# Effects of different sources and rates of sulphur on the growth and foliar nutrition of nitrogen-fertilized lodgepole pine

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**Abstract:** The effects of nitrogen (N) fertilizer, alone and in combination with different sources and rates of sulphur (S), on foliar nutrients and tree growth are reported over 3 and 6 years, respectively. After 3 years, foliar S levels in the N+S treatments were significantly higher than those in N-only treatments at all six study locations. Temporal patterns of foliar S response varied significantly with S source. When applied as ammonium sulphate (AS), foliar levels increased sharply in year 1 and slowly declined over the next 2 years. Conversely, additions of elemental S ($S^0$), in the form of $S^0$ – sodium bentonite fertilizer, usually did not increase foliar S concentration in year 1, but had increasingly positive effects on foliar S in years 2 and 3. An increase in the S application rate from 50 to 100 kg/ha resulted in only a modest improvement in foliar S concentration for both S sources. Differences in individual-tree basal area increment between N and N+S treatments were statistically significant in only two of six trials. Prefertilization levels of foliar N and sulphate S, and probable induced deficiencies of nonadded nutrients following N fertilization, largely explained basal area and height responses to N and N+S additions at the six study sites. Despite delayed oxidation, $S^0$ was as effective as the more readily available AS in stimulating radial growth after 6 years. However, the relative effectiveness of S source varied with S application rate in two trials. In both cases, basal area increment was positively related to application rate when S was applied as AS. Conversely, the effect of application rate was distinctly negative when $S^0$ was applied. Despite large differences in short-term availability of AS and $S^0$, the results from this study support the conclusion that the two S sources are likely equally effective in alleviating S deficiencies and in promoting tree growth of S-deficient lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.).

**Résumé :** Cet article traite des effets d'un fertilisant azoté (N), seul et combiné à différentes sources et plusieurs taux de soufre (S), sur les nutriments foliaires et la croissance des arbres après respectivement 3 et 6 ans. Après 3 ans, le niveau de S dans les aiguilles était significativement plus élevé dans les traitements contenant N+S que dans les traitements contenant seulement N dans les six endroits étudiés. L'évolution de S dans les aiguilles en fonction du temps était significativement différente selon la source de S. Le niveau de S dans les aiguilles a augmenté rapidement la première année et a diminué lentement au cours des 2 années subséquentes lorsqu'il avait été appliqué sous forme de sulfate d'ammonium. À l'inverse, l'addition de S dans sa forme élémentaire ($S^0$), fertilisant à base de sodium de bentonite, n'a habituellement pas provoqué l'augmentation de S dans les aiguilles la première année mais a eu un effet positif croissant au cours des deuxième et troisième années. L'augmentation du taux d'application de S de 50 à 100 kg/ha n'a provoqué qu'une légère amélioration de la concentration de S dans les aiguilles avec les deux sources de S. Les différences dans l'accroissement en surface terrière des arbres individuels entre les traitements N et N+S étaient statistiquement significatives dans seulement deux des six essais. Le niveau préexistant de N et de S sous forme de sulfate dans les aiguilles, ainsi que des déficiences en certains nutriments qui n'avaient pas été ajoutés et qui étaient causées par la fertilisation azotée, expliquent en grande partie les réactions de la surface terrière et de la hauteur aux applications de N et de N+S dans les six endroits étudiés. Malgré le délais dans son oxydation, $S^0$ était aussi efficace que le sulfate d'ammonium, plus facilement disponible, pour stimuler la croissance radiale après six ans. Cependant, l'efficacité relative de différentes sources de S variait avec le taux d'application de S dans deux essais. Dans les deux cas, l'accroissement en surface terrière était positivement relié au taux d'application lorsque S était appliqué sous forme de sulfate d'ammonium. À l'inverse, l'effet du taux d'application était nettement négatif lorsque que $S^0$ était appliqué. Malgré de fortes différences dans la disponibilité à court terme du sulfate d'ammonium et de $S^0$, les résultats de cette étude supportent la conclusion que les deux sources de S sont probablement aussi efficaces pour corriger une déficience en S et favoriser la croissance des tiges de pin lodgepole déficientes en S (*Pinus contorta* Dougl. var. *latifolia* Engelm.).

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## Introduction

Widespread nitrogen (N) deficiencies and favourable growth responses to N fertilization have been well documented in immature lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) forests in the interior of British Columbia (Weetman et al. 1988; Brockley 1991, 1995, 2001*a*; Kishchuk et al. 2002). The response of lodgepole pine to N

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**Table 1.** Initial mean foliar nutrient concentrations at the study sites.

| Trial No. | N (g/kg) | P (g/kg) | K (g/kg) | Ca (g/kg) | Mg (g/kg) | S (g/kg) | $SO_4$ (mg/kg) | B (mg/kg) |
|---|---|---|---|---|---|---|---|---|
| 1 | 12.4 (0.61) | 1.54 (0.06) | 4.83 (0.31) | 1.86 (0.23) | 0.92 (0.09) | 0.90 (0.07) | 79 (21) | 20.6 (1.9) |
| 3 | 11.6 (0.61) | 1.66 (0.05) | 4.58 (0.21) | 1.99 (0.18) | 1.05 (0.05) | 0.74 (0.03) | 59 (5) | 13.9 (2.0) |
| 4 | 12.3 (0.23) | 1.69 (0.03) | 4.60 (0.14) | 2.08 (0.12) | 1.05 (0.06) | 0.83 (0.05) | 67 (9) | 13.4 (1.0) |
| 5 | 12.9 (0.57) | 1.74 (0.10) | 5.29 (0.25) | 2.12 (0.16) | 1.00 (0.06) | 0.88 (0.04) | 50 (9) | 8.6 (1.1) |
| 6 | 13.3 (0.60) | 1.91 (0.09) | 7.04 (0.25) | 1.88 (0.16) | 0.94 (0.06) | 1.02 (0.07) | 71 (13) | 16.0 (1.1) |
| 7 | 10.0 (0.56) | 1.52 (0.08) | 4.07 (0.36) | 1.59 (0.23) | 1.14 (0.06) | 0.81 (0.02) | 102 (7) | 20.7 (1.2) |

**Note:** For each trial, values represent means of nine composite samples (15 samples per composite). Values in parentheses are standard deviations.

fertilization, however, is variable; some stands respond well and others respond poorly. Sulphur (S) deficiency, either induced or exacerbated by N fertilization, has been implicated as a major factor limiting the growth response of N-fertilized lodgepole pine (Yang 1985; Brockley 1989, 1990, 1995; Kishchuk et al. 2002). Examination of interior forest soils has revealed that mineral soil S levels are among the lowest reported in the world literature (Kishchuk and Brockley 2002). Recent studies have confirmed that growth responses may be enhanced by combining S with N in fertilizer applications (Brockley 2000, 2001*a*). However, considerable uncertainty remains regarding appropriate sources and rates of S to include in fertilizer prescriptions for S deficient sites.

The S-containing fertilizers can be divided into two main groups according to their chemical form: sulphate ($SO_4$) and elemental S ($S^0$). Sulphate fertilizers, such as ammonium sulphate, provide a readily available source of S to the plant and usually produce a more rapid increase in foliar S concentration and a more immediate growth response than $S^0$ sources (Noellemeyer et al. 1981; Solberg and Nyborg 1983; Gupta and McLeod 1984; Janzen and Bettany 1986; Karamanos and Janzen 1991). However, sulphate sources are bulky (i.e., low S content) and, therefore, substantially increase product and application costs. Also, the high mobility of sulphate fertilizers in soil may limit their ability to provide long-term amelioration of soil S deficiencies. Although $S^0$ fertilizer contains very high concentrations of S, it must be biologically oxidized to $SO_4$ in the soil before it is available for plant uptake (Germida and Janzen 1993). This may result in slower initial uptake than with more available sulphate forms. However, this “slow release” characteristic may benefit long-term S availability and uptake (Janzen and Karamanos 1991).

Extensive research has documented the effectiveness of various forms and application rates of S fertilizers on stimulating S uptake and growth of agricultural crops (Koeller and Roberts 1983; Solberg and Nyborg 1983; Janzen and Bettany 1984, 1986; Riley et al. 2000). However, very little parallel research has been undertaken in conifer forests. Brockley and Sheran (1994) reported the effects of N fertilizer, applied alone and in combination with different sources and rates of S, on the first-year fascicle mass and foliar nutrient status of young lodgepole pine at seven locations in the interior of British Columbia. However, the effectiveness of using different S sources and S application rates to enhance tree nutrition and growth cannot be fully evaluated unless their effects are documented over the long term. This paper builds on the first-year results of Brockley and Sheran (1994) by examining the effects of S source and rate on lodgepole pine foliar nutrition over 3 years and tree growth response after 6 years. Using six of the sites in the original study, the specific objectives were to determine the longer term effects of two S sources ($SO_4$ and $S^0$) applied at two different rates (50 and 100 kg/ha) on both foliar nutrition and growth of N-fertilized lodgepole pine. In addition, the remeasurement of the stands allowed for a retrospective assessment of how well first-year fascicle mass response predicted longer term stemwood performance.

## Methods

### Location and site description

In 1988 and 1989, seven fertilizer research trials were established in pure, even-aged stands (15–30 years old) of lodgepole pine in the interior of British Columbia. One of the trials (No. 2, Gregg Creek) was inadvertently aerially fertilized with a N+S blended fertilizer in the fall of 1989, 1 year after trial establishment. Therefore, tree growth and foliar nutrient data from only six of the original seven study locations are included in this paper.

The six stands exhibited uniform densities ranging from approximately 1100 to 2200 stems/ha. Two of the stands were planted, and the four naturally regenerated stands had been previously thinned. Five of the trials are located on mesic to submesic sites within various subzones of the Sub-Boreal Spruce biogeoclimatic zone in the north-central interior (Banner et al. 1993; DeLong et al. 1993; DeLong 2003). Previous studies in the Sub-Boreal Spruce zone indicated variable growth responses to N fertilization, likely attributable to the negative impact of N additions on foliar S status on some sites (Brockley 1989, 1990). The remaining trial is located in the Montane Spruce biogeoclimatic zone in the southeast interior (Braumandl and Curran 1992). Results from previous fertilization research in the Montane Spruce zone indicated favourable growth responses to N fertilization and no S deficiency (Brockley 1989). As indicated in Table 1, the initial foliar N status of trees at the six study sites ranged from severe N deficiency to sufficiency (Ballard and Carter 1986; Brockley 2001*b*). Prefertilization foliar S status ranged from moderate S deficiency to sufficiency, based on diagnostic criteria using foliar N/S ratios and $SO_4$ levels to evaluate S status of conifers (Turner et al. 1977; Ballard and Carter 1986; Brockley 2000, 2001*b*). Other plant nutrients were generally well supplied. Additional details regarding location, site, and stand characteristics are provided in Table 2.

