1998. Ammonia volatilization from urea amended with triple superphosphate and potassium chloride. Soil Sci. Soc. Am. J. 62:1443-1447.

Page-Dumroese, D.S., A.E. Harvey, M.F. Jurgensen, and M.P. Amaranthus. 1998. Impacts of soil compaction and tree stump removal on soil properties and outplanted seedlings in northern Idaho, USA. Can. J. Soil Sci. 78:29-34.

Parker, J. 1956. Variations in copper, boron, and manganese in leaves of pinus ponderosa. For. Sci. 2:190-198.

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.

Powers, R.F., S.R. Webster, and P.H. Cochran. 1988. Estimating the response of ponderosa pine forests to fertilization. p. 219-225. *In*: Schmidt, W.C. ed. Proc. Future forests of the mountain west. A stand culture symposium, 1986. USDA For. Serv. Gen. Tech. Rep. INT-243.

Prescott, C.E., J.P. Corbin, and D. Parkinson. 1992. Availability of nitrogen and phosphorus in the forest floors of Rocky Mountain coniferous forests. Can. J. For. Res. **22**:593-600.

Pritchett, W.L. and N.F. Fisher. 1987. Properties and management of forest soils. 2nd edition. John Wiley & Sons, Inc. 494p.

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

Shafii, B., J.A. Moore, and J.R. Olson. 1989. Effects of nitrogen fertilization on growth of grand fir and Douglas-fir stands in Northern Idaho. West. J. Appl. For. **4(2)**:54-57.

Shaw, T.M. 1998. Foliar response to various multi-nutrient fertilizer treatments from Boise Cascade Corp. "add-on" trials in C. Washington. IFTNC Annual Meeting. FWR, Univ. of Idaho, Moscow, 10p.

Steinbrenner, E.C. 1981. Growth response of young Douglas-fir to repeated application of nitrogen and phosphorus. Soil Sci. Soc. Am. J. **45**:953-955.

Stone, E.L. 1968. Microelement nutrition of forest trees: A Review. *In*: Forest fertilization - theory and practice. Symposium on forest fertilization, April 1967, Knoxville, TN. Tennessee Valley Authority, Muscle Shoals, AL, pp.132-175.

Swan, H.S.D. 1972. Foliar nutrient concentrations in lodgepole pine as indicators of tree nutrient status and fertilizer requirement. Pulp Pap. Res. Inst. Can., Woodlands Rep. 42, 19p.

Timmer, V.R. 1991. Interpretation of seedling analysis and visual symptoms. *In*: Mineral nutrition of conifer seedlings. R. van den Driessche (ed.). CRC Press, Boca Raton, FL.

Timmer, V.R., and Morrow, L.D. 1984. Predicting fertilizer growth response and nutrient status of jack pine by foliar diagnosis. *In*: Forest soils and treatment impacts. Edited by E.L. Stone. University of Tennessee. Knoxville. pp. 335-351.

Timmer. V.R. and P.N. Ray. 1988. Evaluating soil nutrient regime for black spruce in the Ontario Claybelt by fertilization. For. Chron. 64:40-46.

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.

Turvey, N.D. and B.R. Grant. 1990. Copper deficiency in coniferous trees. For. Ecol. Manage., **37**:95-122.

Waring, R.H. and S.W. Running. 1998. Forest ecosystems, analysis at multiple scales. 2nd ed. Academic Press, San Diego. 370p.

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

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

Weetman, G.F., R.M. Fournier, and E. Schnorbus. 1988. Lodgepole pine fertilization screening trials: four-year growth response following initial predictions. Soil Sci. Soc. Am. J. **52**:833-839.

Weetman, G.F., M.A. McDonald, C.E. Prescott, and J.P. Kimmins. 1993. Responses of western hemlock, Pacific silver fir, and red cedar plantations on northern Vancouver Island to applications of sewage sludge and inorganic fertilizer. Can. J. For. Res. **23**: 1815-1820.

Zasoski, R.J., H.J. Porada, P.J. Ryan. J. Greenleaf-Jenkins, and S.P. Gessel. 1990. Observations of copper, zinc, iron and manganese status in western Washington forests. For. Ecol. Manage. **37**:7-25.

Table 1. Site and stand characteristics for Central Idaho screening trials.

Site	Abrev.	Species	Rock Type	Elevation (m)	Aspect	At Time of Establishment Age (yrs)	Mean Diameter (cm)	Mean Height (m)
Round Valley West*	RVW	LP	Granodiorite	1455	SE	17-20	7.3	4.8
Little Bogus	LB	PP	Granite	1485	SE	12	6.2	3.1
Flat Creek I	FC I	PP	Granite	1667	NE	12	6.4	3.4
Flat Creek II	FC II	PP	Granite	1667	SE	12	5.4	3.1
Paddy Flat I	PF I	PP	Biotite-rich Tonalite	1636	NE	12	7.9	3.7
Paddy Flat II	PF II	PP	Biotite-rich Tonalite	1636	SE	12	7.7	3.6
Lardo I	LRD I	PP	Tholeiitic Basalt	1575	SE	13-15	6.5	3.0
Lardo II	LRD II	PP	Tholeiitic Basalt	1636	NE	13-15	5.5	2.8

Note: *Round Valley West was a naturally regenerated lodgepole pine installation. All other installations were planted with ponderosa pine.

TREATMENTS	RATE (kg/ha)	PRODUCT
C - Control	NA	NA
#2 - Nitrogen	330	Urea (46-0-0)
#3 - Nitrogen	330	Urea (46-0-0)
		Ammonium Sulfate (20-0-0-24)
Potassium*	187	Potassium Chloride (0-0-51)
Sulfur	99	Ammonium Sulfate (20-0-0-24)
		Copper Sulfate (0-0-0-25-25)
Copper	11	Copper Sulfate (0-0-0-25-25)
Boron	5.5	Boron FG (0-0-0-15)
#4 - Nitrogen	330	Urea (46-0-0)
		Ammonium Sulfate (20-0-0-24)
		MAP (11-52-0)
Potassium*	187	Potassium Chloride (0-0-51)
Sulfur	99	Ammonium Sulfate (20-0-0-24)
		Magnesium Sulfate (0-0-0-13-10)
		Copper Sulfate (0-0-0-25-25)
Phosphorus	110	MAP (11-52-0)
Magnesium	11	Magnesium Sulfate (0-0-0-13-10)
Zinc	11	Blu-Min-Zinc (0-0-0-14)
Copper	11	Copper Sulfate (0-0-0-25-25)
Boron	5 5	Boron FG (0-0-0-15)

Table 2. Treatment rates and fertilizer products (elemental quantities) applied to Central Idaho screening trials

Note: * Potassium treatments were omitted from basalt trials (Lardo I & II).

Table 3 Mineral soil characteristics to a 25 cm depth for screening trials in central Idaho

Site	Description	pH	Extractable Cations cmol(+)/Kg				ECEC*	%BS	0.75N NaOac (ug/g)		O.M. %	2M KCl (ug/g)			
			Ca	Mg	Na	K			P	K		NO3-N	NH4-N	SO4-S	B
RVW	loamy coarse sand, frigid Typic Xerorthents	5.8	3.5	0.37	<0.048	0.56	4.43	100	9.3	148	2.87	0.4	5.8	8.1	0.16
LB	coarse sandy loam, mixed Entic Cryumbrepts	6.2	7.8	0.35	0.06	0.60	8.81	100	6.7	147	3.06	1.4	5.1	5.8	0.22
FC I	loamy coarse sand, frigid Typic Xeropsamments	6.3	6.7	0.36	<0.048	0.79	7.85	100	10.0	254	2.96	1.1	3.1	5.6	0.22
FC II	loamy coarse sand, frigid Typic Xeropsamments	6.3	6.8	0.42	0.05	0.77	8.04	100	6.8	204	3.03	<0.4	2.9	5.5	0.23
PF I	coarse sandy loam, mixed Typic Cryumbrepts	6.2	3.5	0.09	<0.048	0.60	4.19	100	4.3	177	1.76	<0.4	2.4	5.4	0.14
PF II	coarse sandy loam, mixed Typic Cryumbrepts	6.1	5.7	0.07	<0.048	0.62	6.39	100	4.9	178	3.06	<0.4	3.5	5.7	0.18
LRD I	fine loamy, mixed Argic Pachic Cryoborolls	5.9	20.0	4.50	0.12	1.90	26.52	100	5.0	334	3.42	<0.4	3.1	6.3	0.33
LRD II	fine loamy, mixed Argic Pachic Cryoborolls	5.9	18.0	3.30	0.07	2.20	23.57	100	5.4	386	3.28	<0.4	2.9	6.4	0.34

