Fourteen-year growth response of young lodgepole pine to repeated fertilization

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Abstract: Four rates of N (0, 50, 100, and 150 kg·ha^{-1}) with and without a fertilizer mix containing P, K, S, Ca, Mg, and micronutrients were applied to a stand of 8-year-old lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.) in four applications during 7 years. Fourteen years after the first fertilization, mean tree basal area and volume were significantly increased in the treatments containing the two highest rates of N plus the fertilizer mix. Mean tree basal area was 38% greater and mean tree volume was 42% greater in the highest N (525 kg·ha^{-1}) plus mix treatment than in the control treatment. Stand basal area increased 48% over the control in the highest N plus mix treatment. Mean tree basal area and volume were 27 and 25% greater than the control under the intermediate N rate (350 kg·ha^{-1}) with mix, respectively. Height growth was not significantly increased by fertilization. Both higher rates of N (four applications of >100 kg·ha^{-1}) and the fertilizer mix were required for significant growth responses to occur. Addition of N alone or mix alone had a negative effect on mean tree basal area and volume. Addition of higher N rates without the mix decreased foliar total S and SO_4-S concentration and increased the N/S ratio. Addition of the higher rates of N without the mix aggravated slight K deficiencies. The responses to the higher N rates in combination with the fertilizer mix are mainly attributable to S.

Résumé : Quatre taux de N (0, 50, 100 et 150 kg·ha^{-1}) avec ou sans un mélange d'engrais contenant P, K, S, Ca, Mg et des micro-éléments ont été appliqués dans un peuplement de pin lodgepole (*Pinus contorta* var. *latifolia* Engelm.) quatre fois sur une période de sept ans. Quatorze ans après la première application, la surface terrière et le volume moyens étaient significativement plus élevés dans les traitements contenant les deux taux de N les plus élevés avec le mélange d'engrais. La surface terrière et le volume moyens des arbres étaient respectivement 38 et 42% plus élevés dans le traitement avec le plus haut taux de N (525 kg·ha^{-1}) combiné au mélange d'engrais que dans le traitement témoin. La surface terrière et le volume moyens des arbres étaient respectivement 27 et 25% plus élevés dans le traitement avec le taux intermédiaire de N (350 kg·ha^{-1}) combiné au mélange de fertilisant que dans le traitement témoin. La fertilisation n'a pas significativement augmenté la croissance en hauteur. La croissance en hauteur n'a pas été significativement affectée par la fertilisation. Les deux plus hauts taux de N (quatre applications de plus 100 kg N·ha^{-1}) combinés au mélange d'engrais étaient nécessaires pour obtenir une augmentation significative de croissance. L'ajout de N seul ou du mélange d'engrais seul avait un effet négatif sur la surface terrière et le volume moyens des arbres. L'ajout des plus hauts taux de N sans le mélange d'engrais a causé une diminution de la concentration de S total et de S sous forme de SO_4 et a augmenté le rapport N/S. L'ajout des plus hauts taux de N sans le mélange d'engrais a aggravé une légère déficience en K. Les réactions aux plus hauts taux de N combinés au mélange de fertilisant sont attribuables principalement à S.

[Traduit par la Rédaction]

Introduction

The forest land area available for commercial timber production in British Columbia (B.C.) is being reduced through other land-use pressures and recent measures to protect nontimber resource values. The productivity of the remaining working forest must increase if annual allowable cuts and even flows of harvested wood are to be sustained. Interior second-growth forests will undoubtedly play a critical role in B.C.'s future wood production.

Although other silvicultural treatments may redistribute stand volume or improve the value of harvested wood from existing stands, fertilization is about the only treatment that has been shown to consistently improve harvest volumes of established stands. In particular, repeated fertilization has the potential to increase harvest volume and piece size considerably, but there is little experience with repeated applications in B.C. The potential for repeated fertilization to increase the productivity and sustainability of interior forests must be documented so that realistic expectations of growth gains can be included in timber supply analyses.

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Lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.) constitutes 39% of the total harvested volume of interior B.C. forests (B.C. Ministry of Forests 1999). Growth response of lodgepole pine to nitrogen (N) alone and in combination with other elements has been demonstrated in interior B.C., Alberta, and the interior U.S. Northwest, although response to N additions has been variable (Cochran 1979; Yang 1985*a*, 1985*b*, 1998; Brockley 1996). The inconsistency in response has been associated with deficiencies of additional nutrients. Secondary deficiencies of phosphorus (P), potassium (K), sulphur (S), and boron (B) in lodgepole pine have been demonstrated or inferred (Cochran et al. 1979; Brockley 1990; Brockley and Sheran 1994).

