Poster paper

FOLIAR POTASSIUM STATUS EXPLAINS DOUGLAS FIR RESPONSE TO NITROGEN FERTILIZATION IN THE INLAND NORTHWEST, USA

Peter G. Mika and James A. Moore

Department of Forest Resources
University of Idaho
Moscow, Idaho 83843 USA

Abstract. Despite apparently inadequate N levels throughout the Inland Northwest of the United States, trees on some sites showed no increased growth 6 yr after N fertilization. Nor did higher N application rates consistently produce higher response. These facts indicated that other factors are limiting tree growth at these sites. Results suggest that K status is one important factor, influencing N fertilization response in the following general ways: (1) for stands with low pre-treatment foliar K levels, the amount and duration of growth response are reduced, and higher N fertilizer rates produce less response; and (2) for all stands, growth response declines when foliar K decreases after N fertilization.

1. Introduction

In 1980, a group of forestry organizations formed the Intermountain Forest Tree Nutrition Cooperative (IFTNC) to study forest tree nutrition in the Inland Northwest region of the United States. Initial efforts were concentrated on studying the effect of N fertilization on growth and survival of Rocky Mountain Douglas fir (*Pseudotsuga menziesii* var. *glauca* [Beissn.] Franco).

The IFTNC subsequently established a series of N fertilizer trials throughout the area. As expected, N fertilization increased tree growth; after 6 yr, gross basal area and total volume growth were greater on plots treated with N than on untreated plots. Additionally, growth increased with an increasing rate of N application (Moore *et al.*, 1989). However, two results indicated that other factors might be limiting tree response to N fertilization: (1) for a substantial number of trials, growth on treated plots was less than growth on untreated plots; and (2) increasing N dosage often did not increase growth. While these results might be attributed to normal variation in response, the non-responding trials were more prevalent in certain regions, indicating that other factors limiting tree response to N fertilization might be identified.

Other foliar nutrient concentrations (P, K, Ca, Mg, Mn, Zn, Fe, B and Cu) were examined; of these, only K was present at levels thought to be limiting to tree growth. In this paper we present evidence that low K levels, either naturally occurring or induced by additions of N, are related to poor N fertilization response.

2. Methods

2.1 Study area, population and design

The Inland Northwest region shown on the map in Figure 1 is a large, ecologically diverse area stretching from the eastern slopes of the

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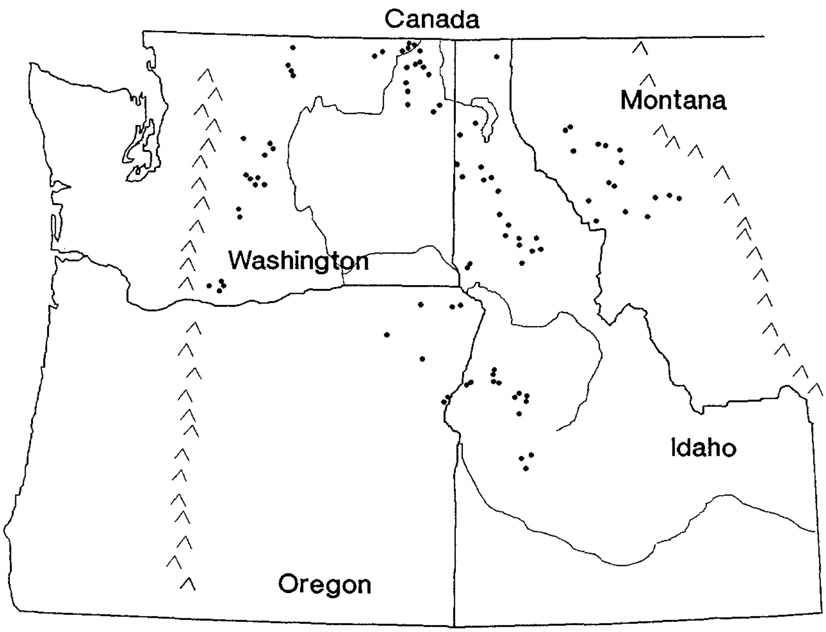


Figure 1. The Inland Northwest region. Points on the map indicate the location of the 94 Douglas fir fertilizer installations established by the Intermountain Forest Tree Nutrition Cooperative.

Cascade Mountains in Washington to the western slopes of the Rocky Mountains in Montana and from the Canadian border in the north to the Snake River plain in southern Idaho. Forested areas are generally limited to the several north-south trending mountain systems. The region has an inland climate strongly influenced by moist air from the north Pacific Ocean, producing mild, cloudy weather for much of the year. Precipitation, generally snow, falls mostly from November to June while summers, particularly July and August, are droughty. Precipitation tends to decrease from west to east and from north to south.

The mountain masses are formed of a variety of igneous, sedimentary and metamorphic rock. Continental and alpine glaciation have helped shape the region and aeolian deposits of loess and volcanic ash are prevalent in certain areas (Daubenmire and Daubenmire, 1968; Franklin and Dyrness, 1973).

From 1980 to 1982 the IFTNC established 94 N fertilizer trials, termed installations, across the study area. By design, these installations fall in 6 geographic regions: central Washington, northeast Washington, north Idaho, western Montana, central Idaho, and northeast Oregon. The distribution of installations is shown in Figure 1. Installations were located in second-growth, even-aged, managed Douglas fir stands. Most stands had been thinned 5 to 12 yr previously; other stands were unthinned, but naturally well-spaced.