Note: *ECEC is the effective cation exchange capacity, which is the sum of the extractable cations less H and Al

Table 4. Mean nutrient concentrations (s d) and needle weights by treatment within rock type for central Idaho screening trials

		Percent												ppm					
Parent Material	Treatment	N		P		K		S		Mg		Needle Weight		Zn		Cu		B	
Basalt	Control	1 306 (074)	d	0 162 (006)	a	0 648 (026)	ab	0 093 (004)	b	0.084 (002)	a	6 303 (302)	c	41 420 (1 054)	b	2 394 (080)	bcd	17.280 (3 228)	b
Basalt	N	1 634 (074)	abc	0 157 (006)	a	0 601 (026)	abc	0 082 (004)	c	0 072 (002)	c	7 149 (302)	b	39 000 (1 054)	b	2.208 (080)	cd	16.180 (3 228)	b
Basalt	NS+micros*	1 760 (062)	ab	0 160 (005)	a	0 588 (022)	bc	0.114 (003)	a	0 084 (002)	a	8 003 (255)	a	44 914 (0.891)	a	2.884 (068)	a	19.686 (2.728)	b
Basalt	NPSMg+micros*	1 579 (062)	bc	0 168 (005)	a	0 600 (022)	abc	0.113 (003)	a	0.078 (002)	b	8 393 (.255)	a	45 457 (0 891)	a	2.520 (068)	bc	30.400 (2.728)	a
Granite	Control	1 352 (044)	d	0 170 (004)	b	0 700 (016)	a	0 099 (002)	c	0 077 (001)	b	6 027 (181)	d	36.343 (0 630)	c	2.460 (.048)	a	18 721 (1 929)	c
Granite	N	1 850 (044)	bc	0 186 (004)	a	0 669 (016)	b	0 086 (002)	d	0 081 (001)	a	6 991 (181)	abc	40 707 (0 630)	a	2.263 (.048)	b	15.007 (1.929)	c
Granite	NKS+micros	1 973 (046)	ab	0 168 (004)	b	0 686 (016)	a	0 109 (002)	b	0 074 (001)	c	7 253 (187)	ab	33 500 (0 654)	d	2 323 (.050)	b	31 015 (2 001)	b
Granite	NPKSMg+micros	1 894 (046)	abc	0 173 (004)	b	0 720 (016)	a	0 117 (002)	a	0 081 (001)	a	6 654 (187)	bc	38 415 (0 654)	b	2 282 (.050)	b	50.400 (2.001)	a
Granodiorite	Control	1 200 (095)	d	0 127 (008)	cd	0 551 (034)	abc	0 010 (005)	b	0.107 (003)	a	1 665 (390)	abc	43 300 (1 361)	a	2.540 (.103)	a	19.500 (4.167)	c
Granodiorite	N	1 660 (095)	bc	0 134 (008)	bcd	0 493 (034)	bc	0 080 (005)	c	0 072 (003)	c	1 480 (390)	bc	38.900 (1 361)	b	1.920 (.103)	c	20.000 (4.167)	c
Granodiorite	NKS+micros	1 900 (095)	ab	0 150 (008)	abc	0 561 (034)	abc	0 120 (005)	a	0 101 (003)	a	2 408 (390)	ab	35 800 (1 361)	b	2.470 (.103)	a	110 00 (4.167)	b
Granodiorite	NPKSMg+micros	1 720 (095)	abc	0 154 (008)	ab	0 610 (034)	ab	0 120 (005)	a	0 086 (003)	b	2 337 (390)	abc	43.700 (1 361)	a	2.190 (.103)	b	153 00 (4.167)	a
Tonalite	Control	1 440 (067)	b	0 183 (006)	bc	0 753 (024)	ab	0 103 (003)	c	0 080 (002)	b	6 286 (276)	c	39 250 (.962)	bc	2.615 (.073)	a	18 600 (2.946)	b
Tonalite	N	2 005 (067)	a	0 197 (006)	ab	0 620 (024)	cd	0 008 (003)	d	0 078 (002)	b	6 511 (276)	c	41.900 (.962)	ab	1 940 (073)	b	13.900 (2 946)	b
Tonalite	NKS+micros	2 100 (067)	a	0 197 (006)	ab	0 716 (024)	abc	0 120 (003)	b	0 080 (002)	b	7 303 (276)	b	40 200 (.962)	abc	2.570 (.073)	a	27.650 (2 946)	a
Tonalite	NPKSMg+micros	2 085 (067)	a	0 195 (008)	abc	0 672 (024)	bcd	0 130 (003)	a	0 096 (002)	a	8.453 (276)	a	41.800 (.962)	ab	2.685 (.073)	a	33.650 (2.946)	a

* Basalt parent materials did not receive K in the fertilizer blends and are identified as separate treatments in statistical analysis

Treatment means with the same letter are not statistically different at the p< 10 level

Table 5. Ponderosa pine mean nutrient concentrations and needle weights by rock type within treatment for central Idaho screening trials.

		Percent					ppm		
Treatment	**Parent Material**	**N**	**P**	**K**	**S**	**Mg**	**Zn**	**Cu**	**B**
Control	Basalt	1.306 (.074) ab	0.162 (.006) b	0.648 (.026) c	0.093 (.004) bc	0.084 (.002) a	41.420 (1.054) a	2.394 (.080) b	17.280 (3.228) a
Control	Granite	1.352 (.044) ab	0.170 (.004) b	0.700 (.016) b	0.099 (.002) abc	0.077 (.001) b	36.343 (0.630) b	2.460 (.048) b	18.721 (1.929) a
Control	Tonalite	1.440 (.067) a	0.183 (.006) a	0.753 (.024) a	0.103 (.003) ab	0.080 (.002) ab	39.250 (0.962) a	2.615 (.073) a	18.600 (2.946) a
N	Basalt	1.634 (.074) c	0.157 (.006) c	0.601 (.026) b	0.082 (.004) a	0.072 (.002) b	39.000 (1.054) b	2.208 (.080) a	16.180 (3.228) a
N	Granite	1.850 (.044) b	0.186 (.004) b	0.669 (.016) a	0.086 (.002) a	0.081 (.001) a	40.707 (0.630) ab	2.263 (.048) a	15.007 (1.929) a
N	Tonalite	2.005 (.067) a	0.197 (.006) a	0.620 (.024) b	0.080 (.003) a	0.078 (.002) a	41.900 (0.962) a	1.940 (.073) b	13.900 (2.946) a
NS+micros*	Basalt	1.760 (.062) c	0.160 (.005) b	0.588 (.022) b	0.114 (.003) ab	0.084 (.002) a	44.914 (0.891) a	2.884 (.068) a	19.686 (2.728) b
NKS+micros	Granite	1.973 (.046) b	0.168 (.004) b	0.686 (.016) a	0.109 (.002) b	0.074 (.001) b	33.500 (0.654) c	2.323 (.050) c	31.015 (2.001) a
NKS+micros	Tonalite	2.100 (.067) a	0.197 (.006) a	0.716 (.024) a	0.120 (.003) a	0.080 (.002) a	40.200 (0.962) b	2.570 (.073) b	27.650 (2.946) a
NPSMg+micros*	Basalt	1.579 (.062) c	0.168 (.005) b	0.600 (.022) c	0.113 (.003) b	0.078 (.002) b	45.457 (0.891) a	2.520 (.068) b	30.400 (2.728) b
NPKSMg+micros	Granite	1.894 (.046) b	0.173 (.004) b	0.720 (.016) a	0.117 (.002) b	0.081 (.001) b	38.415 (0.654) c	2.282 (.050) c	50.400 (2.001) a
NPKSMg+micros	Tonalite	2.085 (.067) a	0.195 (.008) a	0.672 (.024) b	0.130 (.003) a	0.096 (.002) a	41.800 (0.962) b	2.685 (.073) a	33.650 (2.946) b

* Basalt parent materials did not receive K in the fertilizer blends and are identified as separate treatments in statistical analysis.
Means within the same treatment with the same letter are not statistically different at the $p<.10$ level.
Numbers in parentheses represent standard deviations.

