RESEARCH REPORT

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Effects of Fertilization on the Growth and Foliar Nutrition of Immature Douglas-fir in the Interior Cedar–Hemlock Zone of British Columbia: Six-year Results

R.P. Brockley

2006

BRITISH COLUMBIA

Ministry of Forests and Range
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ABSTRACT

The effects of fertilization with nitrogen (N) alone, and in combination with sulphur (S), on the growth and foliar nutrition of six immature, managed Douglas-fir (*Pseudotsuga menziesii* var. *glauca* [Beissn.] Franco) stands in the Interior Cedar–Hemlock (ICH) biogeoclimatic zone of British Columbia are reported 6 years after treatment. Results indicate that interior Douglas-fir stands growing on circummesic sites within the ICH zone are generally responsive to fertilization. Disregarding results from one installation that was damaged by *Armillaria* root disease, average net volume response following fertilization with N alone was 13.5 m^3/ha (range: 6.5–24 m^3/ha) compared to the control treatment. Six-year volume gains from N+S additions averaged 16 m^3/ha (range: 10–23 m^3/ha). In relative terms, stand volume responses to fertilization with N and N+S averaged 24% (range: 8–41%) and 28% (range: 16–39%), respectively. Growth projections generated by the TIPSY growth and yield program indicate that the accelerated stand development following a single fertilizer application will likely reduce biological rotations (i.e., culmination of mean annual increment) and technical rotations (e.g., minimum harvestable age) by 2–3 years. Relative growth responses compare favourably with results from Douglas-fir fertilization studies in other jurisdictions.

Pre- and post-fertilization foliar nutrient analyses indicate that several of the sites were marginally S deficient, and that S status deteriorated 1 year following N fertilization. Added S was readily taken up, thereby maintaining a favourable N:S balance in trees fertilized with N+S. Despite improvements in foliar S status, the incremental growth benefits of added S may be too small on most sites to justify the extra expense involved in blending and applying N+S fertilizers in large-scale aerial operations.

Results from this study, and others, indicate that pre-fertilization levels of foliar N and sulphate S (SO_4) may have utility in selecting candidate stands and in making appropriate fertilizer prescriptions. For example, the largest growth responses following fertilization may be expected in stands with pre-fertilization foliar N levels less than 11.5 g/kg (< 13 g/kg when using dry combustion analytical methods). Also, low foliar N combined with small amounts of pre-fertilization foliar SO_4

(< 200 mg/kg) may indicate that additional growth gains can be achieved by blending S with N in fertilizer prescriptions. Finally, results from this study apparently support previous claims from the Inland Northwest that low pre-fertilization foliar potassium (K) levels (< 6 g/kg) and elevated N:K foliar concentration ratios (> 2) may increase the susceptibility of fertilized Douglas-fir to mortality losses from *Armillaria* root disease. Additional Douglas-fir fertilizer trials are needed to test and refine these preliminary guidelines for wet-belt Douglas-fir in the interior of British Columbia.

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INTRODUCTION

Catastrophic mortality losses caused by the mountain pine beetle (*Dendroctonus ponderosae* Hopk.) are creating serious future timber supply challenges for the forestry sector in the interior of British Columbia. Allowable annual cuts will decline sharply in several interior forest management units after the salvage harvesting of beetle-killed lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.) is completed (B.C. Ministry of Forests 2003). Because virtually all trees to be harvested from interior forests within the next 50 years are already growing, aggressive reforestation efforts, including the extensive planting of genetically improved stock, will likely be of little help in alleviating the looming timber supply crisis. To improve short- and mid-term timber supply, mitigation strategies must focus on increasing the productivity and accelerating the development of established stands of other species.

Pre-commercial thinning and fertilization are the primary silvicultural options for accelerating the harvest operability of established stands. However, because stand and individual-tree growth cannot be maximized simultaneously, thinning prescriptions are typically a compromise between maximum production per unit area and the growth and size of individual trees. Therefore, forest managers must weigh the advantages of shorter rotation length and larger piece size against the possibility of reduced harvest volume. Unlike pre-commercial thinning, fertilization accelerates stand development and increases piece size without sacrificing harvest volume. As such, fertilization may be a particularly valuable tool for mitigating "pinch points" in the timber supply caused by age-class imbalances, and for increasing long-term harvest levels.

Extensive research confirms that the growth of lodgepole pine forests in the interior of British Columbia can be improved by fertilizing with nitrogen (N) and other nutrients (Weetman et al. 1988; Brockley 1991, 1995, 1996, 2000, 2001a, 2003, 2004; Kishchuk et al. 2002; Brockley and Simpson 2004). Nevertheless, accelerating the development of young, managed lodgepole pine by large-scale operational fertilization might potentially put treated stands at risk to attack from the mountain pine beetle. Many future opportunities will likely occur for fertilizing lodgepole pine once the current beetle epidemic runs its course and after beetle populations have declined. In the interim, however, other tree species may afford the best, and least risky, fertilization opportunities.

Four decades of research clearly shows that the growth of Douglas-fir (*Pseudotsuga menziesii* [Mirbel] Franco) is consistently improved by N fertilization over a wide range of soils and climate in coastal British Columbia, Washington, and Oregon (Miller, Barker, et al. 1986; Gardner 1990; Omule 1990; Stegemoeller and Chappell 1990; Chappell et al. 1992). Douglas-fir is also reported to respond to fertilizer additions over a broad range of site and stand conditions in the Inland Northwest (central Washington, northeastern Washington, northeastern Oregon, northern Idaho, central Idaho, and western Montana) (Shafii et al. 1989; Moore et al. 1991; Mika et al. 1992). In southern and south-central British Columbia, immature stands of Douglas-fir growing in the relatively productive Interior Cedar–Hemlock (ICH) biogeoclimatic zone (Meidinger and Pojar 1991) may offer particularly attractive fertilization opportunities.

Examination of interior forest soils reveals that mineral soil sulphur (S) levels are among the lowest reported in the world literature (Kishchuk and Brockley 2002). Sulphur deficiency, either induced or exacerbated by N fertilization, is implicated as a factor limiting the growth response of N-fertilized lodgepole pine in the British Columbia interior (Brockley 1989, 1990, 1995; Kishchuk et al. 2002; Sanborn and Brockley 2005). Several studies confirm that lodgepole pine growth response may be enhanced by combining S with N in fertilizer applications (Brockley 2000, 2001a, 2004). Results from interior spruce (*Picea glauca* [Moench] Voss and *Picea engelmannii* Parry, or naturally occurring hybrids of these species) and Douglas-fir fertilizer screening trials in the British Columbia interior also indicate that induced S deficiencies were likely responsible for the small first-year needle mass responses observed following fertilization with N alone (Brockley and Swift 1990; Swift and Brockley 1994).

Since 1992, the B.C. Ministry of Forests and Range, Research Branch has established a network of 31 standardized, area-based research installations to document the growth response of interior lodgepole pine, interior spruce, and Douglas-fir forests to N fertilization, applied alone and in conjunction with sulphur (S) and other nutrients. This research report examines the effects of fertilization on tree- and stand-level growth of Douglas-fir over 6 years at six individual study sites.

METHODS

LOCATION, SITE, AND STAND DESCRIPTIONS

The six study sites are located in three different subzones of the ICH biogeoclimatic zone in south-central British Columbia. Five of the stands were planted (i.e., Whitepine Creek, Kuskanax Creek, Goldhill, Hazeltine Creek, and Cavanaugh Creek), and one stand was naturally regenerated following a wildfire (i.e., Doreen Lake). Stands ranged in age from 19 to 34 years at the time of trial establishment. All sites were circummesic (i.e., submesic to subhygric soil moisture regime), and exhibited medium to good productivity (e.g., site indices ranged from 24 to 29 m at 50 years [Nigh 1997]) (Table 1). Trees within the overstorey in each stand were predominantly (i.e., > 90%) Douglas-fir. Minor components of western white pine (*Pinus monticola* Dougl.), western larch (*Larix occidentalis* Nutt.), western hemlock (*Tsuga heterophylla* [Raf.] Sarg.), or white birch (*Betula papyrifera* Marsh.) occupied crown positions at some of the sites.

The initial foliar N status of trees at the six study sites ranged from a very severe N deficiency at Doreen Lake to a slight to moderate N deficiency at Hazeltine Creek (Carter 1992) (Table 2). Foliar phosphorus (P), potassium (K), and calcium (Ca) levels were generally adequate, except at Cavanaugh Creek, where a slight to moderate K deficiency was indicated (Carter 1992). Foliar magnesium (Mg) levels indicated a slight to moderate deficiency at five of the six sites according to foliar interpretative criteria suggested by Carter (1992). However, Ballard and Carter (1986) suggested that Mg levels above 1.0 g/kg indicated little, if any deficiency. Pre-fertilization foliar total S, sulphate S (SO_4), and N:S ratios indicated no actual S deficiencies, but that S deficiencies might be induced by N fertilization (Turner et al. 1977; Ballard and Carter 1986). Other plant nutrients were generally well supplied.

Additional location, site, and stand characteristics of the six study sites are described in Table 1. Detailed stand and site descriptions of the individual field installations are provided below.

TABLE 1 *Location, ecological classification, and site and stand characteristics of the study sites*

Installation no.	Location	Forest District	Latitude	Longitude	Map sheet	Opening
23	Whitepine Creek	Columbia	51°35'	117°17'	82N.054	42
25	Kuskanax Creek	Arrow Boundary	50°18'	117°45'	82K.022	26
26	Goldhill	Kootenay Lake	50°23'	117°05'	82K.035	33
28	Hazeltine Creek	Central Cariboo	52°31'	121°32'	93A.053	81
30	Doreen Lake	Central Cariboo	52°18'	121°00'	93A.035	53
37	Cavanaugh Creek	Okanagan Shuswap	50°46'	118°34'	82L.078	203

a P = Planted; N = Natural. b SI, site index (m) at 50 years (Nigh 1997).

TABLE 2 *Initial mean foliar nutrient concentrations at the study sites*

Installation	N (g/kg)	P (g/kg)	K (g/kg)	Ca (g/kg)
Whitepine Creek (#23)	11.38 (0.90)	2.28 (0.17)	8.86 (0.63)	5.03 (0.54)
Kuskanax Creek (#25)	10.47 (0.43)	1.90 (0.14)	7.88 (0.47)	3.28 (0.17)
Goldhill (#26)	11.79 (0.74)	2.54 (0.22)	9.28 (0.65)	4.11 (0.28)
Hazeltine Creek (#28)	12.13 (0.79)	2.60 (0.17)	9.79 (0.51)	4.17 (0.45)
Doreen Lake (#30)	9.54 (0.79)	2.24 (0.16)	8.52 (0.65)	3.39 (0.39)
Cavanaugh Creek (#37)	11.26 (0.34)	1.61 (0.11)	5.70 (0.52)	4.27 (0.29)

Note: For Whitepine Creek, values represent means of 12 composite samples (10 subsamples per composite). For other installations, values represent means of 9 composite samples (10 subsamples per composite). Values in parentheses are standard deviations.

Whitepine Creek

The study site is located approximately 42 km northwest of Golden, B.C., within the Golden variant of the moist warm subzone of the ICH biogeoclimatic zone (ICHmw1) (Braumandl and Curran 1992). Soil and vegetation descriptions indicate that the site has characteristics of both the submesic HwCw–Falsebox–Pipecleaner moss (03) and the CwFd–Soopolallie–

						Averages at trial establishment			
Stand origin[a]	BEC variant	Site series	Elev. (m)	SI[b] (m)	Year estab.	Age (years)	dbh (cm)	Height (m)	SDI[c]
P	ICHmw1	03,04	1010	26	1993	19	9.3	7.1	232
P	ICHmw2	03,04	875	28	1993	23	13.3	11.4	413
P	ICHmw2	01	920	29	1994	23	17.2	12.7	340
P	ICHmk3	01,04	875	24	1994	23	12.5	8.5	375
N	ICHmk3	01	940	24	1996	34	12.2	11.2	365
P	ICHmw2	05	470	29	1997	27	16.2	13.4	415

[c] SDI, stand density index = trees per hectare x $(Dq/25)^{1.6}$ where Dq = quadratic mean diameter (Long 1985).

Mg (g/kg)	S (g/kg)	SO_4 (mg/kg)	B (mg/kg)
1.00 (0.07)	1.09 (0.07)	178 (30)	28.8 (3.0)
1.07 (0.07)	1.10 (0.07)	262 (62)	24.6 (1.8)
1.41 (0.05)	1.10 (0.07)	272 (41)	20.0 (4.2)
1.11 (0.06)	1.02 (0.06)	119 (24)	28.8 (2.7)
1.09 (0.05)	1.03 (0.10)	206 (42)	25.9 (2.0)
1.08 (0.07)	1.18 (0.06)	163 (31)	15.9 (4.5)

Douglas maple (04) site series. The installation occurs on three levels of a well-drained glaciofluvial terrace. The site is flat, with an elevation range between the three levels of approximately 15 m. The rooting zone has a silt loam texture with about 30% coarse fragments consisting mainly of gravels. Considerable carbonate deposition occurs on coarse fragments in the underlying BC horizons. Morphologically, the soils meet the classification criteria for an Orthic Humo-Ferric Podzol (Soil Classification Working Group 1998). The previous stand was clearcut harvested in 1971 and broadcast burned in 1974. The site was planted in the spring of 1976. When the installation was established in 1993, the plantation was 19 years old and had an average Douglas-fir density of approximately 1560 trees per hectare. All treatment plots were pre-commercially thinned to a uniform Douglas-fir density of 1100 trees per hectare during plot establishment. Competing broadleaf vegetation was also removed at that time.