Like other species, lodgepole pine response to a single fertilizer application is usually of short duration, generally from 3 to 6 years (Boyd et al. 1975; McIntosh 1982; Brockley 1996). As an alternative to single-application fertilization, repeated fertilizer applications in optimum nutrition field trials have been undertaken to provide responses of longer duration by approximation of steady-state nutrition in field studies (Axelsson 1985; Ingestad 1987; Tamm et al. 1999). Steady-state nutrition studies are designed to supply small, balanced supplies of nutrients in solution at rates consistent with estimated demand (Ingestad 1987; Linder 1987; Bergh et al. 1999; Raison and Myers 1992), and under these tightly controlled conditions, elevated, steady-state foliar nutrient levels can be readily achieved. Optimum nutrition field experiments are less rigidly controlled, with nutrients applied less frequently, usually in solid form, and in larger amounts per application (Weetman et al. 1995; Tamm et al. 1999). While in both approaches foliar nutrient levels are monitored so that the rates and frequency of nutrient additions can be adjusted to maintain foliar nutrients at specified target levels over a prolonged period, optimum nutrition field trials experiments can only approximate the controlled foliar levels achieved in steady-state experiments. This is approached by addition of nutrients to approximate the elevated target concentrations, monitoring of concentrations to ensure they do not fall below critical levels, and reapplication of nutrients when required. As N is most often limiting to temperate forest growth, target foliar concentrations of N are established for the stand age and species (Miller et al. 1981). Nutrients other than N are added to provide a nutrient balance and to minimize growth limitations resulting from secondary deficiencies.

Fertilization in an optimum nutrition trial is expected to bring about consistently larger and longer growth responses than in conventional single-application fertilization. Where nutrient limitations have been alleviated, it is expected that the maximum productivity of the trees may be approached, and that the upper range of productivity may be determined. This approach is most successful in young stands (Axelsson 1985). The stand–soil system may become nutrient saturated within 10–20 years, and nutrients are cycled to achieve high production rates for the remainder of the rotation (Axelsson 1985).

Elevated and sustained growth responses to repeated fertilization have been demonstrated in optimum nutrition trials in other pines. Fertilization of young Scots pine (*Pinus sylvestris* L.) with 776 kg N·ha^{-1} in six applications over 30 years increased stand volume 36% relative to unfertilized stands (Mälkönen and Kukkola 1991). Fertilization of jack pine (*Pinus banksiana* Lamb.) with 336 kg N·ha^{-1} in six applications over 22 years increased stand volume by 36% (Weetman et al. 1995). Mean annual volume increment of young Scots pine increased 300% in an optimum nutrition trial, representing a two to three times greater response than to conventional fertilization on the same site (Axelsson 1985). In Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), fertilization with 1000 kg N·ha^{-1} in four applications over 10 years increased basal area increment by 40% (Weetman et al. 1997).

An optimum nutrition field trial was established in a young lodgepole pine stand near Okanagan Falls, B.C., in 1982, following the approach of Tamm et al. (1999). Foliar N concentrations were monitored and fertilizer was applied as necessary to approximate target foliar N concentrations over a 10-year period, with and without a mix of other nutrients. Here we present measurements of tree response during the first 14 years after the initial fertilization. Our objectives were to determine the treatment regime associated with the greatest growth response in lodgepole pine, and to evaluate the magnitude and duration of the growth response that can be achieved through optimum nutrition fertilization of young lodgepole pine.

Materials and methods

The study site was located 26 km east of Okanagan Falls, in the Okanagan Highlands variant of the dry mild subzone of the Montane Spruce biogeoclimatic zone (MSdm1; Lloyd et al. 1990) at an elevation of 1525 m. The soil was a Dystric Brunisol on glaciofluvial parent material with a fibrimor forest floor (Agriculture Canada Expert Committee on Soil Survey 1987). Rooting depth ranged from 25 to 36 cm. The previous stand was clear-cut in 1971, followed by slash windrowing. Natural regeneration of lodgepole pine was established by 1974 and the stand was thinned from 5900 to 1100 stems/ha in 1980.

The optimum nutrition trial was established in 1982. Four levels of N as ammonium nitrate were applied with and without other nutrients in a 4 × 2 factorial randomized complete block design. The four N levels were N0 (control), N1 (50 kg·ha^{-1}), N2 (100 kg·ha^{-1}), and N3 (150 kg·ha^{-1}), with total N application rates of 0, 175, 350, and 575 kg·ha^{-1}, respectively (Table 1). Target foliar N concentrations were 12, 16, and 20 g·kg^{-1} for the N1, N2, and N3 treatments, respectively.