Stands were selected to cover a range of stand densities, tree ages and sizes, and site productivities (Table I). The stands are dominated

Table I

Averages and ranges for site and stand conditions across the 94 fertilizer installations at the initiation of the experiment.

	Mean	Minimum	Maximum
Elevation (m)	1090	450	1800
DF site index* (m @ 50 yr)	20.9	12.4	29.4
Basal area in DF (%)	87.3	27.7	100.0
Age (yr)	65	27	100
Mean diameter (cm)	26.1	15.6	42.5
Basal area (m^2 ha^{-1})	32.3	11.0	62.5
Total volume (m^3 ha^{-1})	258	52	582

* Monserud (1984)

by Douglas fir, but other species contributing substantial basal area include ponderosa pine (*Pinus ponderosa* Dougl.), lodgepole pine (*P. contorta* Dougl.), western larch (*Larix occidentalis* Nutt.), and grand fir (*Abies grandis* [Dougl.] Forbes).

An installation consists of 6 rectangular plots from 0.04 to 0.08 ha in size, each containing at least 10 Douglas fir sample trees. Plots were selected to minimize among-plot variation in terrain, vegetation composition, tree stocking, and tree size. Three fertilizer treatments, 0, 225, and 450 kg N ha^{-1}, were randomly assigned to the plots. Nitrogen in the form of urea was applied in the late fall, utilizing hand-held spreaders. To minimize edge effects, a treated buffer strip surrounds all fertilized plots.

2.2 Data collection and compilation

All live plot trees were tagged and measured for heights and diameters at the time of treatment. Every 2 yr, diameters have been remeasured on all trees and any incidence of damage or mortality has been noted. Heights were remeasured 4 yr after treatment on all trees; at 6 yr, heights were measured on a stratified random sample of plot trees. Six yr heights for unmeasured trees were estimated using plot-specific regression equations for 6 yr height based on 4 yr height and 6 yr diameter growth. Tree volumes were calculated using regional species-specific volume equations (Wykoff *et al.*, 1982). Basal areas and total volumes were summed over all trees to obtain plot totals.

One yr after treatment, dormant season foliage samples were obtained from 2 dominant or co-dominant Douglas fir trees on each plot on 85 installations (12 per installation, 1020 total). Foliage was collected from the third whorl from the top of each tree by climbing. Current season foliage was clipped, placed in plastic bags, and stored in ice-cooled containers while in the field. In the laboratory, samples were stored at -18°C until they could be dried. Shoots were oven-dried at 70°C for 24 hr, needles were separated from stems, and removed needles were redried at 70°C for an additional 24 hr before weighing. For each tree, 5 replications of 100 needles each were weighed to determine average needle weight. Foliage was ground in a Wiley mill in preparation for chemical analysis.

Foliar N levels were determined using a micro-Kjeldahl procedure (Bremner and Mulvaney, 1982). Needles were digested with H_2SO_4 and the digestate was distilled with steam. Total N concentration was recorded as a percentage per unit of dry needle weight. Phosphorus concentration was estimated using a Technicon Auto Analyzer II following digestion in H_2SO_4 (Black, 1965; US-EPA, 1979). Estimates of concentration for all other elements (K, Ca, Mg, Mn, Zn, Fe, B and Cu) were obtained using a DC-argon plasma emission spectrometer following perchloric acid digestion (Blanchar *et al.*, 1965; Sommers and Nelson, 1972). Foliar nutrient content was calculated using the information on average needle weight and nutrient concentration.

2.3 Statistical analysis

Fertilizer effects on total plot tree growth were estimated using a split-plot analysis of covariance model; in this study, whole plots correspond to installations and split plots are fertilizer treatment plots. The particular model fit was (after Federer, 1955):

$$Y_{ijk} = \mu + R_i + \beta_1 X_{ij.} + \beta_2 X^2_{ij.} + I_{j(i)} + F_k + RF_{ik} + \beta_3 X_{ijk} + \beta_4 X^2_{ijk} + \beta_3 F_k X_{ijk} + \beta_4 F_k X^2_{ijk} + e_{ijk} \quad (1)$$

where Y_{ijk} is the 6 yr growth for the split plot (*i.e.* the kth fertilizer treatment in the jth installation within the ith region), μ is the overall mean effect, R_i is the effect due to the ith region, $I_{j(i)}$ is a whole-plot random effect due to the jth installation within the ith region, F_k is the split-plot effect due to the kth fertilizer treatment, RF_{ik} is the interaction effect between region and fertilizer, X_{ijk} is the basal area per ha at the start of the experiment for the split plot, $X_{ij.}$ is the installation (whole-plot) initial basal area per ha, β_1 and β_2 are regression coefficients for the whole-plot regression of growth on initial basal area, β_3 and β_4 are regression coefficients for the split-plot regression of growth on initial basal area, $\beta_3 F_k$ and $\beta_4 F_k$ are regression coefficients for the split-plot regression of growth on the interaction of fertilizer treatment with initial basal area, and e_{ijk} is a random split-plot error effect.

Regression coefficients obtained by fitting Equation (1) were used to adjust treatment plot growth rates for within-installation differences in initial basal area per ha. Growth response to fertilization was then calculated by subtracting adjusted growth on control plots from similar growth on fertilized plots. These adjusted fertilizer response rates were used in subsequent analysis. Standard analyses of variance techniques were employed to examine relationships between fertilizer response and foliar nutrient levels. Parameter estimates and adjusted means were obtained using the general linear models procedure (PROC GLM) of the Statistical Analysis System (SAS Institute, Inc., 1985).