Kuskanax Creek

The study site is located approximately 20 km northeast of Nakusp, B.C., within the Columbia-Shuswap variant of the moist warm subzone of the ICH biogeoclimatic zone (ICHmw2) (Braumandl and Curran 1992). Soil and vegetation descriptions indicate that the site has characteristics of both the subxeric to submesic FdCw–Falsebox–Prince's pine (03) and the CwFd–Falsebox (04) site series. The site has a uniform slope of approximately 30% with a southeast aspect. All plots are located on a mid-slope position. The well-drained soil is predominantly derived from morainal and colluvial parent material with evidence of some glaciofluvial activity. The rooting zone has a sandy loam texture with 50–60% coarse fragments (mainly gravels and cobbles). Morphologically, the soils meet the classification criteria for an Orthic Humo-Ferric Podzol (Soil Classification Working Group 1998). The previous stand was burned by wildfire in 1971. Following salvage harvesting, the site was planted in 1972. When the installation was established in 1993, the plantation was 23 years old and had an average Douglas-fir density of approximately 1300 trees per hectare. All treatment plots were pre-commercially thinned to a uniform Douglas-fir density of 1100 trees per hectare during plot establishment. Isolated infection centres of *Armillaria* root disease (*Armillaria ostoyae* [Romagnesi] Herink) are present throughout the plantation, but an effort was made to avoid obvious infection centres during plot location.

Goldhill

The study site is located approximately 80 km north of Kaslo, B.C., within the Columbia-Shuswap variant of the moist warm subzone of the ICH biogeoclimatic zone (ICHmw2) (Braumandl and Curran 1992). Soil and vegetation descriptions indicate that the site belongs predominantly to the zonal HwCw–Falsebox–

Feathermoss (01) site series. Slopes range from 40 to 60% with a northeast aspect. All plots are located on a mid-slope position. Derived from morainal, meta-volcanic parent material, the soil has a silt loam texture with 10–20% coarse fragments (mainly gravels). The moderately well-drained soil has a rooting depth of approximately 50 cm. Morphologically, the soils meet the classification criteria for an Orthic Humo-Ferric Podzol (Soil Classification Working Group 1998). The previous mature stand was clearcut harvested in 1968 and subsequently broadcast burned. The site was planted with Douglas-fir in 1973. The stand was mechanically brushed in 1984 and pre-commercially thinned to a stand density of approximately 800 trees per hectare in 1992. All treatment plots were re-thinned to a uniform Douglas-fir density of 600 trees per hectare during plot establishment. A minor component (< 5%) of the residual stand is comprised of western larch and western white pine. Isolated infection centres of *Armillaria* root disease are present throughout the plantation, but an effort was made to avoid obvious infection centres during plot location.

Hazeltine Creek

The study site is located approximately 22 km northwest of Horsefly, B.C., within the Horsefly variant of the moist cool subzone of the ICH biogeoclimatic zone (ICHmk3) (Steen and Coupé 1997). Soil and vegetation descriptions indicate that the site has characteristics of both the zonal CwSxw–Falsebox–Knight's plume (01) and the slightly moister CwSxw–Oakfern–Cat's-tail moss (04) site series. The soil is well drained to moderately well drained and the site is predominantly flat with small hummocks. Soil textures range from sandy loam to silt loam (20–30% coarse fragments) and are derived from glacial till. Soil classification appears to be transitional between Orthic Humo-Ferric Podzol and Orthic Gray Luvisol (Soil Classification Working Group 1998). The previous mature stand was clearcut harvested in 1970 and subsequently broadcast burned. The site was planted with Douglas-fir in 1973. When the installation was established in 1994, the plantation was 23 years old and had an average Douglas-fir density of approximately 1450 trees per hectare. All treatment plots were pre-commercially thinned to a uniform Douglas-fir density of 1100 trees per hectare during plot establishment.

Doreen Lake

The study site is located approximately 28 km east of Horsefly, B.C., within the Horsefly variant of the moist cool subzone of the ICH biogeoclimatic zone (ICHmk3) (Steen and Coupé 1997). Soil and vegetation descriptions indicate that the site belongs predominantly to the zonal CwSxw–Falsebox–Knight's plume (01) site series. The site is moderately sloped (30–40%) with a westerly aspect. All plots are located on a mid-slope position. The well-drained soils are derived from colluvial material. The soil has a loamy sand texture with 40% coarse fragments (mainly gravels). Morphologically, the soils meet the classification criteria for an Orthic Humo-Ferric Podzol (Soil Classification Working Group 1998). The stand regenerated naturally following a wildfire in 1961. When the plot was established in 1994, the stand consisted of a dominant and codominant overstorey of Douglas-fir (approximately 2500 trees per hectare) with a small component of birch. A non-competing, dense understorey layer of western hemlock, western redcedar (*Thuja plicata* Donn), and willow (*Salix* spp.) was also present. The understorey layer and competing birch were removed in the fall of 1994. The overstorey of Douglas-fir was pre-commercially thinned to a uniform density of 1100 trees per hectare at this time. Fertilization was delayed for 2 years following thinning to reduce the risk of snowpress and wind damage.

Cavanaugh Creek

The study site is located approximately 29 km east of Sicamous, B.C., within the Columbia-Shuswap variant of the moist warm subzone of the ICH biogeoclimatic zone (ICHmw2) (Braumandl and Curran 1992). Soil and vegetation descriptions indicate that the site belongs to the mesic to subhygric CwHw–Oak fern–Foamflower (05) site series. Soils are derived from poorly sorted glaciofluvial material or from glacial till of granitic and mixed lithology. The site is flat and the soil is moderately well drained. The upper 35 cm of mineral soil has a fine sandy loam texture grading to sand at a depth of 35–60 cm. Morphologically, the soils meet the classification criteria for an Orthic Humo-Ferric Podzol (Soil Classification Working Group 1998). The previous mature timber was clearcut harvested in the late 1960s and planted in 1972. When the installation was established in 1997, the plantation was 27 years old and had an average Douglas-fir density of approximately 850 trees per hectare. All treatment plots were pre-commercially thinned to a uniform Douglas-fir density of 800 trees per hectare, and competing conifer and broadleaf vegetation was also removed at that time. Isolated infection centres of *Armillaria* root disease are present throughout the plantation, but an effort was made to avoid obvious infection centres during plot location.

PLOT ESTABLISHMENT

Each of five field installations contains nine circular treatment plots. One installation (Installation #23, Whitepine Creek) contains 12 plots. Each treatment plot consists of a central "assessment" plot surrounded by a 5-m treated buffer. The size of the plots varies depending on the stand density prescribed for the site (see Table 3). At each site, the prescribed stand density for the installation was largely dictated by stand density before installation establishment. All treatment plots within an installation, including unfertilized "control" plots, are the same size and have the same stand density.

Growth analyses for each plot are based on periodic measurement of 50 (±2) permanently tagged trees within the central assessment plot. Surplus trees within the assessment plot were selected and removed at the time of plot establishment. Buffers were also thinned to the same stand density.

At each study site, treatment plots were systematically located so that within- and between-stand characteristics (stand

TABLE 3 *Assessment plot and treatment plot specifications*

			Assessment plot		Treatment plot	
Installation no.	Location	Density (trees per ha)	Radius (m)	Area (ha)	Radius (m)	Area (ha)
23	Whitepine Creek	1100	12.0	0.045	17.0	0.091
25	Kuskanax Creek	1100	12.0	0.045	17.0	0.091
26	Goldhill	600	16.28	0.083	21.28	0.142
28	Hazeltine Creek	1100	12.0	0.045	17.0	0.091
30	Doreen Lake	1100	12.0	0.045	17.0	0.091
37	Cavanaugh Creek	800	14.1	0.062	19.1	0.115

density, tree size) and site conditions (slope, soils, minor vegetation) were as uniform as possible. The outer boundaries of adjacent treatment plots are separated by a minimum distance of 5 m. A minimum distance of 10 m separates the outer treatment plot boundaries from major disturbances (e.g., roads or large stand openings).

TREATMENT DESCRIPTION

Within each of five installations, three treatments are replicated three times for a total of nine treatment plots. The three treatments are:

1. Control (not fertilized)
2. Nitrogen (N): fertilize with 200 kg/ha N (200N)
3. Nitrogen plus sulphur (N+S): fertilize with 200N and 75 kg/ha S (75S)

A "complete" treatment (also replicated three times) was included at one study site (Installation #23, Whitepine Creek) to test for incremental growth responses attributable to other growth-limiting nutrients. In addition to 200N and 75S, the complete treatment included 100 kg/ha phosphorus (P), 100 kg/ha potassium (K), 37 kg/ha magnesium (Mg), and 3 kg/ha boron (B).

At each installation, treatments were randomly assigned to each of the plots such that each treatment was applied to three plots (i.e., one-way completely randomized design). Trees act as subsamples for the analysis of individual-tree characteristics.

FOLIAR SAMPLING AND ANALYSIS

Replicated samples of the current year's foliage were collected from each treatment plot immediately before fertilization, and after the first and third growing season following fertilization. At one study site (Cavanaugh Creek), road access problems prevented the collection of foliage samples in year 3.

Foliage was collected from 10 representative healthy dominant or codominant trees evenly distributed within each central assessment plot. Samples were collected from the lower portion of the top third of the live crown, consistent with standardized foliar sampling guidelines (Brockley 2001b). Whenever possible, the same trees were sampled each year. Individual foliage samples were frozen after field collection, and then dried in a forced-air oven at 70°C for 20 hours before analysis. One composite sample, consisting of 4 g of dried needles from each of the 10 trees per treatment plot, was prepared for chemical analysis.

Dried composite samples were ground in an electric coffee grinder and sent to a commercial laboratory for chemical analysis. A subsample of each composite was digested using a variation of the sulphuric acid–hydrogen peroxide procedure described by Parkinson and Allen (1975). The digests were analyzed colorimetrically for N on a Technicon Autoanalyzer using the Berthelot (phenol-hypochlorite) reaction (Weatherburn 1967). A spectrophotometer measured P using a procedure based on the reduction of the ammonium molybdiphosphate complex by ascorbic acid (Watanabe and Olson 1965). Total K, Mg, and Ca were determined by atomic absorption spectrophotometry. After dry-ashing, B was determined colorimetrically using the azomethine-H method described by Gaines and Mitchell (1979). Total S was determined by combustion using a LECO® sulphur analyzer. Inorganic SO_4 was extracted with boiling 0.01 N hydrochloric acid (HCl) and determined colorimetrically on an HI-Bismuth reducible distillate (Johnson and Nishita 1952).

FERTILIZATION

At each study site, all fertilizers were applied in the fall, immediately after installation establishment. The ground was snow-free and soils were unfrozen at the time of fertilization. Before fertilization, each treatment plot was divided into eight pie-shaped segments to facilitate uniform application. Premeasured amounts of the specified fertilizer were broadcast by hand within each segment.

Urea (N–P–K; 46:0:0) was applied at a rate of 435 kg/ha to all N treatment plots. Urea was also the primary source of the N applied to the N+S treatment plots, but a portion of the added N (33%) was ammonium sulphate (N–P–K–S; 21:0:0:24). At an application rate of 605 kg/ha, the blended fertilizer (N–P–K–S; 33:0:0:12.4) delivered the specified amounts of N and S. The combination of N sources used in the N+S treatment obviously creates a confounding effect of N source when comparing growth responses obtained from the N and N+S treatments. In an earlier fertilization experiment with lodgepole pine, two N-only treatments, with different ratios of urea or ammonium chloride (N–P–K; 26:0:0), were used to test whether response to N was affected by N source. The ammonium chloride was used as a substitute for the ammonium sulphate in the N+S treatment. The effect of N source (i.e., different proportions of urea N and NH_4–N) on needle mass or 6-year basal area (BA) increment was not statistically significant (Brockley 2004). Therefore, unless a significant interaction occurred between N source and the added S, differences between N and N+S were likely due to the added S rather than to differences in N source. It is assumed that the results from the lodgepole pine study apply equally well to Douglas-fir.

Urea was also the primary source of N in the complete treatment. A small amount of N (24%) was added as monoammonium phosphate (N–P–K; 11:52:0), which also served as the P source. Potassium was delivered as potassium chloride (N–P–K; 0:0:60) and sulphate potash magnesia (N–P–K–S–Mg; 0:0:22:22:11). The latter fertilizer was also the source of S and Mg. Boron was added as granular borate (15% B). At an application rate of 1212 kg/ha, the customized blend (N–P–K–S–Mg–B; 16.5:19.1:9.9:6.2:3.1:0.2) delivered the specified amounts of all nutrients.

MEASUREMENT

At each study site, the diameter at breast height (dbh), total height, height to the base of the live crown, and tree form and condition were recorded for all tagged trees within each central assessment plot immediately after fertilization. Diameter measurements were taken with a steel diameter tape at a permanently marked point approximately 130 cm 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). Measurements were repeated after 6 years.

