Lodgepole Pine Nutrition and Fertilization: a Summary of B.C. Ministry of Forests Research Results

by

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EXECUTIVE SUMMARY

The lodgepole pine fertilization research conducted in the interior of British Columbia during the past 15 years has generated a considerable amount of information that may be useful to those forest managers who are presently conducting operational fertilization projects, or who are contemplating such operations. Most of the research has been conducted in 15–35-year-old thinned, fire-origin stands in the Montane Spruce (MS) and Sub Boreal Spruce (SBS) biogeoclimatic zones. The Forest Resource Development Agreements (FRDA I and II) have provided most of the funding for the establishment and remeasurement of these installations.

This report summarizes the results obtained from 33 lodgepole pine fertilization research installations established by the Ministry of Forests, Forest Productivity and Decision Support (FPDS) Field Experiments research group at the Kalamalka Forestry Centre in Vernon. These results are summarized as follows:

**Nutrient Deficiencies**

Nitrogen (N) deficiencies are widespread and serious in lodgepole pine forests throughout the interior of British Columbia, especially in fire-origin stands. Actual or inducible sulphur (S) deficiencies are also common in immature lodgepole pine. Pre-fertilization foliar analyses indicate probable S sufficiency only in the MS biogeoclimatic zone. Hence, S may have a strong controlling influence on lodgepole pine growth response following N fertilization on many Interior sites. Marginal to low foliar boron (B) concentrations occur in various locations, mostly in north-central British Columbia. Nitrogen fertilization further depletes foliar B levels, which may increase the likelihood of induced B deficiencies.

**Response to Nitrogen Additions**

Overall, lodgepole pine responds quite well to N fertilization, with the majority of stands showing a significant response. A mean diameter response of 31% relative to the growth of unfertilized trees has been obtained over a 3-year response period. When converted to area-based estimates, as much as 17 m³/ha of "extra" wood has been produced during the 6 years following treatment. However, the response is quite variable, especially within the SBS biogeoclimatic zone.

The average response of fire-origin stands is high relative to other stand origins. Fire-origin stands within the MS biogeoclimatic zone appear to be particularly responsive to N additions.¹ Harvest-origin stands and plantations in the SBS biogeoclimatic zone have generally responded poorly to N additions. However, insufficient response data are currently available to fully evaluate their growth response potential. Also, most plantations and harvest-origin stands are too young to maximize area-based fertilization volume gains.

¹ no information is available for the MSb biogeoclimatic zone
Response to Nitrogen plus Sulphur

Results indicate that the responsiveness of lodgepole pine to fertilization can be substantially improved on many sites by adding S in conjunction with N. Fire- and harvest-origin stands within the SBS biogeoclimatic zone may be particularly responsive to combined N+S fertilization, whereas lodgepole pine within the MS biogeoclimatic zone does not respond incrementally to S additions. For lodgepole pine, it is recommended that operational fertilizer prescriptions include both N and S (50–75 kg/ha) where pre-fertilization foliar sulphate-S (SO₄) levels are less than 60 ppm.

Response to Boron

Although not as widespread as N-induced S deficiencies, inadequate B nutrition may reduce the responsiveness of lodgepole pine to N additions, and, in cases of severe B deficiency, can cause dramatic top die-back. Small B additions significantly increase foliar B levels for an extended period and effectively prevent top die-back. Because even a single die-back episode may leave persistent stem defects, the addition of a small amount of B (2–3 kg/ha) in the fertilizer prescription may be a wise "insurance policy" when fertilizing stands with marginal (i.e., <10 ppm) pre-fertilization foliar B levels. Alternatively, it may be more cost effective to avoid fertilizing stands where pre-fertilization foliar analysis indicates less than 10 ppm B in foliage.

Duration of Response

The direct effects of fertilization usually last between 6 and 9 years. Additional growth gains beyond this period can be attributed mostly to indirect effects caused by the progressively larger size of the fertilized trees, which is brought on by the direct effect in previous growing seasons.

Nitrogen Application Rate

Comparative research studies have shown a surprisingly small difference in growth response between application rates of 100 and 200 kg N/ha. Results indicate that treatment-related damage and mortality is positively related to N application rate, which may reduce potential volume gains. Also, induced S deficiencies may be more serious at higher N rates, thereby reducing the effectiveness of the additional N when not combined with S additions. However, despite the small incremental gains often detected between N application rates of 100 and 200 kg/ha, it is recommended that no adjustments be made to the N prescriptions currently used in operational aerial fertilization projects (175–200 kg/ha). The benefits of the higher rates are apparent in undamaged stands and on sites where S supplies are adequate to balance the added N. On S-deficient sites, the effectiveness of the higher N application rates may be improved when N is added in combination with S. Also, the fixed costs associated with operational fertilization are high compared to the cost of the additional N.