Table 6. Mean nutrient contents and needle weights by fertilizer treatment within rock type for central Idaho screening trials

Parent Material	Treatment	N		P		K		S		Mg		Needle Weight		Zn		Cu		B	
		grams per 30 needles																	
Basalt	Control	8 262 (555)	c	1 020 (049)	c	4 108 (177)	b	0 585 (037)	b	0 532 (032)	b	6 303 (0 302)	c	0 0261 (0 001)	b	0.0015 (0.0001)	b	0 0109 (0 002)	c
Basalt	N	11 750 (555)	b	1 124 (049)	c	4 304 (177)	b	0 586 (037)	b	0 514 (032)	b	7 150 (0 302)	b	0 0280 (0 001)	b	0 0016 (0.0001)	b	0 0116 (0.002)	c
Basalt	NS+micros*	14 089 (469)	a	1 286 (041)	b	4 711 (150)	a	0 913 (031)	a	0 670 (027)	a	8 003 (0 255)	a	0 0360 (0 001)	a	0 0023 (0.0001)	a	0.0157 (0.002)	b
Basalt	NPSMg+micros*	13 247 (469)	a	1 411 (041)	a	5 039 (150)	a	0.947 (.031)	a	0 660 (027)	a	8 393 (0 255)	a	0 0382 (0.001)	a	0.0021 (0.0001)	a	0.0255 (0.002)	a
Granite	Control	8 194 (332)	d	1 012 (029)	c	4 117 (106)	d	0 593 (.022)	b	[illegible] 467 (.019)	b	6 027 (0 181)	d	0 0218 (0 001)	c	0.0015 (0.0001)	bc	0.0111 (0.001)	c
Granite	N	12 800 (332)	b	1 283 (029)	a	4 669 (106)	bc	0 606 (022)	b	0 572 (.019)	a	6 991 (0 181)	abc	0 0284 (0 001)	a	0 0016 (0.0001)	abc	0.0104 (0.001)	c
Granite	NKS+micros	14 205 (344)	a	1 212 (030)	b	4 942 (110)	ab	0 792 (023)	a	0 535 (020)	a	7 253 (0 187)	ab	0 0244 (0 001)	b	0 0017 (0 0001)	ab	0.0220 (0 001)	b
Granite	NPKSMg+micros	12 465 (344)	b	1 145 (030)	b	4 755 (110)	abc	0 769 (023)	a	0 542 (020)	a	6 654 (0 187)	bc	0.0255 (0 001)	b	0 0015 (0.0001)	bc	0 0326 (0.001)	a
Granodiorite	Control	2 000 (717)	cd	0 210 (063)	b	0 920 (229)	acd	0 167 (047)	b	0 180 (041)	abc	1 665 (0 390)	abc	0 0072 (0 002)	abc	0 0004 (0.0001)	a	0.0033 (0.002)	c
Granodiorite	N	2 460 (717)	bc	0 200 (063)	b	0 730 (229)	cd	0 124 (047)	b	0 110 (041)	bc	1 480 (0 390)	bc	0 0058 (0 002)	bc	0.0003 (0.0001)	a	0 0030 (0 002)	c
Granodiorite	NKS+micros	4 580 (717)	ab	0 360 (063)	a	1 350 (229)	ac	0 289 (047)	a	0 240 (041)	ab	2 408 (0 390)	ab	0 0086 (0 002)	abc	0 0006 (0 0001)	a	0 0265 (0 002)	b
Granodiorite	NPKSMg+micros	4 020 (717)	abc	0 360 (063)	a	1 430 (229)	ac	0 280 (047)	a	0 200 (041)	abc	2 337 (0 390)	abc	0 0102 (0 002)	ab	0.0005 (0 0001)	a	0 0358 (0 002)	a
Tonalite	Control	9 010 (507)	d	1 145 (045)	d	4 735 (162)	c	0 642 (035)	c	0 500 (029)	b	6 286 (0 276)	c	0 0246 (0 001)	dc	0 0016 (0.0001)	c	0 0117 (0 002)	c
Tonalite	N	13 065 (507)	c	1 280 (045)	c	4 025 (162)	d	0 528 (035)	d	0 505 (029)	b	6 511 (0 276)	c	0 0273 (0 001)	bcd	0 0013 (0.0001)	d	0 0090 (0.002)	c
Tonalite	NKS+micros	15 300 (507)	b	1 435 (045)	b	5 225 (162)	b	0 875 (034)	b	0 580 (029)	a	7 303 (0 276)	b	0 0293 (0 001)	bc	0 0019 (0.0001)	b	0 0201 (0.002)	b
Tonalite	NPKSMg+micros	17 635 (507)	a	1 645 (045)	a	5 675 (162)	a	1 099 (034)	a	0 810 (029)	a	8 453 (0 276)	a	0.0353 (0.001)	a	0.0023 (0.0001)	a	0.0284 (0.002)	a

* Basalt parent materials did not receive K in the fertilizer blends and are identified as separate treatments in statistical analysis
Treatment means with the same letter are not statistically different at the p< 10 level
Numbers in parentheses represent standard deviations

Table 7. Ponderosa pine mean nutrient contents and needle weights by rock type within treatment.

		grams per 30 needles																	
Treatment	Parent Material	N		P		K		S		Mg		Needle Weight		Zn		Cu		B	
Control	Basalt	8 262 (555)	a	1 020 (049)	b	4.108 (.177)	b	0.585 (.037)	a	0.532 (.032)	a	6.303 (0.302)	a	0.0261 (0.001)	a	0.0015 (0.0001	ab	0.0109 (0.002)	a
Control	Granite	8.194 (332)	a	1.012 (029)	b	4 117 (.106)	b	0.593 (.022)	a	0.467 (.019)	b	6.027 (0.181)	a	0.0218 (0.001)	b	0.0015 (0.0001	b	0.0111 (0.001)	a
Control	Tonalite	9 010 (507)	a	1.145 (045)	a	4.735 (.162)	a	0.642 (.035)	a	0.500 (.029)	ab	6.286 (0.276)	a	0.0246 (0.001)	a	0.0016 (0.0001	a	0.0117 (0.002)	a
N	Basalt	11 750 (555)	b	1 240 (049)	a	4 304 (.177)	b	0.586 (.037)	ab	0.514 (.032)	b	7.150 (0.302)	a	0.0280 (0.001)	a	0.0016 (0.0001	a	0.0116 (0.002)	a
N	Granite	12 800 (332)	a	1 283 (029)	a	4 669 (106)	a	0.606 (.022)	a	0.572 (.019)	a	6 991 (0.181)	a	0.0284 (0.001)	a	0.0016 (0.0001	a	0.0104 (0.001)	a
N	Tonalite	13 065 (507)	a	1 280 (045)	a	4 025 (162)	b	0.528 (.035)	b	0 505 (.029)	b	6.511 (0.276)	b	0.0273 (0.001)	a	0.0013 (0.0001	b	0.0090 (0.002)	a
NS+micros*	Basalt	14 089 (469)	b	1 286 (041)	b	4 711 (150)	b	0 913 (031)	a	0 670 (027)	a	8 003 (0 255)	a	0.0360 (0.001)	a	0.0023 (0.0001	a	0.0157 (0.001)	b
NKS+micros	Granite	14 205 (344)	b	1 212 (030)	ab	4 942 (110)	b	0 792 (023)	b	0 535 (020)	b	7.253 (0 187)	b	0.0244 (0.001)	c	0.0017 (0.0001	c	0.0220 (0.001)	a
NKS+micros	Tonalite	15 300 (507)	a	1 435 (045)	a	5 225 (162)	a	0 875 (034)	a	0 580 (029)	b	7 303 (0 276)	b	0.0293 (0.001)	b	0.0019 (0.0001	b	0.0201 (0.002)	a
NPSMg+micros*	Basalt	13 247 (469)	b	1 411 (041)	b	5 039 (150)	b	0 947 (031)	b	0 660 (027)	b	8 393 (0 255)	a	0.0382 (0.001)	a	0.0021 (0.0001	a	0.0255 (0.001)	b
NPKSMg+micros	Granite	12 465 (344)	b	1 145 (030)	c	4 755 (110)	c	0 769 (023)	c	0 542 (020)	c	6 654 (0.187)	b	0.0255 (0.001)	c	0.0015 (0.0001	b	0.0326 (0.001)	a
NPKSMg+micros	Tonalite	17 635 (507)	a	1 645 (045)	a	5 675 (162)	a	1 099 (034)	a	0.810 (.029)	a	8.453 (0.276)	a	0.0353 (0.001)	b	0.0023 (0.0001	a	0.0284 (0.002)	b

* Basalt parent materials did not receive K in the fertilizer blends and are identified as separate treatments in statistical analysis.