DATA ANALYSIS

Growth response was analyzed at both the individual-tree and stand level. For each installation, individual-tree growth was examined for all trees alive after 6 years, and also for potential crop trees (largest 250 crop trees per hectare after 6 years). For analyses involving all trees, growth responses were also tabulated across a range of initial tree dbh classes. Variables of interest for individual-tree and crop trees were 6-year height increment, BA increment, and volume increment. Growth increment was defined as the change in the attribute between the initial and 6-year measurements. Stand-level responses were calculated to estimate per-hectare gains attributable to fertilization. The variables of interest at the stand level were net volume increment and net BA increment per hectare. At the stand levels, all trees alive at each measurement were used to determine initial and 6-year stand net BA and volume per hectare by summing individual-tree values in each plot and converting plot area to a per-hectare value. Net growth increments were calculated for each variable by subtracting initial values from 6-year values. Trees that were alive, but that were compromised due to severe health and condition issues (e.g., broken stems, severe top dieback, lean), were excluded from individual-tree and stand-level analyses.

Local volume equations were developed for each study site to determine tree and stand volumes. The general form of these equations was:

$$V = a_1 + a_2D^2H$$

where: V = total volume inside bark in cubic centimetres;
D = dbh outside bark in centimetres;
H = total height in metres.

Each equation was based on sectional measurements of 36 trees selected to cover the range of initial diameters of measurement trees at the study site. Sectional measurements were conducted according to the methodology outlined by Kovats (1977). The inside-bark section volumes were calculated according to Smalian's formula (Chapman and Meyer 1949). Least squares estimates of the coefficients a_1 and a_2 were determined by regressing measured volume per tree against the combined variable of diameter squared times height (D^2H).

For each installation, the effects of fertilization on 6-year tree height, BA, and volume increments were subjected to analysis of covariance (ANCOVA) using the general linear model procedure (SAS Institute Inc. 1989). Tree height, BA, and volume increments were adjusted using initial height, BA, and volume, respectively, as the covariates. Treatment growth response across a range of initial 2-cm tree dbh classes was also analyzed by ANCOVA. For all analyses, *a priori* orthogonal contrasts were used to test for differences between unfertilized and fertilized treatments (i.e., control vs. fertilized), and between different fertilized regimes (e.g., N vs. N+S).

For each installation, the effects of fertilization on net BA and volume increment per hectare were subjected to ANCOVA, using initial stand BA and initial stand volume per hectare as the covariates, respectively. As with individual-tree analyses, planned contrasts were used for *a priori* comparisons.

For each installation, foliar nutrient data for individual nutrients and nutrient concentration ratios were subjected to analysis of variance (ANOVA). Unadjusted treatment means were compared using Duncan's Multiple Range test.

A level of significance of $\alpha = 0.05$ is used throughout the text for inferring statistical significance.

RESULTS

MORTALITY

Virtually no mortality (0–0.4%) was experienced in four of the six field installations during the 6-year response period. At Doreen Lake, scattered mortality (1.5%) was largely caused by stem breakage of small-diameter fertilized trees. The damage occurred 1–2 years after fertilization and likely resulted from the accumulation of snow in the crowns of fertilized trees. At Cavanaugh Creek, a larger amount of mortality was apparently caused by *Armillaria* root disease. Mortality was higher in N and N+S treatments (9% mortality in both) than in control treatments (6%). Symptoms of root disease (i.e., chlorotic foliage, lean, top dieback) were also visible throughout the study site, especially within fertilized plots. No evidence of competition mortality (i.e., suppression) was apparent in any of the Douglas-fir field installations during the 6-year response period.

INDIVIDUAL-TREE ANALYSIS

Basal Area Increment

Figure 1 illustrates the 6-year mean BA increments for individual installations and treatments. Five of the six installations responded significantly to fertilization (Table 4). Average BA increment after fertilizing with N alone was 22% (range: 12–35%) greater than the average increment of unfertilized trees. The corresponding 6-year BA gains from N+S additions averaged 28% (range: 19–42%). The difference in BA increment between N and N+S treatments was statistically significant at only one study site (Cavanaugh Creek) (Table 4). At Whitepine Creek, growth gains after fertilizing with a "complete mix" fertilizer were not larger than gains obtained with N or N+S fertilizers (Figure 1a).

Absolute tree BA responses to fertilizer were often larger for the largest 250 trees per hectare (L250) than for the entire stand component; however, on average, the L250 trees exhibited slightly smaller BA percentage gains (relative to the control) than did the whole stand (Figure 1). Six-year relative BA gains from N and N+S additions for the L250 component were 20% (range: 3–31%) and 25% (range: 17–34%), respectively. For the L250 component, five of the six installations responded significantly to fertilization (Table 5). The difference in BA increment between N and N +S treatments was statistically significant only at Cavanaugh Creek (relative responses of 19% and 28%, respectively). At Whitepine Creek, the difference in BA increment between N alone and N combined with other nutrients (S or "complete mix") was statistically significant (Table 5).

Figure 2 illustrates that, in general, the magnitude of absolute BA incremental gains of fertilized trees was positively related to tree size. Notable exceptions to this trend were found at Hazeltine Creek and Cavanaugh Creek, where the largest trees did not exhibit the largest absolute BA responses. No consistent pattern was evident between relative BA response and tree size. For both absolute and relative response, no consistent pattern of incremental differences was apparent between N and N+S across diameter classes (Figure 2).

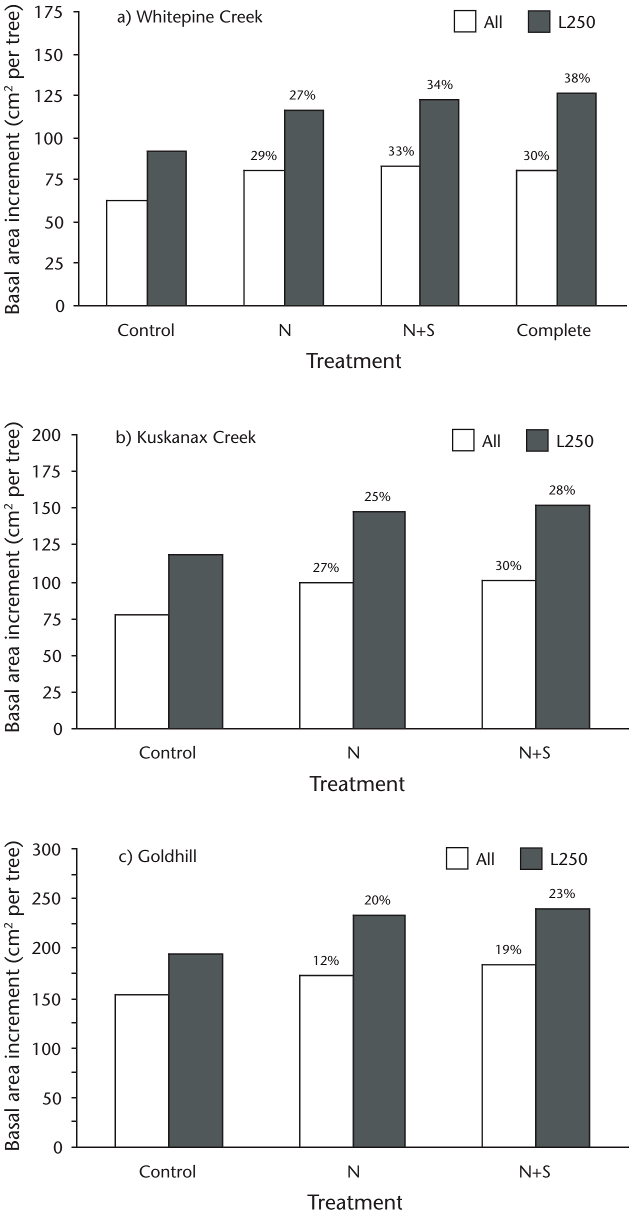

FIGURE 1 *Mean 6-year tree basal area increment by stand component (all trees and largest 250 trees per hectare). Numbers above each bar indicate change relative to the control treatment for each stand component.*

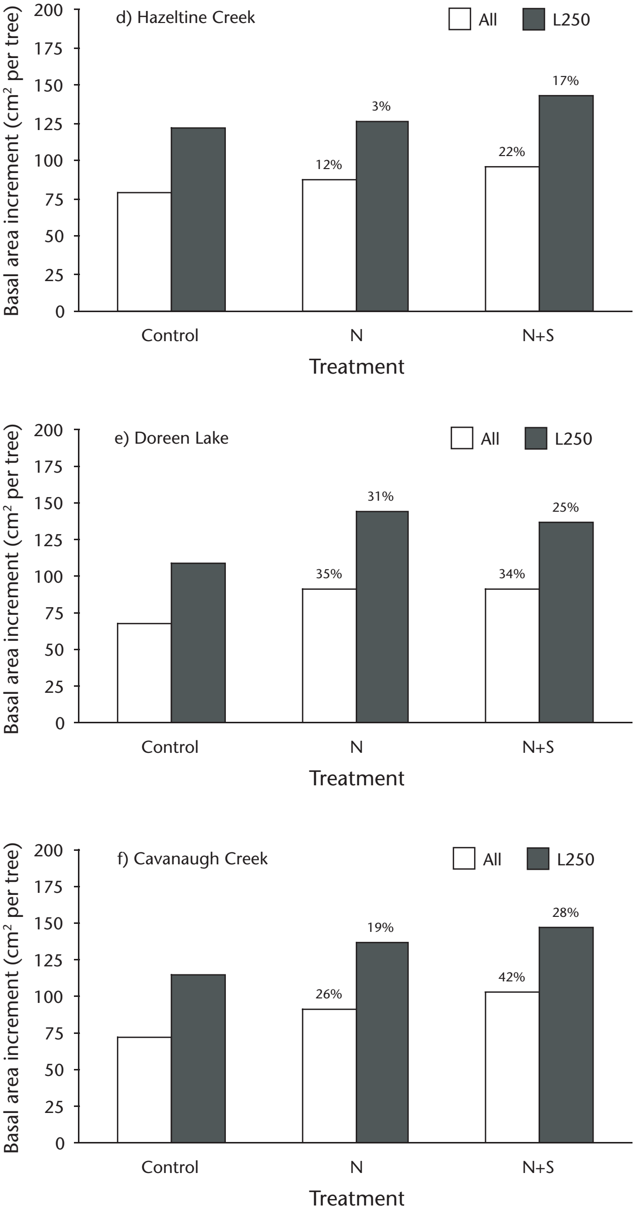

FIGURE 1 *Continued*

TABLE 4 *Analysis of covariance (ANCOVA) summary table for 6-year tree basal area increment, height increment, and volume increment (all trees), showing observed F statistics and probability (p) values*

	Basal area		Height		Volume	
Source of variation	*F*	*p*	*F*	*p*	*F*	*p*
Whitepine Creek (#23)						
Treatment	11.04	0.003	10.86	0.003	14.41	0.001
Control vs. fertilized	32.69	< 0.001	31.61	< 0.001	43.09	< 0.001
N vs. N + others	0.21	0.661	0.78	0.402	0.02	0.880
Kuskanax Creek (#25)						
Treatment	15.24	0.004	51.62	< 0.001	45.88	< 0.001
Control vs. fertilized	30.19	0.001	100.30	< 0.001	91.74	< 0.001
N vs. N+S	0.23	0.647	3.35	0.117	0.00	0.982
Goldhill (#26)						
Treatment	9.61	0.013	6.98	0.027	13.90	0.006
Control vs. fertilized	16.93	0.006	8.15	0.029	24.75	0.002
N vs. N+S	2.27	0.182	6.01	0.050	3.07	0.130
Hazeltine Creek (#28)						
Treatment	2.61	0.153	0.20	0.827	1.14	0.379
Control vs. fertilized	4.11	0.089	0.22	0.653	2.01	0.206
N vs. N+S	1.11	0.333	0.17	0.695	0.28	0.617
Doreen Lake (#30)						
Treatment	43.63	< 0.001	22.82	0.001	86.17	< 0.001
Control vs. fertilized	87.22	< 0.001	44.78	< 0.001	172.33	< 0.001
N vs. N+S	0.07	0.805	0.67	0.444	0.00	0.993
Cavanaugh Creek (#37)						
Treatment	23.33	0.001	1.11	0.390	16.23	0.004
Control vs. fertilized	40.32	< 0.001	2.20	0.189	29.40	0.002
N vs. N+S	6.50	0.043	0.02	0.891	3.23	0.122

TABLE 5 *Analysis of covariance (ANCOVA) summary table for 6-year tree basal area increment, height increment, and volume increment (largest 250 trees per hectare), showing observed F statistics and probability (p) values*

	Basal area		Height		Volume	
Source of variation	*F*	*p*	*F*	*p*	*F*	*p*
Whitepine Creek (#23)						
Treatment	86.26	< 0.001	3.13	0.088	23.16	< 0.001
Control vs. fertilized	240.28	< 0.001	8.94	0.017	66.25	< 0.001
N vs. N + others	14.17	< 0.001	0.06	0.817	1.85	0.210
Kuskanax Creek (#25)						
Treatment	7.54	0.023	6.84	0.028	28.56	< 0.001
Control vs. fertilized	14.39	0.009	13.20	0.011	56.53	< 0.001
N vs. N+S	0.16	0.699	0.60	0.467	0.00	0.992
Goldhill (#26)						
Treatment	51.38	< 0.001	6.49	0.032	76.00	< 0.001
Control vs. fertilized	101.26	< 0.001	12.67	0.012	150.95	< 0.001
N vs. N+S	1.71	0.238	0.27	0.622	1.38	0.285
Hazeltine Creek (#28)						
Treatment	1.49	0.299	0.09	0.915	0.72	0.526
Control vs. fertilized	1.11	0.332	0.18	0.687	0.35	0.576
N vs. N+S	1.86	0.222	0.00	0.990	1.09	0.336
Doreen Lake (#30)						
Treatment	23.48	0.001	8.16	0.019	37.38	< 0.001
Control vs. fertilized	44.78	< 0.001	16.01	0.007	72.40	< 0.001
N vs. N+S	1.94	0.213	0.21	0.661	2.08	0.200
Cavanaugh Creek (#37)						
Treatment	28.26	< 0.001	0.00	0.997	10.58	0.011
Control vs. fertilized	51.52	< 0.001	0.00	0.970	20.11	0.004
N vs. N+S	6.43	0.044	0.00	0.947	1.74	0.235

