Four-Year Foliar and Growth Response to Multinutrient Fertilization in Northeast Oregon

Terry M. Shaw

James A. Moore

Intermountain Forest Tree Nutrition Cooperative

University of Idaho

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SUMMARY

Results from this study show foliar nutrient deficiencies and multi-nutrient fertilization response for ponderosa pine, grand fir and Douglas-fir over a period of four consecutive growing seasons. Generally, through critical level or vector foliar diagnosis, N, S, B, Cu and possibly Mo were identified as being deficient for all species in this study. Additionally, Douglas-fir on the Noregaard site showed foliar K deficiency response. Distinct foliar nutrient response patterns were observed for those "strong responding" nutrients, particularly N and B where foliar response increased, peaked then declined in magnitude relative to the control as the year since fertilization increased. Delayed nutrient response may have been to spring fertilizer application not having manifested itself in time to show strong nutrient response one growing season after fertilization.

Similar to foliar nutrient response, foliar needle weight growth increased, peaked then declined in magnitude relative to the control as the year since fertilization increased. Additionally, needle weight response was delayed due to spring fertilization. Needle weight response was significant for ponderosa pine and Douglas-fir but not for grand fir.

Overall, four-year cubic foot volume response was significantly higher on the multi-nutrient treatment than the controls, with relative gross cubic foot volume response for both sites combined showing a 26.9% increase. Individual site response revealed that much of the combined relative cubic foot volume response was expressed on the Clear Creek site, which showed a 34% increase over the controls while the Noregaard site only showed a 3.9% increase. Periodic relative gross basal area response for both sites combined was greater in the first two-year period (26.9%) than the second two-year period (11.1%). Periodic relative basal area response for the Clear Creek unit was 32% the first two-year period and 23% the second two-year period while the Noregaard site response was 18.6% the first period and –6.5% the second.

STUDY AREA

In spring of 1995 two fertilization trials were installed on Boise Cascade lands in northeast Oregon. Both sites were located in the "Grossman/Noregaard Block", north of Wallowa, Oregon; one at Clear Creek in a young ponderosa pine plantation and the other at "Noregaard" in a natural second growth mixed conifer stand. Both sites are located on Yakima basalt parent material and are grand fir vegetation types. A high amount of root disease occurs on both sites.

METHODS

Plot Establishment

Each study area consists of six growth monitoring plots, three of the six plots on each site were treated operationally by helicopter application and received a multi-nutrient fertilizer; the other three plots were untreated and were experimental controls. The elemental rates of the multi-nutrient fertilizer are shown in Table 2. Plots sizes of 0.05 and 0.1 acres were used at the Clear Creek and Noregaard sites, respectively. Plots were monumented with yellow corner and plot center stakes. In addition, each tree received a yellow painted number and horizontal line at breast height. Trees too small for suitable paint identification were tagged with an aluminum tag at the base of each tree. Diamond shaped, red forest fertilization tags are at each plot center and nailed along adjacent roads to identify the stand as a study area.

Measurements

Initial measurements were made in the spring of 1995. Trees were measured for heights, diameters and defect at the time of treatment. Every two years diameters were re-measured on all trees and any incidence of damage or mortality along with probable cause will be noted. Heights were 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 initial plot summaries are given in Table 1.

Foliage collections were made in fall of 1995, 1996, 1997 and 1998. Two trees were selected from the two most dominant species (ponderosa pine only at Clear Creek, Douglas-fir and grand fir at Noregaard) on each plot. Current year foliage was collected from the third whorl. Samples were oven-dried and sent to laboratories chemical analysis. Foliar N concentrations were determined using a standard micro-Kjeldahl procedure while all other nutrients were determined by ICP emission. Nutrient concentration analyses were performed by Scotts Testing Laboratory, Allentown, PA, while 1998 nutrient chemical analysis was performed by Harris Agronomic Services, Lincoln, Nebraska. Foliar nutrient concentration critical levels, with author citations, by species are given in Table 3. In addition, for each sample tree, three repetitions of thirty needles each were dried and weighed. Foliar nutrient contents (concentration x needle weight) were calculated for all nutrients present in the fertilizer mix. Nitrogen (N), phosphorus (P), potassium (K), sulfur (S), boron (B), copper (Cu), zinc (Zn) and molybdenum (Mo) contents were calculated. Nutrient content is considered an index of treatment response.

Data Analysis

General linear contrasts and differences between means by treatment for foliar nutrient and growth responses were determined using the least-squares routine of the general linear models procedure (PROC GLM) of the Statistical Analysis System (SAS Institute Inc. 1985). Contrasts between basal area and volume means are considered average growth responses to treatments. Combined site growth responses are smoothed estimates which are adjusted to a common initial basal area of 39.9 ft^2/acre. Individual site growth responses are adjusted to the average initial basal area of 23 ft^2/acre for the Clear

Creek site and 57 ft^2/acre for the Noregaard site. Responses for the studies are defined as the growth differences between the control plots and the treated plots. Net and gross growth were calculated using these equations:

$$\text{2-Year Periodic Increment Net Basal Area Growth} = BA_2 - BA_0$$

$$\text{2-Year Periodic Increment Gross Basal Area Growth} = (BA_2 + MBA_2) - BA_0$$

Where: BA_0 = Basal Area (initial two-year period)
BA_2 = Basal Area (after a two-year period)
MBA_2 = Basal Area Mortality (2-Year)

Relative growth and relative periodic increment growth was calculated using the following equations:

$$\%\ \text{Relative Growth} = \frac{\text{Growth}}{\text{Basal Area}_0} \times 100 \qquad \%PI = \frac{PI}{\text{Basal Area}_0} \times 100$$

Note: The same formulas are used to calculate 4-year net and gross volume growth.

Treatment averages by site for foliar nutrient concentrations and contents, and needle weights are given in Tables 4 through 10. Basal area and volume response by treatment and site are given in Tables 11through 14. Species comparisons were confounded by site differences and therefore were not included in this analysis. The overall experimental design model used for 4-year net and gross volume and 2-year increment basal area growth and response took the general form of a covariate model:

$$\text{Growth} = F\,(\text{Site, Treatment}, BA_0)$$

where: Growth – net gross volume (cu. ft/acre)
BA_0 – initial basal area as a covariate variable

Vector Analysis

Current year dormant season needle nutrient concentration, nutrient content, and dry weight are 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 nutrient response of the treatment being analyzed. Figure 1 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

The multi-nutrient fertilization increased foliar N concentrations for all species on both sites showing increased foliar N concentrations (Tables 4-6) and significant ($p \leq 0.10$) foliar N content response (Tables 7-9) over the controls. In addition, N fertilization increased foliar N concentrations above the published N critical level for grand fir (Tables 6). The largest foliar N concentration increases over the control for ponderosa pine and grand fir occurred one growing season after fertilization with 25% and 28% increases over the control, while the largest foliar N concentration increase for Douglas-fir was shown the second growing season after fertilization with a 9% increase over the control. Foliar N content response was significant ($p \leq 0.10$) for all three species with ponderosa pine showing the greatest response at 49%, followed by Douglas-fir at 48% and grand fir at 35%.   Generally foliar N response lasted through three growing seasons after fertilization. (Tables 4-6). Vector analysis shows large magnitude deficiency “C-Shifts” that peak and gradually decreases over time following fertilization (Figures 2a-2c).

Phosphorus

Foliar P concentrations tended to be higher on the multi-nutrient treatment compared the control for all species on both sites (Tables 4-6). According to published critical levels, foliar P concentrations were above levels considered to be deficient for all three species on both the control and multi-nutrient treatments. Significant ($p \leq 0.10$) foliar P response was shown for Douglas-fir in 1996, 1997 and 1998 and for ponderosa pine in 1996 and 1997 (Tables 7 and 9). Douglas-fir showed the greatest P content response with a 50% increase over that of the control in 1996. Additionally, vector analysis showed large magnitude P deficiency “C-Shifts” for Douglas-fir, moderate deficiency “C-Shifts” for ponderosa pine and weak deficiency “C-Shifts” for grand fir (Figure 3a, 3c and 3b, respectively).

Potassium

Douglas-fir showed the largest increase in K concentration while grand fir and ponderosa pine showed little or no K response. As with foliar P concentrations, K concentrations for all three species were above published critical levels. With the exception 1995, Douglas-fir showed significantly ($p \leq 0.10$) greater foliar K concentrations and K contents on the multi-nutrient treatment compared to the control for all sampling years after fertilization (Tables 4 and 7). Douglas-fir foliar K content in 1996 was 61% greater on the multi-nutrient treatment compared to the control. Even though Douglas-fir foliar K concentrations peaked and then gradually decreased over time, vector analysis showed large magnitude deficiency shifts for all sampling years following fertilization (Figure 4a). Grand fir and ponderosa pine K concentrations or contents did not significantly ($p \leq 0.10$) increase K concentrations or content over the controls. However, ponderosa pine foliar K concentrations did significantly ($p \leq 0.10$) decrease in 1996. Additionally, vector analysis showed moderate magnitude dilution “A-Shifts” for ponderosa pine in 1996 and 1997.

Ponderosa pine and grand fir potassium/nitrogen (K/N) ratios tended to be lower on the multi-nutrient fertilizer treatments than the control (Tables 4-6). Ponderosa pine K/N ratios in 1995 and 1996 were significantly ($p \leq 0.10$) lower for the fertilized plots than the controls (Tables 4-6). Douglas-fir and grand fir K/N ratios were above the recommended 0.50 critical ratio suggested by Ingestad (1979), however, 1995 ponderosa pine K/N ratios were below this level, suggesting K to N imbalances (Tables

4-6). Low K/N ratios tended to decrease over time with decreased foliar N concentration response (Tables 4-6).

Sulfur

Foliar S deficiencies were shown for all three species. Douglas-fir foliar S concentrations were below published critical levels in 1995, 1997 and 1998, while grand fir and ponderosa pine foliar S concentrations were below published critical levels in 1997 (Tables 4-6). All three species tended to have greater S concentrations on the multi-nutrient treatment than the control, only grand fir showed a significant ($p \leq 0.10$) foliar S concentration increase of 40 % in 1996. Significant ($p \leq 0.10$) foliar S content increase was seen in 1995 for grand fir and in 1996 for Douglas-fir, grand fir and ponderosa pine. Vector analysis showed large magnitude deficiency "C-Shifts" for nearly all years for Douglas-fir and grand fir and moderate "C-Shifts" for ponderosa pine in 1995 (Figures 5a, 5b and 5c) .

Multi-nutrient fertilization did not significantly ($p \leq 0.10$) increase nitrogen to sulfur (N/S) ratios above the controls. However, Douglas-fir and ponderosa pine did show N/S ratios above the 14.7 critical ratio recommended by Turner and Lambert (1979) on both the control and multi-nutrient treatments in 1997 and 1998, indicating a N/S imbalance (Tables 4 and 6). Grand fir showed the only significant ($p \leq 0.10$) N/S decrease on those plots receiving the multi-nutrient treatment, indicating a greater increase in S concentration than N after fertilization.

Boron

Boron fertilization significantly ($p \leq 0.10$) increased foliar B concentrations for all species (Tables 4-6). Although B concentrations were above published critical levels for all species during all sampling years, foliar B content was significantly ($p \leq 0.10$) greater than the controls following multi-nutrient fertilization (Tables 7-9). Interestingly, each species responded differently to B fertilization.