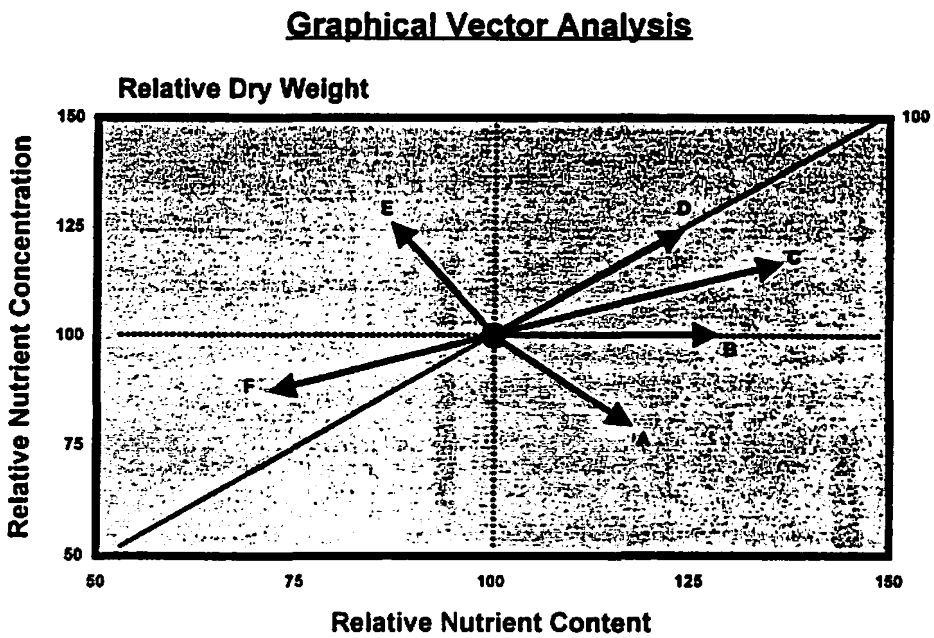
Treatments with the same letter are not statistically different at the p< 10 level

Numbers in parentheses represent standard deviations

Table 8. Percent needle weight increases from fertilizer treatments relative to control treatments for the Central Idaho screening trials.

		Treatments		
Study Sites	**Parent Material**	**% increase from N only**	**% increase from NKS + micros**	**% increase from NPKSMg + micros**
Round Valley West*	granodiorite	-11	45	40
Little Bogus	granite	18	10	8
Flat Creek I	granite	6	24	3
Flat Creek II	granite	24	27	26
Paddy Flat I	tonalite	11	20	43
Paddy Flat II	tonalite	-3	13	27
Lardo I	basalt	16	38	41
Lardo II	basalt	9	13	23

* Lodgepole pine.



DIRECTION OF SHIFT	RESPONSE IN			CHANGE IN	
	NEEDLE WEIGHT	NUTRIENT		NUTRIENT STATUS	POSSIBLE DIAGNOSIS
		Conc.	Content		
A	+	-	+/-	Dilution	Non-limiting
B	+	0	+	Unchanged	Non-limiting
C	+	+	+	Deficiency	Limiting
D	0	+	+	Luxury Consumption	Non-toxic
E	-	+	+/-	Excess	Toxic
F	-	-	-	Excess	Antagonistic

Figure 1. Schematic relationship between nutrient concentration, nutrient content, and dry weight of needles following fertilization. From Timmer and Ray (1988).

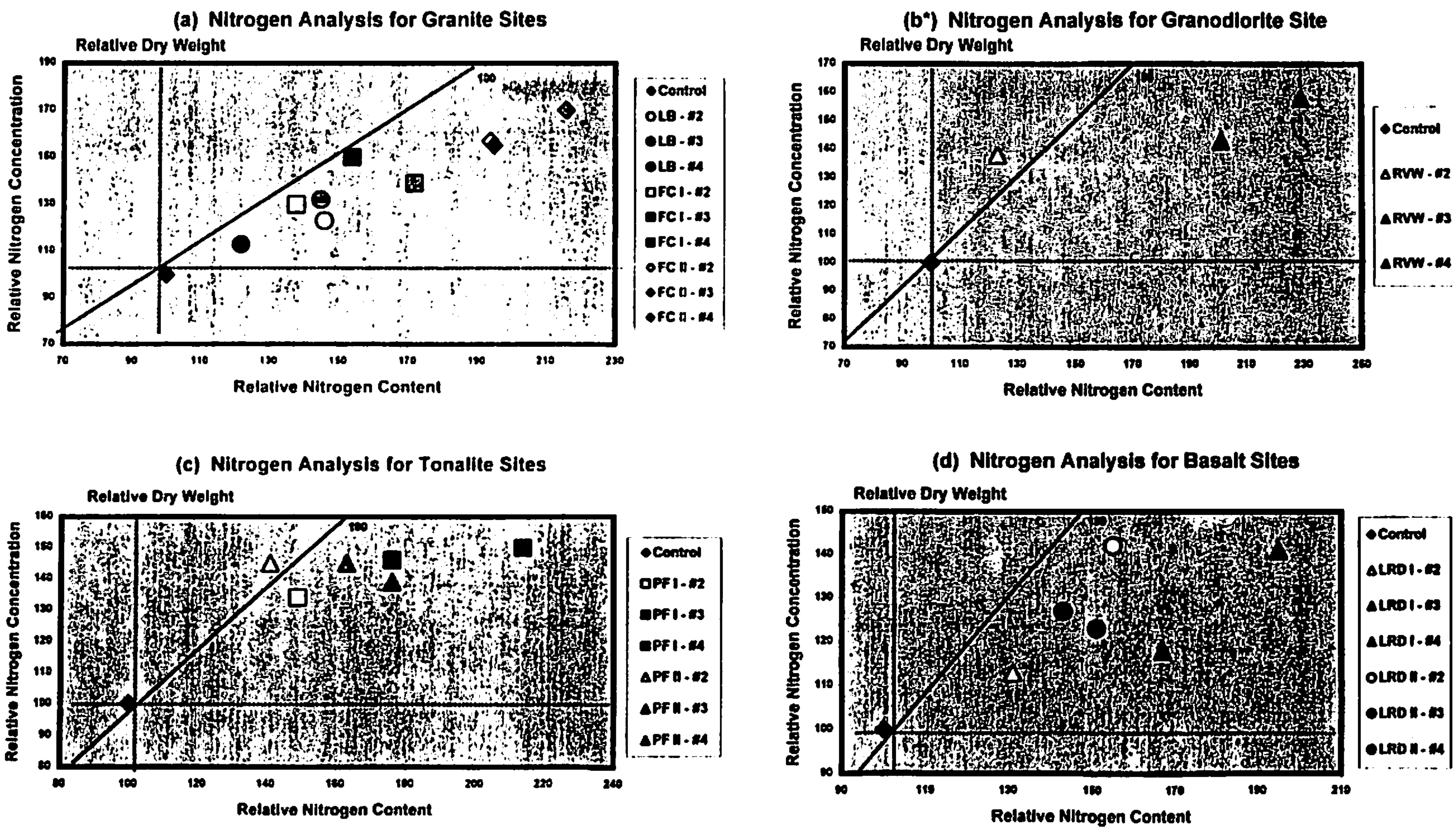
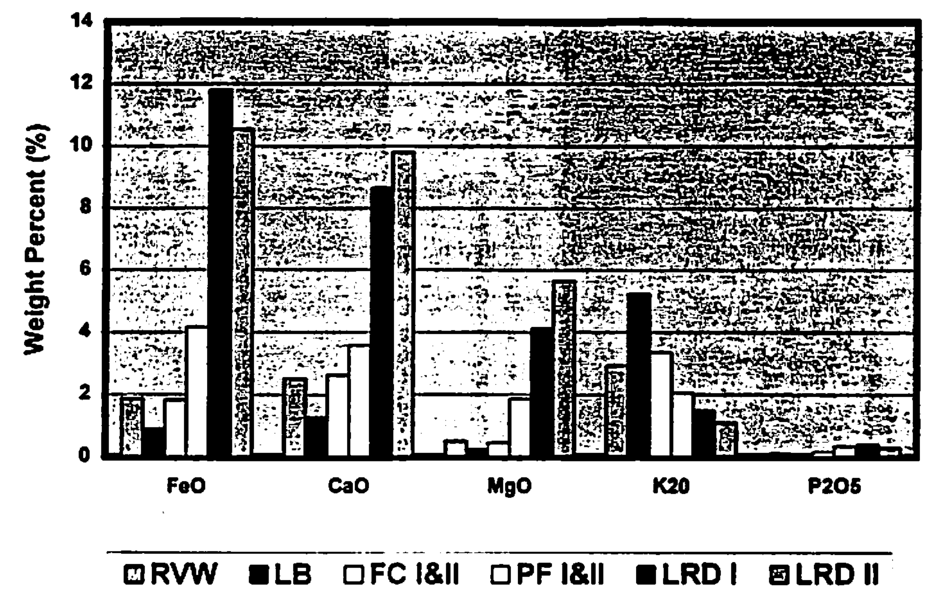