In addition to N, a fertilizer mix was applied at two levels: –mix (no fertilizer mix) and +mix (fertilizer mix at 1170 kg·ha^{-1}). The fertilizer mix contained the following elements (in kg·ha^{-1}): P, 99; K, 102; S, 36; Ca, 129; Mg, 51; Fe, 9; Mn, 3.75; Zn, 3.5; B, 1.5; Cu, 1.5; and Mo, 1. Fertilizer sources for macronutrients were triple super phosphate (0–45–0, N–P–K), muriate of potash (0–0–60), sulphate potash magnesia (0–0–22–22–11, N–P–K–S–Mg), and granular dolomite. Micronutrients were included in a commercially available micronutrient mix. Fertilizer was applied in the spring of 1982, 1983, 1985 (half rate), and 1988 with cyclone seeders. Fertilizer applied at each application time is

Table 1. Individual and total fertilizer applications ($kg \cdot ha^{-1}$).

Element	1982	1983	1985 (half rate)	1988	Total
N1	50	50	25	50	175
N2	100	100	50	100	350
N3	150	150	75	150	525
P	99	99	49.5	99	346.5
K	102	102	51	102	357
S	36	36	18	36	126
Ca	129	129	64.5	129	451.5
Mg	51	51	25.5	51	178.5
Fe	9	9	4.5	9	31.5
Mn	3.75	3.75	1.875	3.75	13.125
Zn	3.5	3.5	1.75	3.5	12.25
B	1.5	1.5	0.75	1.5	5.25
Cu	1.5	1.5	0.75	1.5	5.25
Mo	1	1	0.5	1	3.5

shown in Table 1. The eight N × mix combinations were replicated over three blocks. Each treatment plot was 0.087 ha, but only trees in the inner 0.050-ha plot area were measured or sampled. The mean number of trees per inner plot was 58 in 1995.

Tree height, diameter at stump height (DSH, 30 cm), and diameter outside bark at breast height (DBH, 1.30 m) if greater than 1 cm were measured at establishment in 1982. Trees were remeasured in 1984, 1986, 1990, and 1995. Basal area per tree was calculated as $\pi \times \text{radius}^2$. For measurements prior to 1990, radius was determined from DSH. For the 1990 and 1995 measurements, radius was determined from DBH. Tree volume was determined using a standard volume equation developed for a lodgepole pine stand of similar age and stocking (Brockley 1989): $V = 3235.77 + 32.70(D^2H)$, where V is volume inside bark in cubic centimetres, D is DBH outside bark in centimetres, and H is total height in metres.

Mean tree height, basal area, and volume were calculated as the arithmetic mean of individual tree measurements within a plot. Treatment means were obtained by averaging the three replicate plot means per treatment. Stand basal area per hectare was determined by summing individual tree basal areas in each plot and converting plot area to a per-hectare basis.

Radial increment cores were taken at stump height from 5 trees per plot (15 trees per treatment) in 1996. Annual ring area was determined using a scanner integrated with WINDENDRO™ version 6.0.5. Relative ring-area increment was calculated as mean ring-area increment for each fertilizer treatment relative to the mean ring area of the control treatment.

Current-year foliage from 10 trees per plot was sampled yearly in the fall or early spring beginning prior to trial establishment in 1981–1995, except for 1987, 1993, and 1994. Foliar N concentrations at establishment were used to determine the N application rates that would likely be required to achieve foliar N target levels. Foliage was composited by plot and oven-dried (70°C for 24 h) prior to analysis. Nitrogen concentrations in 1982 and 1983 foliage were measured by distillation and colorimetric determination with a boric acid indicator following a sulphuric acid – copper sulphate digestion (Jackson 1958). Concentrations of P and K in 1982 and 1983 foliage were measured by autoanalysis and atomic absorption spectrophotometry, respectively, following micro-Kjeldahl digestion (Jackson 1958; Steckel and Flannery 1971; Isaac and Johnson 1975). In subsequent years, foliar N and P were determined by Technicon autoanalyzer, and K, calcium (Ca), and magnesium (Mg) were determined by atomic absorption spectrophotometry following a modified Kjeldahl digestion (Jackson 1958; Isaac and Johnson 1975). Foliar total S and SO_4-S were determined from 1988 through 1992 and in 1995. Total S was measured by Leco SC-132 S analyzer. Foliar SO_4-S was determined by extraction of boiling tissue in 0.01 M HCl, followed by hydroiodic-acid reduction of the extract and colorimetric determination (Sanborn and Ballard 1991). Boron (B) was measured colorimetrically in HCl following dry ashing (Jackson 1958). Results are expressed per unit mass of oven-dried tissue.