3. Results and Discussion

3.1 Evidence of other growth limitations

The fertilizer treatments were successful in getting additional N into the trees. Figure 2 shows the average foliar N concentrations (percentage by weight) of dormant season foliage 1 yr after treatment for the various region and treatment combinations. Nitrogen fertilization produced consistent dosage-dependent increases in foliar N across all regions. The horizontal lines at 1.6 and 1.4% concentrations represent marginal and inadequate thresholds, respectively, found by Webster and Dobkowski (1983) for coastal Douglas fir (*Pseudotsuga menziesii* var. *menziesii* [Mirb.] Franco).

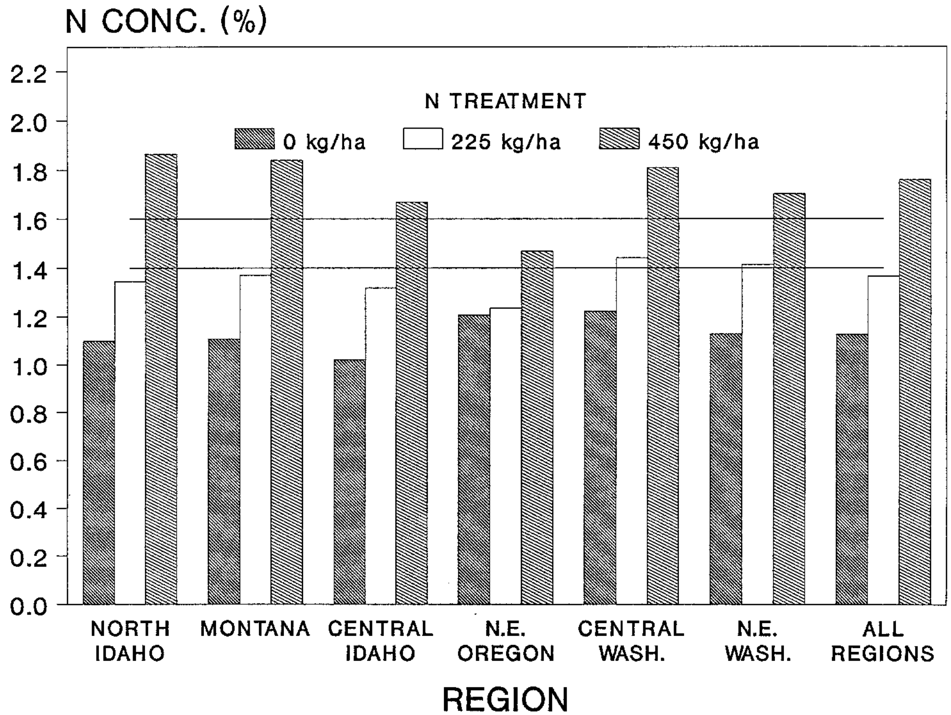


Figure 2. Average dormant season foliar N concentrations (percent by weight) for the various combinations of geographic region and fertilizer treatment. The horizontal lines at 1.4 and 1.6% represent inadequate and marginal thresholds, respectively, for Douglas fir growth (Webster and Dobkowski, 1983).

Trees with foliar N concentrations between marginal and inadequate thresholds can be expected to show growth reductions of 5 to 15% while trees with concentrations less than 1.4% should show reductions of more than 15%, assuming that N was the sole factor limiting growth. Based on these thresholds, untreated trees in all regions had inadequate average N concentrations. Addition of 225 kg N ha^{-1} increased foliar N levels, but only to levels still thought to be marginal for tree growth. Concentrations reached adequate levels only after addition of 450 kg N ha^{-1}. Thus, we would expect to see substantial tree growth gains for additions of 225 kg N ha^{-1} and even greater increases from 450 kg ha^{-1} fertilizer rates.

Analysis of growth data for the 6 yr following treatment shows that trees do respond to N fertilization. Average gross basal area increments for the various combinations of geographic region and fertilizer treatment are shown in Table II. Patterns are similar for gross volume growth and change in average stand diameter. Values have been adjusted to a common initial basal area of 35 m^2 ha^{-1} using Equation (1). The table also includes estimates of differences between treatments and significance levels for tests that those differences are zero. Growth differences between treated and control plots are considered to be fertilizer response.

In all regions fertilized trees grew more on the average than unfertilized trees: across all regions, growth increased by 17.6% and 24.5% on plots fertilized with 225 kg ha^{-1} and 450 kg ha^{-1} of N, respectively. Additionally, trees on 450 kg ha^{-1} plots grew more than those on 225 kg ha^{-1} plots, but not consistently across all regions. In northern Idaho and central Washington the higher N rate increased growth significantly, but significant increases were not obtained in any other region. Some other factor was preventing trees in these other regions from fully benefiting from the additional N.

For example, the control plot growth rates in Table II show central Idaho to be a region of intermediate productivity. As shown in Figure 2, the average control plot N concentration for this region is only 1.02%, lowest of any region and obviously inadequate. Nitrogen fertilization successfully raised foliar N levels to 1.32% for the 225 kg ha^{-1} treatment and 1.67% for the 450 kg ha^{-1} treatment, only the latter being above the inadequate zone. Based on this, the region should show excellent response to the low fertilizer rate and much larger response to the higher rate of application, if N were the sole limiting factor. Yet relative (percent) response is the lowest of any region and the growth differential between fertilizer treatments is almost zero (Table II).