Figure 2. Graphical vector shifts for N concentration, content, and needle weight for 1998 foliage by treatment across soil parent material in central Idaho screening trials.

Note: * Lodepole pine trial.

General Geochemistry for Central Idaho
-Major Elements-



-Trace Elements-

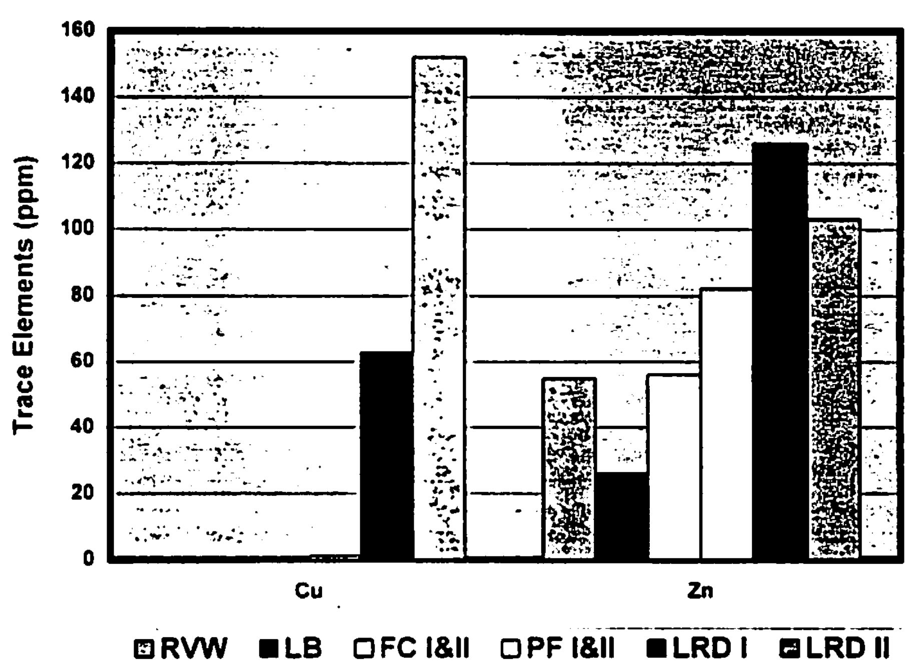


Figure 3. Geochemical analysis of central Idaho screening trials.

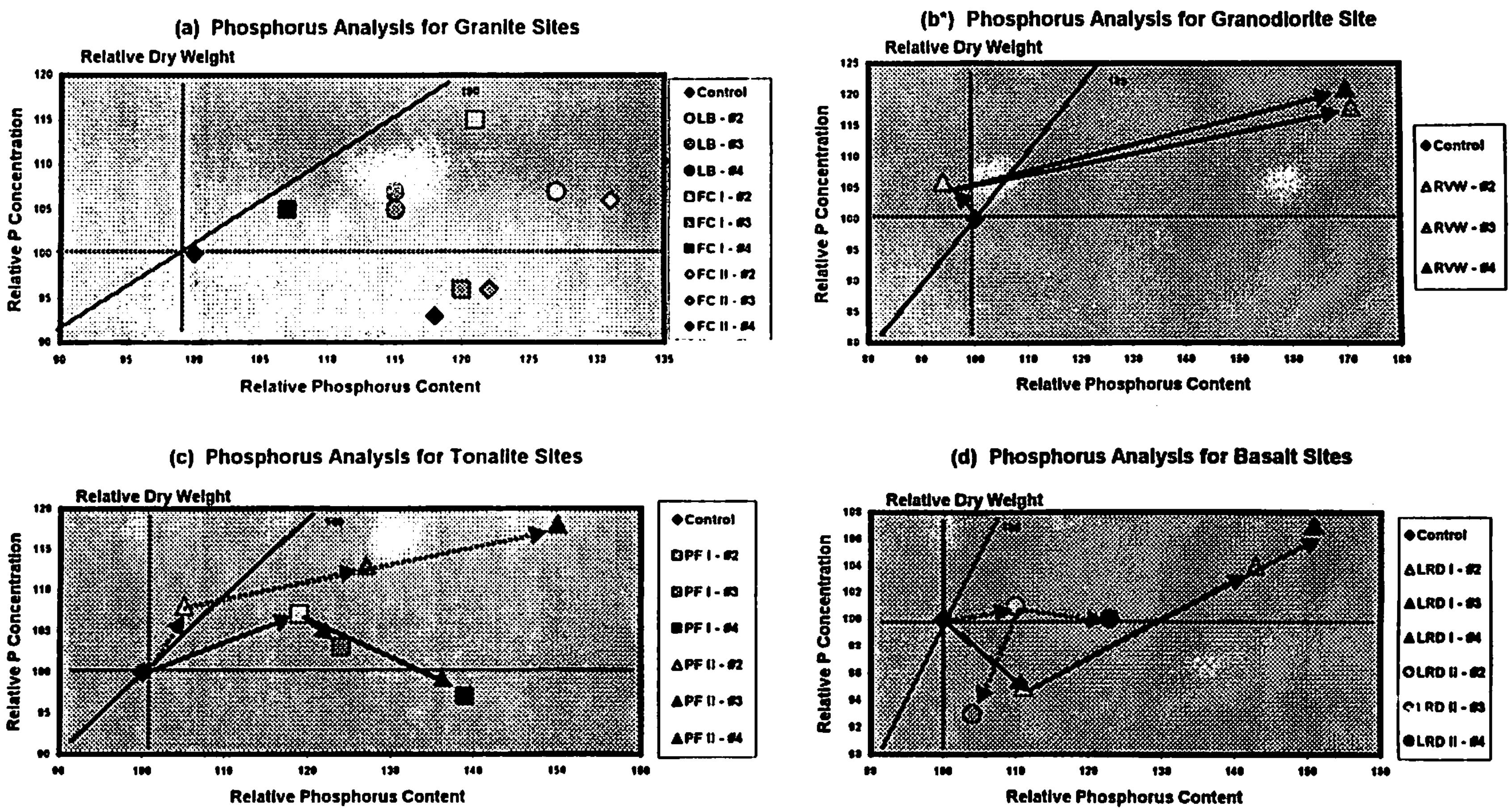


Figure 4. Graphical vector shifts for P concentration, content, and needle weight for 1998 foliage by treatment across soil parent material in central Idaho screening trials.