**Table 2.** Location, ecological classification, and site and stand characteristics of study sites.

| Trial No. | Location | Latitude | Longitude | Stand age at establishment (years) | Biogeoclimatic subzone | Site series | Parent material | Soil texture | Year thinned | At trial establishment DBH[a] (cm) | Height[a] (m) | Density (stems/ha) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Bowron River | 53°30′20″N | 122°00′30″W | 18 | SBSwk1[b] | 03[b] | Glaciofluvial | LS | — | 11.1 | 8.0 | 1600 |
| 3 | Meadow Lake | 53°26′00″N | 123°33′30″W | 30 | SBSdw2[c] | 01[c] | Glacial till | SL | 1981 | 9.4 | 9.6 | 2200 |
| 4 | Tsus Creek | 53°45′45″N | 121°50′24″W | 26 | SBSwk1[b] | 03[b] | Glaciofluvial | LS | 1979 | 9.4 | 9.2 | 2200 |
| 5 | Cobb Lake | 53°57′20″N | 123°34′35″W | 15 | SBSdw3[c] | 01[c] | Glacial till | SL | 1988 | 5.4 | 4.7 | 1440 |
| 6 | Andrew Bay | 53°47′47″N | 126°43′06″W | 18 | SBSmc2[d] | 01[d] | Glaciofluvial | LS | — | 11.2 | 6.6 | 1050 |
| 7 | Gold Creek | 49°18′40″N | 115°31′55″W | 27 | MSdk[e] | 04[e] | Glacial till | Sil | 1979 | 12.7 | 9.9 | 1100 |

**Note:** SBS, Sub-Boreal Spruce biogeoclimatic zone; wk, wet cool subzone; dw, dry warm subzone; mc, moist cold subzone; MSdk, Montane Spruce biogeoclimatic zone dry cool subzone; LS, loamy sand; SL, sandy loam; sil, silt loam.

[a]Mean DBH and height of "plot" trees at trial establishment.

[b]From DeLong (2003).

[c]From DeLong et al. (1993).

[d]From Banner et al. (1993).

[e]From Braumandl and Curran (1992).

## Experimental design

At each study location, parallel grid lines were systematically laid out at 20-m intervals throughout the stand, with sampling points marked every 20 m along the lines. At each sampling point, an attempt was made to select a nearby healthy, dominant lodgepole pine "plot" tree. Sampling points that were unsuitable because of stand or site irregularities were discarded. A deliberate attempt was made to select trees that were similar in both diameter at breast height (DBH) and total height at each sampling point. A minimum distance of 15 m separated adjacent selected trees. Similar techniques, using various replicated single-tree or "mini" research plot designs, have been used with considerable success to rapidly identify nutrient deficiencies and to evaluate the fertilizer response potential of various species in the interior of British Columbia (Weetman and Fournier 1982; Brockley 1990, 1995; Swift and Brockley 1994).

Each of nine treatments was applied to 15 of the single-tree plots in a completely randomized design. Nitrogen was applied at a rate of 200 kg/ha alone or in combination with different sources and application rates of S. Two types of S, elemental S ($S^0$) in the form of a degradable $S^0$ – sodium bentonite prill (0:0:0:90, N–P–K–S) and sulphate S as ammonium sulphate (AS) (21:0:0:24, N–P–K–S) crystals, were applied at rates of 50 kg/ha (50S) and 100 kg/ha (100S). Nitrogen was applied as a mixture of agricultural grade urea (46:0:0, N–P–K) prills and AS, or as urea and ammonium chloride (AC) (26:0:0, N–P–K) crystals. Ammonium chloride was used as a substitute for the ammoniacal N in the AS and was used at two different ratios in N-only treatments ($N_1$: 156 kg N/ha as urea and 44 kg N/ha as AC; $N_2$: 112 kg N/ha as urea and 88 kg N/ha as AC) to test for growth differences attributable to N source. On N-deficient agricultural soils, applications of S alone rarely increase crop or seed yields in the absence of added N (Nyborg 1968; Nyborg and Bentley 1971; Janzen and Bettany 1984). As such, and given the widespread N deficiencies that have been documented in lodgepole pine forests in the British Columbia interior, S-only treatments were not included in this study. The complete set of treatments was as follows:

(1) unfertilized control
(2) $N_1$ (156 kg N/ha as urea and 44 kg N/ha as AC)
(3) $N_2$ (112 kg N/ha as urea and 88 kg N/ha as AC)
(4) N (156 kg N/ha as urea and 44 kg N/ha as AS) + 50S (as AS)
(5) N (112 kg N/ha as urea and 88 kg N/ha as AS) + 100S (as AS)
(6) N (156 kg N/ha as urea and 44 kg N/ha as AC) + 50S (as $S^0$)
(7) N (112 kg N/ha as urea and 88 kg N/ha as AC) + 100S (as $S^0$)
(8) N (156 kg N/ha as urea, 22 kg N/ha as AC, and 22 kg N/ha as AS) + 50S (25 kg S/ha as AS and 25 kg S/ha as $S^0$)
(9) N (112 kg N/ha as urea, 44 kg N/ha as AC, and 44 kg N/ha as AS) + 100S (50 kg S/ha as AS and 50 kg S/ha as $S^0$)

## Fertilizer application

At each study site, fertilizer was applied to a 5-m-radius area (0.0079 ha) surrounding each selected tree, during the

**Table 3.** Mean basal area ($cm^2$/tree) and height (m/tree) increment by trial and treatment for the 6-year period following fertilization.

| | Trial No. | | | | | |
|---|---|---|---|---|---|---|
| Treatment | 1 | 3 | 4 | 5 | 6 | 7 |
| **Basal area** | | | | | | |
| Control | 55.1 (100) | 33.0 (100) | 33.6 (100) | 34.2 (100) | 96.6 (100) | 40.5 (100) |
| $200N_1$ | 61.0 (111) | 39.0 (118) | 43.7 (130) | 38.7 (113) | 105.7 (109) | 60.4 (149) |
| $200N_2$ | 65.5 (119) | 36.9 (112) | 44.8 (133) | 38.0 (111) | 106.9 (111) | 52.6 (130) |
| 200N + 50S (AS) | 67.7 (123) | 43.0 (130) | 50.6 (151) | 47.9 (140) | 99.1 (103) | 59.1 (146) |
| 200N + 100S (AS) | 65.3 (118) | 48.9 (148) | 48.7 (145) | 48.2 (141) | 111.7 (116) | 60.1 (148) |
| 200N + 50S ($S^0$) | 67.8 (123) | 44.4 (135) | 47.7 (142) | 46.5 (136) | 104.1 (108) | 61.8 (153) |
| 200N + 100S ($S^0$) | 70.2 (127) | 39.1 (118) | 43.7 (130) | 51.4 (150) | 100.7 (104) | 47.1 (116) |
| 200N + 50S (AS+$S^0$) | 68.7 (125) | 44.3 (134) | 45.1 (134) | 47.0 (137) | 104.1 (108) | 49.8 (123) |
| 200N + 100S (AS+$S^0$) | 63.5 (115) | 40.3 (122) | 41.7 (124) | 46.6 (136) | 102.5 (106) | 51.7 (128) |
| LSD ($p$ = 0.05) | 8.9 | 6.8 | 8.3 | 6.2 | 13.6 | 9.3 |
| **Height** | | | | | | |
| Control | 2.54 (100) | 2.75 (100) | 2.53 (100) | 2.07 (100) | 2.77 (100) | 2.20 (100) |
| $200N_1$ | 2.84 (112) | 2.79 (101) | 2.45 (97) | 2.11 (102) | 2.51 (90) | 2.40 (109) |
| $200N_2$ | 2.83 (111) | 2.36 (86) | 2.49 (98) | 1.96 (95) | 2.70 (97) | 2.46 (112) |
| 200N + 50S (AS) | 2.68 (106) | 2.83 (103) | 2.91 (115) | 2.28 (110) | 2.43 (88) | 2.47 (112) |
| 200N + 100 (AS) | 2.77 (109) | 2.97 (108) | 2.85 (113) | 2.37 (114) | 2.66 (96) | 2.39 (109) |
| 200N + 50S ($S^0$) | 2.69 (106) | 2.64 (96) | 2.63 (104) | 2.11 (102) | 2.61 (94) | 2.43 (110) |
| 200N + 100S ($S^0$) | 2.58 (102) | 2.66 (97) | 2.78 (110) | 2.38 (115) | 2.65 (96) | 2.36 (107) |
| 200N + 50S (AS+$S^0$) | 2.56 (101) | 2.89 (105) | 2.68 (106) | 2.56 (124) | 2.73 (99) | 2.13 (97) |
| 200N + 100S (AS+$S^0$) | 2.79 (110) | 2.80 (102) | 2.95 (117) | 2.42 (117) | 2.63 (95) | 2.36 (107) |
| LSD ($p$ = 0.05) | 0.32 | 0.27 | 0.41 | 0.37 | 0.35 | 0.36 |

**Note:** For each trial, values in parentheses indicate percent response relative to control ($N$ = 15 for each treatment). All values are adjusted by covariance analysis. N, nitrogen; S, sulphur; AS, ammonium sulphate; $S^0$, elemental sulphur; $N_1$, 78% N as urea and 22% N as ammonium chloride; $N_2$, 56% N as urea and 44% N as ammonium chloride. Values preceding the nutrients indicate the amount of nutrient applied in kilograms per hectare. LSD, least significant difference test.

fall of the year of trial establishment. Before fertilization, each plot was divided into four pie-shaped segments to facilitate uniform application. Premeasured amounts of the specified fertilizers were applied by hand within each segment.

### Measurement

At the time of establishment and again after 6 years, the DBH and total height of all 135 plot trees at each study site were measured. None of the other lodgepole pine trees within the 5-m-radius fertilized area surrounding each plot tree were measured. Diameter measurements were taken with a steel diameter tape at a permanently marked point approximately 1.30 m above the ground. Heights were measured with a telescoping height pole or with an electronic measuring device (Criterion 400® survey laser or Forestor Vertex® hypsometer).

### Foliar analysis

At all study sites, samples of current-year's foliage were collected from two lateral branches within the upper one-third of the live crown of each plot tree immediately prior to fertilization and in the fall after one, two, and three growing seasons. Samples were frozen prior to oven-drying at 70 °C for 16–24 h. For prefertilization sampling, one composite foliage sample per treatment was prepared for total chemical analysis, each composite consisting of equal amounts of foliage from each of the 15 trees. For all other sampling years, three composite foliage samples per treatment were prepared, each sample consisting of equal amounts of foliage from five of the trees. Composite samples were ground in an electric coffee grinder prior to shipment to a commercial laboratory for chemical analysis. The same laboratory was used for all sample years.

Composite samples were digested using a variation of the sulphuric acid – hydrogen peroxide procedure described by Parkinson and Allen (1975). The digests were analyzed colorimetrically for N using the Berthelot (phenol-hypochlorite) reaction (Weatherburn 1967) in a Technicon Autoanalyzer II. Total S was determined by combustion with a Leco SC-132 sulphur analyzer, using the procedures of Guthrie and Lowe (1984). Inorganic $SO_4$-S was extracted with 0.1 mol/L HCl (1 g foliage per 20 mL of HCl boiled for 20 min) followed by hydriodic acid reduction of the extract and bismuth colorimetry using the procedure of Johnson and Nishita (1952). Methodologies for the digestion and determination of other nutrients were the same as those reported by Brockley and Sheran (1994).