Moisture is considered the primary factor limiting tree growth in the Inland Northwest (Haig *et al.*, 1941). Control plot growth rates shown in Table II substantiate this: best growth is attained in northern Idaho, the region with greatest precipitation, while Montana, the driest area, produces the lowest growth rates. However, differences in available moisture do not seem to explain the differential fertilization response among regions. While northern Idaho does show large response to N fertilization and significant additional response to the higher N rate, response obtained in central Washington is similar despite the latter region showing only average control plot growth rates. Conversely, northeast Washington, a region with fairly high control plot growth, shows only half the fertilization response of central Washington and little additional response to the higher N rate.

Table II

Average 6 yr gross basal area growth and response by geographic region and fertilizer treatment. Estimates have been adjusted to a common initial basal area of 35 m^2 ha^{-1} using Equation (1). Values in parentheses are significance levels for tests that the treatment contrasts are equal to zero.

Region	Treatment (kg N ha^{-1})	Growth (m^2 ha^{-1})	Contrast	Response (m^2 ha^{-1})	Response Percent
Northern	0	7.72			
Idaho	225	9.21	225 - 0	1.49 (.001)	19.4
	450	10.02	450 - 0	2.30 (.001)	29.8
			450 - 225	0.81 (.001)	8.8
Northeast	0	6.10			
Washington	225	6.95	225 - 0	0.85 (.001)	13.9
	450	7.06	450 - 0	0.96 (.001)	15.7
			450 - 225	0.11 (.617)	1.6
Central	0	5.84			
Idaho	225	6.59	225 - 0	0.76 (.003)	12.9
	450	6.73	450 - 0	0.89 (.001)	15.3
			450 - 225	0.14 (.588)	2.1
Central	0	5.58			
Washington	225	7.01	225 - 0	1.43 (.001)	25.6
	450	7.84	450 - 0	2.26 (.001)	40.5
			450 - 225	0.83 (.001)	11.9
Northeast	0	4.64			
Oregon	225	5.26	225 - 0	0.62 (.044)	13.3
	450	5.48	450 - 0	0.84 (.011)	18.0
			450 - 225	0.22 (.504)	4.1
Montana	0	4.26			
	225	4.93	225 - 0	0.66 (.003)	15.5
	450	4.96	450 - 0	0.69 (.002)	16.3
			450 - 225	0.03 (.888)	0.6
All Regions	0	5.83			
	225	6.86	225 - 0	1.03 (.001)	17.6
	450	7.26	450 - 0	1.43 (.001)	24.5
			450 - 225	0.40 (.001)	5.8

The relative growth response to fertilization of all 94 installations is shown in Figure 3. Gross basal area growth response is expressed as a percentage of control plot growth, thus scaling the response of each installation to its productivity level. Within-installation growth variation attributable to differences in initial stand density was removed using Equation (1). Values are presented in an empirical cumulative distribution function: the vertical axis indicates the proportion of all installations with response less than or equal to a

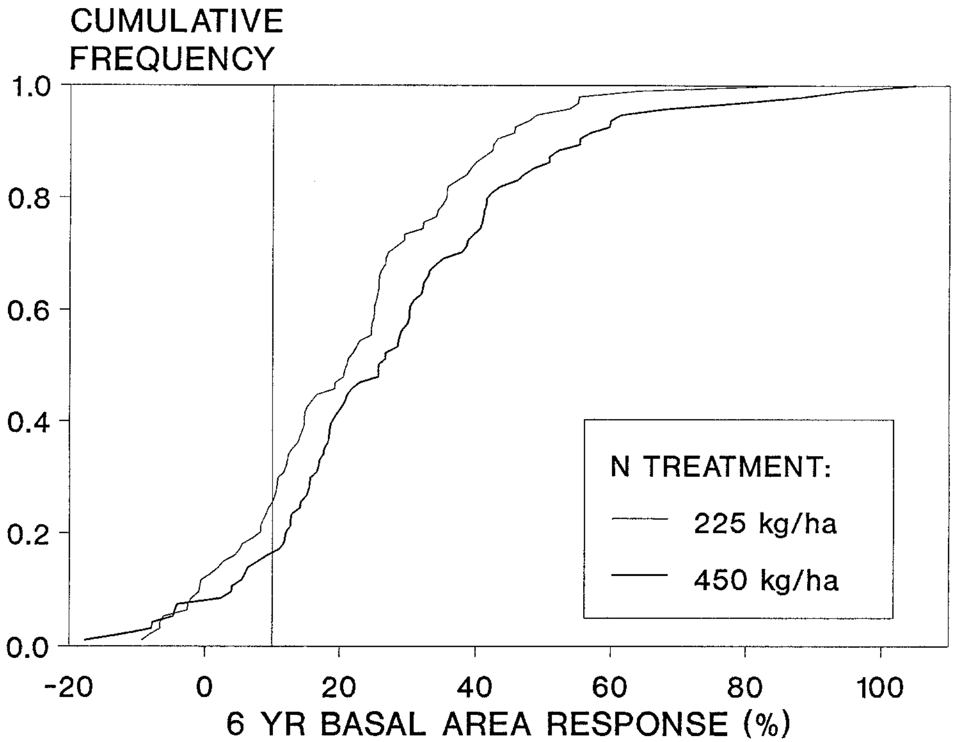


Figure 3. The empirical cumulative frequency distribution of relative gross basal area response (percent of control growth) across all regions by fertilizer treatment.

particular value shown on the horizontal axis. For example, of all the 225 kg N ha^{-1} treatments, approximately half of them responded less than 20% and about 90% responded less than 40%.