Douglas-fir foliar B content peaked one growing season after fertilization with a 150% increase in foliar B content over the controls. Douglas-fir B contents gradually decreased to 140%, 83% and 50% above the control two, three and four years after fertilization, respectively. Grand fir B content also peaked (179%) one growing season after fertilization, however, B content response remained high (171%) two growing seasons after fertilization and then decreased three (67%) and four (65%) growing seasons after fertilization. Similar to Douglas-fir and grand fir, ponderosa pine foliar B content was greatest one year (243%) after fertilization, however, foliar B content dropped sharply two, three and four years after fertilization with 94%, 28% and 13% greater contents than the control, respectively. Boron vector analyses shown in Figures 6a, 6b and 6c depict B vector response patterns by species, treatment and year.

Copper

Response to Cu fertilization was generally inconsistent between sampling years, species and treatment. Ponderosa pine and grand fir showed Cu concentrations below published critical levels on both the multi-nutrient and control treatments while Douglas-fir did not show any Cu concentrations below recommended critical levels (Tables 6 and 7). Ponderosa pine showed significant ($p \leq 0.10$) Cu concentration increases on the multi-nutrient treatment relative to the control in 1995, however Cu concentrations were significantly ($p \leq 0.10$) lower on the mutli-nutrient treatment relative to the control in 1996 and 1997. In contrast, grand fir did not show a significant ($p \leq 0.10$) increase in foliar Cu concentrations on the multi-nutrient treatment relative to the control in 1995 but did show significant ($p \leq 0.10$) Cu concentration increases over the control in 1996 and 1997 (Table5). Douglas-fir foliar Cu concentrations showed no significant differences by treatment and year. Results for foliar Cu contents were similar to Cu concentrations except Douglas-fir showed a significant ($p \leq 0.10$) Cu content increase on the multi-nutrient treatment relative to the control in 1995. Vector analysis showed dilution "A-shifts" for ponderosa pine in 1996 and 1997 and for grand fir in 1998. Deficiency "C-Shifts" were shown for grand fir and ponderosa pine in 1995 and grand fir as well as Douglas-fir in 1996 (Figures 7a-7c).

Zinc

Foliar Zn concentrations were above published critical levels for all species and for both treatments. Douglas-fir and ponderosa pine foliar Zn concentrations tended to be lower on the multi-nutrient treatment relative to the controls (Tables 4 and 6) while grand fir foliar Zn concentrations were not significantly different by treatment and year (Table 5). No significant ($p \leq 0.10$) foliar Zn content response was seen for any species. Vector analysis showed large to moderate deficiency "C-Shifts" for grand fir in 1996 and 1998 (Figure 8b). Generally, vector analysis showed dilution "A-Shifts" for all three species (Figures 8a-8c).

Molybdenum

Molybdenum foliar concentrations for all three species tended to increase on multi-nutrient treatments relative to the control, except for ponderosa pine in 1995 (Tables 4-6). Ponderosa pine was the only species that showed significant ($p \leq 0.10$) increases in Mo content for the multi-nutrient treatment relative to the control in both 1996 and 1997 (Table 9). Molybdenum concentrations in this study were well above the suggested 0.01 ppm for all three species by treatment and year. Vector analysis showed deficiency "C-Shifts" for all three species, indicating Mo fertilizer response (Figures 9a-9c). In addition, ponderosa pine showed a dilution "A-Shift" in 1995 (Figure 9c).

Needle Weight Response

Needle weights were greater on the multi-nutrient treatments than the controls (Table 10).

Notably, needle weight increase due to fertilization was low one growing season after fertilization with grand fir showing a 5% increase, ponderosa pine increased 3% and Douglas-fir 1%, compared to the control. Needle weight response was greatest for all species in 1996 with Douglas-fir showing a significant ($p \leq 0.10$) 33% increase, followed by ponderosa pine with a significant ($p \leq 0.10$) 31% and then grand fir with a 9% increase over that of the control (Table 10). Needle weight response declined over time with 1998 needle weights showing ponderosa pine with a 2.7% decrease, Douglas-fir a 13% increase and grand fir a 4% increase relative to the control.

Volume and Basal Area Growth Response

Overall, absolute four-year net and gross volume growth response was significantly ($p \leq 0.10$) greater on the plots receiving the fertilizer treatments than the control plots (Table 11). The average absolute gross 4-year growth response for the multi-nutrient treatment was 69 cu. ft/ac (16.6%) while the average absolute net growth response was 82 cu. ft/ac (20.4%) (Table 11). Relative gross and net volume response (expressing the growth as a percentage of the initial volume) was greater than gross and net absolute volume response, with significant ($p \leq 0.10$) relative gross response at 26.9% and relative net response at 27.8%, over the controls (Table 12).

Four-year volume response was much greater on the Clear Creek site then the Noregaard site. Four-year relative gross volume response for the Clear Creek site was a significant ($p \leq 0.10$) 34.2% while the Noregaard site was nonsignificant ($p \leq 0.10$) (3.9%), a 30.3% difference in response between the two sites. Absolute and relative, gross and net volume responses by site are given in Tables 11 and 12.

Periodic relative gross and net basal area response was significantly ($p \leq 0.10$) greater than the controls in the first two-year period, while the second two-year period was not significantly ($p \leq 0.10$) greater for gross but was for net (Table 16) for the combined analysis of both sites. Relative gross basal area increase due to treatment was 26.9% in the first two-year period and 11.1% in the second two-year period (Table 16). Similar response was seen for periodic absolute gross basal area response with 25.5% during the first two-year period and 16.3% during the second two-year period (Table 13). Absolute and relative net basal area response was the same as gross response during the first two-year period. However, net response was greater the second two-year period with a 25% increase over the control for absolute net and a 18.9% increase for relative net response.

Similar to volume response, basal area response by site was greater on the Clear Creek site than on the Noregaard site. Relative gross basal area response during the first two-year period was a significant ($p \leq 0.10$) 32% for the Clear Creek site and a non-significant ($p \leq 0.10$) 18.6% on the Noregaard site, relative to the controls. Both sites showed less relative gross basal area response the second two-year period than the first two-year period with Clear Creek showing a significant ($p \leq 0.10$) 23% response over the controls while Noregaard response was non-significant (Tables 17 and 18).

Periodic absolute basal area response by site paralleled periodic relative basal area response, except on the Clear Creek site where absolute gross basal area response during the first two-year period was less (28.8%) than the second two-year period response (35.8%). Relative gross basal area response (32%) was greater than the second two-year period (23%) (Tables 14 and 17), reflecting higher control growth the first two-year period than the second two-year period.

DISCUSSION

Foliar Nutrient Response

Nitrogen

According to published critical levels, nitrogen concentrations on the control plots were deficient for Douglas-fir and grand fir on the Noregaard site but sufficient for ponderosa pine on the Clear Creek site. Application of N significantly increased N concentrations above published critical levels for grand fir but unsuccessful for Douglas-fir. Although ponderosa pine N concentrations were sufficient on the control plots, N fertilization in significantly increased N concentrations for ponderosa pine. Importantly, significant foliar N content response over the control was shown for all species on both sites. Vector analyses also showed deficiency shifts N response relative to the controls for all species on both sites.

Generally, this study showed good N response one growing season after fertilization for ponderosa pine and grand fir but not for Douglas-fir. Vector analyses showed that N foliar vector magnitudes were greatest two growing seasons after fertilization and then declined by the third and fourth years for all three species. Notably, all three species showed delayed foliar N response to the fertilizer treatment, where peak foliar nutrient response was not shown until 1996, two growing seasons after fertilization. Delayed foliar N response may have resulted from spring fertilization in which the effect of the fertilizer application may not have manifested itself in time to fully express the nutrient treatments. Similarly, Shaw and Moore (2000) reported delayed foliar nutrient response due to spring fertilization for Douglas-fir and ponderosa pine on IFTNC sites in central Washington.

Phosphorus

Even though P was found to be adequate for all species on both sites, application of P at the 100#P/ac rate significantly increased foliar P contents above the controls for ponderosa pine on the Clear Creek site and Douglas-fir on the Noregaard site. Douglas-fir was the best responder showing significant foliar P content response in 1996, 1997 and 1998. Ponderosa pine foliar P response was also significant in 1996 and 1997. Although grand fir P content responses were not significant foliar P contents were greater on the multi-nutrient treatments. Perhaps the lack of grand fir foliar P response reflects the high control foliar P concentrations that were above the critical level of 0.15%. This result suggests that P was not limiting thus for the low P foliar response. Increases in ponderosa pine and Douglas-fir P concentrations could reflect luxury consumption for those species since foliar P was above critical, although vector analysis did not show these trends. Similar to the delayed response shown for foliar N, no significant P response was shown for any species in 1995. Furthermore, vector analysis showed increased P vector shifts two and three years after fertilization. Vector shifts then decreased by the fourth year after application for Douglas-fir and ponderosa pine.

Potassium

Only Douglas-fir significantly responded to the application of K in the fertilizer mix. Moreover, Douglas-fir foliar K concentrations and K contents were significantly greater than the control for all sampling years except for 1995, suggesting K deficiencies. In addition, vector analysis shows strong deficiency "C-Shifts" or response shifts for Douglas-fir every foliar sampling year after fertilization. Ponderosa pine and grand fir, however, did not show K deficiencies and did not respond to the application of K in the fertilizer mix. According to published K critical levels, K was sufficient on the controls for all species. The lack of foliar response by ponderosa pine and grand fir may reflect the high control foliar K concentrations that were above critical levels for these species, suggesting that K was not limiting and thus low K foliar response. However, K/ N ratios also suggest K deficiencies or imbalances on these sites. Generally K/N ratios for ponderosa pine and grand fir tend to be lower on those plots receiving the fertilizer application then the control. Additionally, K/N ratios were significantly lower than the control and below the 0.50 critical level for ponderosa pine, suggesting K/N imbalances. Douglas-fir K/N ratios, however, were not lower on the fertilized plots relative to the control. Good foliar K uptake by Douglas-fir kept K/N ratios above the recommended critical levels while poor K uptake by ponderosa pine and grand fir did not.

Similar to the delayed response shown for foliar N and P, no significant Douglas-fir K response was evident one growing season after fertilization. In addition, vector analysis showed strong Douglas-fir K vectors two and three years after fertilization. The vector magnitudes decreased by the fourth year after application.

Sulfur

According to published S critical levels, all three species showed S deficiencies. However, the addition of S in the fertilizer mix only significantly increased foliar S concentrations for grand fir in 1996 while ponderosa pine and Douglas-fir did not show any significant S concentration increases over the controls. Significant S content response was shown for grand fir in 1995 and for all three species in 1996. Additionally, vector analysis showed large magnitude deficiency "C-Shifts" for Douglas-fir and grand fir and moderate magnitude deficiency "C-Shifts" for ponderosa pine. Other studies have shown tree growth response after S fertilization (Cochran 1973, Powers et al 1988, and Brockley and Sherman 1994). However, foliar S response can be variable between species and sites. Garrison et al. (1998) found S deficiencies for Douglas-fir and grand fir but not for ponderosa pine. Furthermore, Garrison et al. (1998) found no foliar S increases following N + S fertilization for grand fir and Douglas-fir and no change in foliar S occurred for ponderosa pine. Similar results were seen in this study with grand fir responding better than both Douglas-fir and ponderosa pine.