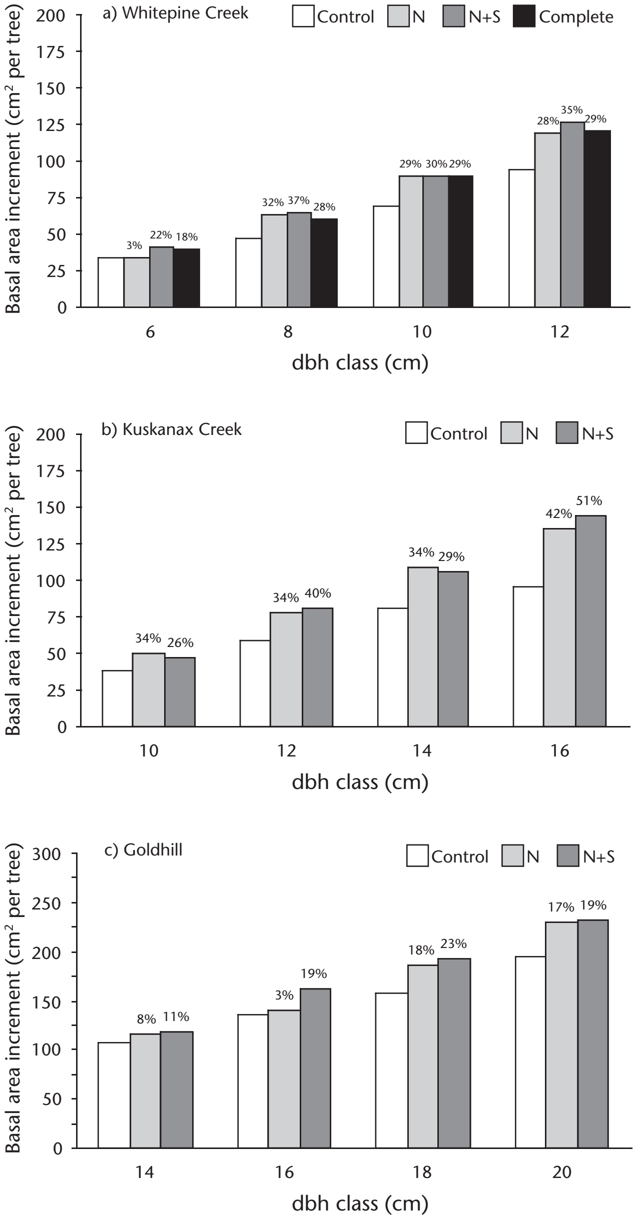

FIGURE 2 *Mean 6-year tree basal area increment by 2-cm dbh class. Numbers above each bar indicate change relative to the control treatment for each dbh class.*

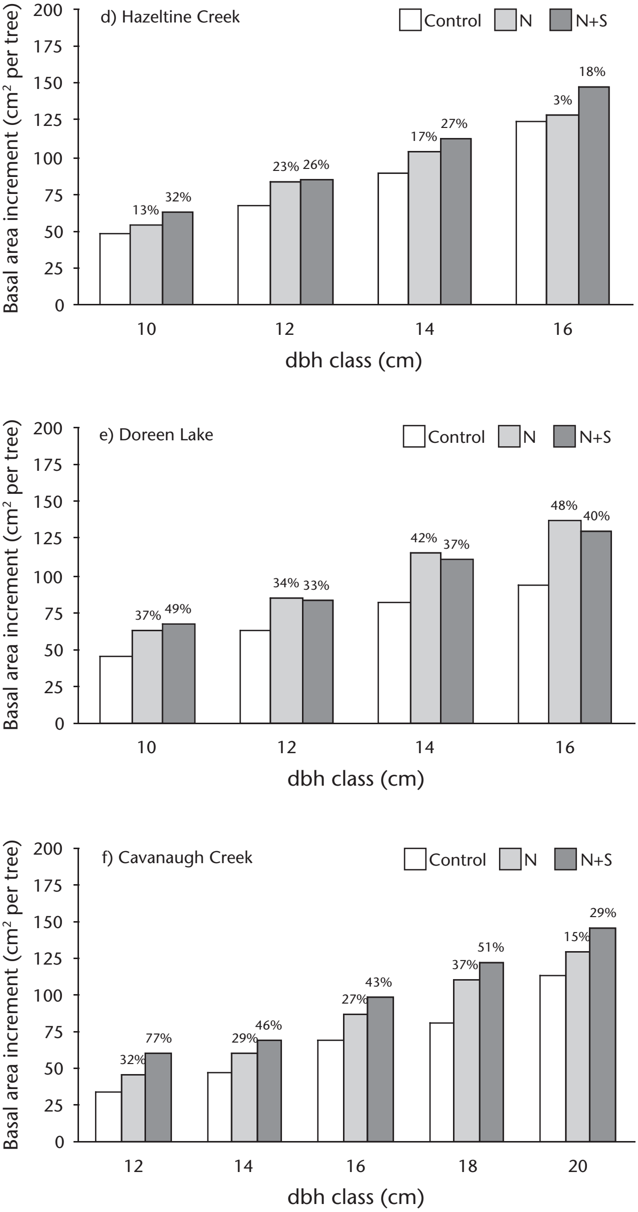

FIGURE 2 *Continued*

Height Increment

Figure 3 illustrates the 6-year mean height increments for individual installations and treatments. Height response to fertilization was statistically significant in four of the six installations (Table 4). Average height response after fertilizing with N alone was 38 cm (range: 7–80 cm) compared to the control treatment. Six-year height gains from N+S additions averaged 36 cm (range: 4–65 cm). In relative terms, height responses to N and N+S fertilization averaged 14% (range: 2–34%) and 13% (range: 1–28%), respectively (Figure 3). The difference in height increment between N and N+S treatments was statistically significant at only the Goldhill study site (Table 4); however, the absolute incremental gain between the N and N+S treatments at Goldhill was only 13 cm after 6 years. At Whitepine Creek, growth gains after fertilizing with a "complete mix" fertilizer were no larger than gains obtained with N or N+S fertilizers (Figure 3a).

In both absolute and relative terms, 6-year tree height responses to fertilizer were generally smaller for the largest 250 trees per hectare (L250) than for the entire stand component. Six-year absolute height gains from N and N+S additions for the L250 component averaged 28 cm (range: −10 to 77 cm) and 23 cm (range: −10 to 60 cm), respectively. The corresponding relative gains averaged 9% (range: −3 to 30%) and 7% (range: −3 to 23%) (Figure 3). For the L250 component, four of the six installations showed statistically significant height responses to fertilization (Table 5). As with the entire stand component, nutrient additions failed to stimulate height increment at either Hazeltine Creek or Cavanaugh Creek. The difference in height increment between N and N+S treatments for the L250 component was not statistically significant at any of the six study sites.

As illustrated in Figure 4, no consistent pattern was evident between the magnitude of absolute and relative height incremental gains of fertilized trees and tree size. In relative terms, however, the incremental difference between N and N+S was often slightly larger in smaller trees compared to the larger dbh classes (Figure 4); however, the apparent positive effect of S on height increment was not statistically significant (data not shown).

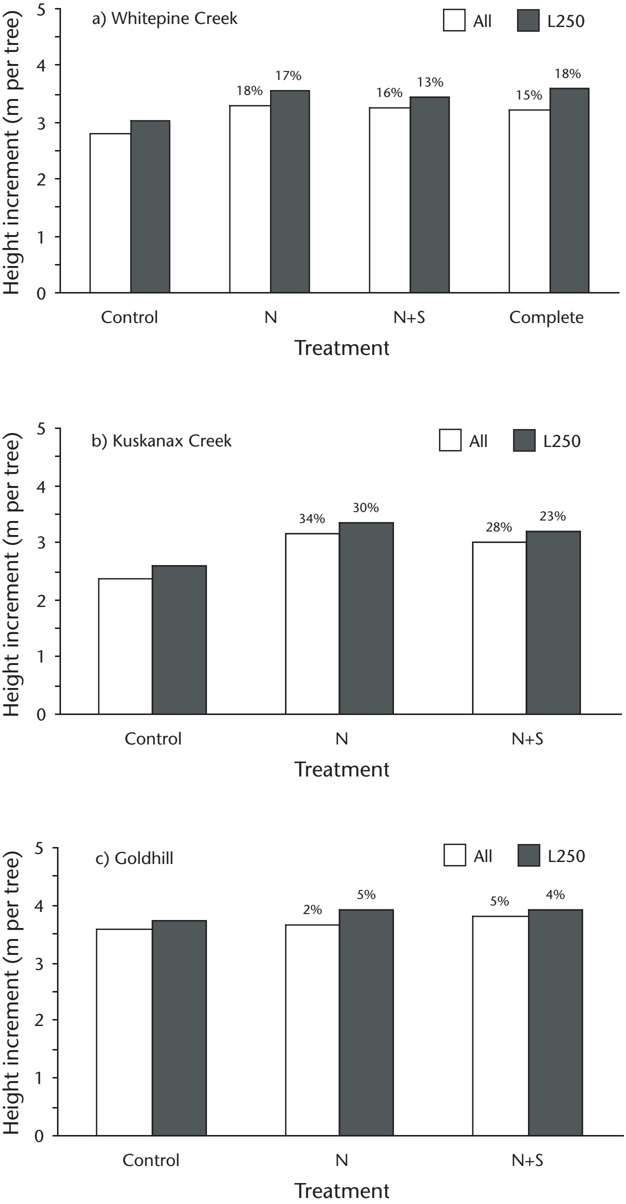

FIGURE 3 *Mean 6-year tree height increment by stand component (all trees and largest 250 trees per hectare). Numbers above each bar indicate change relative to the control treatment for each stand component.*