While N fertilization does produce a general dosage-dependent growth response, Figure 3 also shows that a number of installations produced little or no response to fertilization. We might attribute this result to random variation in response except that the non-responding installations tend to be grouped by region. Only 2.6% of the plots in northern Idaho and central Washington responded less than 10% to fertilization, while 14.3% of the plots in the other regions responded at that level.

3.2 Evidence of inadequate potassium

In an effort to explain this lack of response, we examined tree nutritional status. Distributions of both major and minor nutrients were scrutinized, including P, K, Ca, Mg, Mn, Zn, Fe, B and Cu. For an element to be considered potentially growth limiting, we felt that: (1) some installations should show inadequate levels for that nutrient, and (2) the number of installations with inadequate levels should increase with fertilization. Only K fulfilled these criteria.

The distribution of K concentration in $\mu g\ g^{-1}$ is shown in Figure 4. Data points are averages of 4 trees in each installation-fertilizer treatment combination. Each curve represents the relative cumulative frequency distribution for a particular fertilizer treatment. The vertical lines at 6000 and 8000 $\mu g\ g^{-1}$ are inadequate and marginal thresholds for coastal Douglas fir (van den Driessche, 1979; Webster and Dobkowski, 1983). Two important features are apparent. First, K concentrations are low; only 10% of the population show concentrations at a level considered adequate for tree growth. Second, trees receiving N fertilizer tend to have reduced K concentrations; while 30% of the control plots had inadequate K concentrations, about 50% of the concentrations from fertilized plots were inadequate. The latter results from growth dilution (Jarrel and Beverly, 1981), as average K content in the needles showed a slight increase with fertilization treatment. Thus, while total accumulation was slightly greater, needle growth increased relatively more, resulting in a net concentration reduction or dilution.

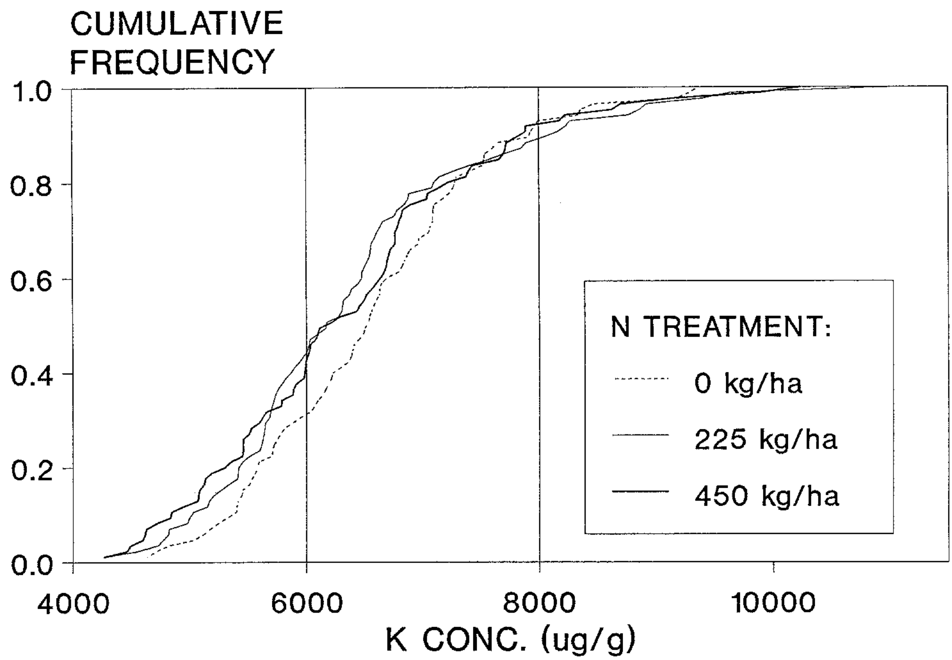


Figure 4. The empirical cumulative frequency distribution of foliar K concentration ($\mu g\ g^{-1}$) by fertilizer treatment. The vertical lines at 6000 and 8000 $\mu g\ g^{-1}$ represent inadequate and marginal thresholds, respectively, for Douglas fir growth in western Washington (van den Driessche, 1979; Webster and Dobkowski, 1983).

The addition of N also appears to have caused an appreciable imbalance in K to N, as shown in Figure 5. The cumulative frequency distribution of the K/N ratio in percent is displayed; again, different curves show the distribution for different fertilizer treatments. Addition of N has resulted in a dramatic decrease in the K/N ratios, primarily due to the increase in N concentrations, but also due to associated decreases in K. The vertical lines at 50 and 65% represent balanced K/N ratios for Douglas fir (Ingestad, 1967, 1979). Nitrogen amendment has shifted the ratios to the left, producing a large number of plots with insufficient K to balance the N levels present.