Boron

Boron behaved as if it was deficient although control B concentrations were above critical levels for all species. Furthermore, B concentrations one year after fertilization on the multi-nutrient treatment were double the control B concentrations for all species. Boron response remained significantly high through all four sampling years for Douglas-fir and grand fir and significantly high through the first two sampling years for ponderosa pine. The decline in ponderosa pine foliar B response is probably due to the fact that ponderosa pine only carries its needles two years, thus loosing B reserves that would be retranslocated back within the plant during the next year. Generally B concentrations are diluted by N fertilization (Lambert and Turner 1977, Shaw and Moore 2000), however, B fertilization at the 10#B/ac rate was more than sufficient to alleviate any dilution effects caused by N fertilization. Although some concern was expressed that the 10#B/ac rate was too high and could have toxic effects, vector analysis did not show toxic response or even strong luxury vectors to the B fertilizer treatment.

Generally, B response patterns over time were similar for all species, though the magnitude of response differed. Vector analysis showed very large magnitude vector deficiency "C-Shifts" that decreased over time, for all species. Foliar B response remained high for grand fir two growing seasons following fertilization while Douglas-fir response fell gradually and ponderosa pine response fell sharply. Furthermore, grand fir foliar B response fell sharply three growing seasons after fertilization, although still significantly higher than the control, and remained at that level four seasons after fertilization. Douglas-fir foliar B response decreased gradually three and four growing seasons after fertilization, but still remained at a magnitude significantly higher than the control. In contrast, ponderosa pine B response again fell sharply three growing seasons after fertilization to magnitudes similar to the control.

Copper

Copper deficiencies were shown for both ponderosa pine and grand fir but not for Douglas-fir. Application of Cu at the 5#Cu/ac rate increased foliar Cu concentrations above reported critical levels for grand fir but not for ponderosa pine. Moreover, ponderosa pine Cu concentrations were significantly decreased below critical levels following multi-nutrient fertilization for both the 1996 and 1997 sampling periods, demonstrating dilution effects. Additionally, vector analysis showed dilution "A-Shifts" for ponderosa pine in 1996 and 1997. Apparently, application of Cu at the 5#Cu/ac rate was sufficient for grand fir on the Noregaard site but insufficient for ponderosa pine on the Clear Creek site. Even though Douglas-fir Cu concentration response was non-significant for all sampling years, Douglas-fir did show significant foliar Cu content response in 1996. Lack of Douglas-fir response may reflect the fact that foliar Cu concentrations were above critical levels for Douglas-fir, suggesting that Cu was not limiting, thus producing low foliar Cu response.

Zinc

Application of Zn at the 10#Zn/ac rate did not significantly increase foliar Zn concentration above the controls for all species. Additionally, no significant foliar content response was shown for any of the species on either site. However, Douglas-fir and ponderosa pine foliar B concentration did tend to be lower on those plots receiving the multi-nutrient treatment relative to the control. Additionally, vector analysis showed dilution "A-Shifts" for all three species, possibly demonstrating that application of Zn at the 10#Zn/ac rate is not sufficient to maintain Zn levels in the multi-nutrient fertilizer blend tested in this study. Nonetheless, the multi-nutrient fertilization treatment did not dilute Zn concentration below critical levels for any species. Even though Zn concentrations were above critical levels, Zn deficiency vectors were evident for grand fir in 1996 and 1998, although neither vector was statistically significant. Zinc deficiencies are not common, although 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 levels and removal of organic matter on Noregaard site may have contributed to grand fir Zn deficiency response.

Molybdenum

Operational fertilization of Mo at the 1#Mo/ac rate appears to have increased Mo concentrations for all species on both sites. Although Mo concentration response was not significant, all species expressed substantial Mo concentration increases over the control with ponderosa pine showing a 23% increase in 1996, grand fir 22% in 1996 and Douglas-fir 20% in 1995. Similar Mo content increase was shown for each species. Moreover, ponderosa pine showed significant Mo content responses in 1996 and 1997. Additionally, vector analysis showed large magnitude Mo deficiency “C-Shifts” for all three species, indicating Mo response. Another IFTNC multi-nutrient study in central Washington (Shaw and Moore 2000) reported foliar Mo deficiencies relative to N alone fertilization on basalt parent material. In that study, both Douglas-fir and ponderosa pine expressed Mo dilution and deficiency (response) effects relative to an N alone treatment. According to unpublished Mo critical levels, none of the species were deficient in Mo. However, respect to our study, nutrient deficiencies are apparent and perhaps the unpublished 0.01 Mo critical level is questionable. Information regarding foliar Mo nutrition for conifers is not common in the literature. Given our study results and lack of information on Mo nutrition for conifers, more work is needed.

Needle Weight Response

Needle weight response was positive on the multi-nutrient treatment relative to the control for all species on both sites although grand fir response was not statistically significant. Moreover, the largest grand fir needle weight response for all sampling years was only 9% over that of the control grand fir needle weights. Needle weights for the multi-nutrient treatments were similar to control plots by the fourth growing season after fertilization. Importantly, needle weight response was low one growing season after fertilization for all species. Low needle weight response shown after one growing season for all species may in part be due to spring fertilization. As shown in the foliar nutrient response, nutrient effect of spring fertilization may not have manifested itself in time for the trees to show a strong needle growth response in 1995.

Volume and Basal Area Growth Response

Four-year cubic foot volume response for both the Clear Creek and Noregaard sites combined was significantly greater on the multi-nutrient treatment than the controls. Net response was slightly higher than gross response due to mortality on the controls at the Noregaard site. Examination of four-year relative response by site revealed that much of the overall response derived from the Clear Creek site rather than the Noregaard site. Site characteristics, past management practices or species differences could contribute to the large response differences shown between the two sites. Foliar needle weights for grand fir did not respond to the fertilizer treatment. Furthermore, grand fir is the most dominant species on the Noregaard site with 31.3% of the total species composition. This result suggests that the low growth response on the Noregaard site may have been due to low needle weight response for grand fir. Evidence from other studies (Margolis and Waring 1986, Shaw 1996) has shown that increased needle or crown mass due to enhanced nutrition can lead to greater growth rates.

Generally, basal area response was similar to volume response showing significant overall response on the multi-nutrient treatment relative to the controls. The Clear Creek site showed much greater basal area response than the Noregaard site. Periodic relative basal area response for each site and both sites combined showed greater response the first two-year period then the second two-year period. However, in contrast, absolute basal area response on the Clear Creek site showed greater basal area response the second two-year period than the first two-year period.

CONCLUSIONS

Operational fertilization increased foliar macro-nutrients (N,P,K,S) as well as foliar micro-nutrients (B, Cu, Zn, Mo) for all three species on both the Clear Creek and Noregaard sites. Foliar nutrients applied in this study expressed distinct response patterns over time such that foliar nutrients generally increased and peaked two-years after fertilization, declined the third year, and by the fourth showed concentrations similar to controls. Additionally, significant foliar response usually persisted three growing seasons after fertilization. Delayed foliar nutrient and growth response may have been caused by spring fertilization where the fertilization effect may not have completely manifested itself in strong foliar nutrient or growth response in 1995. Importantly, grand fir did not show any significant needle weight response to the fertilizer treatment while ponderosa pine and Douglas-fir did. Volume and basal area response for both sites combined was significant, however, results show that most of the response derived from by the Clear Creek site not the Noregaard site. Lower volume and basal area response on the Noregaard site may have been caused by low grand fir needle weight response.

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Table 1. Nutrient element rates for multi-nutrient fertilization test sites in northeast Oregon.

Nutrient	Rate (lbs/ac)	Source	Rate (lbs/ac)
Nitrogen	200	Urea Ammonium Phosphate	387 193
Potassium	200	**Potassium Sulfate**	400
Phosphorus	100	**Ammonium Phosphate**	
Sulfur	90	**Potassium Sulfate** **Copper Sulfate**	40
Boron	10	Borate FG	69
Zinc	10	Blu-Min-Zinc	55
Molybdenum	1	Sodium Molybdate	2.5

Table 2. Site characteristics and average initial stand conditions for the two multi-nutrient fertilizer installations in northeast Oregon.

	Clear Creek	**Noregaard**
Site Characteristics		
Parent Material	Basalt / Grande Ronde	Basalt / High P
Vegetation Series	ABGR	ABGR
Aspect	N-NE	NE
Stand Conditions		
Trees (Stems/ac.)	237	220
Basal Area (ft^2/ac.)	22.6	57.1
Total Volume (ft^3/ac.)	143	751
Crown Competition Factor	22.8	71.8
Quadratic Mean Diameter (in.)	4.19	6.9
Relative Density	11.1	21.7
Species Composition (% of BA)		
Ponderosa pine	99.5	3.2
Grand fir	0.0	31.3
Douglas-fir	0.0	29.0
Engelmann Spruce	0.3	19.7
Western Larch	0.1	15.7
Lodgepole pine	0.1	1.0

Table 3. Critical foliar nutrient concentrations for several conifer species in the interior northwest.

Foliar **Conc.**	**Doug-Fir**[a]	**True Fir**[b]	**Lodgepole**[c]	**Ponderosa**[d]	**White Pine**[e]	**Englemann**[f]	**Cedar**[g]	**Hemlock**[h]
N (%)	1.40[1]	1.15[3]	1.20[1]	1.10[3]	1.00[3]	1.50	1.50[1]	1.20[1]
P (%)	0.12[1]	0.15[3]	0.12[1]	0.08[3]	0.15[3]	0.18	0.13[1]	.13[1]
K (%)	0.60[1]	0.58[2]	0.50[1]	0.48[2]	0.70[3]	0.60	0.60[1]	.75[1]
S (%)	0.11[2]	0.08[4]	0.09[4]	0.08[4]	0.20[3]		0.40[1]	
Ca (%)	0.15[1]	0.12[2]	0.08[1]	0.05[2]	0.30[3]	0.15	0.20[1]	.08[1]
Mg (%)	0.08[1]	0.06[2]	0.09[1]	0.05[2]	0.10[3]	0.10	0.12[1]	.09[1]
Mn (ppm)	15[1]	100[1]	293[1]	60[3]	400[3]	15[5]	15[5]	15[5]
Fe (ppm)	25[1]	50[1]	58[1]	50[3]	40[3]	100	25[5]	25[5]
Zn (ppm)	10[1]	10[1]	52[1]	30[3]	15[3]	10[5]	10[5]	10[5]
Cu (ppm)	2[1]	3[1]	2.7[1]	3[3]	5[3]	2.6[5]	2.6[5]	2.6[5]
B (ppm)	10[1]	10[5]	4.3[1]	20[3]	10[3]	5	15[1]	10[5]

Values obtained by:

[1] Best estimate by cited author based on literature review and personal experience
[2] Derived by cited author using optimal proportions
[3] Derived by cited author experimentally
[4] Critical S values derived for this paper using an N:S ratio of 14.7 in conjunction with the given critical N values (Blake et al. 1990, Turner and Lambert 1978)
[5] General value established for all conifer species, not yet species-specific (Ballard and Carter 1986)

[a] From Webster and Dobkowski (1983), these values are considered inadequate for growth, critical values would be somewhat higher.
[b] All values except S from Powers (1983). S value calculated as noted above.
[c] All values except S from Ballard and Carter (1986), based on Everard (1973) and Swan (1972). S value calculated as noted above. Micronutrient values from Van den Driessche (1979)
[d] Value for N from Powers et al. (1985), values for P, K, Ca and Mg from Powers (1983). S value calculated as noted above. Micronutrients from Boyer (1984, unpublished)
[e] All values from Boyer (1984, unpublished)
[f] All values except S from Van den Driessche (1974), value for S from Cole and Gessel (1992)
[g] All values from Cole and Gessel (1992)
[h] Values from Ballard and Carter (1986)

Table 4. Douglas-fir foliar nutrient critical levels and Douglas-fir average foliar nutrient concentrations by year for Noregaard operational multi-nutrient fertilization test site in northeast Oregon.