### Data analysis

For each installation, the effects of fertilization on individual-tree basal area (BA) and height increments and on foliar nutrient concentrations and ratios were subjected to analysis of variance (ANOVA) using the general linear model procedure (SAS Institute Inc. 1989). Basal area and height increments were calculated for all trees alive after 6 years and were adjusted by covariance analysis, using initial BA and height, respectively, as the covariates. For tree growth and foliar variables, a set of orthogonal contrasts was

**Table 4.** ANOVA summary table for 6-year basal area and height increment by trial showing variance ratios ($F$), $p$ values, and error mean squares.

| | | Trial No. | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | | 3 | | 4 | | 5 | | 6 | | 7 | |
| Source of variation | df | $F$ | $p > F$ | $F$ | $p > F$ | $F$ | $p > F$ | $F$ | $p > F$ | $F$ | $p > F$ | $F$ | $p > F$ |
| **Basal area** | | | | | | | | | | | | | |
| Treatment | 8 | 2.09 | 0.041 | 3.72 | <0.001 | 2.60 | 0.011 | 6.56 | <0.001 | 0.84 | 0.566 | 4.58 | <0.001 |
| Control vs. N | 1 | 4.21 | 0.042 | 2.69 | 0.103 | 8.03 | 0.005 | 2.19 | 0.142 | 2.56 | 0.112 | 15.12 | <0.001 |
| $N_1$ vs. $N_2$ | 1 | 0.98 | 0.325 | 0.36 | 0.547 | 0.07 | 0.796 | 0.04 | 0.842 | 0.03 | 0.862 | 2.65 | 0.106 |
| N vs. N+S | 1 | 2.21 | 0.139 | 7.48 | 0.007 | 0.72 | 0.399 | 25.22 | <0.001 | 0.43 | 0.515 | 0.32 | 0.573 |
| AS vs. $S^0$ | 1 | 0.63 | 0.430 | 2.90 | 0.091 | 1.63 | 0.204 | 0.16 | 0.692 | 0.38 | 0.536 | 2.32 | 0.131 |
| 50S vs. 100S | 1 | 0.43 | 0.514 | 0.36 | 0.550 | 1.56 | 0.213 | 0.72 | 0.398 | 0.42 | 0.520 | 2.05 | 0.155 |
| S source × S rate | 1 | 0.58 | 0.449 | 5.43 | 0.021 | 0.12 | 0.725 | 1.04 | 0.310 | 2.73 | 0.101 | 5.40 | 0.022 |
| Error mean square | 126 | 151.9 | | 88.1 | | 133.2 | | 74.4 | | 353.9 | | 164.3 | |
| **Height** | | | | | | | | | | | | | |
| Treatment | 8 | 0.99 | 0.446 | 3.22 | 0.002 | 1.60 | 0.132 | 2.23 | 0.030 | 0.75 | 0.646 | 0.78 | 0.621 |
| Control vs. N | 1 | 4.24 | 0.042 | 2.15 | 0.145 | 0.11 | 0.742 | 0.05 | 0.829 | 1.25 | 0.266 | 2.20 | 0.141 |
| $N_1$ vs. $N_2$ | 1 | 0.01 | 0.925 | 9.28 | 0.003 | 0.05 | 0.830 | 0.51 | 0.475 | 1.13 | 0.290 | 0.10 | 0.756 |
| N vs. N + S | 1 | 2.67 | 0.105 | 7.54 | 0.007 | 7.58 | 0.007 | 8.08 | 0.005 | 0.02 | 0.885 | 0.48 | 0.490 |
| AS vs. $S^0$ | 1 | 0.59 | 0.443 | 6.38 | 0.013 | 1.40 | 0.239 | 0.35 | 0.554 | 0.47 | 0.495 | 0.06 | 0.807 |
| 50S vs. 100S | 1 | 0.53 | 0.468 | 0.08 | 0.778 | 1.00 | 0.318 | 0.49 | 0.485 | 0.34 | 0.562 | 0.05 | 0.832 |
| S source × S rate | 1 | 0.75 | 0.389 | 0.37 | 0.544 | 0.50 | 0.482 | 0.44 | 0.509 | 0.58 | 0.448 | 0.00 | 0.980 |
| Error mean square | 126 | 0.198 | | 0.144 | | 0.320 | | 0.259 | | 0.230 | | 0.246 | |

**Note:** N, nitrogen; S, sulphur; AS, ammonium sulphate; $S^0$, elemental S; $N_1$, 78% N as urea and 22% N as ammonium chloride; $N_2$, 56% N as urea and 44% N as ammonium chloride.

**Table 5.** Mean foliar nitrogen concentration (g/kg) 1, 2, and 3 years following fertilization by trial and treatment.

| Treatment | Trial No. 1 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|
| **Year 1** | | | | | | |
| Control | 13.7 | 10.5 | 12.3 | 11.9 | 11.3 | 9.3 |
| $200N_1$ | 19.5 | 15.4 | 17.3 | 18.7 | 15.7 | 13.4 |
| $200N_2$ | 19.7 | 17.9 | 17.9 | 19.4 | 16.6 | 14.5 |
| 200N + 50S (AS) | 16.6 | 14.9 | 15.6 | 15.0 | 14.3 | 14.2 |
| 200N + 100S (AS) | 17.6 | 15.0 | 16.5 | 15.5 | 13.8 | 14.5 |
| 200N + 50S ($S^0$) | 18.8 | 17.2 | 17.9 | 18.9 | 13.8 | 14.2 |
| 200N + 100S ($S^0$) | 19.6 | 18.3 | 17.4 | 17.2 | 15.7 | 14.7 |
| 200N + 50S (AS + $S^0$) | 19.2 | 15.6 | 15.6 | 15.7 | 14.3 | 14.4 |
| 200N + 100S (AS + $S^0$) | 18.9 | 15.7 | 16.7 | 16.2 | 15.2 | 15.0 |
| LSD ($p$ = 0.05) | 1.8 | 1.8 | 1.5 | 1.9 | 2.5 | 1.5 |
| **Year 2** | | | | | | |
| Control | 13.3 | 11.6 | 11.2 | 12.4 | 11.4 | 12.1 |
| $200N_1$ | 14.5 | 13.4 | 14.6 | 17.2 | 12.7 | 12.7 |
| $200N_2$ | 15.2 | 14.1 | 15.5 | 18.3 | 12.5 | 13.2 |
| 200N + 50S (AS) | 14.6 | 12.0 | 13.3 | 13.3 | 12.6 | 12.6 |
| 200N + 100S (AS) | 15.3 | 12.3 | 13.4 | 13.4 | 12.7 | 13.4 |
| 200N + 50S ($S^0$) | 14.3 | 11.8 | 13.6 | 13.3 | 14.2 | 12.5 |
| 200N + 100S ($S^0$) | 15.0 | 11.8 | 13.0 | 14.1 | 15.1 | 14.0 |
| 200N + 50S (AS + $S^0$) | 15.0 | 11.0 | 11.9 | 13.4 | 13.5 | 12.6 |
| 200N + 100S (AS + $S^0$) | 15.3 | 11.4 | 12.1 | 13.6 | 14.3 | 12.8 |
| LSD ($p$ = 0.05) | 0.9 | 1.5 | 1.3 | 1.5 | 1.0 | 1.7 |
| **Year 3** | | | | | | |
| Control | 11.7 | 10.2 | 11.8 | 14.0 | 10.7 | 9.3 |
| $200N_1$ | 12.2 | 10.0 | 12.9 | 15.6 | 11.7 | 10.0 |
| $200N_2$ | 12.3 | 10.5 | 13.2 | 15.3 | 11.3 | 10.7 |
| 200N + 50S (AS) | 12.4 | 10.1 | 12.2 | 13.2 | 11.5 | 9.3 |
| 200N + 100S (AS) | 12.6 | 10.0 | 13.2 | 13.6 | 11.5 | 9.9 |
| 200N + 50S ($S^0$) | 11.8 | 10.0 | 13.0 | 12.7 | 11.7 | 10.4 |
| 200N + 100S ($S^0$) | 12.2 | 9.6 | 13.5 | 13.2 | 12.8 | 11.0 |
| 200N + 50S (AS + $S^0$) | 12.0 | 9.7 | 12.9 | 12.4 | 11.0 | 10.5 |
| 200N + 100S (AS + $S^0$) | 13.3 | 10.3 | 12.8 | 12.2 | 11.8 | 10.5 |
| LSD ($p$ = 0.05) | 1.1 | 0.8 | 1.0 | 1.4 | 0.9 | 0.9 |

**Note:** N, nitrogen; S, sulphur; AS, ammonium sulphate; $S^0$, elemental sulphur; $N_1$, 78% N as urea and 22% N as ammonium chloride; $N_2$, 56% N as urea and 44% N as ammonium chloride. Values preceding the nutrients indicate the amount of nutrient applied in kilograms per hectare. LSD, least significant difference test.

**Table 6.** Mean foliar sulphur concentration (g/kg) 1, 2, and 3 years following fertilization by trial and treatment.

| Treatment | Trial No. 1 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|
| **Year 1** | | | | | | |
| Control | 0.95 | 0.88 | 0.92 | 0.91 | 0.98 | 0.93 |
| $200N_1$ | 0.85 | 0.75 | 0.87 | 0.73 | 0.92 | 0.88 |
| $200N_2$ | 0.82 | 0.80 | 0.83 | 0.75 | 0.90 | 0.88 |
| 200N + 50S (AS) | 0.94 | 1.12 | 1.06 | 1.21 | 0.99 | 0.99 |
| 200N + 100S (AS) | 1.00 | 1.17 | 1.09 | 1.21 | 1.01 | 1.02 |
| 200N + 50S ($S^0$) | 0.83 | 0.79 | 0.96 | 0.85 | 0.85 | 0.94 |
| 200N + 100S ($S^0$) | 0.86 | 0.77 | 0.95 | 0.87 | 0.92 | 1.00 |
| 200N + 50S (AS + $S^0$) | 0.95 | 1.00 | 0.95 | 1.03 | 0.89 | 0.97 |
| 200N + 100S (AS + $S^0$) | 1.07 | 1.05 | 1.04 | 1.20 | 0.96 | 1.00 |
| LSD ($p$ = 0.05) | 0.06 | 0.07 | 0.05 | 0.07 | 0.08 | 0.11 |
| **Year 2** | | | | | | |
| Control | 0.99 | 0.81 | 0.80 | 1.02 | 0.87 | 0.90 |
| $200N_1$ | 0.85 | 0.59 | 0.67 | 0.78 | 0.78 | 0.82 |
| $200N_2$ | 0.84 | 0.75 | 0.70 | 0.79 | 0.81 | 0.82 |
| 200N + 50S (AS) | 1.06 | 0.88 | 0.88 | 1.17 | 0.95 | 0.81 |
| 200N + 100S (AS) | 1.06 | 0.89 | 0.89 | 1.14 | 0.90 | 0.95 |
| 200N + 50S ($S^0$) | 0.90 | 0.66 | 0.81 | 1.11 | 0.93 | 0.87 |
| 200N + 100S ($S^0$) | 0.95 | 0.67 | 0.86 | 1.19 | 1.02 | 0.94 |
| 200N + 50S (AS + $S^0$) | 0.96 | 0.77 | 0.86 | 1.06 | 0.94 | 0.95 |
| 200N + 100S (AS + $S^0$) | 1.06 | 0.87 | 0.93 | 1.28 | 0.97 | 0.97 |
| LSD ($p$ = 0.05) | 0.10 | 0.15 | 0.06 | 0.12 | 0.12 | 0.10 |
| **Year 3** | | | | | | |
| Control | 0.82 | 0.77 | 0.95 | 0.90 | 0.92 | 0.80 |
| $200N_1$ | 0.73 | 0.63 | 0.72 | 0.74 | 0.86 | 0.78 |
| $200N_2$ | 0.66 | 0.63 | 0.74 | 0.68 | 0.81 | 0.78 |
| 200N + 50S (AS) | 0.89 | 0.82 | 0.87 | 0.97 | 0.91 | 0.80 |
| 200N + 100S (AS) | 0.96 | 0.78 | 0.98 | 1.03 | 0.92 | 0.85 |
| 200N + 50S ($S^0$) | 0.79 | 0.70 | 0.91 | 1.06 | 0.92 | 0.95 |
| 200N + 100S ($S^0$) | 0.90 | 0.69 | 0.93 | 1.21 | 0.97 | 0.95 |
| 200N + 50S (AS + $S^0$) | 0.87 | 0.79 | 0.92 | 1.01 | 0.91 | 0.87 |
| 200N + 100S (AS + $S^0$) | 1.00 | 0.80 | 1.00 | 1.14 | 1.07 | 0.90 |
| LSD ($p$ = 0.05) | 0.08 | 0.08 | 0.10 | 0.11 | 0.11 | 0.09 |

**Note:** N, nitrogen; S, sulphur; AS, ammonium sulphate; $S^0$, elemental sulphur; $N_1$, 78% N as urea and 22% N as ammonium chloride; $N_2$, 56% N as urea and 44% N as ammonium chloride. Values preceding the nutrients indicate the amount of nutrient applied in kilograms per hectare. LSD, least significant difference test.

used to test the main effects of S source and S application rate as well as the S source × S rate interaction effects. Additional single degree of freedom contrasts were selected to answer specific a priori questions (Milliken and Johnson 1984). A level of significance of $\alpha = 0.05$ is used throughout the text for inferring statistical significance.