Differences in growth response to fertilizer treatments were determined using analysis of covariance. For tree height, initial height was used as a covariate, and for basal area and volume initial diameter at stump height was used as the covariate (SPSS Inc. 1998). Adjusted means were determined for growth response variables. Treatment differences in foliar chemistry were determined using analysis of variance. All data were tested for homogeneity of variance prior to analysis of covariance or variance. Where variances were heterogeneous, data were transformed, and analyses performed on the transformed data. Treatment differences for both growth response and foliar nutrition were determined using Duncan's multiple range test at the 0.05 level of significance.

Results and discussion

Mean tree height and basal area 14 years after the initial fertilization (1995) with differences from the N0 (control) treatment are shown in Table 2. Tree height was greatest in the highest N with mix treatment (N3 + mix). However, this was only an 8% increase over the N0 treatment and was not significantly different. Height was significantly less in the high N without mix treatments (N2 and N3) than in the N0 and N3 + mix treatments. Mean tree basal area was significantly greater in the N3 + mix and N2 + mix treatments than in the N0 treatment by 38 and 27%, respectively (Table 2).

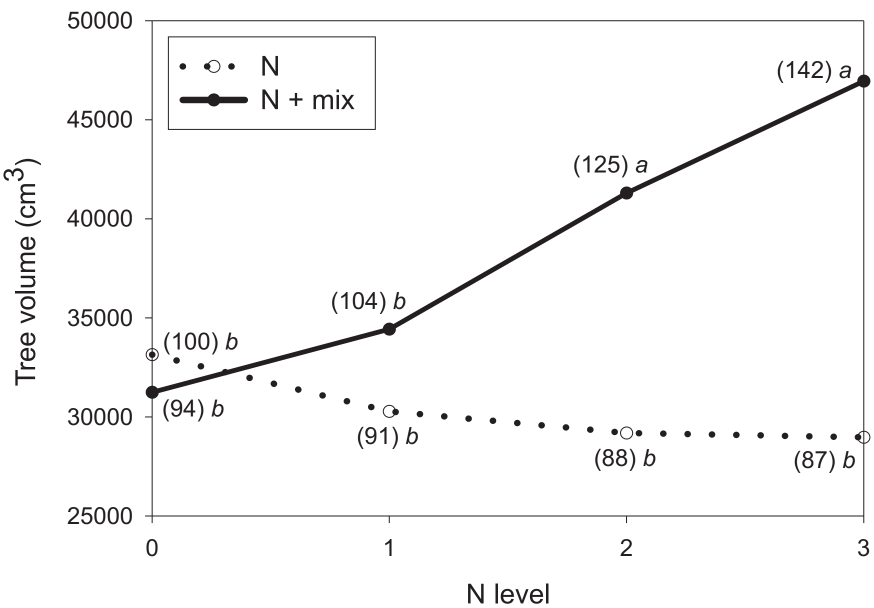
There were statistically significant treatment differences in 1995 mean tree volume (Fig. 1). The effect of N level at each mix level was not significant; however, the mix effects and the N × mix interaction were significant ($p < 0.001$ and $p = 0.005$, respectively). Volume was significantly greater in the N3 + mix (42% increase) and the N2 + mix (25% increase) treatments than in the N0 treatment. Lower volume and basal area in the mix-alone and N-alone treatments than in the N0 treatment suggest a negative, although nonsignificant, effect of both mix alone and N alone. Significantly greater basal area and volume in the N2 + mix and N3 + mix treatments indicate that inclusion of the mix at the higher N levels was required to obtain a positive growth response. Treatment differences in basal area rather than

Table 2. Mean tree height and basal area of lodgepole pine 14 years following initial fertilization.

Treatment	Tree height (m)	% of control	Basal area (cm^2)	% of control
N0 (control)	6.34 (0.19)*a*	100	106 (0.1)*b*	100
N0 + mix	6.27 (0.21)*ab*	99	100 (0.1)*b*	94
N1	6.19 (0.20)*a*	98	95 (0.1)*b*	90
N1 + mix	6.39 (0.19)*a*	101	111 (0.1)*b*	105
N2	5.53 (0.21)*c*	87	99 (0.1)*b*	94
N2 + mix	6.26 (0.20)*a*	99	135 (0.1)*a*	127
N3	5.52 (0.20)*bc*	87	97 (0.1)*b*	92
N3 + mix	6.83 (0.19)*a*	108	146 (0.1)*a*	138
Analysis of covariance *p*	0.015		0.002	

Note: Values are adjusted means from analysis of covariance using initial height as covariate (height) or initial diameter at stump height as covariate (basal area) with SEs given in parentheses. Differences from control treatment are shown as percent difference from control as set to 100%.