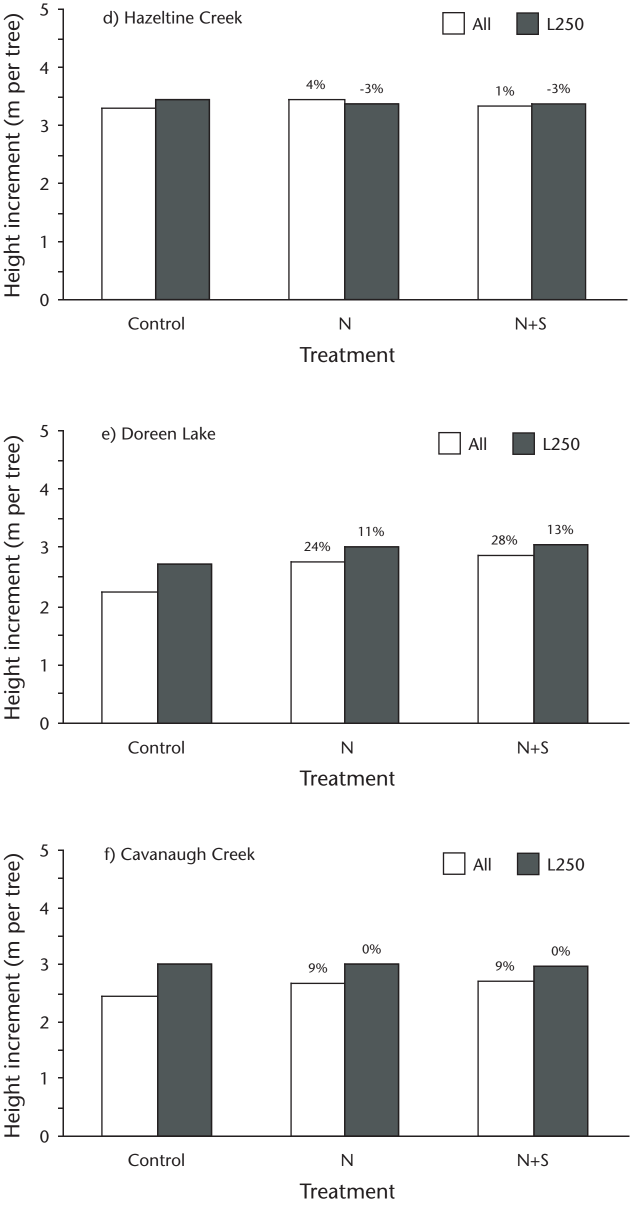

FIGURE 3 *Continued*

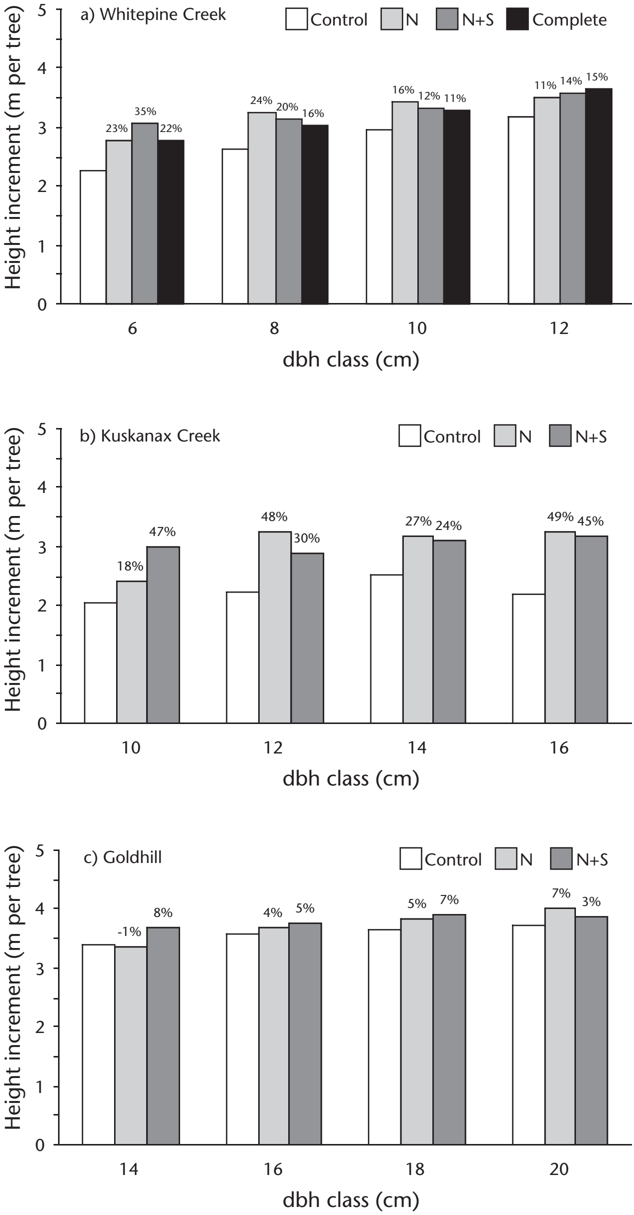

FIGURE 4 *Mean 6-year tree height increment by 2-cm dbh class. Numbers above each bar indicate change relative to the control treatment for each dbh class.*

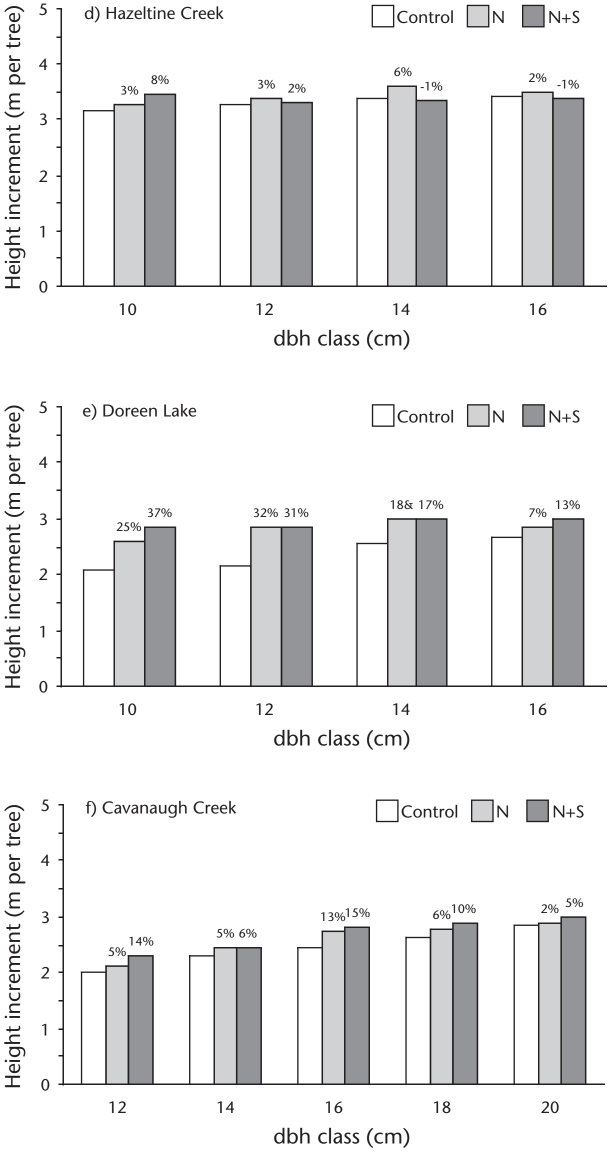

FIGURE 4 *Continued*

Volume Increment

Figure 5 illustrates the 6-year mean volume increments for individual installations and treatments. Five of the six installations responded significantly to fertilization (Table 4). Average volume increment after fertilizing with N alone was 21% (range: 10–34%). The corresponding 6-year volume gains from N+S additions averaged 25% (range: 15–34%) greater than the growth of unfertilized trees. The difference in volume increment between N and N+S treatments was not statistically significant at any of the study sites (Table 4). At Whitepine Creek, growth gains after fertilizing with a "complete mix" fertilizer were no larger than gains obtained with N or N+S fertilizers (Figure 5a).

Absolute tree volume responses to fertilizer were often larger for the largest 250 trees per hectare (L250) than for the entire stand component. On average, however, the L250 exhibited slightly smaller volume incremental gains relative to the control than did the whole stand (Figure 5). Six-year volume gains from N and N+S additions for the L250 component were 19% (range: 0–31%) and 22% (range: 10–35%), respectively. For the L250 component, five of the six installations responded significantly to fertilization (Table 5). The difference in volume increment between N and N+S treatments for the L250 component was not statistically significant at any of the study sites.

Figure 6 illustrates that, in general, the magnitude of absolute volume incremental gains of fertilized trees was positively related to tree size. Notable exceptions to this trend were found at Hazeltine Creek and Cavanaugh Creek, where the largest trees did not exhibit the largest absolute volume responses. No consistent pattern was evident between relative volume response and tree size. In relative terms, the incremental difference between N and N+S was often slightly greater in smaller trees compared to the larger dbh classes (Figure 6); however, the apparent positive effect of S on volume increment was not statistically significant (data not shown).

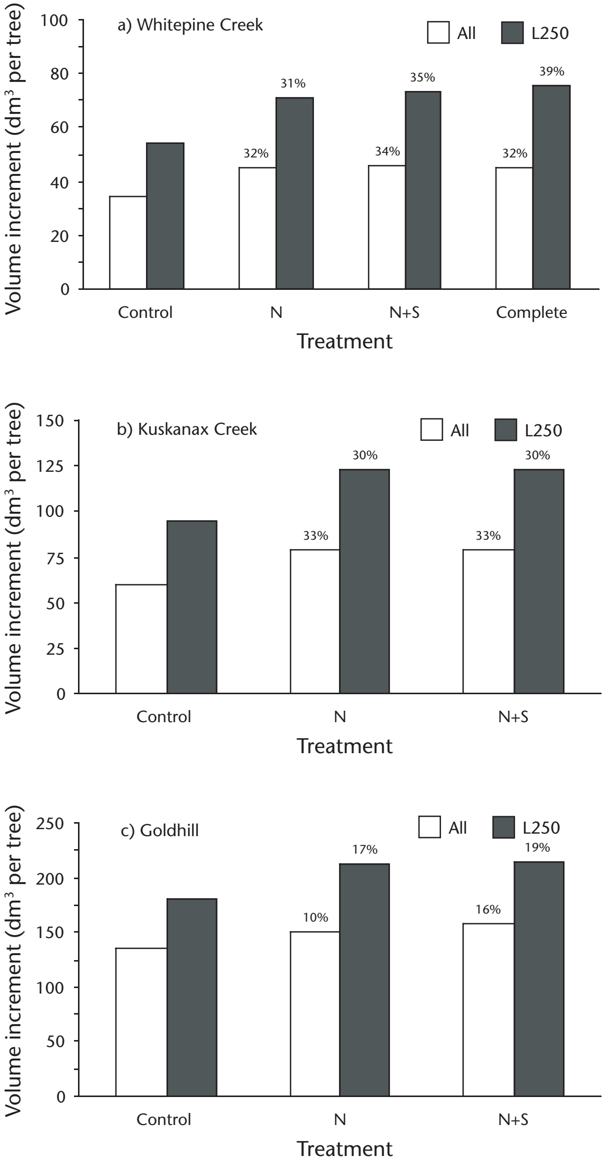

FIGURE 5 *Mean 6-year tree volume increment by stand component (all trees and largest 250 trees per hectare). Numbers above each bar indicate change relative to the control treatment for each stand component.*

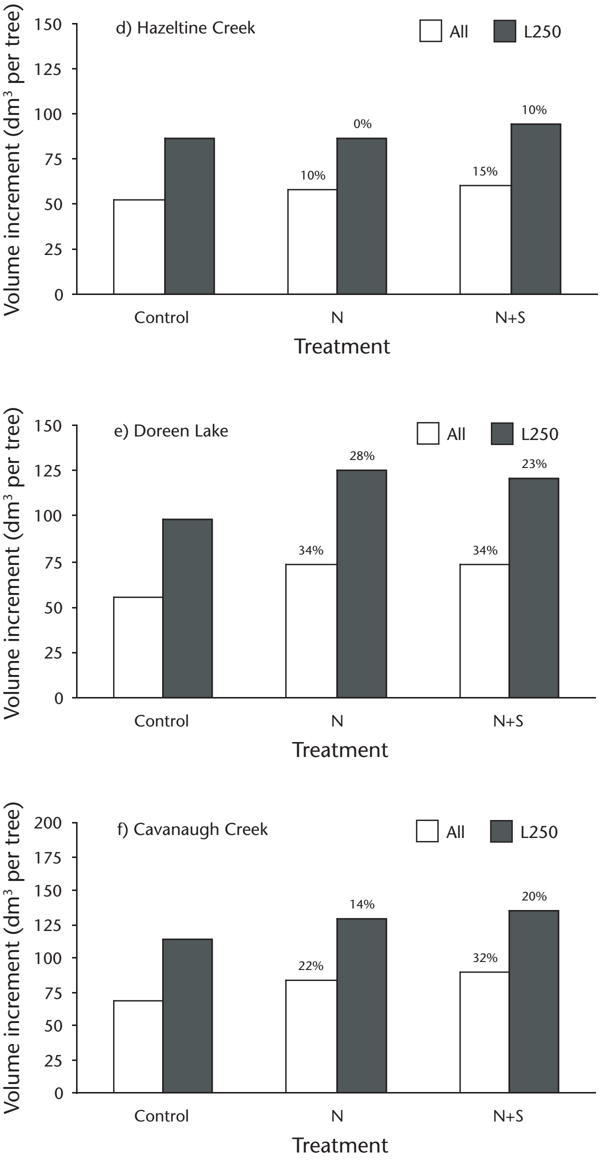

FIGURE 5 *Continued*

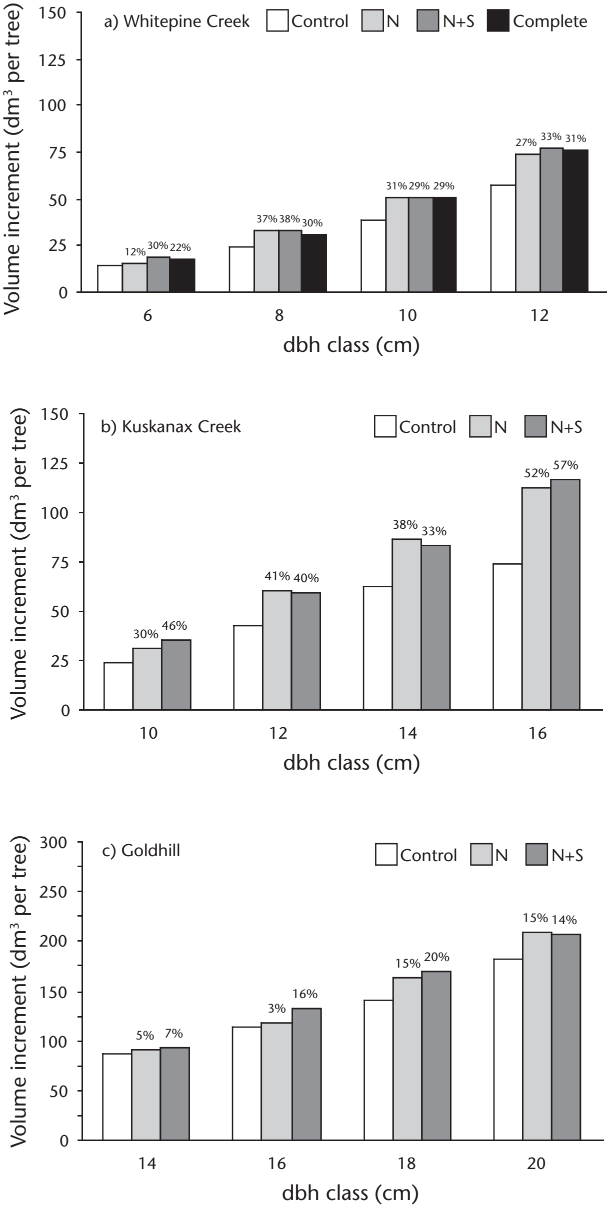

FIGURE 6 *Mean 6-year tree volume increment by 2-cm dbh class. Numbers above each bar indicate change relative to the control treatment for each dbh class.*