## Results

### Basal area

The effects of fertilization on mean 6-year BA increment for individual trials are shown in Tables 3 and 4. Treatment effects were statistically significant in five of the six trials. In no case was the effect of N source (i.e., the different proportions of urea and ammonium chloride used in treatments 2 and 3) statistically significant ($N_1$ vs. $N_2$; Table 4).

Overall, BA responses relative to unfertilized trees averaged 18% and 24%, for the N and N+S treatments, respectively (Table 3). The differences in BA increment between N and N+S treatments were statistically significant in two trials (Nos. 3 and 5; Table 4). Fertilization with N alone was not effective in stimulating BA increment at either of these two study sites. Basal area responses relative to unfertilized trees in these two trials averaged 13% and 36%, for N and

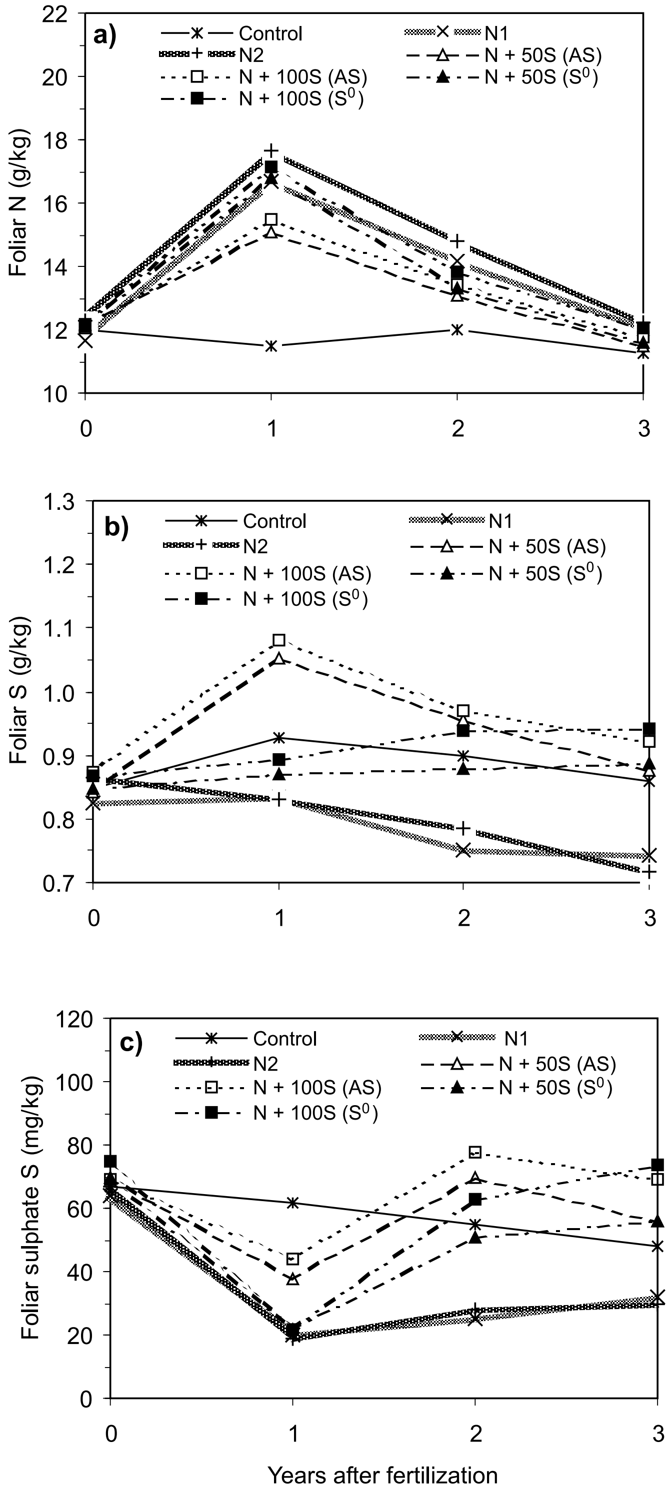



**Fig. 1.** The effects of nitrogen, alone and in combination with different sources and rates of sulphur, on (*a*) foliar nitrogen concentration, (*b*) foliar total sulphur concentration, and (*c*) sulphate sulphur concentration for the 3-year period following fertilization. For year 0, each plotted point represents the mean of six composite foliage samples (six trials × one composite sample per trial). For all other years, each plotted point represents the mean of 18 composite samples (six trials × three composite samples per trial). Control, unfertilized; $N_1$, 78% N as urea and 22% N as ammonium chloride; $N_2$, 56% N as urea and 44% N as ammonium chloride; 50S, 50 kg S/ha; 100S, 100 kg S/ha; AS, ammonium sulphate; $S^0$, elemental sulphur.

N+S treatments, respectively. Radial growth response was significantly improved by fertilization with N alone at three of the other study sites (Nos. 1, 4, and 7), and incremental gains between N and N+S were not significant (Table 4). One trial did not respond significantly to any of the fertilizer treatments (No. 6).

In no case was the effect of S source or S application rate statistically significant (Table 4). In two trials (Nos. 3 and 7), however, the S source × S rate interaction was statistically significant (i.e., the relative effectiveness of S application rate varied differentially with S source). In both cases, 100 kg S/ha resulted in greater BA increment than 50 kg S/ha when S was applied as ammonium sulphate (AS). Conversely, BA increment was inversely related to S application rate where $S^0$ was applied (Table 3).

### Height

The effects of fertilization on mean 6-year height increment for individual trials are shown in Tables 3 and 4. Treatment effects were statistically significant in only two of the six trials. Differences in height increment between the two N sources ($N_1$ and $N_2$) were generally small and were statistically significant at only one study site (No. 3).

The differences in height increment between N and N+S treatments were statistically significant in three trials (Nos. 3, 4, and 5; Table 4). In these trials, fertilization with N alone often resulted in a slight negative height response, whereas a modest positive response was usually obtained when S was combined with N (Table 3).

The effect of S source was statistically significant in one trial (No. 3; Table 4). In this case, fertilization with AS resulted in a small positive height response, whereas $S^0$ additions caused a slightly negative height increment (Table 3).

### Foliar nitrogen

The effects of fertilization on mean foliar N concentration by treatment and year for each of the individual trials are shown in Table 5. These effects (averaged over all six trials) are illustrated in Fig. 1*a*. At each study site, foliar N levels in all fertilized treatments increased sharply in year 1 and declined gradually thereafter. By year 3, however, treatment effects remained statistically significant in four of the six trials (data not shown).

Except for N+$S^0$ treatments in year 1, mean foliar N concentrations were often slightly lower in trees fertilized with N+S than in those fertilized with N alone in each of the 3 years following fertilization (Fig. 1*a*). However, by year 3, these differences remained statistically significant in only one installation (data not shown).

Although statistically significant in only one installation (No. 3 in year 1), foliar N levels in the $N_2$ treatment (112 kg N/ha as urea and 88 kg N/ha as AC) were almost always slightly higher than N levels in the $N_1$ treatment (156 kg N/ha as urea and 44 kg N/ha as AC) in years 1 and 2 following fertilization.

**Table 7.** ANOVA summary table for foliar sulphur concentration 1 year following fertilization by trial showing variance ratios ($F$), $p$ values, and error mean squares.

| | | Trial No. | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | | 3 | | 4 | | 5 | | 6 | | 7 | |
| Source of variation | df | $F$ | $p>F$ | $F$ | $p>F$ | $F$ | $p>F$ | $F$ | $p>F$ | $F$ | $p>F$ | $F$ | $p>F$ |
| Treatment | 8 | 18.29 | <0.001 | 53.91 | <0.001 | 28.26 | <0.001 | 67.73 | <0.001 | 3.48 | 0.013 | 1.94 | 0.116 |
| Control vs. N | 1 | 21.08 | <0.001 | 16.42 | <0.001 | 13.93 | 0.001 | 32.54 | <0.001 | 3.94 | 0.063 | 0.98 | 0.336 |
| $N_1$ vs. $N_2$ | 1 | 1.45 | 0.244 | 2.89 | 0.106 | 3.49 | 0.078 | 0.35 | 0.561 | 0.27 | 0.612 | 0.00 | 0.950 |
| N vs. N + S | 1 | 41.85 | <0.001 | 136.06 | <0.001 | 144.67 | <0.001 | 267.08 | <0.001 | 1.19 | 0.289 | 11.97 | 0.003 |
| AS vs. $S^0$ | 1 | 39.75 | <0.001 | 271.14 | <0.001 | 53.50 | <0.001 | 223.52 | <0.001 | 16.09 | 0.001 | 0.89 | 0.359 |
| 50S vs. 100S | 1 | 17.42 | <0.001 | 1.51 | 0.235 | 7.49 | 0.013 | 11.33 | 0.003 | 5.67 | 0.028 | 1.74 | 0.204 |
| S source × S rate | 1 | 0.73 | 0.405 | 2.49 | 0.132 | 0.66 | 0.427 | 0.18 | 0.680 | 0.95 | 0.344 | 0.10 | 0.757 |
| Error mean square | 18 | 0.001 | | 0.001 | | 0.001 | | 0.002 | | 0.002 | | 0.004 | |

**Note:** N, nitrogen; S, sulphur; AS, ammonium sulphate; $S^0$, elemental S; $N_1$, 78% N as urea and 22% N as ammonium chloride; $N_2$, 56% N as urea and 44% N as ammonium chloride.

## Foliar total sulphur

The effects of fertilization on mean foliar S concentration by treatment and year for each of the individual trials are shown in Table 6. These effects (averaged over all six trials) are illustrated in Fig. 1*b*. Fertilization had a large impact on S levels in current-year's foliage for the 3-year period following fertilization. As shown in Table 6 and Fig. 1*b*, fertilization with N alone caused foliar S levels to decline relative to S levels in unfertilized foliage. The difference in foliar S concentration between control and N-only treatments was statistically significant in four of six trials after 1 year (Table 7). At these four study sites, these differences remained statistically significant 3 years after fertilization.

The difference in foliar S concentration between N-only and N+S treatments was large and prolonged (Table 6; Fig. 1*b*). After 1 year, foliar S levels in N+S treatments were significantly higher than those in N-only treatments in five of the six trials (Table 7). After 3 years, foliar S levels in N+S treatments were significantly higher than those in N-only treatments at all six study sites (data not shown).