Fig. 1. Mean 1995 tree volume in the eight fertilization treatments (N0, N1, N2, N3 with and without mix). Values are adjusted means with initial diameter at stump height as the covariate. Values in parentheses are percentages of control (N0) level. Values with different letters are significantly different at $\alpha = 0.05$.



height appear to be responsible for the observed volume differences. Lack of, or negative, height growth response to fertilization is consistent with other fertilization studies in pine (Brockley 1991; Tamm et al. 1999). Trees in this study fertilized with higher rates of nitrogen developed large, distorted branches and were only approaching crown closure in 1995, indicating that branch growth was more affected by fertilization than height growth. The density of 1100 stems/ha in this stand is lower than would normally be used for operational fertilization of precommercially thinned stands of lodgepole pine in B.C. and likely contributed to large responses in branch size.

Stand basal area ($m^2 \cdot ha^{-1}$) from the time of trial establishment in 1982 until 1995 is shown in Fig. 2. Treatment differences in stand basal area were evident by 1984, with the greatest basal area occurring in the N3 + mix treatment. Treatment differences were amplified by 1990, when the greatest basal area was observed in the N3 + mix, N2 + mix, and N1 + mix treatments, and the lowest basal areas in the N0 + mix, N0, and N2 treatments. These differences were not significant. Treatment differences increased further by 1995 but were still not statistically significant. Stand basal area was 48% greater in the N3 + mix treatment than in the N0 treatment by 1995.

Although it is difficult to compare these results with other studies of different duration, using different N application rates, and in different species, it appears that response to the highest rate of repeated N fertilization in combination with the nutrient mix in this study was greater and occurred sooner than in other optimum nutrition trials in pine. Stand volume of both Scots pine and jack pine increased 36% with repeated N applications over 30- and 22-year periods, re-

Fig. 2. Stand basal area in the eight fertilization treatments (N0, N1, N2, N3 with and without mix), 1982–1995 ($m^2 \cdot ha^{-1}$). Arrows show fertilizer applications, and asterisk shows half-rate application.

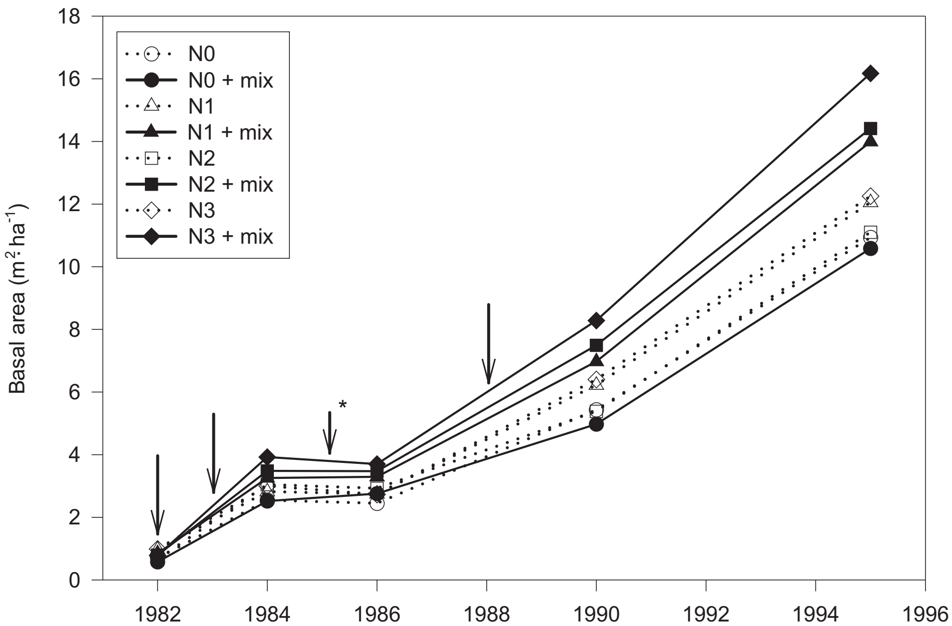
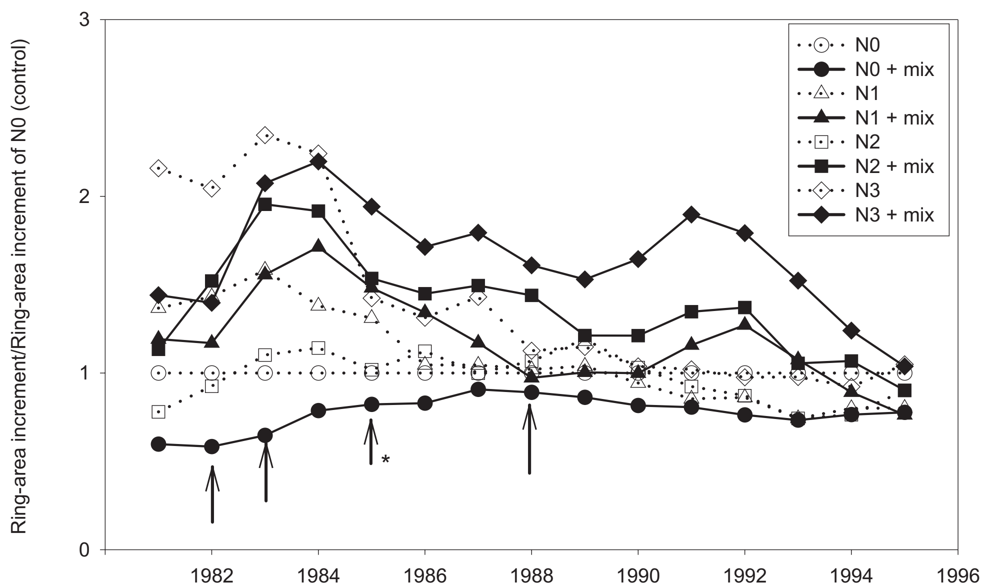