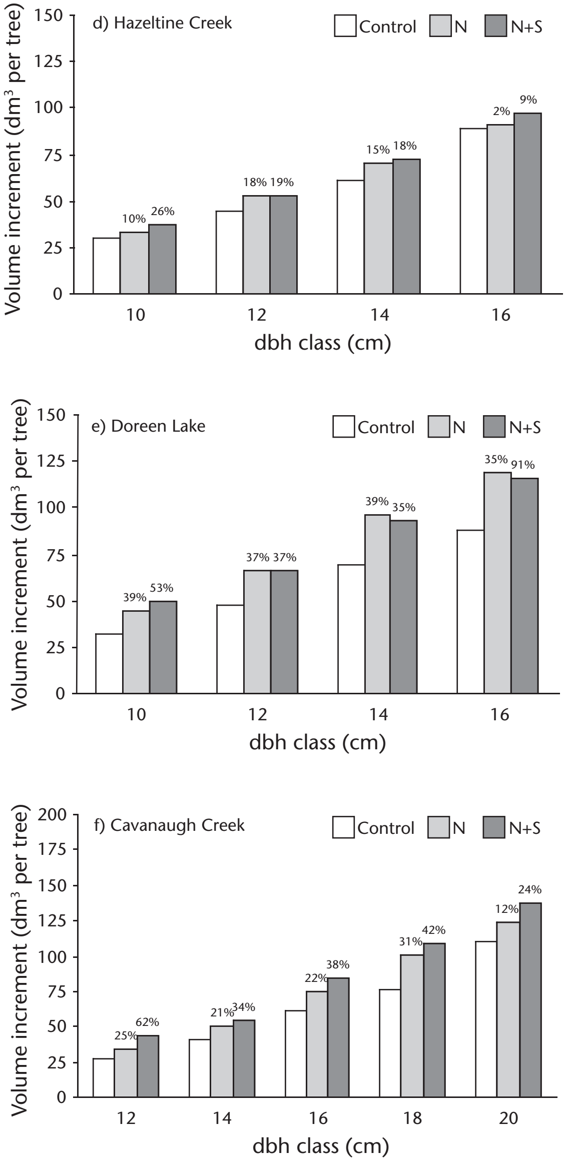

FIGURE 6 *Continued*

AREA-BASED ANALYSIS

Basal Area Increment

Figure 7 illustrates the 6-year mean net stand BA increments for individual installations and treatments. Five of the six installations responded significantly to fertilization (Table 6). Moderate amounts of mortality from *Armillaria* root rot in the fertilized treatment plots negated area-based growth response at Cavanaugh Creek (Figure 7f). For the five healthy installations, average net BA response after fertilizing with N alone was 24% (range: 10–43%). Six-year net BA gains from N+S additions averaged 31% (range: 19–42%). The difference in BA increment between N and N+S treatments was statistically significant at the Doreen Lake study site (Table 6).

Volume Increment

Figure 8 illustrates the 6-year mean net stand volume increments for individual installations and treatments. Four of the six installations responded significantly to fertilization (Table 6). Moderate amounts of mortality from *Armillaria* root rot in the fertilized treatment plots negated area-based growth response at Cavanaugh Creek (Figure 8f). For the five healthy installations, average net volume increment after fertilizing with N alone was 13.5 m^3/ha (range: 6.5–24 m^3/ha) larger than the control treatment. Six-year volume gains from N+S additions averaged 16 m^3/ha (range: 10–23 m^3/ha). In relative terms, stand volume responses to N and N+S fertilization averaged 24% (range: 8–41%) and 28% (range: 16–39%), respectively (Figure 8). The difference in stand volume increment between N and N+S treatments was not statistically significant at any of the study sites (Table 6). At Whitepine Creek, growth gains after fertilizing with a "complete mix" fertilizer were no larger than gains obtained with N or N+S fertilizers (Figure 8a).

FOLIAR NUTRITION

Nitrogen

Foliar N levels in the N and N+S treatments increased sharply in year 1 at each of the study sites (Table 7). Differences in foliar

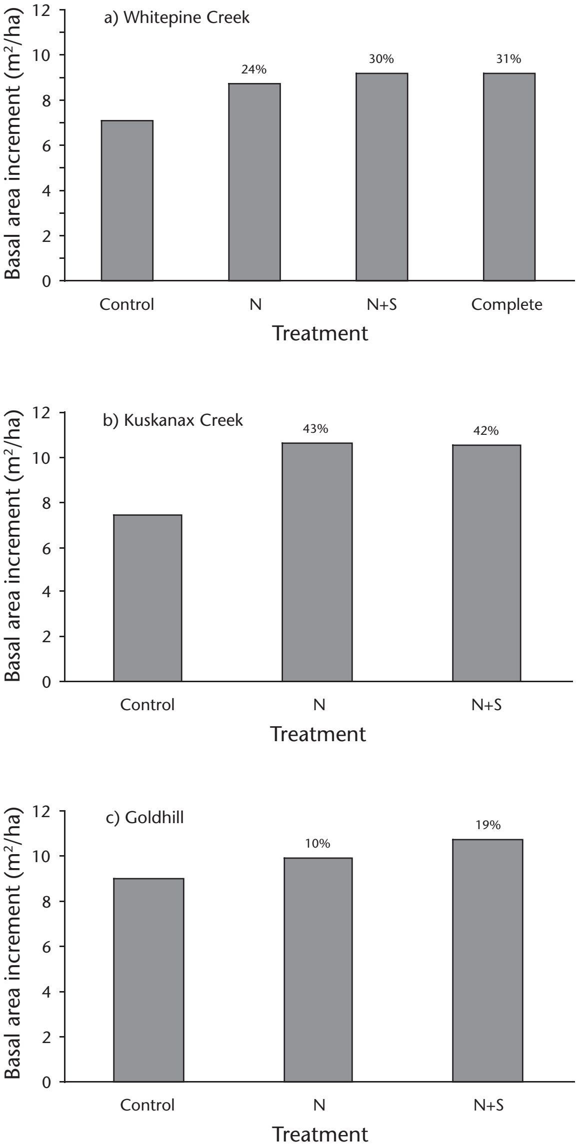

FIGURE 7 *Mean 6-year net stand basal area increment. Numbers above bars indicate change relative to the control treatment.*

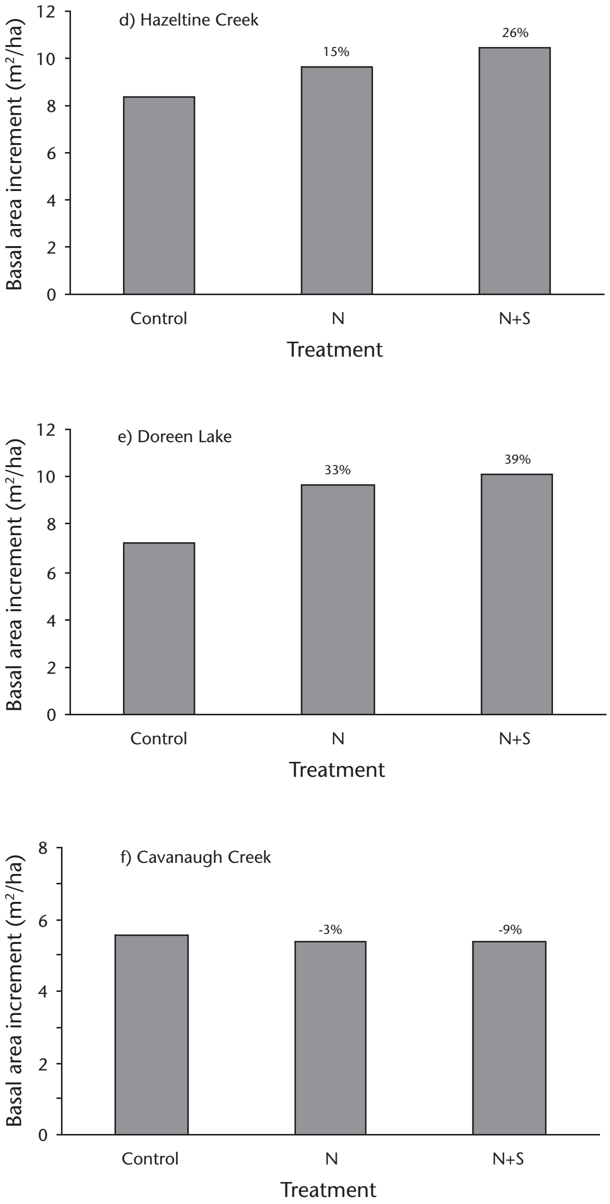

FIGURE 7 *Continued*

TABLE 6 *Analysis of covariance (ANCOVA) summary table for 6-year stand basal area increment and stand volume increment, showing observed F statistics and probability (p) values*

	Basal area		Volume increment	
Source of variation	*F*	*p*	*F*	*p*
Whitepine Creek (#23)				
Treatment	21.38	< 0.001	27.86	< 0.001
Control vs. fertilized	60.56	< 0.001	81.48	< 0.001
N vs. N + others	2.90	0.132	1.52	0.258
Kuskanax Creek (#25)				
Treatment	16.55	0.006	32.16	0.001
Control vs. fertilized	31.89	0.002	61.05	< 0.001
N vs. N+S	0.02	0.902	0.09	0.773
Goldhill (#26)				
Treatment	9.62	0.019	7.70	0.030
Control vs. fertilized	14.88	0.012	11.65	0.019
N vs. N+S	5.70	0.063	5.49	0.066
Hazeltine Creek (#28)				
Treatment	4.52	0.076	1.81	0.256
Control vs. fertilized	7.50	0.041	3.29	0.129
N vs. N+S	1.46	0.281	0.30	0.606
Doreen Lake (#30)				
Treatment	210.87	< 0.001	124.51	< 0.001
Control vs. fertilized	419.87	< 0.001	248.83	< 0.001
N vs. N+S	10.31	0.024	4.00	0.102
Cavanaugh Creek (#37)				
Treatment	0.02	0.977	0.02	0.979
Control vs. fertilized	0.05	0.839	0.03	0.864
N vs. N+S	0.00	0.990	0.02	0.897

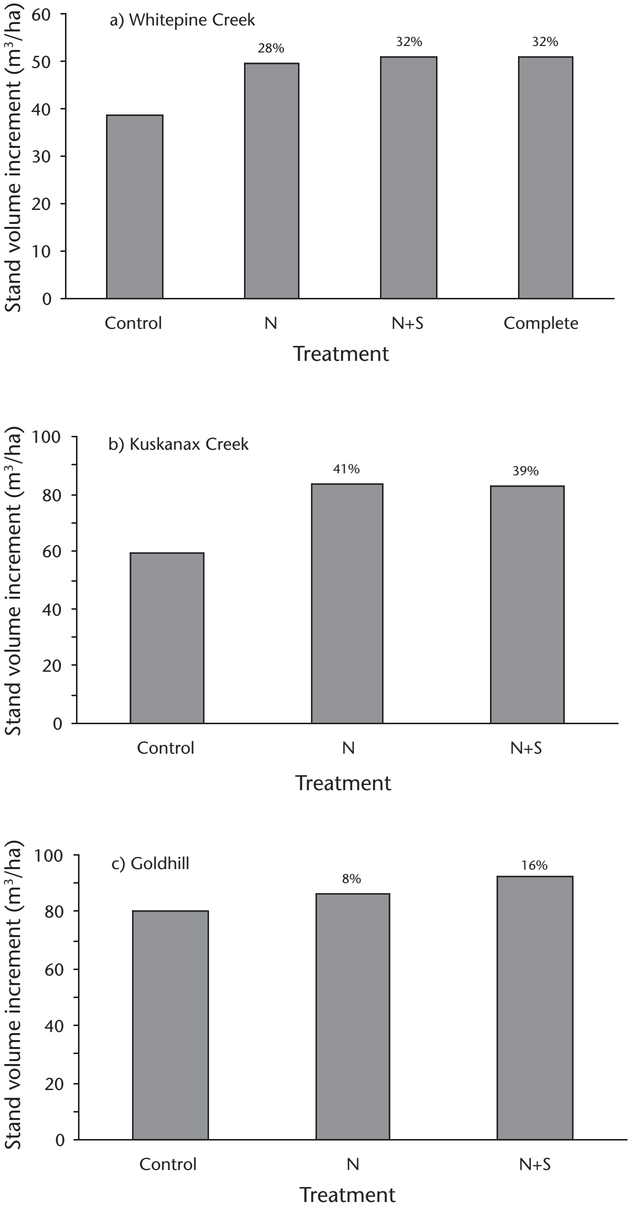

FIGURE 8 *Mean 6-year net stand volume increment. Numbers above bars indicate change relative to the control treatment.*