Temporal patterns of foliar S response varied significantly with S source. When applied as AS, foliar S levels generally increased sharply in year 1 and slowly declined over the next 2 years (Table 6; Fig. 1*b*). Conversely, additions of $S^0$ usually did not increase foliar S concentration in year 1, but had increasingly positive effects on foliar S in years 2 and 3. Ammonium sulphate was clearly superior to $S^0$ at increasing first-year foliar S concentration, with statistically significant differences between AS and $S^0$ in five of the six trials (Table 7). However, neither S source was consistently superior by year 3, when the effect of S source (AS vs. $S^0$) was statistically significant in four of six trials (data not shown). In two installations, foliar S levels were significantly higher in AS treatments than in $S^0$ treatments. In contrast, $S^0$ gave higher foliar S levels than AS in the other two trials. Combined applications of AS + $S^0$ usually resulted in foliar S levels that were between those of AS and $S^0$ (Table 6).

An increase in the S application rate from 50 to 100 kg/ha usually resulted in a modest improvement in foliar S for individual S sources and combined sources during each of the 3 years following fertilization (Table 6; Fig. 1*b*). In year 1 (also in years 2 and 3), the effect of S application rate was statistically significant in four of six trials (Table 7). In no case was the sulphur source × S rate interaction statistically significant.

## Foliar sulphate sulphur

The effects of fertilization on mean foliar inorganic $SO_4$ concentration by treatment and year for each of the individual trials are shown in Table 8. These effects (averaged over all six trials) are illustrated in Fig. 1*c*. Fertilization generally resulted in a steep decline in foliar $SO_4$ levels 1 year after fertilization, especially when N was added alone or in combination with $S^0$ (Table 8; Fig. 1*c*). However, whereas foliar $SO_4$ levels in N-only treatments remained low in subsequent years, the amount of $SO_4$ in S-fertilized trees usually increased sharply in years 2 and 3. On average, foliar $SO_4$ levels were higher in AS than in $S^0$ treatments in years 1 and 2. For individual trials, the effect of S source was statistically significant in three of six installations in both years 1 and 2 (data not shown). Overall, the effect of S source on foliar $SO_4$ had largely disappeared by year 3 (Table 8; Fig. 1*c*). Sulphate levels remained significantly higher in AS than in $S^0$ treatments in two trials (Nos. 1 and 3). However, $SO_4$ levels were higher in $S^0$ than in AS treatments in another trial (No. 3).

As with foliar total S, an increase in the S application rate from 50 to 100 kg/ha often resulted in higher foliar $SO_4$ levels during the 3 years following fertilization (Table 8; Fig. 1*c*). In fact, the effect of S application rate became stronger over time, and by year 3, it was statistically significant in five of six installations (data not shown).

## Foliar nitrogen/sulphur ratio

The effects of fertilization on mean foliar nitrogen/sulphur (N/S) ratio by treatment and year for each of the individual trials are shown in Table 9. The overall effects of S source on foliar N/S ratio (averaged over all six trials) are illustrated in Fig. 2. Fertilization with N alone caused a large, and prolonged, increase in foliar N/S ratio relative to unfertilized trees at most study sites (Table 9; Fig. 2). Foliar N/S differences between N-only and unfertilized trees remained statistically significant in all six installations after 3 years (data not shown).

Ammonium sulphate was much more effective than $S^0$ in maintaining favourable N/S balance in foliage during the

**Table 8.** Mean foliar sulphate sulphur concentration (mg/kg) 1, 2, and 3 years following fertilization by trial and treatment.

| Treatment | Trial No. 1 | 3 | 4 | 5 | 6 | 7 |
|---|---|---|---|---|---|---|
| **Year 1** | | | | | | |
| Control | 57 | 46 | 48 | 39 | 47 | 136 |
| $200N_1$ | 37 | 18 | 15 | 14 | 14 | 24 |
| $200N_2$ | 35 | 15 | 9 | 14 | 18 | 24 |
| 200N + 50S (AS) | 44 | 41 | 15 | 72 | 16 | 37 |
| 200N + 100S (AS) | 53 | 53 | 22 | 72 | 26 | 41 |
| 200N + 50S ($S^0$) | 40 | 18 | 17 | 16 | 20 | 20 |
| 200N + 100S ($S^0$) | 31 | 15 | 20 | 16 | 15 | 35 |
| 200N + 50S (AS + $S^0$) | 33 | 26 | 13 | 22 | 18 | 41 |
| 200N + 100S (AS + $S^0$) | 43 | 37 | 25 | 54 | 28 | 48 |
| LSD ($p$ = 0.05) | 11 | 9 | 10 | 26 | 9 | 26 |
| **Year 2** | | | | | | |
| Control | 41 | 55 | 42 | 52 | 54 | 84 |
| $200N_1$ | 13 | 22 | 22 | 22 | 27 | 44 |
| $200N_2$ | 17 | 46 | 22 | 20 | 29 | 36 |
| 200N + 50S (AS) | 37 | 93 | 33 | 132 | 45 | 81 |
| 200N + 100S (AS) | 48 | 105 | 38 | 130 | 43 | 102 |
| 200N + 50S ($S^0$) | 22 | 24 | 25 | 121 | 31 | 86 |
| 200N + 100S ($S^0$) | 30 | 20 | 31 | 181 | 35 | 77 |
| 200N + 50S (AS + $S^0$) | 28 | 57 | 34 | 99 | 40 | 71 |
| 200N + 100S (AS + $S^0$) | 72 | 90 | 52 | 233 | 42 | 95 |
| LSD ($p$ = 0.05) | 17 | 37 | 12 | 70 | 15 | 33 |
| **Year 3** | | | | | | |
| Control | 60 | 41 | 40 | 30 | 37 | 76 |
| $200N_1$ | 42 | 31 | 20 | 18 | 20 | 61 |
| $200N_2$ | 33 | 37 | 18 | 20 | 25 | 46 |
| 200N + 50S (AS) | 56 | 56 | 35 | 92 | 40 | 59 |
| 200N + 100S (AS) | 64 | 70 | 58 | 92 | 58 | 71 |
| 200N + 50S ($S^0$) | 38 | 31 | 37 | 118 | 40 | 71 |
| 200N + 100S ($S^0$) | 38 | 41 | 46 | 171 | 78 | 71 |
| 200N + 50S (AS + $S^0$) | 47 | 57 | 37 | 83 | 71 | 60 |
| 200N + 100S (AS + $S^0$) | 72 | 65 | 77 | 201 | 73 | 69 |
| LSD ($p$ = 0.05) | 13 | 18 | 17 | 62 | 26 | 25 |

**Note:** N, nitrogen; S, sulphur; AS, ammonium sulphate; $S^0$, elemental sulphur; $N_1$, 78% N as urea and 22% N as ammonium chloride; $N_2$, 56% N as urea and 44% N as ammonium chloride. Values preceding the nutrients indicate the amount of nutrient applied in kilograms per hectare. LSD, least significant difference test.

first year after fertilization (Table 9; Fig. 2). The effect of S source in year 1 was statistically significant in all six trials. However, foliar N/S ratios in $S^0$-fertilized trees declined rapidly thereafter, and by year 3, they were significantly higher than ratios in AS-fertilized foliage in only two trials (Nos. 3 and 5).

Overall, S application rate had little effect on foliar N/S ratio, regardless of S source (Fig. 2). The effect of S rate was statistically significant in only one trial (No. 1) in year 1, one trial (No. 4) in year 2, and two trials (Nos. 1 and 5) in year 3. In each case, N/S ratios were lower in 100 kg S/ha treatments than in 50 kg S/ha treatments (Table 9).

### Other foliar nutrients and nutrient ratios

Averaged over all installations, the effects of fertilization on nonadded foliar nutrients (i.e., other than N and S) in years 1 and 3 are shown in Table 10. Overall, foliar levels of Ca, Mg, Cu, Zn, and Fe were largely unaffected by fertilization. Additions of N and N+S often had a slightly positive effect on foliar P (especially in N-only treatments). The differences in foliar P levels between unfertilized and N-only treatments were statistically significant in two trials (Nos. 5 and 6) in year 1, three trials in year 2 (Nos. 3, 4, and 5), and one trial (No. 5) in year 3 (data not shown).

Additions of N alone generally had a negative effect on foliar K concentration (Table 10). Foliar K differences between unfertilized and N-only treatments were statistically significant in two trials (Nos. 1 and 5) in each of years 1 and 2 (data not shown). Over the same period, foliar K levels in N+S treatments were significantly higher than those in N-only treatments in three of six trials (Nos. 1, 3, and 5). Foliar K levels were generally higher in AS-fertilized treatments than in $S^0$ treatments. In year 1, the effect of S source was statistically significant in three of six trials (Nos. 3, 4, and 5) (data not shown).

Overall, the effects of fertilization on foliar B were large and prolonged (Table 10). In all six trials, foliar B levels in fertilized trees remained significantly lower than those in unfertilized trees after 3 years (data not shown). In five of six trials, foliar levels in most of the fertilized treatments were <10 mg/kg, indicating possible B deficiency (Ballard and Carter 1986; Brockley 2003).

In all trials, the ratios of foliar N to nonadded macronutrients (e.g., N/P, N/K, N/Mg) increased sharply in fertilized treatments 1 year after treatment, with the highest ratios generally occurring in the N-only and N+$S^0$ treatments (Table 11). The N/P, N/K, and N/Mg ratios were significantly different between the control and N-only treatments at all seven study sites. In year 1, foliar N/P and N/K ratios were significantly higher in N-only treatments than in N+S treatments in three trials (Nos. 1, 3, and 4) and four trials (Nos. 1, 3, 5, and 6), respectively. For foliar N/P and N/K in year 1, the effect of S source was statistically significant in four of six trials (Nos. 1, 3, 4, and 5), with the highest ratios occurring in the $S^0$ treatments (Table 11). All foliar nutrient ratios peaked in year 1 and declined thereafter (Fig. 3). However, foliar N/P and N/K ratios in N-only treatments remained significantly higher than control values in three trials (Nos. 3, 6, and 7) and two trials (Nos. 3 and 5), respectively, after 3 years.