Note: * Lodgepole pine trial.

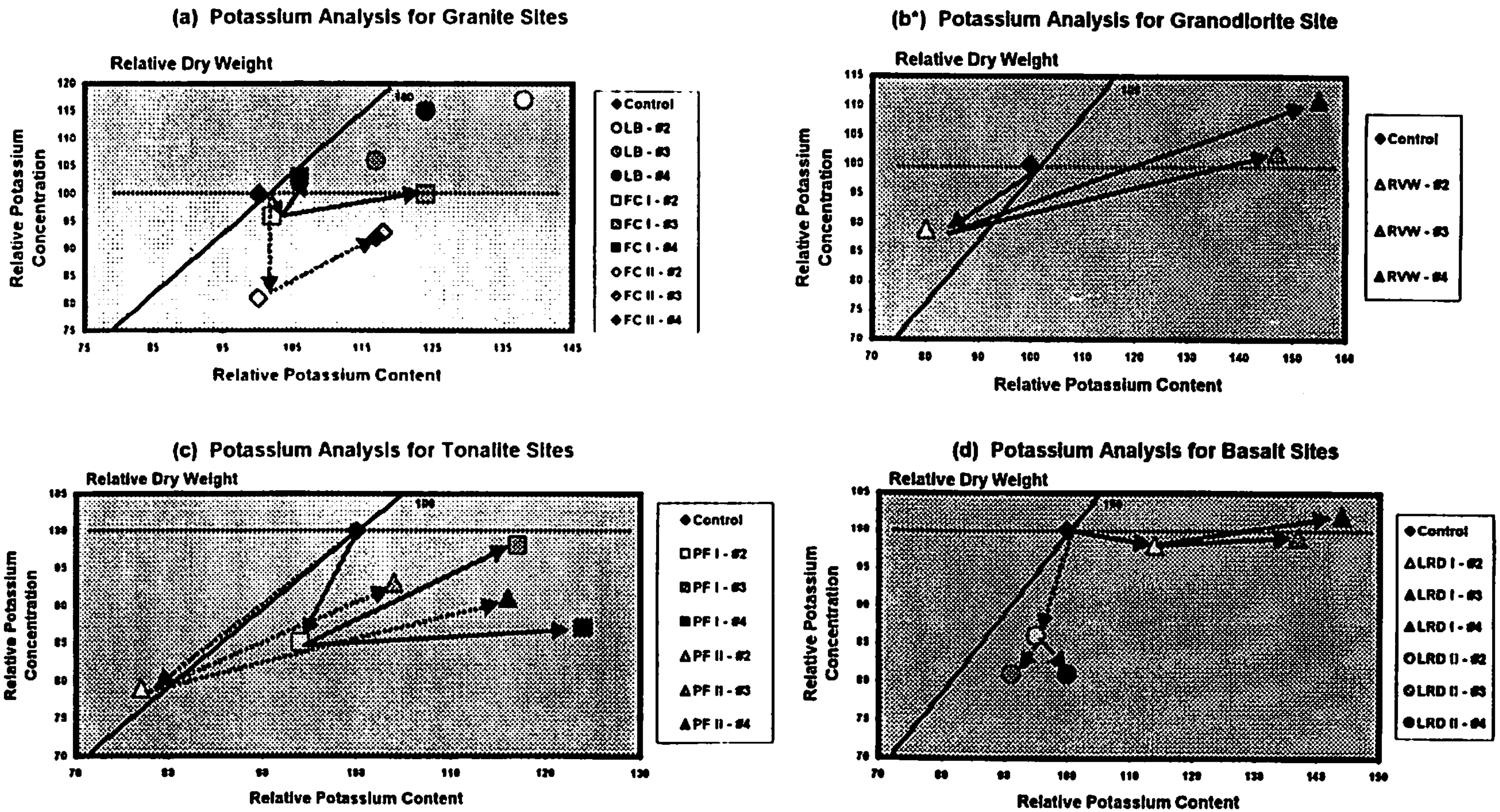


Figure 5. Graphical vector shifts for K concentration, content, and needle weight for 1998 foliage by treatment across soil parent material in central Idaho screening trials.

Note: * Lodgepole pine trial.

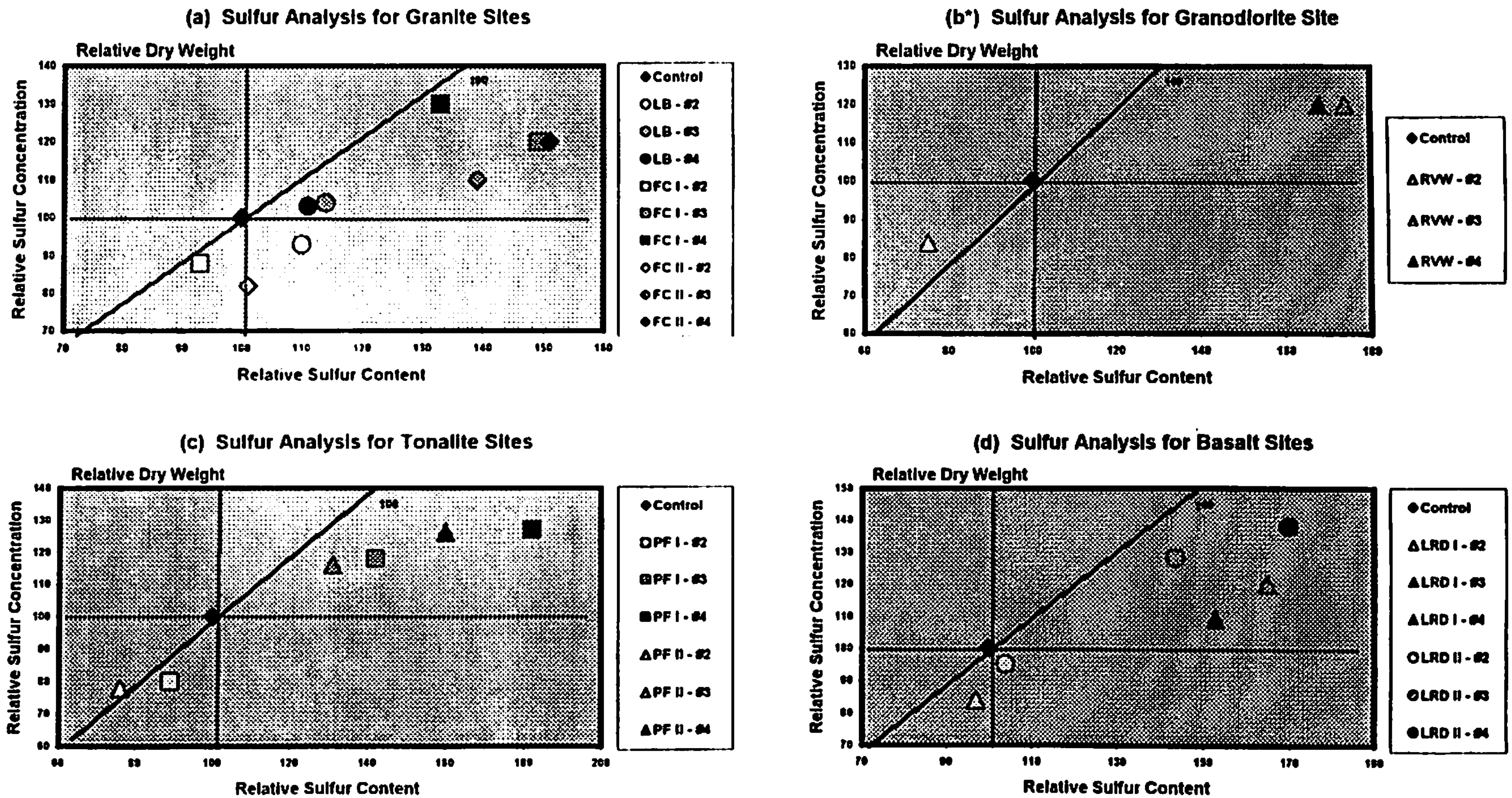


Figure 6. Graphical vector shifts for S concentration, content, and needle weight for 1998 foliage by treatment across soil parent material in central Idaho screening trials.