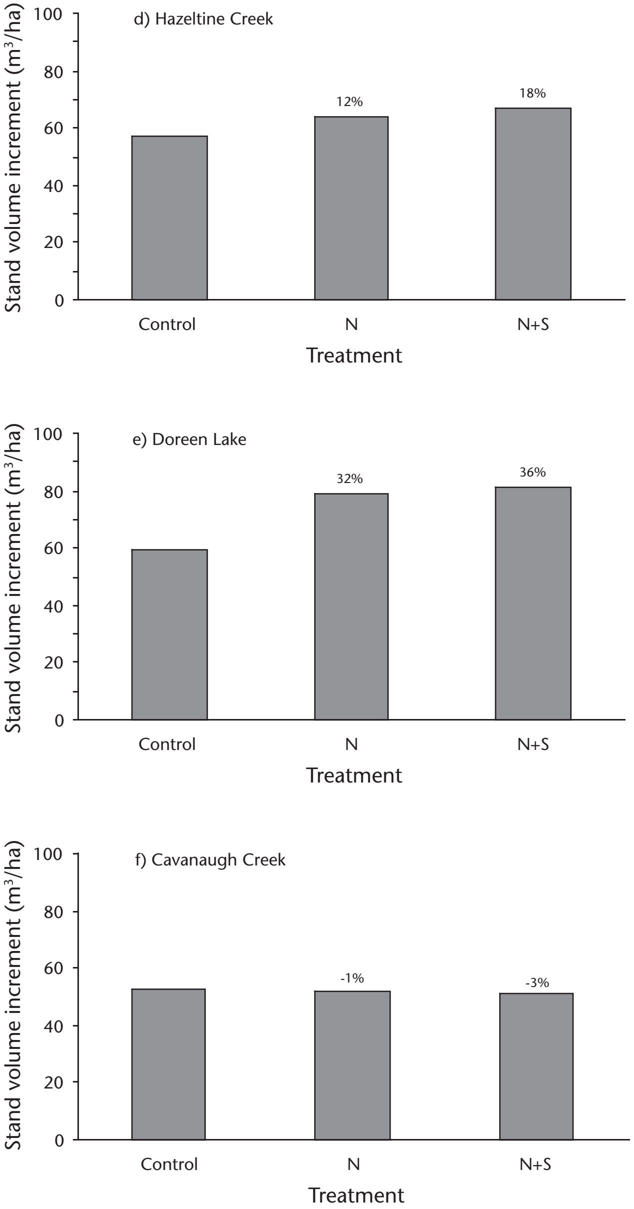

FIGURE 8 *Continued*

TABLE 7 *Mean foliar nutrient concentrations (by installation and treatment) 1 year after fertilization*

	Installation no.					
Treatment	23	25	26	28	30	37
N (g/kg)						
Control	10.3a	10.5a	12.4a	11.7a	9.9a	12.3a
N	12.7a	15.8c	16.9c	14.9b	15.8b	18.1c
N+S	12.6a	13.3b	14.9b	14.4b	15.5b	15.5b
P (g/kg)						
Control	2.3a	2.3a	2.6a	2.2a	2.5a	1.8a
N	2.0a	1.9b	2.3a	2.1a	2.4a	2.2b
N+S	1.9a	1.7b	2.1a	2.0a	2.1a	1.8a
K (g/kg)						
Control	9.7a	8.4a	9.4a	8.2a	7.5a	5.7a
N	9.5a	8.0a	8.3b	6.9b	7.3a	5.3a
N+S	10.1a	8.1a	8.1b	7.8a	8.1a	5.0a
Ca (g/kg)						
Control	4.6a	3.5a	4.3a	3.4a	4.2a	3.8a
N	4.5a	3.7a	3.6b	3.5a	4.3a	3.8a
N+S	5.0a	3.4a	3.8ab	3.1a	4.4a	3.9a
Mg (g/kg)						
Control	0.90a	1.14a	1.40a	0.95a	0.86a	1.01a
N	0.88a	1.25a	1.36a	0.98a	0.92a	1.05a
N+S	0.91a	1.16a	1.38a	0.97a	0.93a	1.03a
S (g/kg)						
Control	0.96a	1.04a	1.41a	1.10a	1.11a	1.02a
N	0.83a	0.94a	1.12b	0.92b	0.89b	0.89b
N+S	1.09a	0.99a	1.34a	1.08a	1.09a	0.99a
SO_4 (mg/kg)						
Control	136a	280a	335a	105a	270a	105a
N	18b	24b	37c	40b	13b	14b
N+S	124a	45b	158b	45b	22b	20b
B (mg/kg)						
Control	23a	22a	26a	29a	25a	15a
N	22a	21a	23a	26b	22ab	12a
N+S	21a	20a	24a	28ab	21b	12a

Note: For each nutrient, column values with different letters are significantly different ($p < 0.05$).

N between unfertilized and fertilized trees were statistically significant at five of the six sites. At three sites, foliar N levels in year 1 were significantly higher in N than in N+S treatments (Table 7). By year 3, treatment effects on foliar N were not statistically significant (Table 8).

Sulphur

Fertilization with N alone caused foliar S levels to decline relative to S levels in unfertilized foliage in year 1 (Table 7). The difference in foliar S concentration between control and N-only treatments was statistically significant in four of the six trials after 1 year. At three of these four sites, the differences remained statistically significant 3 years after fertilization (Table 8). After 1 year, four of the six trials showed significantly higher foliar S levels in N+S treatments than in N-only treatments (Table 7). Differences in foliar S between N and N+S treatments remained statistically significant after 3 years (Table 8).

Sulphate Sulphur

Fertilization resulted in a steep decline in foliar SO_4 levels 1 year after fertilization, especially in N-only treatments (Table 7). Foliar SO_4 levels in N-only treatments remained significantly lower than in control treatments after 3 years, whereas SO_4 levels in N+S-fertilized trees had risen to levels comparable with those in unfertilized trees (Table 8). In most cases, SO_4 levels were significantly higher in N+S than in N treatments in year 3 (Table 8).

Other Nutrients

Overall, foliar levels of non-added macronutrients (P, K, Ca, and Mg) and micronutrients (copper, zinc, iron, manganese, and boron) were largely unaffected by fertilization. Foliar levels of P and K were often slightly lower in N and N+S treatments than in the control 1 year after fertilization, but treatment differences were usually not statistically significant (Table 7). At one site (Kuskanax Creek; #25), significantly lower foliar P levels in N and N+S treatments persisted until year 3 (Table 8). For the micronutrients, foliar B levels were apparently slightly lower in fertilized than in unfertilized treatments after years

TABLE 8 *Mean foliar nutrient concentrations (by installation and treatment) 3 years after fertilization*

	Installation no.					
Treatment	23	25	26	28	30	37
N (g/kg)						
Control	9.6a	10.5a	11.3a	10.7a	9.3a	na
N	10.3a	10.9a	12.2a	11.1a	9.3a	na
N+S	1.01a	10.1a	11.7a	11.0a	9.8a	na
P (g/kg)						
Control	2.1a	2.1a	2.3a	2.2a	1.9a	na
N	2.1a	1.7b	2.0a	2.2a	1.8a	na
N+S	2.2a	1.7b	2.2a	2.3a	1.8a	na
K (g/kg)						
Control	9.8a	8.3a	7.6a	7.8a	7.3a	na
N	10.0a	7.8a	8.0a	8.0a	6.6a	na
N+S	10.0a	7.5a	8.0a	7.8a	6.7a	na
Ca (g/kg)						
Control	4.0a	3.5a	4.9a	4.5a	4.1a	na
N	3.8a	3.4ab	4.1a	4.6a	3.8a	na
N+S	4.1a	3.0b	4.4a	4.3a	4.1a	na
Mg (g/kg)						
Control	0.92a	1.21a	1.08a	0.82a	0.97a	na
N	0.92a	1.17ab	1.08a	0.86a	0.90a	na
N+S	0.96a	1.05b	1.17a	0.86a	0.95a	na
S (g/kg)						
Control	0.87a	1.19a	1.17a	1.01a	0.86a	na
N	0.85a	0.99b	0.93b	0.93b	0.75b	na
N+S	0.97b	1.10a	1.11a	1.08a	0.90a	na
SO_4 (mg/kg)						
Control	82a	246a	189a	110a	185a	na
N	32b	68c	29c	32b	67b	na
N+S	128c	159b	126b	106a	141ab	na
B (mg/kg)						
Control	21a	20a	18a	20a	16a	na
N	20a	14b	17a	18a	14a	na
N+S	18a	16ab	15a	19a	15a	na

Note: For each nutrient, column values with different letters are significantly different ($p < 0.05$).

1 and 3 (Tables 7 and 8); however, the treatment differences were small and were not usually statistically significant. Other micronutrients were generally unaffected by fertilization (data not shown).

Nutrient Concentration Ratios

Fertilization resulted in large, and statistically significant, increases in foliar N:P, N:K, N:Mg, and N:S concentration ratios 1 year after fertilization at all study sites (Table 9). For non-added nutrients (P, K, Mg), differences in the ratio values between N and N+S treatments were usually not statistically significant. For N:S ratios, however, values were consistently higher in N than in N+S treatments (Table 9). In most cases, nutrient concentration ratios were similar to control values by year 3 (Table 10); however, third-year N:S ratios in N-only treatments remained significantly higher than in control and N+S treatments.

TABLE 9 *Mean foliar nutrient concentration ratios (by installation and treatment) 1 year after fertilization*

	Installation no.					
Treatment	23	25	26	28	30	37
N:P ratio						
Control	4.6a	4.6a	4.7a	5.4a	3.9a	6.9a
N	6.3b	8.4b	7.4b	7.0b	6.7b	8.3b
N+S	6.5b	7.8b	7.1b	7.2b	7.4b	8.6b
N:K ratio						
Control	1.1a	1.3a	1.3a	1.4a	1.3a	2.2a
N	1.3b	2.0b	2.0b	2.2c	2.2b	3.4b
N+S	1.3b	1.6ab	1.8b	1.9b	1.9b	3.1b
N:Mg ratio						
Control	11.5a	9.2a	8.9a	12.3a	11.6a	12.2a
N	14.4b	12.6b	12.5c	15.3b	17.2b	17.3b
N+S	13.8b	11.5b	10.8b	14.9b	16.7b	15.3ab
N:S ratio						
Control	10.8a	10.1a	8.8a	10.7a	9.0a	12.0a
N	15.2b	16.8b	15.2c	16.2c	17.8c	20.4c
N+S	11.6a	13.6b	11.1b	13.4b	14.2b	15.6b

Note: For each nutrient concentration ratio, column values with different letters are significantly different ($p < 0.05$).

TABLE 10 *Mean foliar nutrient concentration ratios (by installation and treatment) 3 years after fertilization*

	Installation no.					
Treatment	23	25	26	28	30	37
N:P ratio						
Control	4.6a	4.9a	4.9a	5.0a	5.1a	na
N	4.8a	6.4c	6.0a	5.1a	5.3a	na
N+S	4.7a	5.8b	5.4a	4.8a	5.6a	na
N:K ratio						
Control	0.97a	1.3a	1.5a	1.4a	1.3a	na
N	1.03a	1.4b	1.5a	1.4a	1.4a	na
N+S	1.01a	1.3ab	1.5a	1.4a	1.5a	na
N:Mg ratio						
Control	10.4a	8.7a	10.5ab	13.1a	9.7a	na
N	11.3a	9.3a	11.3a	13.1a	10.3a	na
N+S	10.6a	9.7a	10.0b	12.9a	10.2a	na
N:S ratio						
Control	11.0a	8.8a	9.7a	10.6a	10.8a	na
N	12.2b	11.1b	13.1b	12.0b	12.4b	na
N+S	10.4a	9.2a	10.5a	10.2a	10.9a	na

Note: For each nutrient concentration ratio, column values with different letters are significantly different ($p < 0.05$).

DISCUSSION

The apparent absence of competition mortality during the 6-year measurement period is not surprising given the low stand density indices of these young stands. At year 6, stand density index (SDI) in control treatments ranged from a low of 394 at Whitepine Creek to a high of 555 at Kuskanax Creek. These values represented only 27% and 38%, respectively, of a maximum SDI of 1450 for Douglas-fir (Long 1985). In fertilized plots, SDIs ranged from a low of 442 (30% of maximum SDI) at Whitepine Creek to a high of 670 (46% of maximum SDI) at Kuskanax Creek after 6 years. The largest SDI values are well below the lower limit of self-thinning (870) that was indicated by Long (1985). After 6 years, most SDI values in control and fertilized treatments approximated the lower limit (510) for full site occupancy of Douglas-fir (Long 1985).

Disregarding the one installation damaged by root disease, the average relative 6-year net per-hectare volume gains from N fertilization (200 kg N/ha) reported for this study (24%) compare favourably with gross responses reported previously for young (< 30 years old), thinned coastal Douglas-fir forests in Washington and Oregon (Heath and Chappell 1989; Hopmans and Chappell 1994). The two coastal studies reported the average gross response to N applied at 224 kg/ha to be about 18–20% over a 6–8 year response period; however, the average gross 6- to 8-year per-hectare volume gains (18–25 m^3/ha, respectively) in the coastal studies were larger than the average net 6-year volume responses to N additions measured in this study (13.5 m^3/ha). Notwithstanding differences associated with the reporting of gross versus net increment, the young coastal Douglas-fir stands had, on average, larger amounts of initial standing BA and greater periodic annual increments than were measured in the interior stands. Nitrogen application rates in the coastal studies were also slightly higher than those used in this study. These differences probably explain the larger average absolute responses reported for the coastal sites.