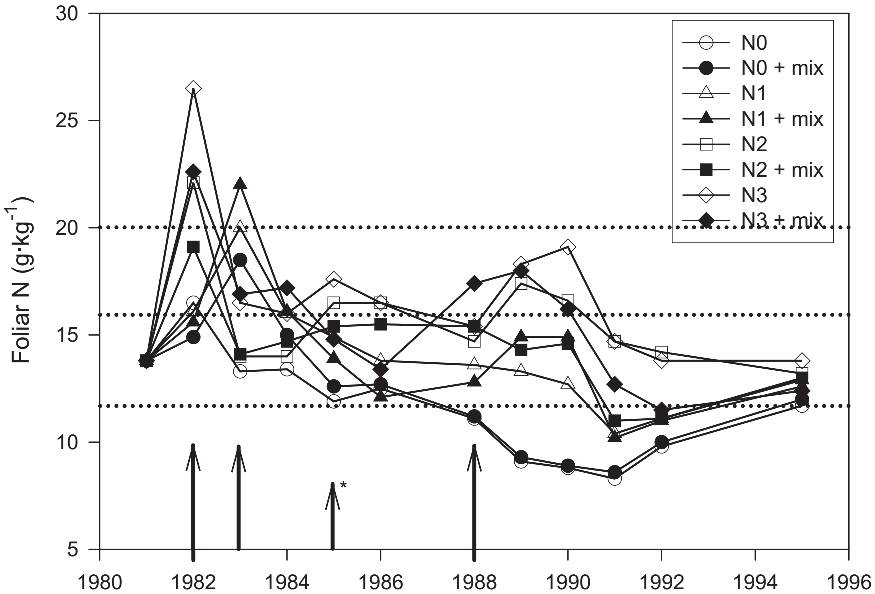
Fig. 3. Relative ring-area increment in the eight fertilization treatments (N0, N1, N2, N3 with and without mix), 1982–1995. Arrows show fertilizer applications, and asterisk shows half-rate application.



spectively (Mälkönen and Kukkola 1991; Weetman et al. 1995). These results contrast the response of Scots pine to repeated N-alone or N + mix fertilization, in which growth response to N alone occurred, with relatively small responses to N + mix treatments (Tamm et al. 1999).

Ring-area increment from 1982 to 1995 relative to the control treatment indicated that the greatest response in ring area occurred in the N3 + mix and N2 + mix treatments (Fig. 3), which is consistent with stand basal area. Ring-area increments in the N3 + mix, N2 + mix, and N1 + mix treatments increased after the first two fertilizer applications in 1982 and 1983 and declined again by 1985. The half-rate of fertilizer application in 1985 was apparently insufficient to cause an additional increase in ring area. Ring-area increment increased again in the N3 + mix, N2 + mix, and N1 + mix treatments after the 1988 fertilization and declined again by 1995, although the response did not occur as immediately after the 1988 fertilization as it did with earlier fertilizations. Ring-area increment in these treatments declined again by 1995. Ring-area increment in the mix-alone treatment was lower than in the control treatment, which is consistent with mean tree basal area and volume. These results indicate that although substantial growth responses to the higher N + mix treatments occurred, the responses declined

Fig. 4. Foliar N concentration in the eight fertilization treatments (N0, N1, N2, N3 with and without mix), 1981–1995. Arrows show fertilizer applications, and asterisk shows half-rate application. Broken lines indicate target foliar N concentrations: N1, 12 g·kg^{-1}; N2, 16 g·kg^{-1}; N3, 20 g·kg^{-1}.



within several years following each fertilization and were not sustained to the seventh year following the last fertilization.