Note: * Lodgepole pine trial.

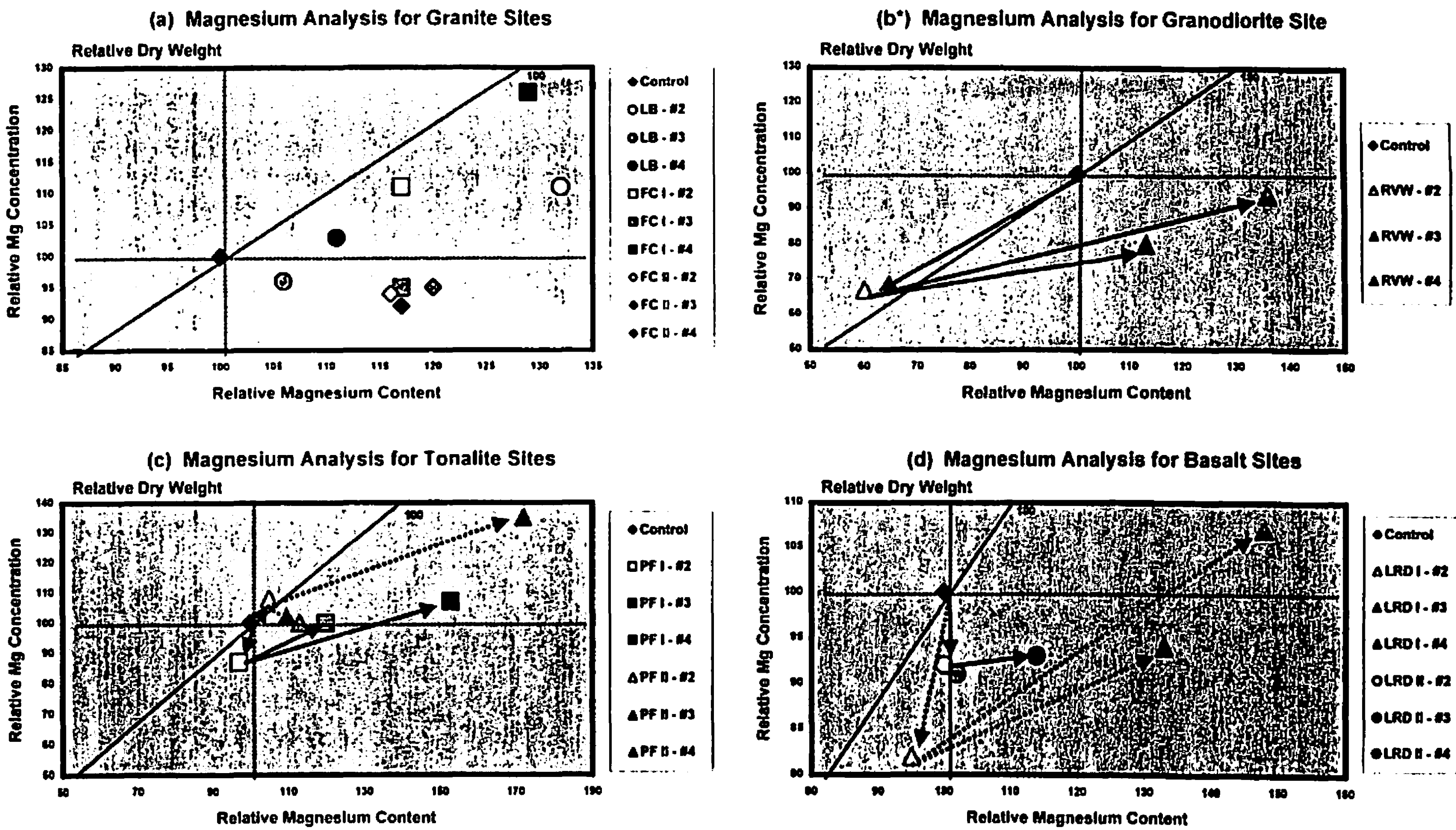


Figure 7. Graphical vector shifts for Mg concentration, content, and needle weight for 1998 foliage by treatment across soil parent material in central Idaho screening trials.

Note: * Lodgepole pine trial.

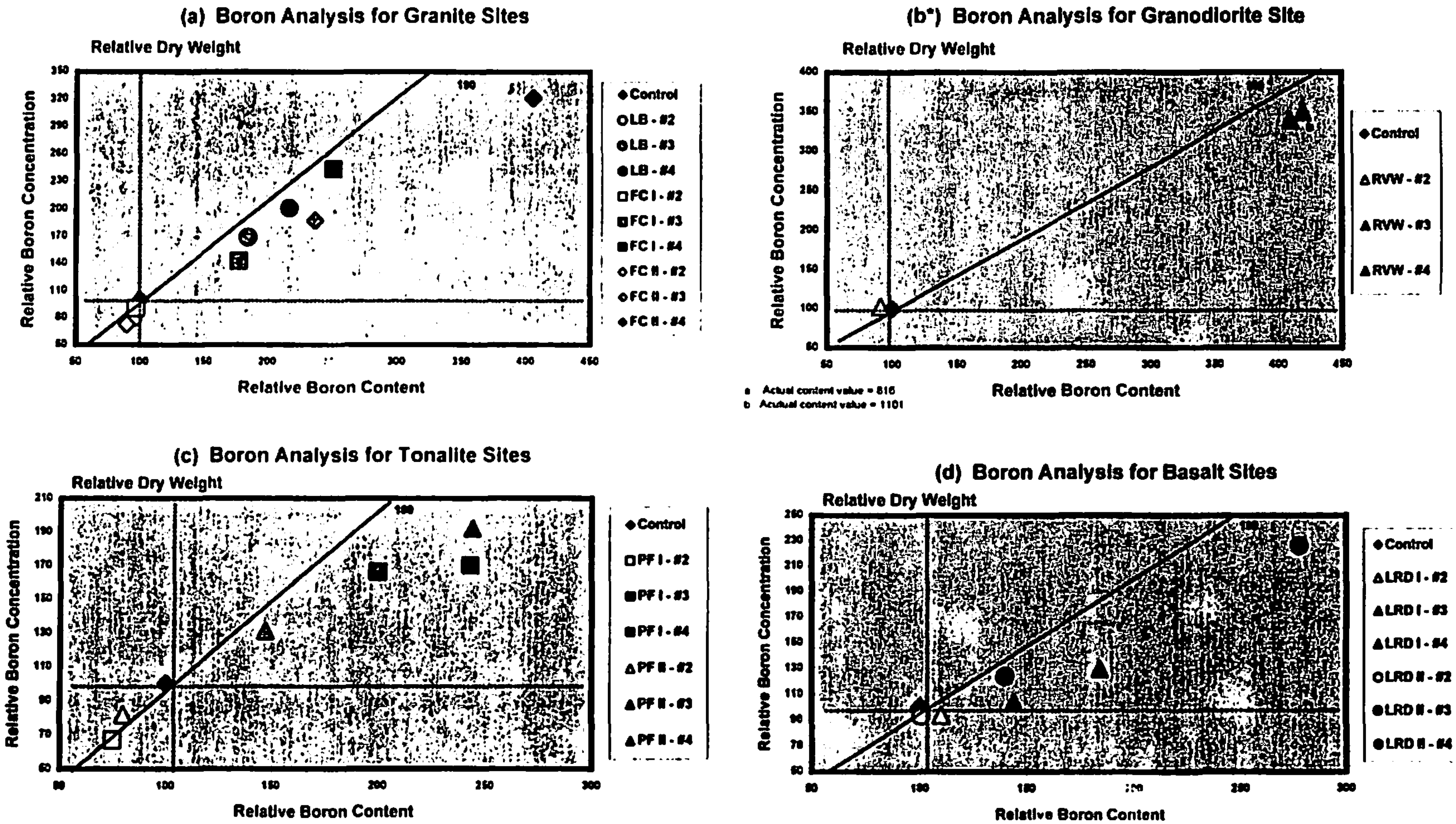


Figure 8. Graphical vector shifts for B concentration, content, and needle weight for 1998 foliage by treatment across soil parent material in central Idaho screening trials.