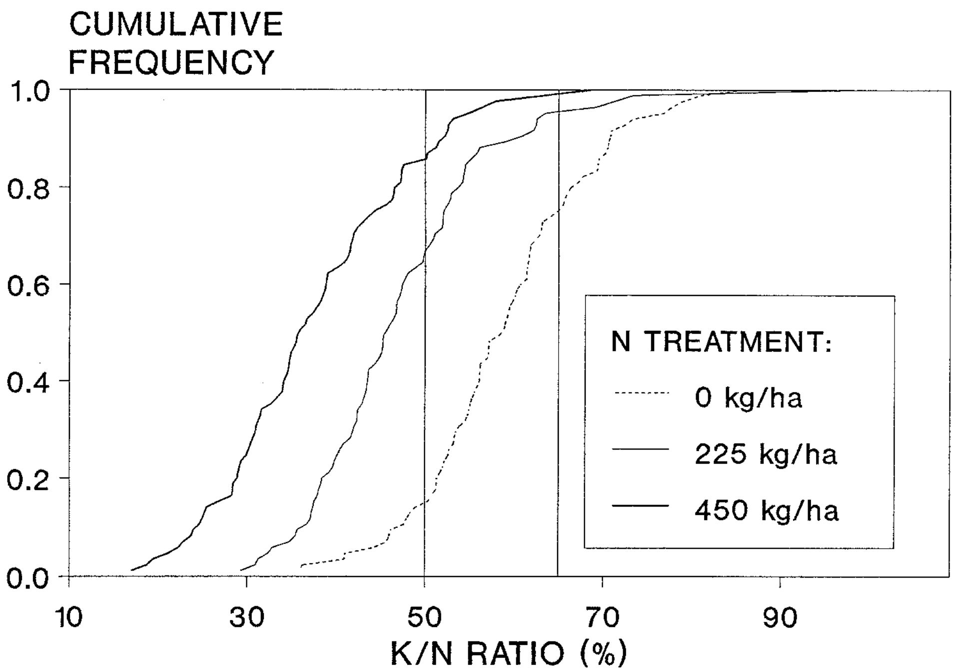


Figure 5. The empirical cumulative frequency distribution of the ratio of foliar K and foliar N concentration, expressed as a percent, by fertilizer treatment. The vertical lines at 50 and 65% represent balanced K/N ratios for Douglas fir growth (Ingestad, 1967, 1979).

3.3 Associations between potassium concentrations and fertilizer response

Two analytic approaches were used to determine relationships between foliar K concentrations and growth response to N fertilization. In the first, installations were grouped according to the K concentration of the trees on the untreated plots. Based on threshold values found in the literature, we defined three categories:

(1) installations with inadequate K, defined by K concentrations less than 6000 $\mu g\ g^{-1}$ and K/N ratios less than 50% ("poor" status),
(2) installations with adequate K, defined by K concentrations greater than 6000 $\mu g\ g^{-1}$ and K/N ratios greater than 65% ("good" status), and
(3) all other conditions.

Fertilization response differences between these K status categories were estimated by analysis of variance. A univariate split-split plot model was used, where whole plots are installations, split plots are N fertilizer treatments, split-split plots are 2 yr growth periods, and the dependent variable is periodic annual basal area response (treated-control). Tests of sphericity from a preliminary repeated measures analysis indicated that the univariate model was appropriate for this data.

Average gross basal area periodic annual response ($m^2\ ha^{-1}\ yr^{-1}$) by N fertilizer and K status category is shown in Figure 6. Response is further delineated by the 2 yr growth period in which it occurred; period 1 corresponds to the first 2 yr following treatment, while period 3 consists of the fifth and sixth yr following treatment. Results conform exactly with the hypothesis that inadequate K limits response to N fertilization. Installations with "good" K status show significantly higher ($p = 0.0132$) response than those with "poor" status. Furthermore the higher N fertilization rate produces greater response ($p = 0.0248$) in installations with adequate K, but a large though non-significant ($p = 0.4719$) decline in response in those where K appears lacking.

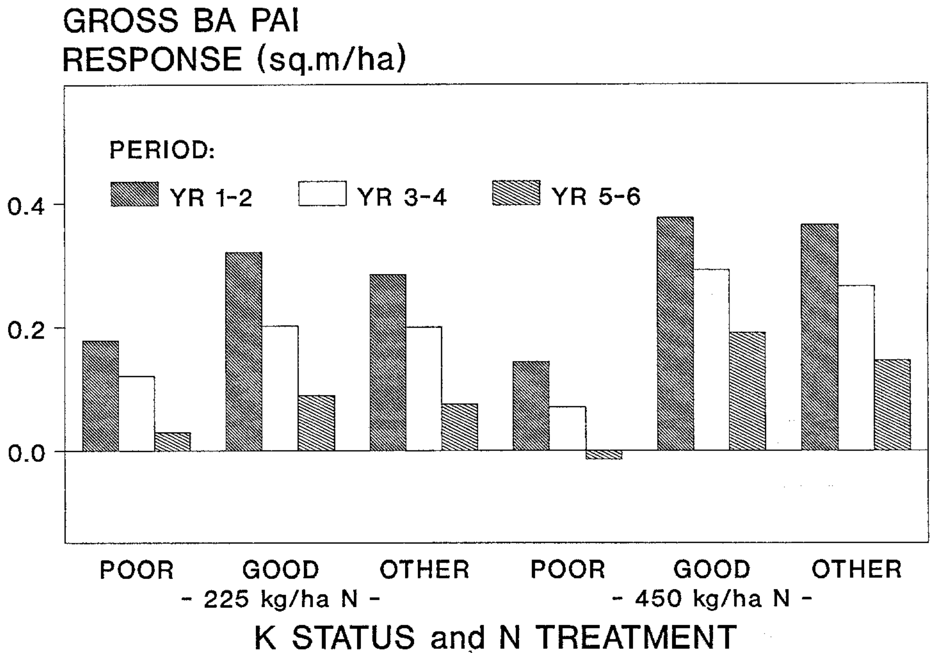


Figure 6. Gross basal area periodic annual response ($m^2\ ha^{-1}\ yr^{-1}$) by 2 yr period for all combinations of fertilizer treatment and K status.