Foliar N concentrations from 1981 to 1995 are shown in Fig. 4. Target foliar N concentrations were 12, 16, and 20 g·kg^{-1} for the N1, N2, and N3 treatments, respectively. Attempts to reach or maintain target foliar N concentrations by fertilizer additions were not entirely successful. Foliar N in all treatments had converged to a mean value of 12.7 g·kg^{-1} by 1995. Studies of repeated nitrogen additions to simulate chronic nitrogen deposition indicate that pine stands reaching N saturation showed sustained increases in foliar N concentrations (Magill et al. 1997), which were not observed in this study.

Foliar nutrient concentrations and balances were affected by fertilization treatments in 1995, eight years after the last fertilization (Table 3). There was no significant difference in foliar N concentration among treatments in 1995. In general, concentrations of most other elements were higher in the foliage of N + mix treatments than N-alone treatments, although differences were not significant. Significant treatment differences occurred only in foliar total S and SO_4-S. Sulphur in excess of that required to balance N in protein formation accumulates as SO_4-S (Kelly and Lambert 1972). This S reserve is available to act with N in protein formation and growth. Foliar SO_4-S has been found to be a better indicator of foliar S status than total S and has been used in conjunction with total S and N/S to predict conifer responsiveness to N fertilization (Lambert and Turner 1977; Turner et al. 1977; Brockley and Sheran 1994; Brockley 2000).

In lodgepole pine, foliar SO_4-S is deficient below 80 mg·kg^{-1} and response to N fertilization in stands with foliar SO_4-S below 60 mg·kg^{-1} is unlikely (Ballard and Carter 1985; Brockley 2000). Foliar SO_4-S in the control treatment was 61 mg·kg^{-1} in 1995, indicating S deficiency in this stand and a low likelihood of response to N-alone fertilization. Foliar SO_4-S was substantially depressed in the N2 and N3 treatments, indicating depletion of existing foliar SO_4-S reserves with the addition of N and a N-induced exacerbation of S deficiency. Foliar SO_4-S was significantly greater in the N3 + mix treatment than in the N2 and N3 treatments.

Foliar total S was significantly greater in the N1 + mix, N2 + mix, and N3 + mix treatments than in the same levels of N alone. Total-S concentrations were depressed in the N1, N2, and N3 treatments relative to the control but were not significantly different from the control. Foliar total-S concentrations in all treatments were at or below that considered to be deficient (1.2 g·kg^{-1}) (Ballard and Carter 1985).

The foliar N/S ratio is also indicative of conifer S status and potential responsiveness to N fertilization. Growth response of lodgepole pine to N fertilization is not expected where N/S ratios are ≥13 (Brockley 2000). The foliar N/S ratio in the control treatment was 11.5 (Table 3). This ratio increased to above 13 in the N1, N2, and N3 treatments, indicating an accumulation of N relative to S and insufficient S for growth response. Treatment differences in N/S were not significant.

It is evident from basal area and volume responses that both the higher N levels and the mix were required for a significant growth response. A positive growth response was obtained with the higher levels of N + mix, while growth was either unaffected or slightly depressed in the mix-alone and N-alone treatments. Foliar nutrition responses indicate that S was the nutrient most affected by the addition of both N and the mix and is the element of the mix most responsible for the observed growth responses. This is consistent with previous observations in S-deficient lodgepole pine stands where growth responses occurred with the addition of both N and S but were lacking with the addition of N alone (Brockley and Sheran 1994; Brockley 2000). Actual or inducible S deficiencies are common in immature lodgepole pine stands in the Sub-Boreal Spruce (SBS) and Sub-Boreal Pine–Spruce (SBPS) biogeoclimatic zones in the central

Table 3. Foliar nutrient concentrations in N and mix combinations, 1995.