Note: * Lodgepole pine trial.

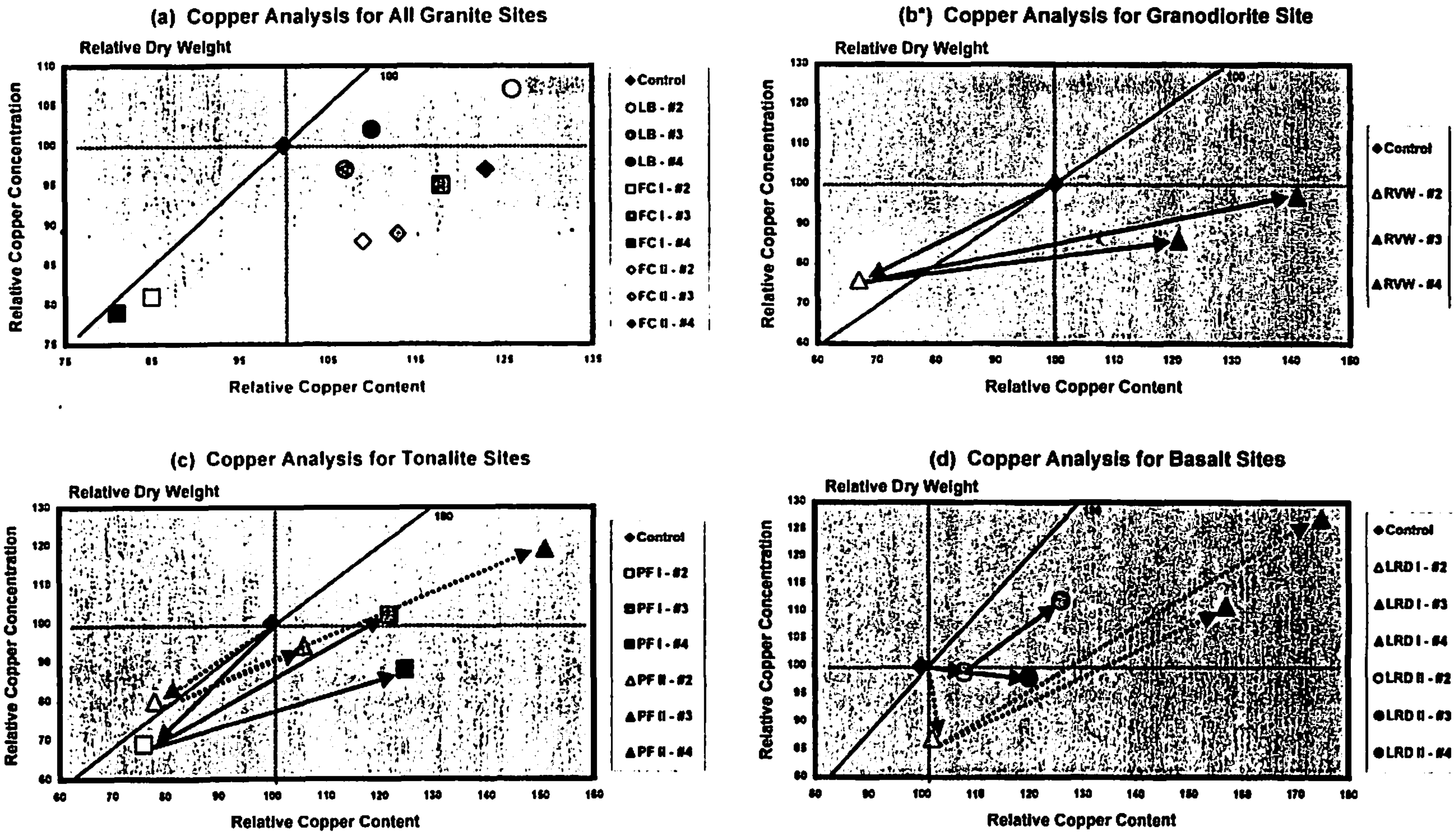


Figure 9. Graphical vector shifts for Cu concentration, content, and needle weight for 1998 foliage by treatment across soil parent material in central Idaho screening trials.

Note: * Lodgepole pine trial.

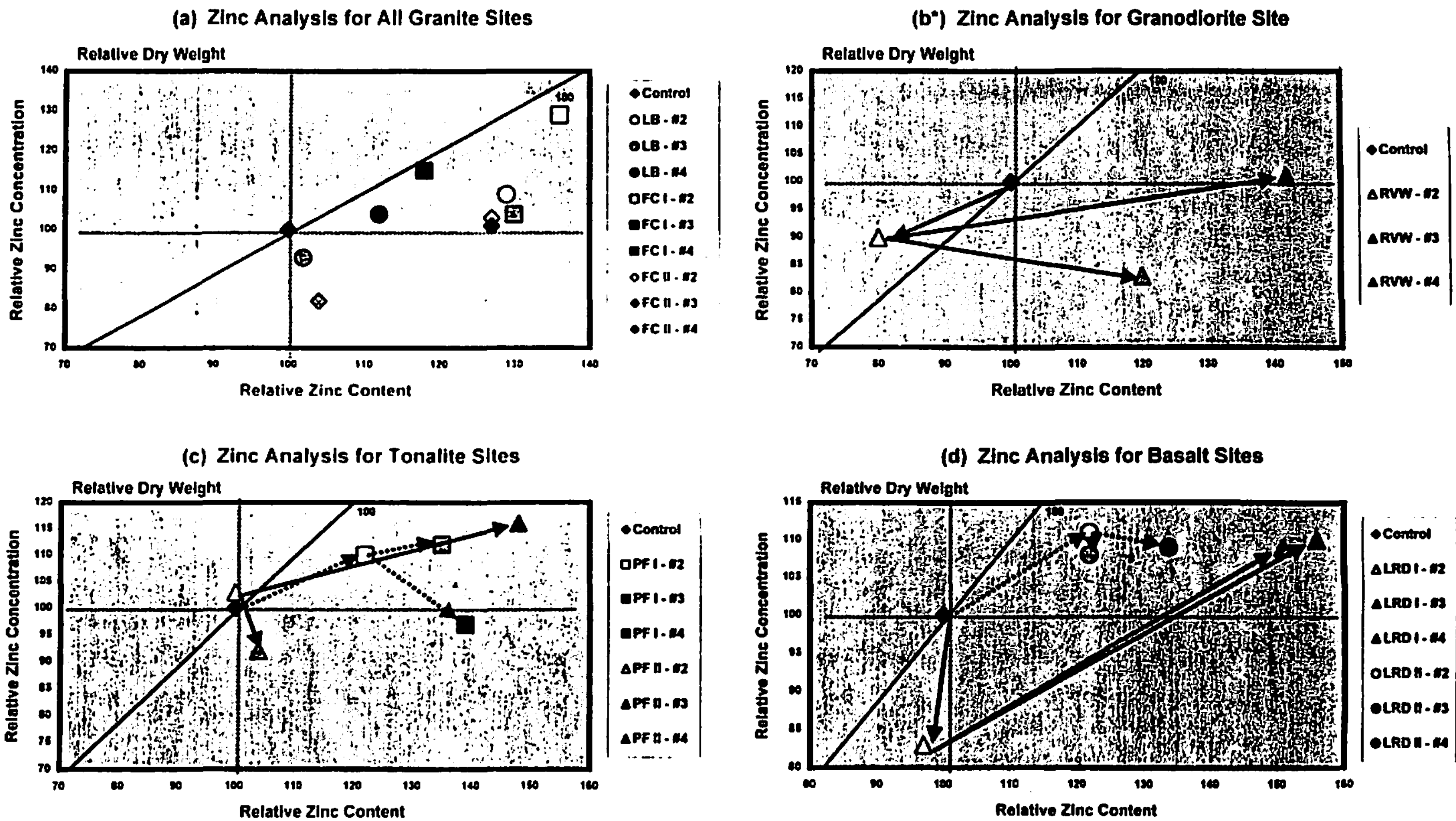


Figure 10. Graphical vector shifts for Zn concentration, content, and needle weight for 1998 foliage by treatment across soil parent material in central Idaho screening trials.

Note: * Lodgepole pine trial.