## Discussion

Overall, the effects of N and N+S fertilization on BA increment over 6 years were relatively consistent with the effects on first-year fascicle mass response reported by Brockley and Sheran (1994). As with fascicle mass response, BA treatment effects were statistically significant in five of the six trials. In the remaining trial (No. 6), neither fascicle mass response nor BA response was detected following fertilization. In no case was the effect of N source

**Table 9.** Mean foliar nitrogen/sulphur ratio 1, 2, and 3 years following fertilization by trial and treatment.

| | Trial No. | | | | | |
|---|---|---|---|---|---|---|
| Treatment | 1 | 3 | 4 | 5 | 6 | 7 |
| **Year 1** | | | | | | |
| Control | 14.5 | 11.9 | 13.3 | 13.1 | 11.6 | 10.0 |
| $200N_1$ | 22.9 | 20.6 | 19.9 | 25.5 | 17.1 | 15.2 |
| $200N_2$ | 24.0 | 22.5 | 21.7 | 25.7 | 18.4 | 16.4 |
| 200N + 50S (AS) | 17.7 | 13.3 | 14.7 | 12.4 | 14.5 | 14.4 |
| 200N + 100S (AS) | 17.7 | 12.9 | 15.2 | 12.7 | 13.7 | 14.3 |
| 200N + 50S ($S^0$) | 22.7 | 21.7 | 18.7 | 22.3 | 16.1 | 15.1 |
| 200N + 100S ($S^0$) | 22.9 | 23.9 | 18.3 | 19.9 | 17.0 | 14.9 |
| 200N + 50S (AS + $S^0$) | 20.1 | 15.6 | 16.4 | 15.3 | 16.1 | 14.8 |
| 200N + 100S (AS + $S^0$) | 17.7 | 14.9 | 16.0 | 13.4 | 15.8 | 15.0 |
| LSD ($p$ = 0.05) | 2.0 | 2.4 | 1.7 | 2.1 | 2.8 | 1.9 |
| **Year 2** | | | | | | |
| Control | 13.4 | 14.4 | 14.0 | 12.2 | 13.1 | 13.4 |
| $200N_1$ | 17.0 | 22.9 | 21.7 | 22.1 | 16.4 | 15.4 |
| $200N_2$ | 18.0 | 19.7 | 22.1 | 23.3 | 15.3 | 16.2 |
| 200N + 50S (AS) | 13.8 | 13.7 | 15.1 | 11.4 | 13.3 | 15.6 |
| 200N + 100S (AS) | 14.4 | 14.0 | 15.1 | 11.8 | 14.1 | 14.1 |
| 200N + 50S ($S^0$) | 16.0 | 18.0 | 16.8 | 12.1 | 15.3 | 14.3 |
| 200N + 100S ($S^0$) | 15.8 | 17.7 | 15.1 | 11.9 | 14.8 | 14.9 |
| 200N + 50S (AS + $S^0$) | 15.7 | 14.9 | 13.9 | 12.7 | 14.4 | 13.2 |
| 200N + 100S (AS + $S^0$) | 14.4 | 13.2 | 13.0 | 10.6 | 14.7 | 13.1 |
| LSD ($p$ = 0.05) | 1.2 | 4.9 | 1.5 | 2.1 | 2.1 | 1.4 |
| **Year 3** | | | | | | |
| Control | 14.3 | 13.3 | 12.4 | 15.5 | 11.7 | 11.8 |
| $200N_1$ | 16.7 | 16.0 | 17.8 | 21.2 | 13.7 | 12.8 |
| $200N_2$ | 18.5 | 16.6 | 17.9 | 22.6 | 14.1 | 13.7 |
| 200N + 50S (AS) | 14.0 | 12.4 | 14.0 | 13.6 | 12.6 | 11.7 |
| 200N + 100S (AS) | 13.1 | 12.7 | 13.6 | 13.2 | 12.4 | 11.7 |
| 200N + 50S ($S^0$) | 14.9 | 14.4 | 14.3 | 12.0 | 12.9 | 10.9 |
| 200N + 100S ($S^0$) | 13.5 | 14.0 | 14.4 | 10.9 | 13.2 | 11.6 |
| 200N + 50S (AS + $S^0$) | 13.8 | 12.4 | 14.0 | 12.2 | 12.0 | 12.1 |
| 200N + 100S (AS + $S^0$) | 13.3 | 12.9 | 12.8 | 10.7 | 11.0 | 11.7 |
| LSD ($p$ = 0.05) | 1.5 | 1.4 | 1.2 | 1.7 | 1.5 | 1.3 |

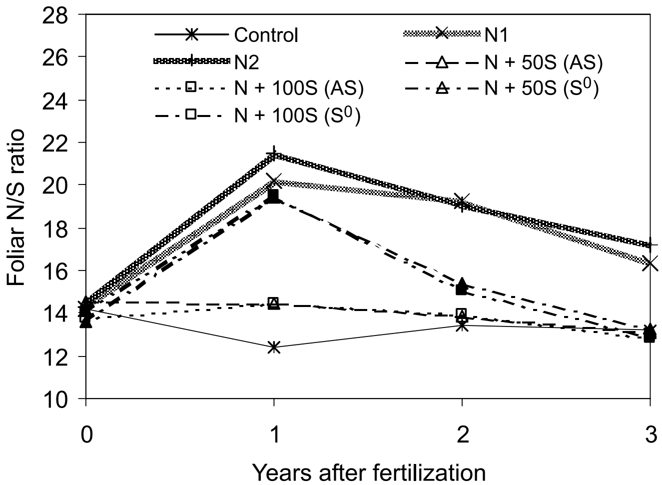
**Note:** N, nitrogen; S, sulphur; AS, ammonium sulphate; $S^0$, elemental sulphur; $N_1$, 78% N as urea and 22% N as ammonium chloride; $N_2$, 56% N as urea and 44% N as ammonium chloride. Values preceding the nutrients indicate the amount of nutrient applied in kilograms per hectare. LSD, least significant difference test.

(i.e., different proportions of urea N and $NH_4$-N) on fascicle mass or 6-year BA increment statistically significant. Therefore, unless there is a significant interaction between N source and one or both of S source and S application rate (which cannot be tested given the makeup of the S fertilizers), differences between N and N+S and between the various N+S treatments can be attributed to S source or application rate rather than to differences in N source.

Sulphur-only treatments were not applied in this study, and as such, it is not possible to differentiate the additive effects of N and S from possible interactions between these two nutrients on BA and height response. Studies with cereal grains and seed crops in western Canada indicate a strong interaction between added N and S (Nyborg 1968; Nyborg and Bentley 1971; Janzen and Bettany 1984). When added alone, neither N nor S was effective in improving yields. However, combined applications of N and S produced large yield increases. In a study with ponderosa pine (*Pinus ponderosa* Dougl. ex P. & C. Laws.) in Oregon, the effects of N and S appeared to be largely additive (Will and Youngberg 1978). Given the widespread occurrence of N deficiencies in lodgepole pine forests in the interior of British Columbia, it seems unlikely that meaningful responses to S additions will be obtained unless N deficiencies are also addressed.

The differences in BA increment between N and N+S treatments were statistically significant in two of the three

**Fig. 2.** The effects of nitrogen, alone and in combination with different sources and rates of sulphur, on foliar nitrogen/sulphur ratio for the 3-year period following fertilization. For year 0, each plotted point represents the mean of six composite foliage samples (six trials × one composite sample per trial). For all other years, each plotted point represents the mean of 18 composite samples (six trials × three composite samples per trial). Control, unfertilized; $N_1$, 78% N as urea and 22% N as ammonium chloride; $N_2$, 56% N as urea and 44% N as ammonium chloride; 50S, 50 kg S/ha; 100S, 100 kg S/ha; AS, ammonium sulphate; $S^0$, elemental sulphur.




trials (Nos. 3 and 5) in which differential fascicle mass responses between N and N+S were reported by Brockley and Sheran (1994). Poor BA growth response to fertilization with N alone in these stands and significant incremental gains from adding S in combination with N were expected given the low prefertilization foliar $SO_4$ levels (<60 mg/kg) and high N/S ratios (>14.6). A constant ratio (0.030 on a gram atom basis) between organic N and organic S has been identified in the foliage of conifers, which corresponds to a mass ratio of total N to organic S of about 14.6 (Kelly and Lambert 1972). Any S in excess of that required to balance foliar N in protein formation (i.e., if the mass ratio of total N to total S is less than 14.6) accumulates in the foliage as inorganic $SO_4$-S. Because the addition of nitrogenous fertilizer to a stand results in partial utilization of the inorganic S reserve, foliar $SO_4$ concentration and N/S mass ratio have been used to diagnose actual and potential S deficiencies in conifers (Lambert and Turner 1977; Turner et al. 1977, 1979; Brockley 2000). A prefertilization $SO_4$ reserve below 80 mg/kg indicates S deficiency in Douglas-fir (*Pseudotsuga menziessi* (Mirb.) Franco) and radiata pine (*Pinus radiata* D. Don) (Turner et al. 1977). Brockley (2000) suggested a slightly lower threshold (60 mg/kg) for lodgepole pine.

Growth response and foliar data from both S-responsive trials (Nos. 3 and 5) clearly indicate that S additions significantly improved foliar S status and the utilization of added N in protein synthesis. Conversely, small first-year fascicle mass and BA responses, combined with high foliar N and N/S levels and minimal $SO_4$, indicate a severe foliar N/S imbalance and poor utilization of foliar N in the N-only treatments at both study sites. Where there is insufficient S to fully utilize added N in protein formation, the surplus N is commonly diverted into soluble nonprotein N-containing compounds (e.g., free amino acids), which possibly provides a mechanism for detoxifying foliar tissue of excess ammonia (Rabe 1990). The estimated portion of foliar total N ($N_T$) used in protein synthesis for any given fertilizer treatment can be crudely estimated by using total S ($S_T$) and $SO_4$ ($S_S$) values to calculate the amount of organic S ($S_O$) ($S_O = S_T - S_S$), and then applying the calculated $S_O$ values to the theoretical $S_O/N_T$ atom ratio ($S_O/N_T \times 0.4365 = 0.030$) reported by Kelly and Lambert (1972). These calculations may help explain BA response differences between N and N+S fertilization, and between S sources, at the two S-responsive (Nos. 3 and 5) sites. For example, the calculated values indicate that only about 66% and 55% of the total foliar N were utilized in protein formation in N-only treatments at Meadow Lake (No. 3) and Cobb Lake (No. 5), respectively, in year 1. The portions of N utilized in the N+$S^0$ treatments at these sites in year 1 were only slightly higher (63% and 68%), which may partially explain the smaller first-year fascicle mass responses in the $S^0$ treatments relative to AS-fertilized trees reported by Brockley and Sheran (1994). Conversely, calculations indicate that the favourable S uptake from N+AS fertilization resulted in complete utilization of of foliar N at both sites in year 1.

Assuming foliar N in unfertilized trees is fully utilized, the $S_O/N_T$ atom ratio and foliar $N_T$ values can be used to calculate expected $S_O$ and $SO_4$ ($S_S$) levels ($S_S = S_T - S_O$). These calculations indicate that the expected foliar $SO_4$ levels in control plots are often higher than the actual reported $SO_4$ values. Differences between estimated and actual $SO_4$ do not necessarily reflect negatively on the accuracy or precision of the methodology used to extract and determine foliar $SO_4$. In fact, the HCl extraction and hydriodic acid reduction methodology used in this study is well developed and standardized (Johnson and Nishita 1952). Also, recent interlaboratory comparisons utilizing identical extraction techniques but different determination methodology (colorimetric vs. ion chromatography) gave virtually identical results (data not shown). Discrepancy between expected and actual $SO_4$ is more likely explained by incomplete recovery of total N in the sulphuric acid – hydrogen peroxide foliage digestion procedure used in this study. Dry combustion analyzers will recover more N than wet oxidation procedures in most plant tissues (Simonne et al. 1994). Oxidized forms such as nitrate ($NO_3$) and nitrite ($NO_2$) are not recovered by wet oxidation of plant tissue unless a predigestion procedure is conducted. Several interlaboratory comparisons undertaken by the author have shown that the sulphuric acid – hydrogen peroxide procedure consistently yields lower N results than total combustion methodology for lodgepole pine foliage (data not shown). The discrepancy between actual and expected foliar $SO_4$ levels in control plots in this study suggests that the calculated N utilization estimates should likely be viewed with caution.