	N (%)	(%)	K (%)	S (%)	B (ppm)	Cu (ppm)	Zn (ppm)	Mo (ppm)	K/N	N/S
Critical Levels	**1.40**	**0.12**	**0.60**	**0.11**	**20**	**2**	**10**	******	**0.50**	**14.7**
	1995 Foliar Nutrients									
Treatments	N (%)	(%)	K (%)	S (%)	B (ppm)	Cu (ppm)	Zn (ppm)	Mo (ppm)	K/N	N/S
Control	1.24	0.19	0.91	0.10	28	2.8	42	0.25	0.74	12.4
Multi-Nutrient	1.23	0.19	1.18	0.10	67*	2.6	24	0.30	0.97	12.3
	1996 Foliar Nutrients									
Treatments	N (%)	(%)	K (%)	S (%)	B (ppm)	Cu (ppm)	Zn (ppm)	Mo (ppm)	K/N	N/S
Control	1.21	0.27	1.32	0.11	25	3.4	32	**	1.09	11.0
Multi-Nutrient	1.32	0.31	1.65*	0.12	42*	3.8	29	**	1.25	11.0
	1997 Foliar Nutrients									
Treatments	N (%)	(%)	K (%)	S (%)	B (ppm)	Cu (ppm)	Zn (ppm)	Mo (ppm)	K/N	N/S
Control	1.18	0.23	1.15	0.06	29	3.5	31	0.68	0.99	19.7
Multi-Nutrient	1.22	0.24	1.44	0.07	42*	3.3	30	0.72	1.20	17.4
	1998 Foliar Nutrients									
Treatments	N (%)	(%)	K (%)	S (%)	B (ppm)	Cu (ppm)	Zn (ppm)	Mo (ppm)	K/N	N/S
Control	1.28	0.20	1.03	0.08	33	2.5	27	**	0.80	16.0
Multi-Nutrient	1.19	0.21	1.24*	0.09	42*	2.2	24	**	1.04	13.2

*Significantly different than the control @ $p \leq 0.10$

**Data not Available

Table 5. Grand fir foliar nutrient critical levels and grand fir average foliar nutrient concentrations by year for Noregaard operational multi-nutrient fertilization test site in northeast Oregon.

	N (%)	(%)	K (%)	S (%)	B (ppm)	Cu (ppm)	Zn (ppm)	Mo (ppm)	K/N	N/S
Critical Level	**1.15**	**0.15**	**0.58**	**0.08**	**20**	**3**	**10**	******	**0.50**	**14.7**
	1995 Foliar Nutrients									
Treatments	N (%)	(%)	K (%)	S (%)	B (ppm)	Cu (ppm)	Zn (ppm)	Mo (ppm)	K/N	N/S
Control	1.08	0.15	1.29	0.10	31	2.1	26	0.34	1.18	10.8
Multi-Nutrient	1.35*	0.16	1.19	0.13	78*	2.2	20	0.35	0.91	10.4
	1996 Foliar Nutrients									
Treatments	N (%)	(%)	K (%)	S (%)	B (ppm)	Cu (ppm)	Zn (ppm)	Mo (ppm)	K/N	N/S
Control	1.08	0.22	1.77	0.10	25	2.2	30	0.75	1.64	10.8
Multi-Nutrient	1.29*	0.24	1.60	0.14*	60*	3.2*	37	0.85	1.24*	9.2*
	1997 Foliar Nutrients									
Treatments	N (%)	(%)	K (%)	S (%)	B (ppm)	Cu (ppm)	Zn (ppm)	Mo (ppm)	K/N	N/S
Control	0.94	0.19	1.40	0.07	33	2.6	37	1.02	1.58	13.4
Multi-Nutrient	1.15*	0.21	1.43	0.08	54*	3.3*	30	1.24	1.23	14.3
	1998 Foliar Nutrients									
Treatments	N (%)	(%)	K (%)	S (%)	B (ppm)	Cu (ppm)	Zn (ppm)	Mo (ppm)	K/N	N/S
Control	1.03	0.20	1.59	0.08	34	3.5	32	**	1.53	12.9
Multi-Nutrient	1.03	0.22	1.67	0.10	55*	3.0	34	**	1.62	10.3

*Significantly different than the control @ $p \leq 0.10$

**Data not Available

Table 6. Ponderosa pine foliar nutrient critical levels and ponderosa pine average foliar nutrient concentrations by year for Clear Creek operational multi-nutrient fertilization test site in northeast Oregon.

	N (%)	(%)	K (%)	S (%)	B (ppm)	Cu (ppm)	Zn (ppm)	Mo (ppm)	K/N	N/S
Critical Level	**1.20**	**0.08**	**0.48**	**0.08**	**20**	**3.0**	**30**	**	**0.50**	**14.7**
	1995 Foliar Nutrients									
Treatments	N (%)	(%)	K (%)	S (%)	B (ppm)	Cu (ppm)	Zn (ppm)	Mo (ppm)	K/N	N/S
Control	1.27	0.16	0.77	0.10	21	2.1	41	0.19	0.61	12.7
Multi-Nutrient	1.63*	0.16	0.75	0.11	70*	2.6*	37	0.16	0.46*	14.8
	1996 Foliar Nutrients									
Treatments	N (%)	(%)	K (%)	S (%)	B (ppm)	Cu (ppm)	Zn (ppm)	Mo (ppm)	K/N	N/S
Control	1.46	0.24	1.10	0.12	21	3.6	52	0.74	0.75	12.2
Multi-Nutrient	1.67*	0.23	0.94*	0.12	31*	1.9*	48	0.91	0.56*	13.9
	1997 Foliar Nutrients									
Treatments	N (%)	(%)	K (%)	S (%)	B (ppm)	Cu (ppm)	Zn (ppm)	Mo (ppm)	K/N	N/S
Control	1.28	0.20	0.91	0.06	23	3.1	53	0.65	0.72	21.3
Multi-Nutrient	1.37	0.21	0.84	0.06	24	2.3*	51	0.73	0.63	22.8
	1998 Foliar Nutrients									
Treatments	N (%)	(%)	K (%)	S (%)	B (ppm)	Cu (ppm)	Zn (ppm)	Mo (ppm)	K/N	N/S
Control	1.19	0.19	0.84	0.08	22	3.8	38	**	0.71	14.9
Multi-Nutrient	1.20	0.20	0.87	0.08	26	3.8	36	**	0.73	15.0

*Significantly different than the control @ $p \leq 0.10$

**Data not Available

Table 7. Douglas-fir average foliar nutrient contents by year for the Noregaard operational multi-nutrient fertilization test site in northeast Oregon.

1995								
Treatment	**Nutrients**							
	N	**P**	**K**	**S**	**B**	**Cu**	**Zn**	**Mo**
Control	0.28	0.04	0.20	0.02	6	0.65	10	0.06
Multi-Nutrient	0.29	0.05	0.28	0.04	15*	0.60	6	0.07
1996								
Treatment	**Nutrients**							
	N	**P**	**K**	**S**	**B**	**Cu**	**Zn**	**Mo**
Control	0.25	0.06	0.28	0.02	5	0.72	7	**
Multi-Nutrient	0.37*	0.09*	0.45*	0.03*	12*	1.05*	8	**
1997								
Treatment	**Nutrients**							
	N	**P**	**K**	**S**	**B**	**Cu**	**Zn**	**Mo**
Control	0.24	0.05	0.23	0.01	6	0.72	6	0.14
Multi-Nutrient	0.31*	0.06*	0.36*	0.02	11*	0.82	8	0.18
1998								
Treatment	**Nutrients**							
	N	**P**	**K**	**S**	**B**	**Cu**	**Zn**	**Mo**
Control	0.31	0.05	0.25	0.02	8	0.59	7	**
Multi-Nutrient	0.32	0.06*	0.34	0.02	12*	0.58	7	**

*Significantly different than the control @ $p \leq 0.10$
**Data not Available

Table 8. Grand fir average foliar nutrient content by year for the Noregaard operational multi-nutrient fertilization test site in northeast Oregon.

1995								
Treatment	**Nutrients**							
	N		**K**	**S**	**B**	**Cu**	**Zn**	**Mo**
Control	0.68	0.10	0.80	0.06	19	1.32	16	0.21
Multi-Nutrient	0.92*	0.11	0.77	0.09*	53*	1.48	13	0.21
1996								
Treatment	**Nutrients**							
	N		**K**	**S**	**B**	**Cu**	**Zn**	**Mo**
Control	0.61	0.12	1.01	0.06	14	1.25	17	0.44
Multi-Nutrient	0.79	0.15	1.02	0.09*	38*	2.04*	23	0.34
1997								
Treatment	**Nutrients**							
	N		**K**	**S**	**B**	**Cu**	**Zn**	**Mo**
Control	0.53	0.11	0.78	0.04	18	1.47	21	0.57
Multi-Nutrient	0.65*	0.12	0.81	0.05	30	1.85*	17	0.70
1998								
Treatment	**Nutrients**							
	N	**P**	**K**	**S**	**B**	**Cu**	**Zn**	**Mo**
Control	0.52	0.10	0.82	0.04	17	1.79	16	**
Multi-Nutrient	0.53	0.11	0.88	0.05	28*	1.60	18	**

*Significantly different than the control @ $p \leq 0.10$
**Data not Available

Table 9. Ponderosa pine average foliar nutrient contents by year for the Clear Creek operational multi-nutrient fertilization test site in northeast Oregon.

1995								
Treatment	**Nutrients**							
			K	**S**	**B**	**Cu**	**Zn**	**Mo**
Control	9.7	1.2	5.9	0.75	155	15.8	299	1.43
Multi-Nutrient	12.6*	1.2	5.8	0.85	532*	20.2*	289	1.26
1996								
Treatment	**Nutrients**							
	N		**K**	**S**	**B**	**Cu**	**Zn**	**Mo**
Control	9.6	1.6	7.3	0.75	133	23.0	342	4.81
Multi-Nutrient	14.3*	1.9*	8.0	1.02*	258*	15.8*	405	7.28*
1997								
Treatment	**Nutrients**							
	N		**K**	**S**	**B**	**Cu**	**Zn**	**Mo**
Control	8.7	1.2	5.5	0.33	138	18.3	317	3.90
Multi-Nutrient	10.1*	1.5*	6.3	0.46	177*	17.2	377	5.38*
1998								
Treatment	**Nutrients**							
	N		**K**	**S**	**B**	**Cu**	**Zn**	**Mo**
Control	9.7	1.6	6.7	0.64	178	31.2	313	**
Multi-Nutrient	9.4	1.5	6.8	0.65	202	29.9	278	**

*Significantly different than the control @ $p \leq 0.10$

**Data not Available

Table 10. Average Douglas-fir, grand fir and ponderosa pine needle weights (g/30needles) by year and treatment for Noregaard and Clear Creek multi-nutrient operational fertilization test sites in northeast Oregon.