Treatment	N ($g \cdot kg^{-1}$)	P ($g \cdot kg^{-1}$)	K ($g \cdot kg^{-1}$)	Ca ($g \cdot kg^{-1}$)	Mg ($g \cdot kg^{-1}$)	Total S ($g \cdot kg^{-1}$)	SO_4-S ($mg \cdot kg^{-1}$)	B ($mg \cdot kg^{-1}$)	N/S
N0 (control)	11.70 (0.36)	1.23 (0.06)	3.80 (0.36)	2.03 (0.25)	1.33 (0.21)	1.02 (0.04)*ab*	61.3 (27.5)*ab*	20.0 (3.6)	11.5 (0.6)
N0 + mix	11.97 (0.95)	1.23 (0.15)	3.83 (0.46)	1.80 (0.10)	1.47 (0.15)	1.01 (0.11)*ab*	30.3 (18.7)*ab*	25.3 (7.6)	12.0 (1.8)
N1	12.93 (0.40)	1.27 (0.06)	4.03 (0.32)	2.20 (0.26)	1.30 (0.10)	0.88 (0.03)*b*	42.0 (26.0)*ab*	20.3 (0.6)	14.8 (0.6)
N1 + mix	12.57 (0.46)	1.33 (0.06)	3.97 (0.75)	2.40 (0.44)	1.53 (0.32)	1.22 (0.08)*a*	54.0 (11.3)*ab*	32.7 (6.4)	10.3 (0.3)
N2	13.15 (0.49)	1.25 (0.07)	3.45 (0.49)	2.15 (0.21)	1.30 (0.14)	0.86 (0.04)*b*	13.8 (4.6)*b*	20.0 (2.8)	15.4 (0.1)
N2 + mix	13.03 (0.81)	1.40 (0.10)	4.27 (0.29)	2.00 (0.17)	1.43 (0.15)	1.15 (0.09)*a*	53.7 (19.5)*ab*	32.7 (1.5)	11.3 (0.6)
N3	13.83 (0.81)	1.30 (0.10)	3.27 (0.23)	2.00 (0.26)	1.27 (0.21)	0.87 (0.22)*b*	16.7 (1.5)*b*	20.7 (4.2)	16.6 (4.6)
N3 + mix	12.37 (0.78)	1.33 (0.06)	4.00 (0.70)	2.07 (0.25)	1.37 (0.21)	1.18 (0.18)*a*	95.0 (99.7)*a*	25.7 (4.2)	10.6 (0.9)
Analysis of variance *p*	0.109	0.672	0.28	0.462	0.862	0.031	0.011*	0.391	0.06

Note: Values are means of composited foliage of 10 trees per plot with SEs given in parentheses. Treatment values within a column with different letters are significantly different at $\alpha = 0.05$.
*Analysis of variance was performed on log-transformed data.

interior of B.C. However, S deficiencies have not been documented in previously established research installations in the MS biogeoclimatic zone in the southern B.C. interior (Brockley and Sheran 1994; Brockley 1996).

Foliar K concentrations and N/K ratios indicate moderate to severe deficiency of this element in the N3 and N2 treatments (Brockley 2001). The N/K ratios in the remaining treatments including the control indicate possible slight K deficiency. Potassium deficiencies appear to have been aggravated in the higher N treatment without additional K.

Conclusions

The greatest increases in stand basal area, mean tree basal area and volume, and tree height occurred in the treatment containing the highest level of N in addition to the nutrient mix (N3 + mix). Differences in individual tree basal area and volume were statistically significant. The N3 + mix treatment resulted in a 48% increase in stand basal area over the 14-year period. Individual tree basal area and volume also increased significantly in the N2 + mix treatment. Response to the N1 + mix treatment was less evident, indicating that both higher levels of N and the nutrient mix were required for a significant growth response. Response to the highest rate of repeated N fertilization in combination with the nutrient mix appears to be greater than response of pine to repeated fertilization in other optimum nutrition trials. Growth responses occurred following individual fertilizer applications but decreased within several years. Elevated foliar N concentrations and a sustained increase in productivity were not realized with the four fertilizer applications in this study.

Sulphur appears to be the element in the nutrient mix contributing the most to the growth response in the N3 + mix and N2 + mix treatments. Positive growth responses were achieved where both N and S deficiencies were alleviated. Addition of N at the N2 and N3 levels without S substantially decreased foliar SO_4-S and total S, increased foliar N/S, and resulted in lower basal area and volume growth than in the control treatment. Potassium deficiencies may also have been aggravated by N fertilization in this stand.

These results confirm the existence of nutrient limitations other than N in young interior lodgepole pine forests and show that repeated fertilization regimes will have to take these into account if productivity gains are to be achieved. The results indicate the potential of repeated fertilization to substantially improve the productivity of lodgepole pine forests in interior B.C.

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