Differential BA responses between N and N+S were not obtained at Tsus Creek (No. 4) despite the incremental benefits of added S on first-year fascicle mass reported by Brockley and Sheran (1994). The BA response to N alone at this site was considerably larger than that predicted by a regression model using prefertilization foliar N and $SO_4$ as independent variables (Brockley 2000). Favourable BA

**Table 10.** Mean foliar concentrations of nonadded nutrients by treatment 1 and 3 years following fertilization.

| Treatment | P (g/kg) | K (g/kg) | Ca (g/kg) | Mg (g/kg) | B (mg/kg) | Cu (mg/kg) | Zn (mg/kg) | Fe (mg/kg) |
|---|---|---|---|---|---|---|---|---|
| **Year 1** | | | | | | | | |
| Control | 1.59 (0.16) | 5.38 (0.60) | 1.97 (0.32) | 1.09 (0.12) | 15.7 (8.5) | 4.8 (0.9) | 47 (7) | 38 (5) |
| $200N_1$ | 1.67 (0.15) | 5.20 (0.68) | 1.87 (0.30) | 1.05 (0.15) | 11.8 (3.8) | 4.3 (0.9) | 49 (7) | 42 (9) |
| $200N_2$ | 1.72 (0.16) | 5.29 (0.70) | 1.91 (0.36) | 1.09 (0.14) | 12.4 (3.9) | 4.0 (0.7) | 50 (8) | 39 (5) |
| 200N + 50S (AS) | 1.71 (0.08) | 5.89 (0.81) | 1.82 (0.27) | 1.03 (0.18) | 11.1 (3.8) | 4.1 (0.8) | 46 (8) | 39 (5) |
| 200N + 100S (AS) | 1.68 (0.14) | 5.91 (0.77) | 1.86 (0.36) | 1.02 (0.19) | 11.3 (3.2) | 4.1 (0.8) | 47 (7) | 41 (7) |
| 200N + 50S ($S^0$) | 1.68 (0.17) | 5.38 (0.63) | 1.90 (0.37) | 1.06 (0.15) | 11.2 (3.3) | 3.9 (0.9) | 48 (9) | 41 (7) |
| 200N + 100S ($S^0$) | 1.69 (0.13) | 5.42 (0.79) | 1.96 (0.48) | 1.08 (0.13) | 11.9 (3.8) | 4.1 (0.8) | 48 (10) | 40 (6) |
| 200N + 50S (AS + $S^0$) | 1.68 (0.12) | 5.76 (0.89) | 1.82 (0.35) | 1.07 (0.18) | 10.7 (3.8) | 4.4 (1.1) | 47 (8) | 40 (8) |
| 200N + 100S (AS + $S^0$) | 1.71 (0.18) | 5.79 (0.49) | 1.88 (0.32) | 1.03 (0.14) | 11.4 (3.4) | 4.4 (1.0) | 46 (7) | 42 (6) |
| **Year 3** | | | | | | | | |
| Control | 1.43 (0.15) | 5.29 (0.51) | 1.74 (0.27) | 0.93 (0.08) | 12.4 (4.1) | 3.3 (0.7) | 44 (7) | 29 (9) |
| $200N_1$ | 1.44 (0.20) | 5.23 (0.74) | 1.72 (0.17) | 0.95 (0.10) | 8.6 (2.9) | 2.8 (0.4) | 41 (5) | 29 (8) |
| $200N_2$ | 1.46 (0.23) | 5.14 (0.65) | 1.79 (0.39) | 0.95 (0.08) | 9.1 (2.5) | 2.7 (0.5) | 41 (5) | 28 (10) |
| 200N + 50S (AS) | 1.50 (0.17) | 5.41 (0.39) | 1.69 (0.29) | 0.94 (0.08) | 8.4 (3.2) | 3.0 (0.7) | 46 (6) | 30 (6) |
| 200N + 100S (AS) | 1.54 (0.20) | 5.47 (0.50) | 1.76 (0.30) | 0.93 (0.10) | 8.3 (2.7) | 2.9 (0.6) | 45 (5) | 29 (6) |
| 200N + 50S ($S^0$) | 1.46 (0.16) | 5.34 (0.59) | 1.66 (0.20) | 0.93 (0.09) | 8.4 (2.9) | 2.5 (0.6) | 42 (5) | 29 (6) |
| 200N + 100S ($S^0$) | 1.49 (0.21) | 5.50 (0.78) | 1.75 (0.21) | 0.93 (0.10) | 8.3 (2.4) | 2.7 (0.6) | 44 (6) | 31 (7) |
| 200N + 50S (AS + $S^0$) | 1.47 (0.16) | 5.68 (0.83) | 1.73 (0.34) | 0.96 (0.11) | 8.1 (2.9) | 2.8 (0.6) | 45 (5) | 31 (7) |
| 200N + 100S (AS + $S^0$) | 1.58 (0.37) | 5.46 (0.64) | 1.92 (0.37) | 0.97 (0.11) | 8.9 (3.0) | 2.9 (0.8) | 46 (6) | 31 (6) |

**Note:** For each year and treatment, values represent means of 18 composite foliage samples (six trials × three composite samples per trial). Values in parentheses represent standard deviation. N, nitrogen; S, sulphur; AS, ammonium sulphate; $S^0$, elemental sulphur; $N_1$, 78% N as urea and 22% N as ammonium chloride; $N_2$, 56% N as urea and 44% N as ammonium chloride. Values preceding the nutrients indicate the amount of nutrient applied in kilograms per hectare.

response to N alone (~30%) is particularly surprising given that first-year foliar nutrient ratios (N/S, ~21; N/P, ~10.4; N/K, ~3.3) indicated probable imbalances of N relative to S, P, and K (Kelly and Lambert 1972; Ingestad 1979; Linder 1995). Also, the calculated N utilization estimate for the N-only treatments was relatively low (~69%). Despite favourable S uptake following AS application, foliar $SO_4$ levels were much lower, and N/S ratios were higher, in the N+AS treatments at Tsus Creek (No. 4) than in corresponding treatments in the two S-responsive trials (Nos. 3 and 5) in each of the 3 years after fertilization. These results indicate that S deficiency may not have been fully alleviated by S fertilization at Tsus Creek.

As with fascicle mass, BA response was significantly improved by fertilization with N alone at two of the remaining three study sites (Nos. 1 and 7), and incremental gains between N and N+S were not significant. In both trials, relatively high prefertilization foliar $SO_4$ levels (79 and 102 mg/kg, respectively) indicated that S reserves were likely adequate to effectively utilize N fertilizer (Turner et al. 1977, 1979; Brockley 2000). At Gold Creek (No. 7), the large BA response to N (with no incremental benefit of adding S) was expected given the severe N deficiency (~10.0 g/kg foliar N) and the favourable supply of S and other essential nutrients indicated in prefertilization foliar analyses. Postfertilization N/S ratios in all treatments remained below or only slightly above a threshold value (~15) above which S deficiency is indicated (Ballard and Carter 1986). Nitrogen utilization calculations indicate that most of the foliar N (>90%) was fully utilized in all fertilizer treatments. Basal area responses at Bowron River (No. 1) were smaller, possibly because of less severe N deficiency (12.4 g/kg prefertilization foliar N). Also, first-year foliar N/K ratios (3.4–4.6) in N and N+S treatments indicated probable K deficiencies at this study site (Ingestad 1979; Linder 1995). Induced K deficiency may have suppressed BA growth in N and N+S treatments at this site and may also partially explain the relatively poor estimated N utilization in N-only (63%), N+$S^0$ (61%), and N+AS (78%) treatments in year 1. The soil texture at the Bowron River site is similar to the sandy outwash soils of the northeastern U.S.A. and southeastern Canada, where K deficiencies have been well documented (Truong Dinh Phu and Gagnon 1975; Shepard and Mitchell 1990).

The unresponsiveness of the Andrew Bay trial (No. 6) to any fertilizer treatment is likely explained by foliar nutrition and tree growth characteristics. As shown in Table 1, prefertilization foliar N and $SO_4$ levels (13.3 g/kg and 71 mg/kg, respectively) indicate that lodgepole pine trees at this site were not particularly N or S deficient, and that nonadded nutrients were in good supply (Ballard and Carter 1986; Brockley 2001*b*). The fact that unfertilized trees at this site were growing much more rapidly than trees at the other study sites (see Table 3) is another indication that nutrient availability was not a major growth-limiting factor. Dilution caused by rapid growth and an expanding crown mass may partially explain the lower foliar levels of N and $SO_4$ in control trees in the years following fertilization.

The relative ineffectiveness of fertilization on stimulating tree height increment is consistent with the results from

**Table 11.** Mean foliar nitrogen/phosphorus, nitrogen/potassium, and nitrogen/ magnesium ratios 1 year following fertilization by trial and treatment.

| | Trial No. | | | | | |
|---|---|---|---|---|---|---|
| Treatment | 1 | 3 | 4 | 5 | 6 | 7 |
| **N/P ratio** | | | | | | |
| Control | 7.5 | 7.3 | 7.4 | 7.4 | 7.4 | 6.2 |
| 200N$_1$ | 10.6 | 10.5 | 10.6 | 10.4 | 9.1 | 8.5 |
| 200N$_2$ | 10.7 | 11.2 | 10.2 | 10.2 | 9.9 | 9.2 |
| 200N + 50S (AS) | 9.4 | 9.0 | 9.2 | 8.5 | 8.8 | 8.4 |
| 200N + 100S (AS) | 9.4 | 9.8 | 9.8 | 8.8 | 8.8 | 8.9 |
| 200N + 50S (S$^0$) | 10.1 | 11.0 | 10.8 | 10.8 | 9.2 | 8.4 |
| 200N + 100S (S$^0$) | 10.5 | 11.2 | 9.9 | 11.0 | 9.4 | 9.0 |
| 200N + 50S (AS + S$^0$) | 10.3 | 9.8 | 8.8 | 10.0 | 8.8 | 8.8 |
| 200N + 100S (AS + S$^0$) | 9.4 | 10.2 | 9.1 | 10.1 | 9.4 | 8.8 |
| LSD ($p$ = 0.05) | 1.1 | 0.8 | 1.0 | 1.2 | 1.1 | 0.6 |
| **N/K ratio** | | | | | | |
| Control | 2.8 | 1.8 | 2.4 | 2.1 | 2.0 | 2.0 |
| 200N$_1$ | 4.4 | 2.7 | 3.3 | 3.8 | 2.7 | 2.6 |
| 200N$_2$ | 4.6 | 3.0 | 3.3 | 4.2 | 2.8 | 2.6 |
| 200N + 50S (AS) | 3.4 | 2.1 | 2.9 | 2.4 | 2.4 | 2.5 |
| 200N + 100S (AS) | 3.6 | 2.1 | 2.9 | 2.5 | 2.4 | 2.6 |
| 200N + 50S (S$^0$) | 4.0 | 3.1 | 3.6 | 3.6 | 2.2 | 2.6 |
| 200N + 100S (S$^0$) | 4.3 | 3.3 | 3.3 | 3.5 | 2.5 | 2.5 |
| 200N + 50S (AS + S$^0$) | 4.1 | 2.4 | 3.2 | 2.7 | 2.3 | 2.4 |
| 200N + 100S (AS + S$^0$) | 3.8 | 2.5 | 2.9 | 2.7 | 2.5 | 2.6 |
| LSD ($p$ = 0.05) | 0.6 | 0.4 | 0.4 | 0.6 | 0.4 | 0.4 |
| **N/Mg ratio** | | | | | | |
| Control | 13.3 | 10.2 | 10.5 | 11.3 | 11.4 | 7.6 |
| 200N$_1$ | 20.0 | 12.7 | 16.1 | 18.3 | 19.2 | 11.0 |
| 200N$_2$ | 19.7 | 14.9 | 17.6 | 16.9 | 17.2 | 11.9 |
| 200N + 50S (AS) | 18.7 | 12.3 | 15.3 | 15.7 | 17.9 | 10.9 |
| 200N + 100S (AS) | 18.8 | 14.3 | 16.5 | 16.0 | 17.3 | 10.7 |
| 200N + 50S (S$^0$) | 20.6 | 13.9 | 17.6 | 17.6 | 15.7 | 11.6 |
| 200N + 100S (S$^0$) | 19.3 | 15.0 | 17.3 | 16.2 | 16.4 | 12.2 |
| 200N + 50S (AS + S$^0$) | 18.7 | 13.9 | 13.8 | 16.7 | 16.9 | 10.6 |
| 200N + 100S (AS + S$^0$) | 18.0 | 14.9 | 16.0 | 17.0 | 18.0 | 12.2 |
| LSD ($p$ = 0.05) | 3.1 | 1.6 | 2.7 | 2.6 | 3.1 | 1.1 |