Ponderosa pine Needle Weight (g/30 needles)				
Site/Treatment	**1995**	**1996**	**1997**	**1998**
Control	7.52	6.54	6.00	8.06
Muti-Nutrient	7.76	8.60*	7.41*	7.84

Douglas-fir Needle Weight (g/30 needles)				
Site/Treatment	**1995**	**1996**	**1997**	**1998**
Control	0.22	0.21	0.20	0.24
Muti-Nutrient	0.24	0.28*	0.25	0.27
Grand fir Needle Weight (g/30 needles)				
Control	0.63	0.56	0.56	0.50
Multi-Nutrient	0.66	0.61	0.56	0.52

*Significantly different than the control @ $p \leq 0.10$.

Table 11. Combined and individual four-year average absolute gross and net volume growth response for Clear Creek and Noregaard multi-nutrient fertilization test sites in northeast Oregon.

---------------------------- Overall Volume ------------------------					
	Growth		**Response**		
Treatment	**Cu/ft/ac.**	**Contrast**	**Cu/ft/ac.**	***p***	**%**
-------------------------Gross Volume ------------------------					
Control	415				
Multi-nutrient	484	Cont - Multi	69	0.07	16.6
------------------------- Net Volume ---------------------------					
Control	402				
Multi-Nutrient	484	Cont - Multi	82	0.09	20.4
--------------------------Clear Creek ------------------------					
	Growth		**Response**		
Treatment	**Cu/ft/ac.**	**Contrast**	**Cu/ft/ac.**	***p***	**%**
---------------------- Gross Volume ----------------------					
Control	281				
Multi-nutrient	357	Cont - Multi	76	0.01	27.0
------------------------- Net Volume ------------------------					
Control	281				
Multi-Nutrient	357	Cont - Multi	76	0.01	27.0
-------------------------- Noregaard ------------------------					
	Growth		**Response**		
Treatment	**Cu/ft/ac.**	**Contrast**	**Cu/ft/ac.**	***P***	**%**
------------------- Gross Volume -----------------					
Control	557				
Multi-nutrient	600	Cont - Multi	43	0.54	7.7
------------------------- Net Volume -----------------------					
Control	531				
Multi-Nutrient	601	Cont - Multi	70	0.49	13.2

Table 12. Combined and individual four-year average relative gross and net volume growth response for Clear Creek and Noregaard multi-nutrient fertilization test sites in northeast Oregon.

--------------------------- Overall Volume -------------------------					
	Growth		**Response**		
Treatment	**% of Initial Volume**	**Contrast**	**Difference**	***p***	**% Difference**
---------------------------- Gross Volume ------------------------					
Control	134				
Multi-nutrient	170	Cont - Multi	36	0.03	26.9
------------------------- Net Volume ---------------------------					
Control	133				
Multi-Nutrient	170	Cont - Multi	37	0.02	27.8
---------------------------Clear Creek ------------------------					
	Growth		**Response**		
Treatment	**% of Initial Volume**	**Contrast**	**Difference**	***p***	**% Difference**
------------------------ Gross Volume ----------------------					
Control	193				
Multi-nutrient	259	Cont - Multi	66	0.01	34.2
------------------------- Net Volume ---------------------------					
Control	193				
Multi-Nutrient	259	Cont - Multi	66	0.01	34.2
---------------------------Noregaard ------------------------					
	Growth		**Response**		
Treatment	**% of Initial Volume**	**Contrast**	**Difference**	***p***	**% Difference**
-------------------------- Gross Volume ----------------------					
Control	76				
Multi-nutrient	79	Cont- Multi	3.0	0.81	3.9
------------------------- Net Volume ---------------------------					
Control	73				
Multi-Nutrient	80	Cont - Multi	7.0	0.70	9.6

Table 13. Average periodic absolute gross and net basal area growth response for both the Clear Creek and Noregaard multi-nutrient fertilization test sites combined in northeast Oregon.

	Growth		Response		
Treatment	**Sq/ft/ac.**	**Contrast**	**sq/ft/ac.**	***p***	**%**
Gross Basal Area					
---------------------------1st Two Years -------------------------					
Control	10.2				
Multi-nutrient	12.8	Cont - Multi	2.6	0.01	25.5
------------------------- 2nd Two Years ----------------------------					
Control	12.9				
Multi-Nutrient	15.0	Cont - Multi	2.1	0.13	16.3
Net Basal Area					
---------------------------1st Two Years -------------------------					
Control	10.2				
Multi-nutrient	12.8	Cont - Multi	2.6	0.01	25.5
------------------------- 2nd Two Years ----------------------------					
Control	12.0				
Multi-Nutrient	15.0	Cont - Multi	3.0	0.11	25.0

Table 14. Average periodic absolute gross and net basal area growth response for Clear Creek multi-nutrient fertilization test site combined in northeast Oregon.

	Growth		Response		
Treatment	**% of Initial Basal Area**	**Contrast**	**Difference**	***p***	**% Difference**
Gross Basal Area					
----------------------------1st Two Years -------------------------					
Control	10.4				
Multi-nutrient	13.4	Cont - Multi	3.0	0.01	28.8
--------------------------2nd Two Years ----------------------------					
Control	12.3				
Multi-Nutrient	16.7	Cont - Multi	4.4	0.01	35.8
Net Basal Area					
----------------------------1st Two Years -------------------------					
Control	10.4				
Multi-nutrient	13.4	Cont - Multi	3.0	0.01	28.8
--------------------------2nd Two Years ----------------------------					
Control	12.3				
Multi-Nutrient	16.7	Cont - Multi	4.4	0.01	35.8

Table 15. Average periodic absolute gross and net basal area growth response for Noregaard multi-nutrient fertilization test site in northeast Oregon.

	Growth		Response		
Treatment	**% of Initial Basal Area**	**Contrast**	**Difference**	***p***	**% Difference**
		Gross Basal Area			
		---------------------------1st Two Years -------------------------			
Control	10.1				
Multi-nutrient	12.0	Cont - Multi	1.9	0.22	18.8
		--------------------------2nd Two Years ----------------------------			
Control	13.7				
Multi-Nutrient	13.0	Cont - Multi	-0.7	0.75	-5.1
		Net Basal Area			
		---------------------------1st Two Years -------------------------			
Control	10.1				
Multi-nutrient	12.0	Cont - Multi	1.9	0.22	18.8
		--------------------------2nd Two Years ----------------------------			
Control	11.9				
Multi-Nutrient	13.1	Cont - Multi	1.2	0.77	10.1

Table 16. Average periodic relative gross and net basal area growth response for Clear Creek and Noregaard multi-nutrient fertilization test sites combined in northeast Oregon.

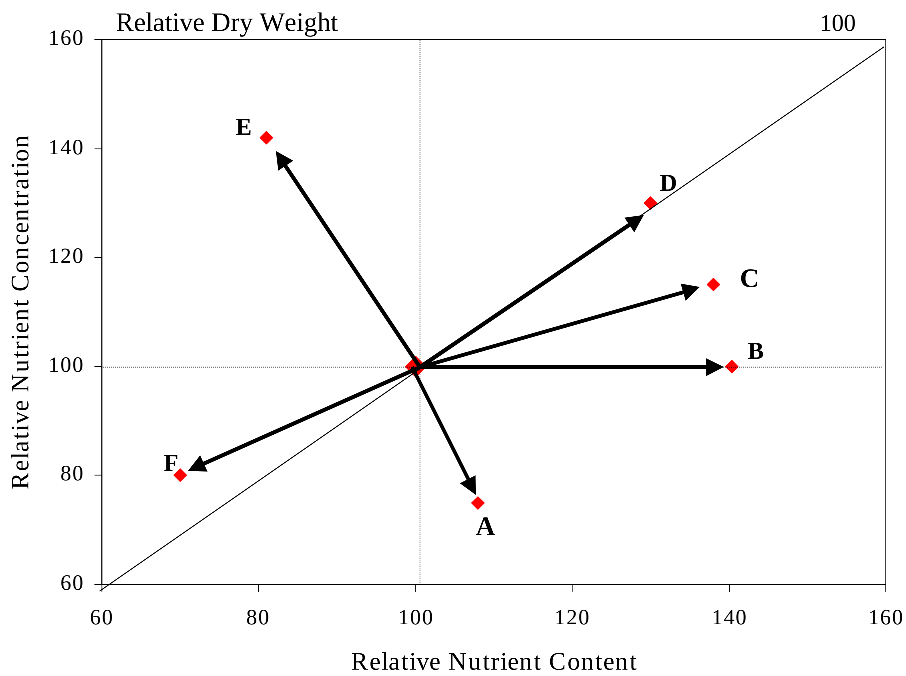
	Growth		**Response**		
Treatment	**% of Initial Basal Area**	**Contrast**	**Difference**	***p***	**% Difference**
Gross Basal Area					
---------------------------1st Two Years -------------------------					
Control	32.0				
Multi-nutrient	40.6	Cont - Multi	8.6	0.01	26.9
-------------------------2nd Two Years ---------------------------					
Control	28.8				
Multi-Nutrient	32.7	Cont - Multi	3.2	0.11	11.1
Net Basal Area					
---------------------------1st Two Years -------------------------					
Control	32.0				
Multi-nutrient	40.6	Cont - Multi	8.6	0.01	26.9
-------------------------2nd Two Years ---------------------------					
Control	27.5				
Multi-Nutrient	32.7	Cont - Multi	5.2	0.08	18.9

Table 17. Average periodic relative gross and net basal area growth response for Clear Creek multiti-nutrient fertilization test site in northeast Oregon.

	Growth		Response		
Treatment	**% of Initial Basal Area**	**Contrast**	**Difference**	***p***	**% Difference**
Gross Basal Area					
---------------------------1st Two Years -------------------------					
Control	43.5				
Multi-nutrient	57.4	Cont - Multi	13.9	0.01	32.0
-------------------------2nd Two Years ----------------------------					
Control	39.3				
Multi-Nutrient	48.4	Cont - Multi	9.1	0.02	23.0
Net Basal Area					
---------------------------1st Two Years -------------------------					
Control	43.5				
Multi-nutrient	57.4	Cont - Multi	13.9	0.01	32.0
-------------------------2nd Two Years ----------------------------					
Control	39.3				
Multi-Nutrient	48.4	Cont - Multi	9.1	0.02	23.0

Table 18. Average periodic relative gross and net basal area growth response for Noregaard multiti-nutrient fertilization test site in northeast Oregon.