Average control plot gross basal area growth was not significantly different ($p = 0.5989$) across the three K categories. Thus the reduced response for installations with inadequate K is not an effect of lower inherent growth rates.

The overall pattern for 6 yr response is consistent over the three growth periods. The "good" K status installations show better average response for all periods. They also increased their response when fertilized at the higher N rate. Conversely, in "poor" K status installations, plots fertilized with 450 kg N ha^{-1} responded less than those fertilized with 225 kg N ha^{-1} during all periods. These installations show non-significant fertilization response in the third period, while those with "good" K status continue to respond significantly. Thus inadequate K appears to also reduce the duration of response.

Mortality rates after N treatment also appear to be influenced by K status. Average net basal area periodic annual response for K status, N fertilizer, and growth period categories is shown in Figure 7. Due to the high variability introduced by mortality events, most means are not significantly different. However mortality tends to increase when K is low and N is added at the higher rate, suggesting that treatment-induced mortality is occurring. Mortality was sufficient to produce a negative net 6 yr response for this category.

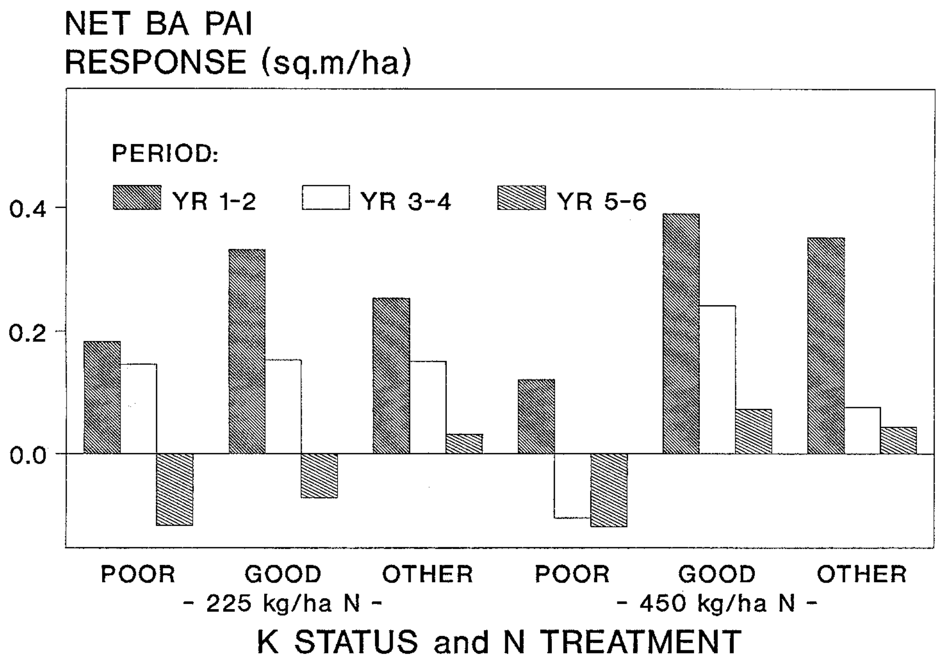
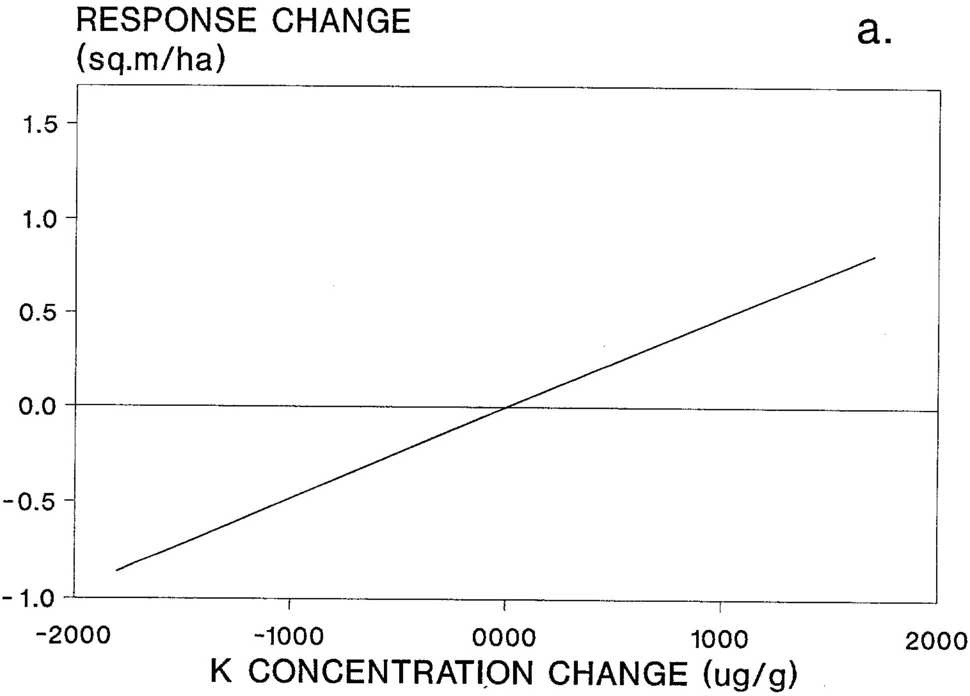


Figure 7. Net basal area periodic annual response (m^2 ha^{-1} yr^{-1}) by 2 yr period for all combinations of fertilizer treatment and K status.