**Note:** N, nitrogen; S, sulphur; AS, ammonium sulphate; S$^0$, elemental sulphur; N$_1$, 78% N as urea and 22% N as ammonium chloride; N$_2$, 56% N as urea and 44% N as ammonium chloride. Values preceding the nutrients indicate the amount of nutrient applied in kilograms per hectare. LSD, least significant difference test.

most other fertilization studies with lodgepole pine (Brockley 2001*a*). Only in severely height-repressed lodgepole pine (caused by excessive stand density) have large height responses been documented following fertilization (Farnden and Herring 2002; Newsome and Perry 2003). However, the apparent small negative and positive effects of N alone and N+S, respectively, on tree height in three trials indicates that height development in these stands may be at least partially controlled by S nutrition. Foliar imbalances of N relative to nonadded nutrients (e.g., P and K) in the first year or two following fertilization may also have negatively affected height increment in the N-only and N+S$^0$ treatments at these study sites. Also, it is possible that the negative effect of fertilization on foliar B status may have played some role in controlling height development of fertilized trees in this study. Low foliar B levels are quite common in immature lodgepole pine forests in the interior of British Columbia (Brockley 2001*c*). Nitrogen fertilization further depletes foliar B levels and has occasionally resulted in visible B deficiency symptoms (i.e., top dieback) (Brockley 1989, 1990, 2003). In this study, acute symptoms of B deficiency were not observed in any of the trials. However, foliar levels in fertilized trees at some sites approached a threshold level (6 mg/kg) below which acute symptoms have been documented and above which subacute B deficiency likely suppresses height growth of lodgepole pine (Brockley 1990, 2003; Stone 1990).

Elevated foliar nutrient ratios (e.g., N/P, N/K, N/Mg) in fertilized trees 1 year following treatment can be largely explained by the combined effects of increased foliar N and the dilution of foliar levels of nonadded nutrient caused by increased foliage mass. As already noted, foliar imbalances of N relative to P and K (often prolonged beyond the first year) may have contributed to smaller BA and height responses in some treatments at some study sites. Higher foliar N levels in N+S$^0$ treatments than in N+AS treatments likely partially explain the higher foliar N/P and N/K ratios in S$^0$-fertilized trees in year 1. However, lower absolute foliar K levels in N+S$^0$ treatments than in N+AS treatments in year 1 also contributed to the N/K imbalance at some study sites. Dilution is apparently not a factor, since first-year fascicle mass responses were significantly larger in AS treatments than in S$^0$ treatments in two of these trials (Nos. 3 and 5) (Brockley and Sheran 1994). These results indicate that AS (but not S$^0$) stimulated K uptake, at least during the first year following fertilization. Increased fascicle mass and foliar concentration of a nonadded nutrient following fertilization with another nutrient was termed "protagonism" by Valentine and Allen (1990).

There were large differences between the effects of S source on BA response and the effects of S source on first-year fascicle mass reported by Brockley and Sheran (1994). Ammonium sulphate was clearly superior to S$^0$ in stimulating first-year fascicle mass in the four trials responsive to S additions (Brockley and Sheran 1994). In contrast, 6-year BA increment was not affected by S source at any of the study sites. However, the relative effectiveness of S source varied with S application rate in two trials (Nos. 3 and 7). In both cases, BA increment was positively related to S application rate when S was applied as AS. Conversely, the effect of application rate was distinctly negative when S$^0$ was applied. Although supporting data are unavailable, the apparent negative impact of large applications of S$^0$ on BA increment at two sites (Nos. 3 and 7) may be related to soil acidification. Following soil application, S$^0$ is oxidized to $SO_4$ according to the following generalized reaction:

$$S^0 + H_2O + 3/2O_2 \Leftrightarrow 2H^+ + SO_4^{-2}$$

For every mole of S$^0$ applied and oxidized, two moles of $H^+$ are produced, thus decreasing soil pH. Although AS is also a potential source of acidity, soil acidification following AS

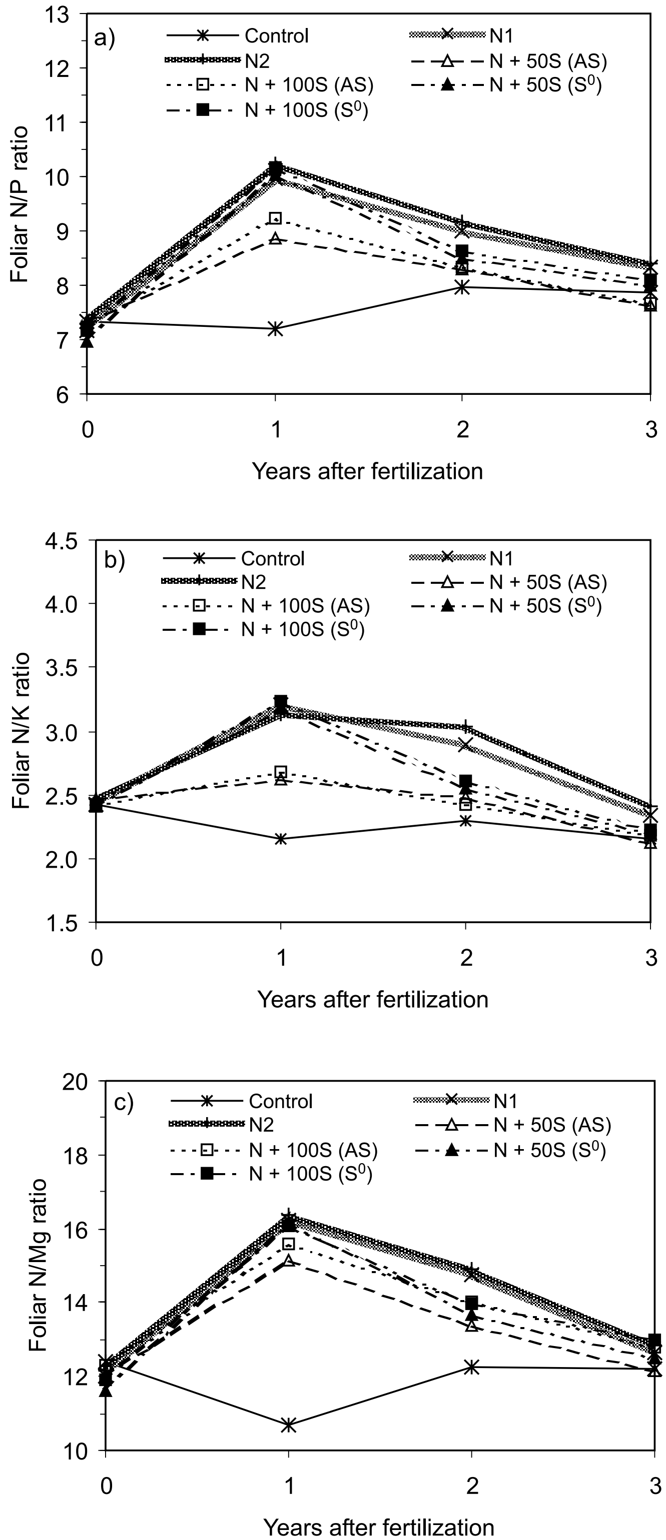



**Fig. 3.** The effects of nitrogen, alone and in combination with different sources and rates of sulphur, on (*a*) foliar nitrogen/phosphorus ratio, (*b*) foliar nitrogen/potassium ratio, and (*c*) foliar nitrogen/magnesium ratio for the 3-year period following fertilization. For year 0, each plotted point represents the mean of six composite foliage samples (six trials × one composite sample per trial). For all other years, each plotted point represents the mean of 18 composite samples (six trials × three composite samples per trial). Control, unfertilized; $N_1$, 78% N as urea and 22% N as ammonium chloride; $N_2$, 56% N as urea and 44% N as ammonium chloride; 50S, 50 kg S/ha; 100S, 100 kg S/ha; AS, ammonium sulphate; $S^0$, elemental sulphur.

fertilization is dependent on the microbial oxidation of ammonium to nitrate. Under forest conditions, the nitrification process may be inhibited by low populations of nitrifying bacteria and by acidic soil conditions (Nason and Myrold 1992). Overrein (1967) reported little nitrification following the addition of AS. Soil acidification leads to several changes in the soil environment including displacement of base cations from exchange sites and increased concentration and activity of potentially toxic metals, such as aluminum, in the soil solution (Brady and Weil 1998). The effects of different S sources and application rates on forest soil acidity and chemistry require further investigation.

As discussed by Brockley and Sheran (1994), the poor S uptake and limited fascicle mass response from $S^0$ in year 1 indicate delayed oxidation of the degradable $S^0$ – sodium bentonite fertilizer. In most cases, the added S apparently became available too slowly to balance foliar N in protein synthesis during the period immediately after fertilization. Similar delays in S oxidation from coarse $S^0$ granules and $S^0$ – sodium bentonite prills (similar to those used in this study) have been reported in agricultural crops (Solberg and Nyborg 1983; Boswell et al. 1988; Nuttall et al. 1990; Janzen and Karamanos 1991). However, the progressively higher foliar S levels in the foliage of $S^0$-fertilized trees indicate favourable oxidation of the $S^0$ – sodium bentonite prills in years 2 and 3. Several investigations with different $S^0$ products have found that the rate of oxidation of $S^0$ varies considerably depending on size and (or) composition (Solberg and Nyborg 1983; Janzen and Bettany 1986). The effects of different rates of finely divided $S^0$ powder and sulphate S on tree growth and foliar nutrition are being tested in a companion study. In addition, a stable isotope tracer study has recently been initiated to track the pathways of sulphate and elemental S sources through the soil–plant system.

Despite large differences in short-term availability of AS and $S^0$, the results from this study support the conclusion that the two S sources are likely equally effective in alleviating S deficiencies and promoting tree growth following N+S fertilization of lodgepole pine. Based on BA growth responses presented in this paper, first-year fascicle mass response previously reported by Brockley and Sheran (1994) was shown to be unreliable for evaluating the relative effectiveness of different S sources in alleviating S deficiency over the long term. Because $S^0$ fertilizers are less bulky (i.e., higher S content) than sulphate products, and assuming they are compatible for blending with nitrogenous fertilizer (e.g., urea), $S^0$ may be the most cost-effective option where there is a requirement for N and S in operational fertilizer prescriptions.

To minimize costs, it is important operationally not to add more S than is needed to satisfy the S requirements of the stand. The 6-year results from this study indicate that 50 kg S/ha is usually as effective as 100 kg S/ha in promoting tree growth. In fact, results suggest that when applied as $S^0$, 100 kg/ha may be detrimental to tree growth on some interior sites.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