	Growth		Response		
Treatment	**% of Initial Basal Area**	**Contrast**	**Difference**	***p***	**% Difference**
		Gross Basal Area			
		---------------------------1st Two Years -------------------------			
Control	17.7				
Multi-nutrient	21.0	Cont - Multi	3.3	0.17	18.6
		-------------------------2nd Two Years ----------------------------			
Control	21.5				
Multi-Nutrient	20.1	Cont - Multi	-1.4	0.49	-6.5
		Net Basal Area			
		---------------------------1st Two Years -------------------------			
Control	17.7				
Multi-nutrient	21.0	Cont - Multi	3.3	0.17	18.6
		-------------------------2nd Two Years ----------------------------			
Control	18.0				
Multi-Nutrient	19.2	Cont - Multi	1.2	0.75	6.7



Nutrient (%)	**Nutrient Content**	**Needle Weight**	**Shift**	**Nutrient Status**	**Diagnosis**
-	+/-	+	A	Dilution	Non-Limiting
-	0	+	A	Dilution	Non-Limiting
-	-	0	A	Dilution	Non-Limiting
0	+	+	B	Unchanged	Non-Limiting
+	+	+	C	Deficiency	Limiting
+	+	0	D	Luxury	Non-toxic
+	+/-	-	E	Excess	Toxic
+	0	-	E	Excess	Toxic
0	-	-	E/F	Excess	Toxic/Antagonistic
-	-	-	F	Excess	Antagonistic

Figure 1. Schematic relationship between nutrient concentration, nutrient content and dry weight of needles following fertilization.

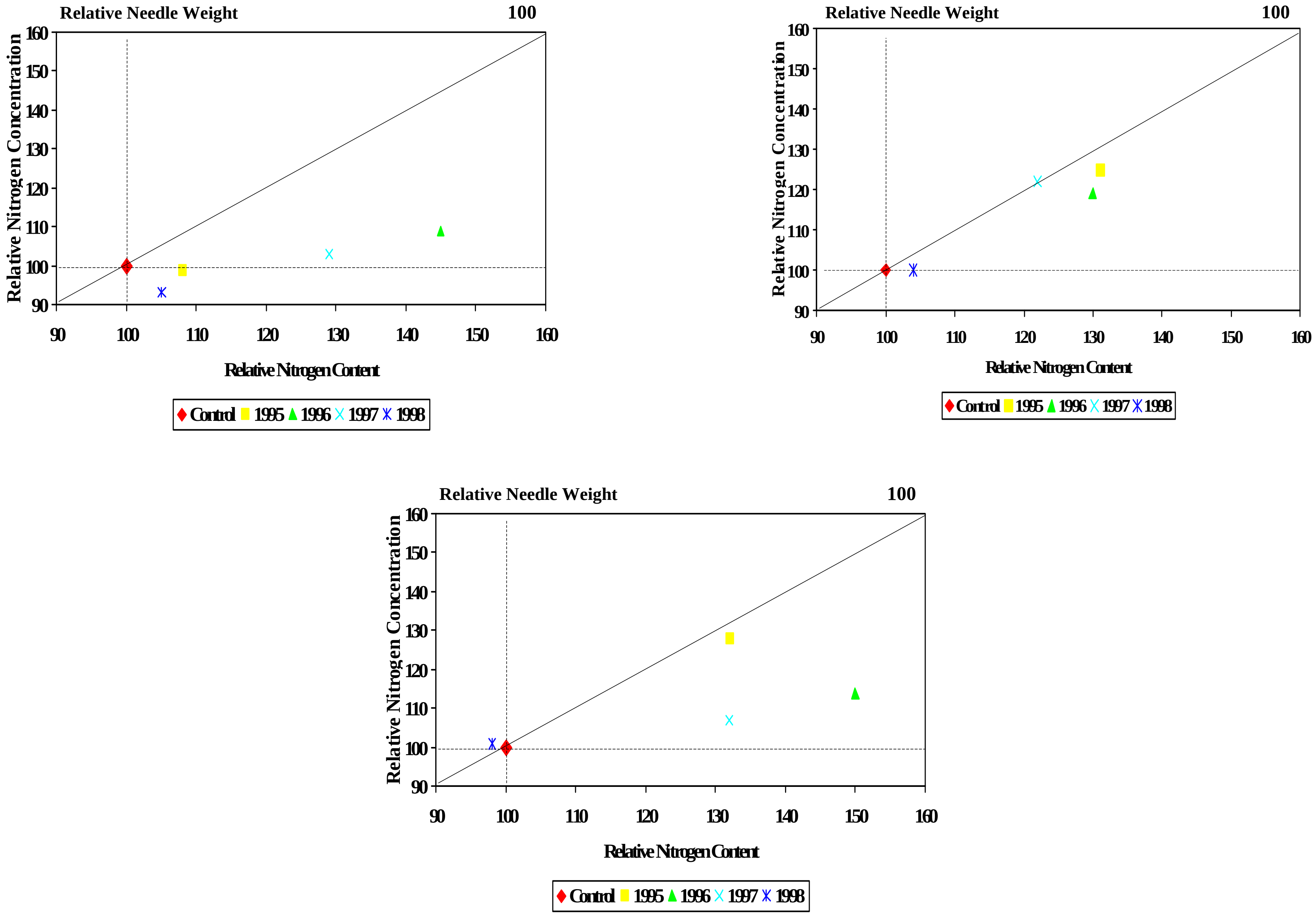


Figure 2. Douglas-fir (a), grand fir (b) and ponderosa pine (c) nitrogen vector shifts by year for the Noregaard and Clear Creek operational fertilization test sites in northeast Oregon.

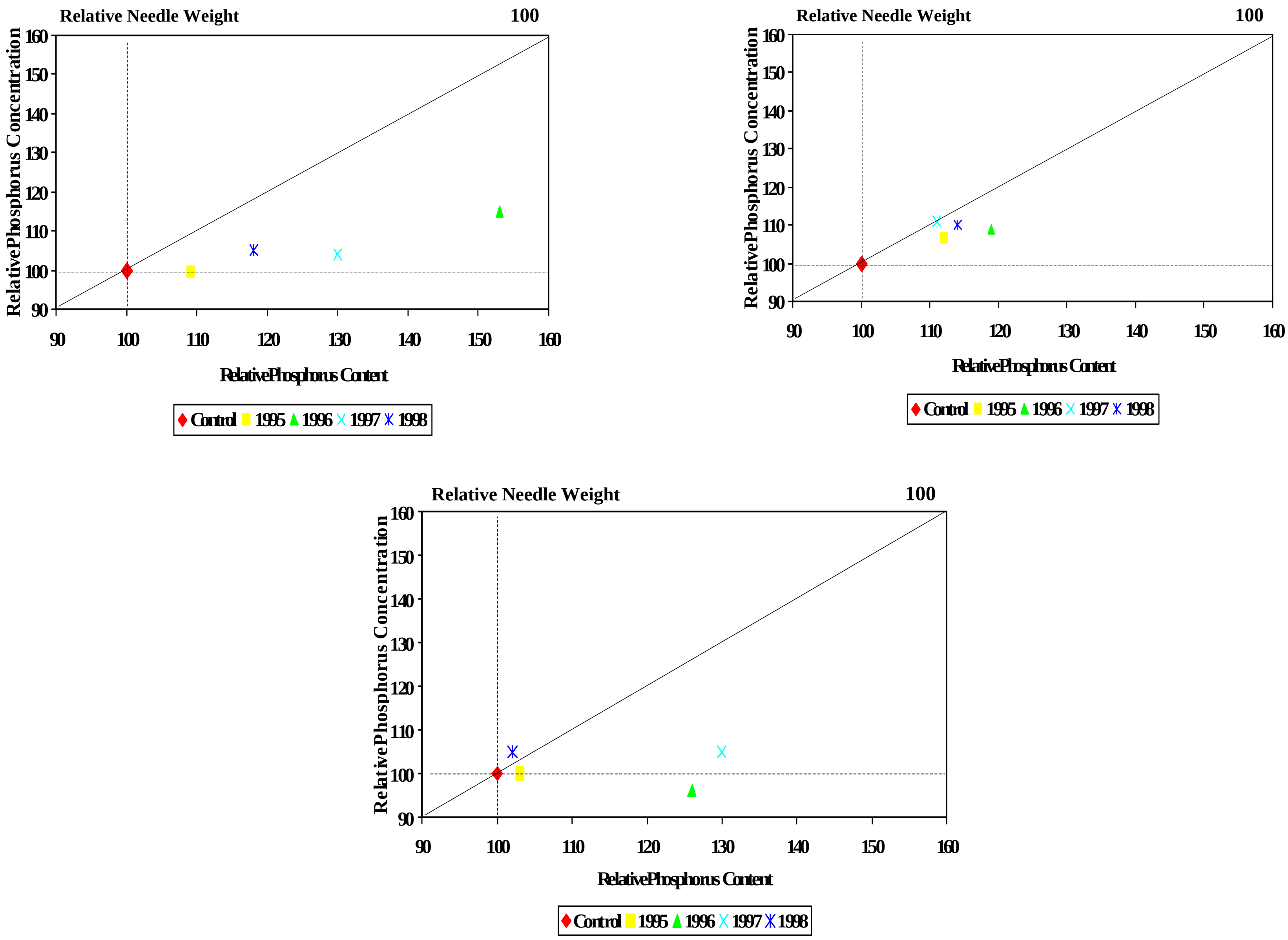


Figure 3. Douglas-fir (a), grand fir (b) and ponderosa pine (c) phosphorus vector shifts by year for the Noregaard and Clear Creek operational fertilization test sites in northeast Oregon.