Six-year growth responses in this study also compare favourably with growth responses reported for N-fertilized Douglas-fir in the Inland Northwest of the United States (i.e., east of the Cascade Mountains in Washington and Oregon, and in Idaho and Montana), where 94 fertilizer trials were established in even-aged, managed Douglas-fir stands between 1980 and 1982. The average age of the treated stands was 65 years (range: 27–100 years). Across all regions, average gross volume growth increased by 16% relative to control growth in the 6 years after fertilizing with 200 kg N/ha (Moore et al. 1991). Absolute per-hectare volume gains averaged 11 m^3/ha. In northern Idaho, where the average site index of treated stands (25 m at 50 years) most closely approximated the site index of stands in this study, gross volume gains averaged 14.5 m^3/ha; however, large amounts of mortality in fertilized treatments resulted in much smaller net 6-year volume gains (8.3 m^3/ha) (Moore et al. 1991).

Variable growth responses have been reported from Douglas-fir fertilizer studies in both the Pacific and Inland Northwest. Hopmans and Chappell (1994) reported that volume response at 16 of the 35 coastal installations was less than 10%, whereas volume responses at 12 sites exceeded 40%. For the Inland Northwest installations, volume response was less than 15% in approximately one-half of the fertilized stands, and exceeded 45% in about one-tenth of the stands (Moore et al. 1991). Similar variations have been reported for immature Douglas-fir stands in coastal British Columbia (Carter et al. 1998). In contrast, the magnitude of growth responses that were measured in this study was relatively consistent across the study area. Individual-tree volume responses were statistically significant at five of the six installations, and relative volume responses occurred within a fairly narrow range (10–34%). Fertilization experiments in other regions, however, were typically established across a wide range of site and stand conditions, whereas the six installations in this study were established in similar-aged stands growing on circummesic sites within only three ICH biogeoclimatic subzones.

An attractive feature of fertilization from a timber supply perspective is its potential to accelerate stand development, thus allowing fertilized stands to be harvested sooner. This is a particularly important consideration in the interior of British Columbia, where fertilization is currently used as a silvicultural tool in immature stands to partially mitigate the negative effects of the mountain pine beetle on short- and mid-term timber supply. Therefore, instead of quantifying fertilization response as the amount of "extra" wood produced, an alternative approach would determine its effect on biological rotation length (i.e., culmination of mean annual increment) and technical rotation length (e.g., minimum harvestable age). With just 6 years of growth response data in this study, it is difficult to accurately determine the effect of fertilization on the rotation lengths of the Douglas-fir stands. However, with the customized fertilization features of TIPSY (Version 3.2, Mitchell et al. 2004) the probable effects of various fertilization scenarios can be assessed. For example, results from this study indicate that a 25% gain in 10-year periodic increment is likely in several of the Douglas-fir stands. Fertilization of a 25-year-old plantation (SI = 26) would result in culmination of mean annual increment (MAI) at about 85 years compared to about 88 years in the unfertilized stand. Alternatively, and assuming that a economically viable harvest requires at least 150 m^3/ha of merchantable stand volume, fertilization would lower the minimum harvestable age by about 2 years compared to an unfertilized stand (36 and 38 years, respectively). Re-fertilization of the SI 26 stand at age 35 (and assuming a similar relative response) would lower culmination age to about 82 years. At age 45, the quadratic mean diameter and merchantable volume of the re-fertilized stand would be equivalent to that of a 50-year-old unfertilized stand.

Results from several coastal Douglas-fir research studies indicate that differences in site quality may explain some of the variation in N fertilization response, with greater absolute and relative responses often occurring on sites with lower site index (Heath and Chappell 1989; Chappell et al. 1992; Carter et al. 1998). Weak relationships between growth response and site quality have been reported for thinned Douglas-fir in coastal regions (Miller, Barker, et al. 1986), however. Because only a small number of Douglas-fir stands were tested in this study, the relationship between growth response following fertilization and site index could not be reliably evaluated. Of the two stands with the highest estimated site index (SI = 29), one responded quite well and the other responded quite poorly. Results were similar for the two stands at the low end of the site index range tested (SI = 24); one stand responded much better than the other stand. For the Inland Northwest, a weak relationship between site index and growth response was reported for fertilized Douglas-fir (Moore et al. 1991).

Pre-fertilization foliar SO_4 levels at all study sites were below the suggested threshold of 400 mg/kg (Turner et al. 1979) required for favourable growth response following N addition. In N-only treatments, lower foliar S concentrations and elevated N:S ratios 1 year following fertilization indicated S deficiencies at several study sites (Ballard and Carter 1986; Carter 1992). Sulphur additions clearly improved the foliar S status of fertilized stands. Added S was effective in maintaining favourable foliar N:S balance in N+S-fertilized treatments. The effectiveness of added S on improving foliar S status differs from other studies with Douglas-fir. Miller, Atherton, and Wilcox (1986) and Carter et al. (1998) reported that N+S fertilizers failed to increase foliar S levels above those in N-fertilized trees. Likewise, Blake et al. (1990) found that only small quantities of S were accumulated following N+S additions as evidenced by the minor differences in foliar N:S ratios and SO_4 levels between the N and N+S treatments. These differences may be partially explained by the greater leaching losses of the highly soluble SO_4 attributed to the higher precipitation in coastal areas.

Despite the effectiveness of added S on improving foliar S status, mean 6-year tree volume response differences between

N and N+S treatments in this study were relatively small (21% and 25%, respectively) and not statistically significant. These findings contradict results from Douglas-fir fertilizer screening trials in the interior of British Columbia, where first-year increases in needle mass were generally small unless other nutrients were added in combination with N (Brockley and Swift 1990). In these trials, high post-fertilization foliar N:S ratios (25–30) in N-only treatments strongly indicated that added S was likely responsible for the beneficial effects of the multi-nutrient fertilizer on Douglas-fir needle mass. However, S deficiencies in the N-only treatments were likely exacerbated by the rapid uptake of N and high foliar N levels (18–23 g/kg) after spring applications of ammonium nitrate fertilizer. The effect of fall-applied urea on foliar N was considerably smaller in subsequent area-based field experiments. These findings also differ from previous studies with lodgepole pine in the interior of British Columbia, in which growth response was often enhanced by combining S with N in fertilizer applications (Brockley 2000, 2001a, 2004). In 17 pine installations fertilized with both N and N+S, the combined N+S application resulted in a larger mean 6-year BA response than N alone (28 vs. 19%, respectively) (Brockley 2000). Six (35%) of the 17 pine installations responded significantly to N alone; 88% (15 of 17) responded significantly to combined N+S fertilization. Blake et al. (1988) also demonstrated larger growth responses to N+S than to N alone in greenhouse and field studies with coastal Douglas-fir, and identified S-responsive stands on the basis of subsoil SO_4 concentrations. However, Carter et al. (1998) reported that growth responses were not improved when S was included in multi-nutrient blends applied to 48 immature Douglas-fir field trials in coastal British Columbia. Similar growth responses to repeated application of N and N+S fertilizers also indicated that S deficiencies did not occur in a 27-year-old Douglas-fir stand on Vancouver Island (Weetman et al. 1997).

Previous studies with Douglas-fir have reported strong negative relationships between growth responses to N fertilizer and pre-treatment foliar nutrient levels. For example, Turner et al. (1988) reported that the level of N in the foliage of unfertilized Douglas-fir accounted for 61% of the variation in 4-year BA response to N fertilizer. Hopmans and Chappell (1994) showed that 8-year relative BA response was strongly related to the level of N in the foliage of unfertilized Douglas-fir at 11 sites, accounting for as much as 94% of the variation among sites. Other studies have used pre-fertilization levels of foliar SO_4 to predict whether Douglas-fir stands will respond to N and N+S additions (Turner et al. 1977, 1979). By modifying deficiency and sufficiency diagnostic criteria developed for foliar SO_4 in radiata pine, Turner et al. (1979) used pre-fertilization foliar SO_4 to identify Douglas-fir stands that were responsive and unresponsive to N fertilization. The correct prediction was made in 17 of 19 stands. Brockley (2000) used pre-fertilization levels of foliar N and SO_4 to explain 68% of the variation in the relative growth response of lodgepole pine to fertilization with N alone. Foliar nutrients were also useful in determining whether lodgepole pine would respond incrementally to S when added in combination with N. Stands in which pre-fertilization foliar SO_4 was 60 mg/kg or less and the N:S ratio was 13 or more did not respond significantly to N alone, but always responded significantly to N+S. Conversely, a foliar SO_4 level greater than 60 mg/kg combined with an N:S ratio of 12 or less always resulted in a favourable response to N with no incremental benefit of added S (Brockley 2000). In this study in the interior of British Columbia, the reliable assessment of pre-fertilization foliar N and SO_4 levels as predictors of growth response in Douglas-fir to N and S additions is precluded by the small number of field installations. Interestingly, however, all four installations in which pre-fertilization foliar N was less than 11.5 g/kg responded significantly to N alone. Average tree BA response in these stands was 29% (range: 26–35%) larger than control growth over 6 years. Conversely, relative BA response was only 12% in the two installations in which pre-fertilization foliar N was greater than 11.5 g/kg. Turner et al. (1979) used a foliar N threshold of 11.2 g/kg to differentiate between N-deficient and N-sufficient Douglas-fir stands. Pre-fertilization foliar SO_4 was ineffective in separating responsive and non-responsive stands to N additions. The three installations in which pre-fertilization foliar SO_4 was greater than 200 mg/kg had mean 6-year relative BA responses of 25%. Corresponding BA gains for the three installations with less than 200 mg/kg SO_4 averaged 22%. However, pre-fertilization SO_4 showed potential utility in identifying S-responsive stands. For example, virtually no difference was evident in average BA response between N and N+S fertilization (31 and 32%, respectively) in the two installations with less than 11.5 g/kg foliar N and more than 200 mg/kg foliar

SO_4. In contrast, the two installations with less than 11.5 g/kg N and less than 200 mg/kg SO_4 had average 6-year BA responses of 27% and 37%, respectively. To further test these relationships, additional fertilizer trials are required in stands exhibiting a wider range of pre-fertilization foliar N and SO_4 levels. Also, note that the foliar N and SO_4 thresholds indicated above were based on the specific analytical procedures outlined in this research report. For example, the dry combustion analyzers used by some laboratories consistently recover more N from plant tissues than the wet digestion procedure used in this study (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 pre-digestion procedure is conducted. Based on the results of several inter-laboratory comparisons (R.P. Brockley, unpublished data), a foliar N deficiency threshold of 13 g/kg (below which a favourable response to N fertilization is expected) is likely appropriate for foliar analyses using dry combustion methodology. Similarly, SO_4 analytical results are very sensitive to determination methodology. HI-reduction and ion chromatography procedures give similar results, whereas results from an inductively coupled plasma (ICP) spectrophotometer are generally much higher (Brockley 2000).

Studies in the Inland Northwest have identified that foliar K may be an important factor in controlling the growth and health of Douglas-fir stands following N fertilization (Mika and Moore 1990; Moore et al. 1994). The growth response of stands with good pre-treatment K status (foliar K > 6 g/kg; N:K ratio < 1.5) was significantly better than stands with poor K status (foliar K < 6 g/kg; N:K ratio > 2) (Mika and Moore 1990). Mortality was also higher in K-poor stands, partially negating per-hectare volume gains. Foliar N:K imbalance and subsequent mortality due to *Armillaria* root disease may be related to fertilizer-induced changes in root biochemistry (i.e., a reduced phenol:sugar ratio) that favour the spread of root disease (Entry et al. 1991; Shaw et al. 1998). Interestingly, the only occurrence of root disease in this study was at the Cavanaugh Creek site, which had the poorest pre-fertilization foliar K status (foliar K = 5.7 g/kg; N:K ratio = 2). Further deterioration of foliar N:K balance following fertilization (N:K = 3.1–3.4) may partially explain the disproportionate amounts of mortality and the absence of per-hectare volume gains in N and N+S treatments.

CONCLUSIONS

Six-year results from this study indicate that managed immature Douglas-fir stands growing on circummesic sites within the ICH biogeoclimatic zone in the interior of British Columbia are generally responsive to fertilization. Relative responses compare favourably with results from Douglas-fir fertilization studies in other jurisdictions. Results from coastal studies indicate that the duration of growth response from a single fertilizer application is at least 8 years in thinned stands (Chappell et al. 1992). Therefore, the mean per-hectare volume gains over the entire response period will likely exceed the mean stand volume responses from N and N+S additions (14–16 m^3/ha) that have been achieved in this study after 6 years. The 6-year results from this study suggest that the incremental growth benefits of added S may be too small on most sites to justify the extra expense involved in blending and applying multi-nutrient fertilizers in large-scale aerial operations.

Growth and foliar data from six field installations are insufficient to reliably predict responsiveness to N fertilization, or to evaluate the need to include S in Douglas-fir fertilizer prescriptions. Nevertheless, results from this study, and others, indicate that pre-fertilization levels of foliar N and SO_4 may have potential utility in selecting candidate stands and in making appropriate fertilizer prescriptions. For example, the largest growth responses after fertilization may be expected in stands with pre-fertilization foliar N levels of less than 11.5 g/kg (< 13 g/kg when using dry combustion analytical methods). Also, low foliar N combined with small amounts of pre-fertilization foliar SO_4 (< 200 mg/kg) may indicate that some additional growth gains can be achieved by blending S with N in fertilizer prescriptions. Finally, results from this study apparently support previous claims from the Inland Northwest that low pre-fertilization foliar K levels (< 6 g/kg) and elevated N:K foliar concentration ratios (> 2) may increase the susceptibility of fertilized Douglas-fir to mortality losses from *Armillaria* root disease. Additional Douglas-fir fertilizer trials are needed to test and refine these preliminary guidelines for wet-belt Douglas-fir in the interior of British Columbia.

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