In the second analytic approach, foliar K information was used to model the within-installation response differences between the two N treatments. Recall that there was a significant average increase of 0.4 m^2 ha^{-1} in response when the higher fertilizer rate was applied (Table II). Knowledge of which treatment was used could explain 13% of the variaton in within-installation response. However, we can substitute information of foliar N and K levels and explain 20% of that same variation. The form of the relationship is given by the equation:

$$R_{ij} = I_i + 4.7928 \times 10^{-4} K_{ij} - 4.1363 \times 10^{-2} K/N_{ij} \quad (2)$$

where R_{ij} is the 6 yr gross basal area response for the jth treatment in installation i, I_i is the average response for installation i, K_{ij} is the difference in K concentration between treatment j and the control for installation i, and K/N_{ij} is the similar difference in K/N ratio. The influence of changes in foliar K and N on response indicated in Equation (2) is portrayed in Figure 8. When K concentration decreases with treatment, response will also decrease (Figure 8a); a reduction of 1043 $\mu g\ g^{-1}$ in K concentration reduces basal area response by 0.5 m^2 ha^{-1} in 6 yr. Furthermore, for a given K difference, N increases produce decreases in the K/N ratio and increases in response (Figure 8b); a reduction of 12% in the K/N ratio increases 6 yr response by 0.5 m^2 ha^{-1}. Similar estimates of foliar K and N effects along with increased significance were obtained when installations with "poor" initial K status were removed from the analysis. Thus changes in foliar K induced by N fertilization have an impact on response even when initial K levels for the site seem adequate.



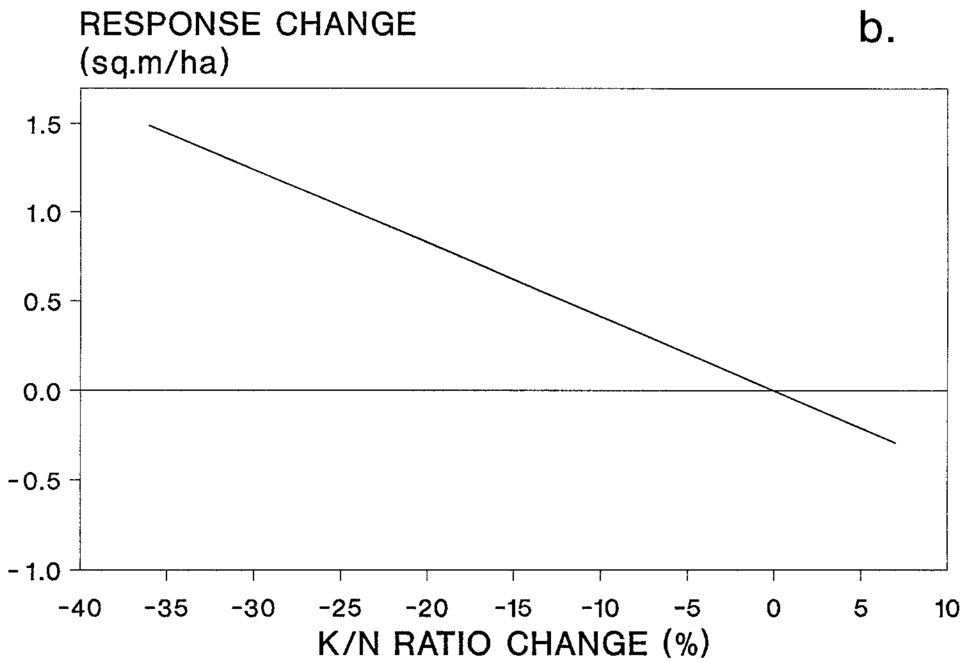


Figure 8. The influence of fertilization-induced changes in foliar nutrients on 6 yr gross basal area response to N fertilization across all geographic regions: a) the relationship between basal area response and changes in foliar K concentration ($\mu g\ g^{-1}$); and b) the relationship between basal area response and changes in K/N ratio (percent).

4. Summary

In the Inland Northwest region we have found evidence that some sites lack sufficient K to allow the maximum expression of tree growth. Under present conditions this inadequacy is masked by a universal lack of N. However, when additional N is made available through fertilization, the effect of low K is expressed in reduced amount and duration of fertilization response. Adding even more N to these K-poor sites exacerbates the situation; higher N fertilization rates produce lower responses. Growth dilution effects and nutrient imbalances involving K appear to be involved.

The nutrient budget of sites may be altered in ways other than by direct nutrient amendments. Forest practices may remove or redistribute substantial amounts of biomass and, with that, significant amounts of nutrients. Atmospheric depositions may differentially increase or decrease nutrient availability. When these effects produce the kinds of dilution or imbalances observed in this study, the consequences for tree growth are also likely to be similar.

Acknowledgements

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