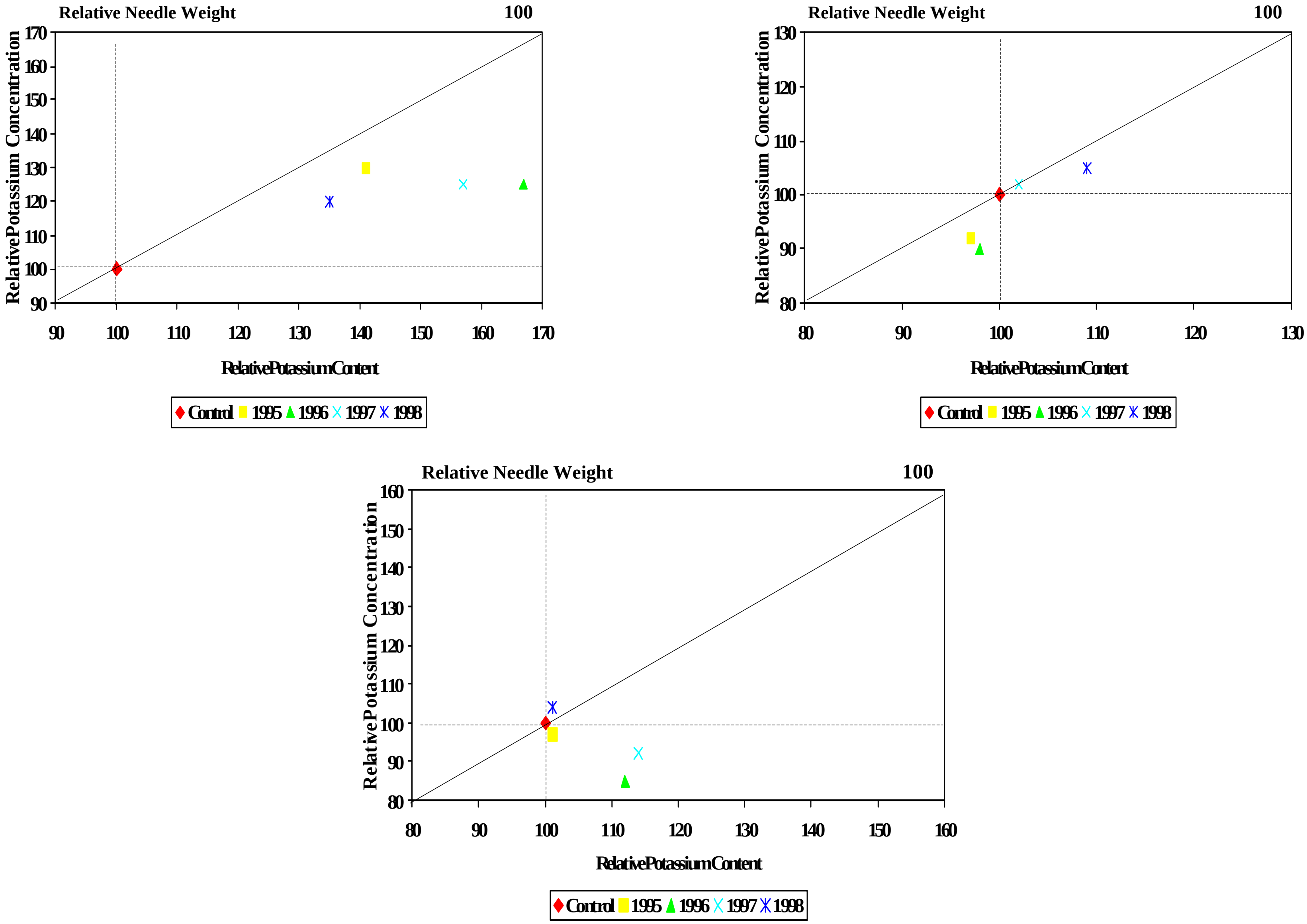


Figure 4. Douglas-fir (a), grand fir (b) and ponderosa pine (c) potassium vector shifts by year for the Noregaard and Clear Creek operational fertilization test sites in northeast Oregon.

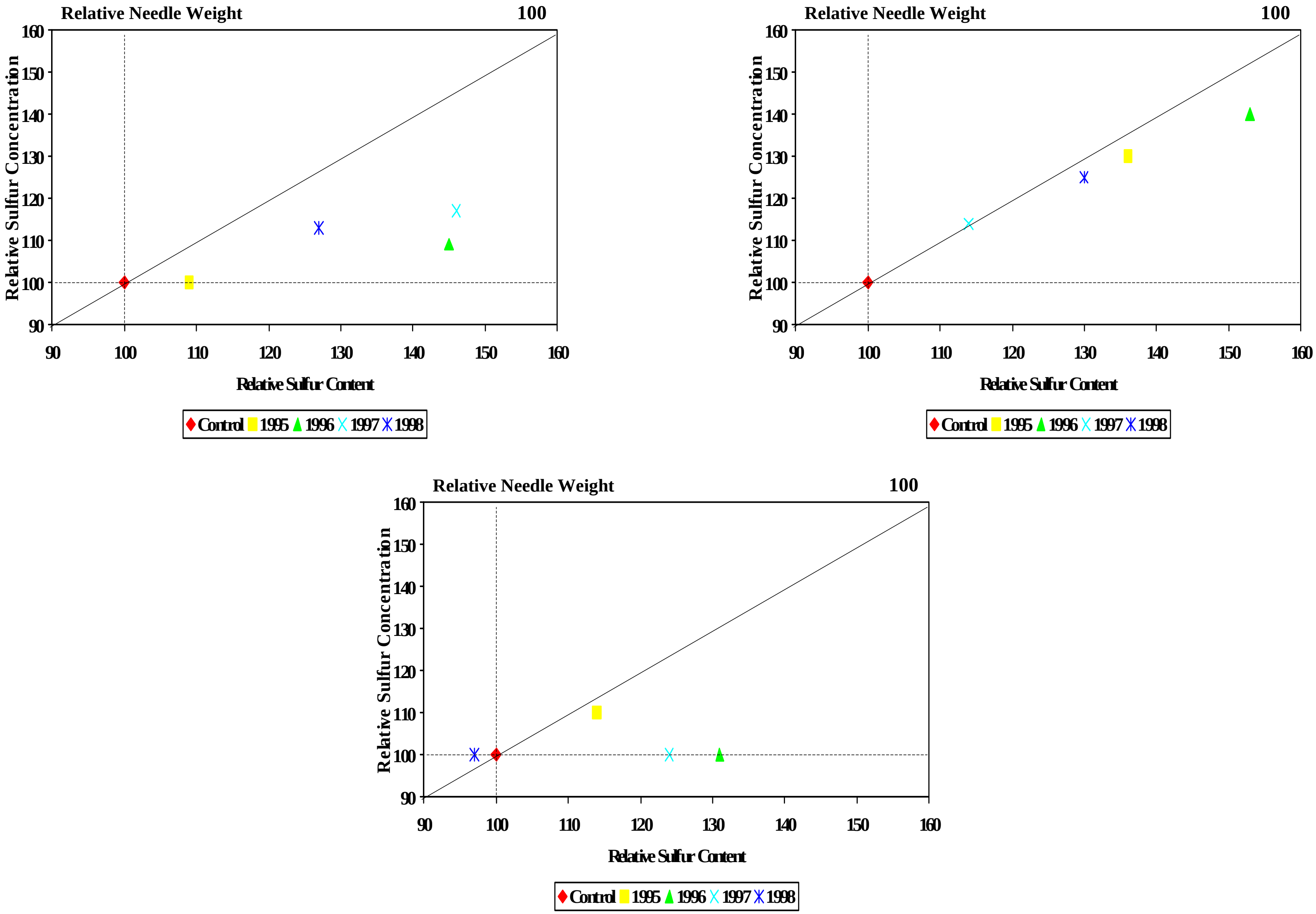


Figure 5. Douglas-fir (a), grand fir (b) and ponderosa pine (c) sulfur vector shifts by year for the Noregaard and Clear Creek operational fertilization test sites in northeast Oregon.

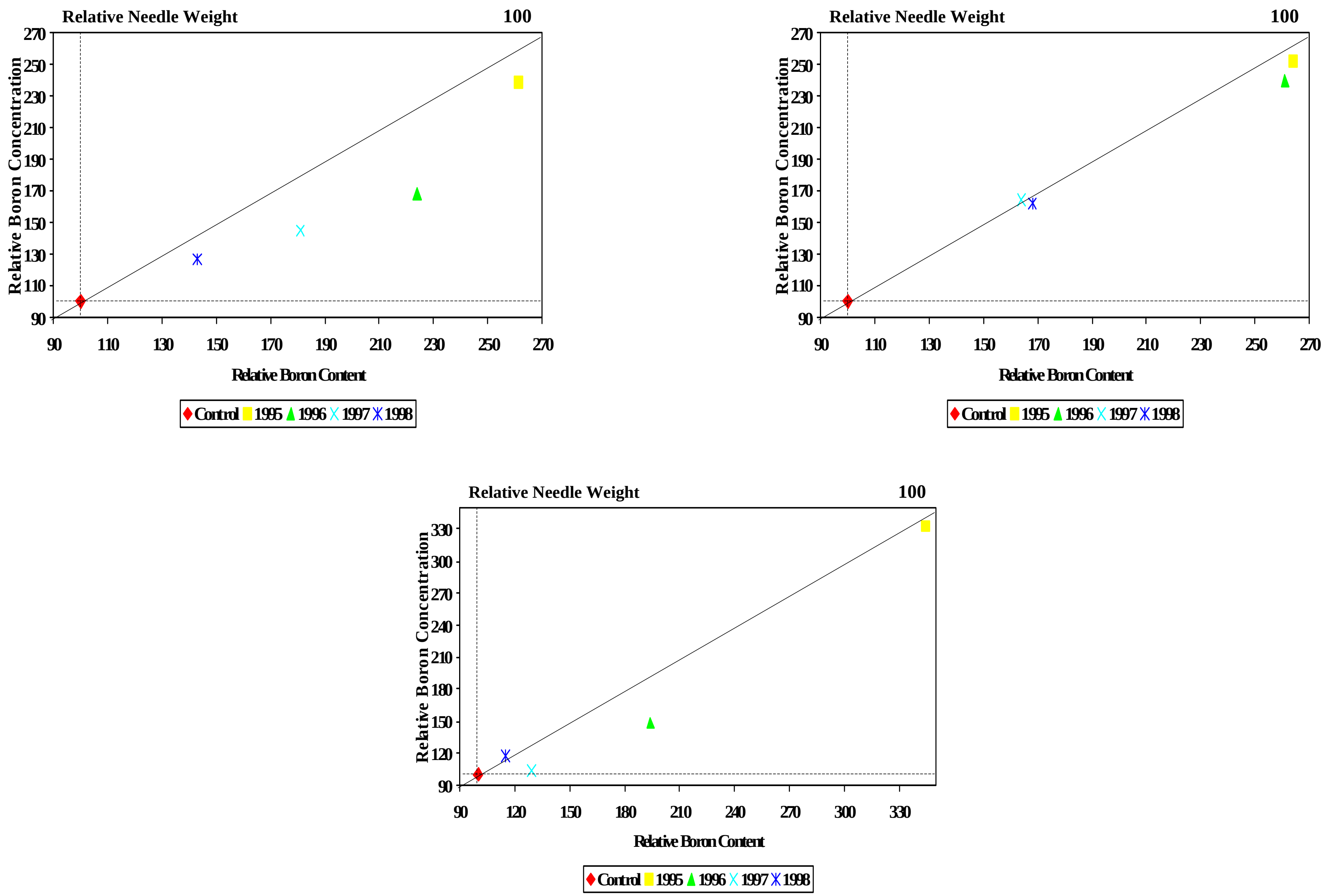


Figure 6. Douglas-fir (a), grand fir (b) and ponderosa pine (c) boron vector shifts by year for the Noregaard and Clear Creek operational fertilization test sites in northeast Oregon.

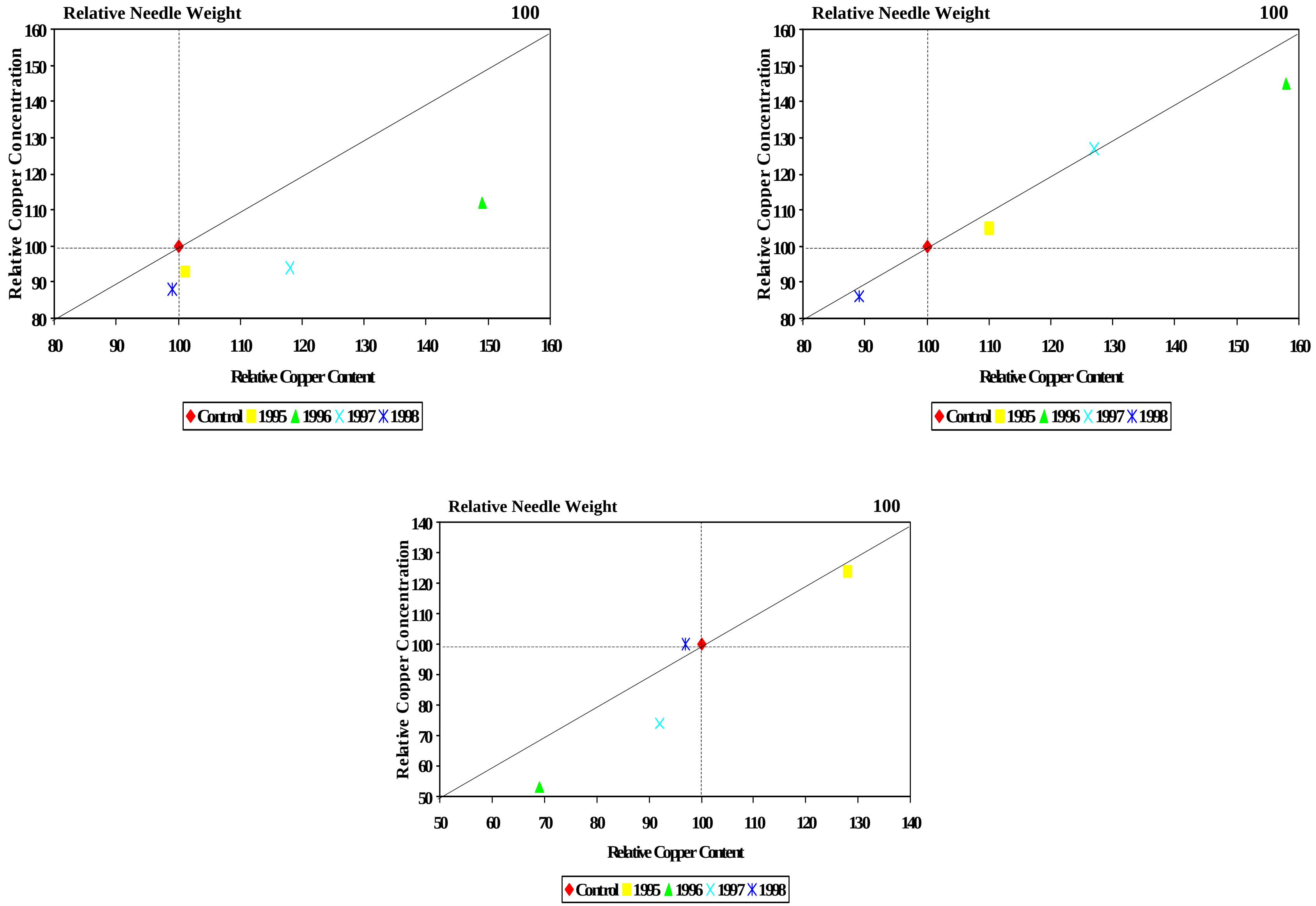


Figure 7. Douglas-fir (a), grand fir (b) and ponderosa pine (c) copper vector shifts by year for the Noregaard and Clear Creek operational fertilization test sites in northeast Oregon.

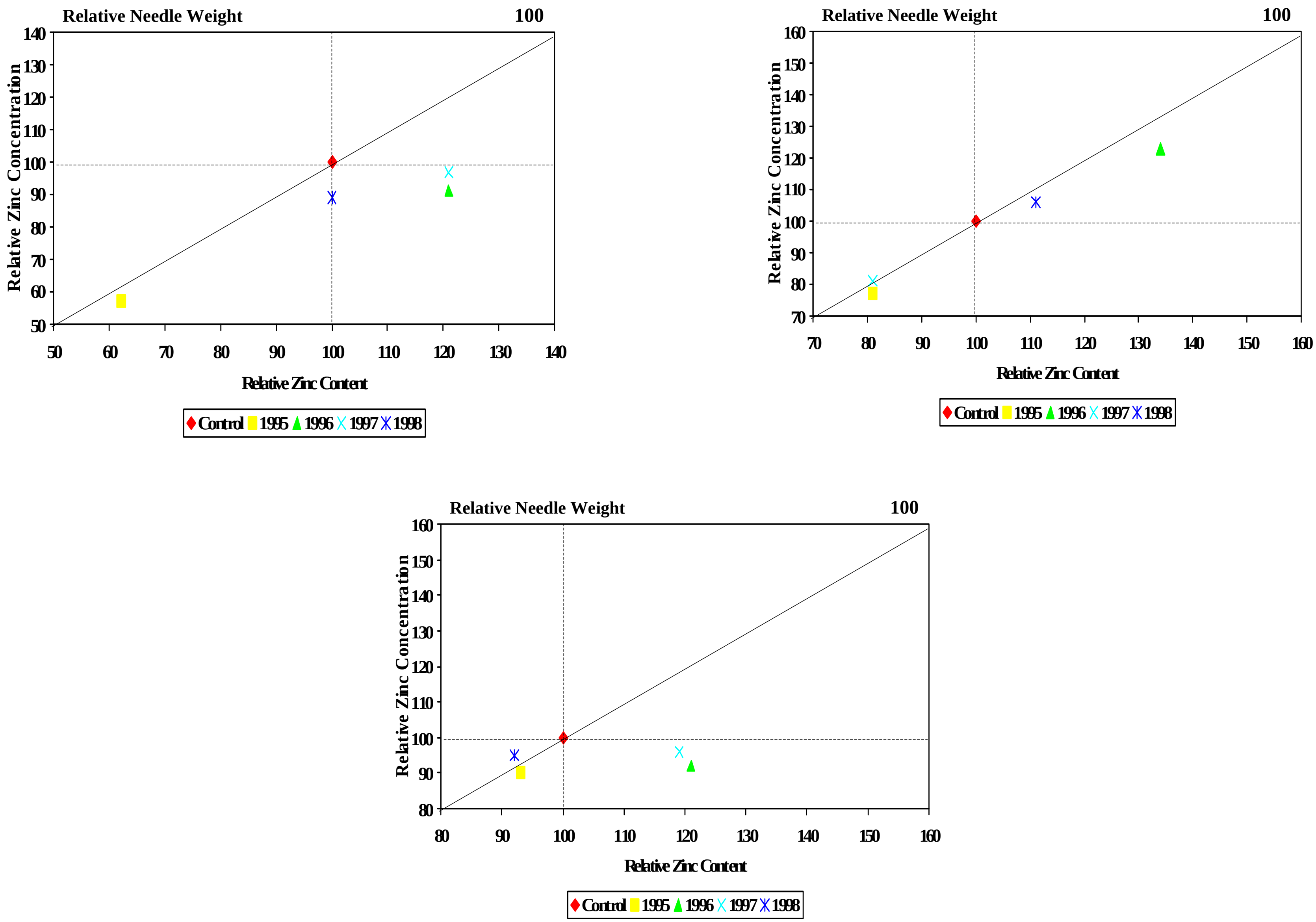


Figure 8. Douglas-fir (a), grand fir (b) and ponderosa pine (c) zinc vector shifts by year for the Noregaard and Clear Creek operational fertilization test sites in northeast Oregon.

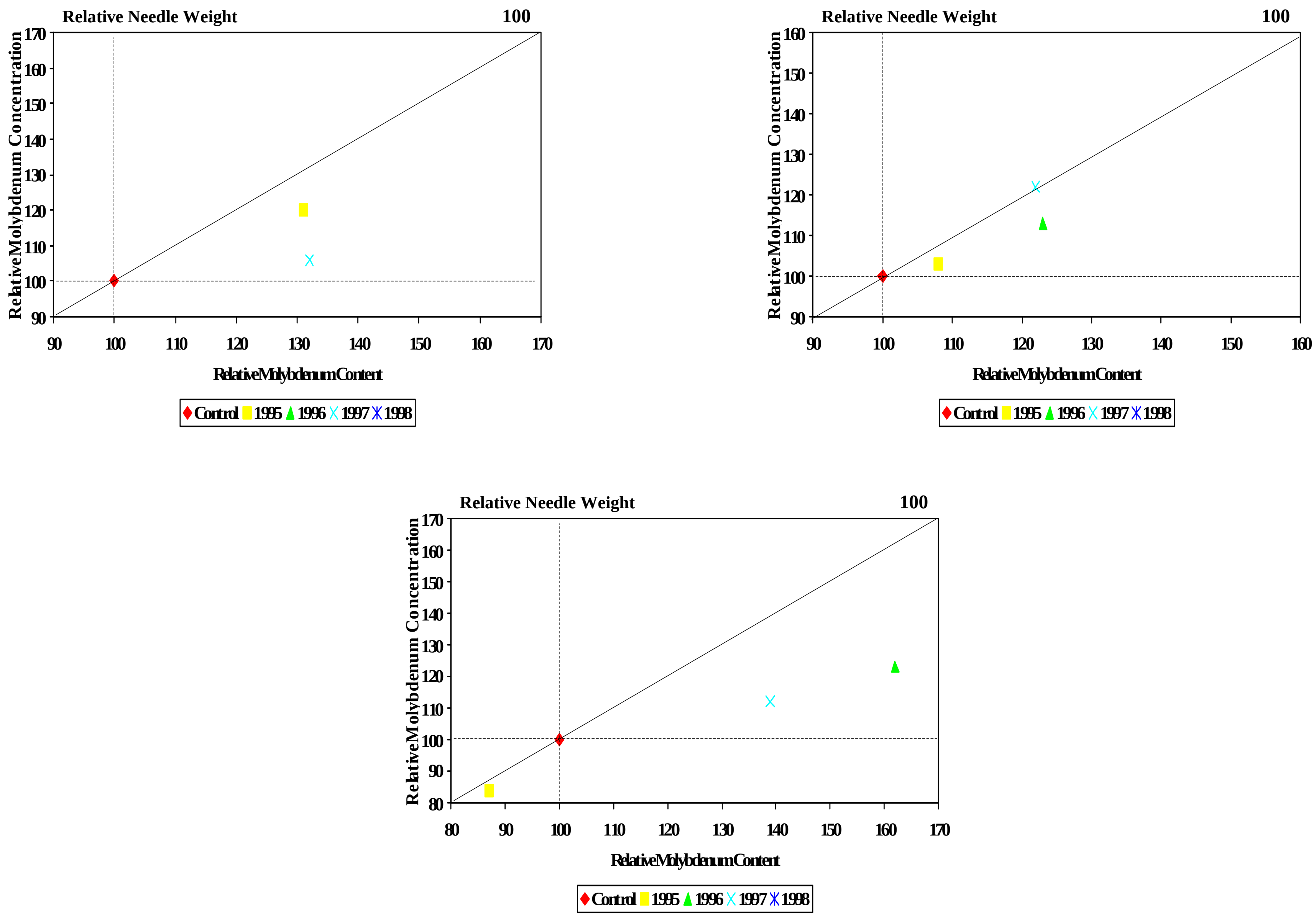


Figure 9. Douglas-fir (a), grand fir (b) and ponderosa pine (c) molybdenum vector shifts by year for the Noregaard and Clear Creek operational fertilization test sites in northeast Oregon.