Nitrogen Source and Season of Application

Limited comparisons between N sources and seasons of application indicate there is no reason for changing the current operational practice of fertilizing with urea in the fall. However, additional field trials over a wider range of sites are needed before the relative merits of different N sources and seasons of applications can be fully evaluated.
Stand Density

The different post-thinning densities (i.e., 1100, 1600, and 2100 stems per hectare) that have been used in lodgepole pine fertilization research studies have not been tested at the same location. Therefore, definitive conclusions about the effect of post-thinning density on the magnitude of fertilization growth response cannot be made because of the confounding effects of site and stand age. Research with coastal Douglas-fir indicates that, on an individual-tree basis, fertilization growth response is inversely related to post-thinning density. This inverse relationship will probably be less pronounced for lodgepole pine within the tested density range (1100–2100 stems per hectare) because their smaller crowns afford greater room for crown expansion. Therefore, for a given lodgepole pine stand and fertilizer treatment, the magnitude of area-based growth response (m³/ha) following a single fertilizer treatment will probably be larger at 2100 stems per hectare than at 1100 stems per hectare. However, the higher-density stand will spend the latter portion of the rotation within the upper zone of imminent competition-mortality. Consequently, a portion of the fertilized volume may be unavailable at final harvest unless a commercial thinning is undertaken. Also, there are fewer opportunities for repeated fertilization in higher-density stands because of the negative effects of crown competition on fertilization response. Consequently, the potential for increasing lodgepole pine harvest volume (or reducing rotation length) by fertilization is probably greater at lower post-thinning densities.

Timing of Fertilization in Relation to Thinning

Stands thinned at the time of fertilization apparently respond slightly better to N additions than do stands thinned at least 2 years before fertilization. When undertaken in conjunction with thinning, however, fertilized stands may be more susceptible to small-mammal feeding injuries and snowpress than are previously thinned stands. Although a small amount of growth response may be sacrificed, these risks can be significantly reduced by delaying fertilization for a short period after thinning.

Site Index

Fertilization studies with lodgepole pine indicate that there is no relationship between relative growth response and site index. This is contrary to evidence from coastal areas, where Douglas-fir response usually increases as site index decreases. Within the lower portion of the site index scale for lodgepole pine, site productivity may be strongly controlled by non-nutritional factors such as low soil moisture availability and short growing season. Also, other nutritional factors such as S may limit the responsiveness of some stands to N additions, even though soil N may be in short supply. On the other hand, lodgepole pine rarely regenerates extensively, and is rarely planted on extremely productive sites in the interior of British Columbia. Despite favourable relative growth responses, the absolute stand volume gains and piece size on lower-productivity sites (e.g., SI <16) may be too small to make fertilization profitable. Therefore, where nutrient deficiencies are indicated, preference should be given to fertilizing medium to good lodgepole pine sites in the interior of British Columbia.

Stand Age

Thinned, 25–35-year-old lodgepole pine currently exhibits the greatest area-based fertilization growth response potential. From an economic perspective, however, mid- to late-rotation lodgepole pine stands are better candidates for operational fertilization, since
the cost of fertilizing is carried for fewer years before harvest. Because the amount of "extra" wood produced following fertilization depends in part on the amount of standing volume at the time of treatment, semi-mature stands with favourable stand structure should also result in attractive volume gains. Unfortunately, many older stands have poor live-crown ratios and marginal stand health due to the absence of early stand density control. Consequently, there may be few opportunities in the short term for fertilizing older lodgepole pine. However, early stand density control in fire- and harvest-origin stands, combined with extensive planting of lodgepole pine, will create many future opportunities for mid- to late-rotation fertilization.

**Predictive Tools**

Pre-fertilization N and S status, as evaluated by foliar analysis, may offer a fairly reliable method of evaluating the N fertilization response potential of candidate sites, and help identify those sites that would benefit from combined N and S fertilizer applications. Stands with greater than 80 ppm foliar SO₄ before fertilization respond very well to N additions, whereas levels of less than 40 ppm indicate that the stand will respond poorly. The responsiveness of stands with low initial SO₄ can often be significantly improved by combining N and S in fertilizer prescriptions. A strong negative correlation has been shown between pre-fertilization foliar N concentration and subsequent stemwood response. Stands with more than 1.20% foliar N before fertilization usually respond poorly to N additions. Seventy-nine percent of the variation in 3-year relative dbh response to N fertilization can be explained by a multiple regression model using pre-fertilization N and SO₄ levels as independent variables.

**Small-mammal Damage**

Feeding injuries to the stems of fertilized crop trees caused by red squirrel are a significant threat in some lodgepole pine stands. Squirrels will preferentially attack fertilized trees, and the resulting damage and mortality can all but wipe out the per-hectare volume gains. The risk of feeding injuries to the stems of crop trees is high if evidence of damage is found during the pre-thinning survey. However, the risk is minimal for stands with no pre-treatment damage.

**Snowpress**

The accumulation of snow in the fuller crowns of fertilized trees may increase the likelihood of irreversible bending and breakage of stems in stands fertilized at the time of thinning, especially where pre-thinning stand density is high and average height/dbh ratio is greater than 90.
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1 INTRODUCTION

During the past 15 years, approximately 121 forest fertilization research trials have been established by the British Columbia Ministry of Forests, the Canadian Forest Service, and the University of British Columbia to document the nutrition and fertilization response potential of major tree species in the interior of British Columbia. Approximately two-thirds of these trials have been established by the Ministry of Forests (MOF), Forest Productivity and Decision Support (FPDS) Field Experiments research group at the Kalamalka Forestry Centre in Vernon. The Forest Resource Development Agreements (FRDA I and II) have provided the majority of funding for the establishment and remeasurement of these trials.

Approximately one-half of the FPDS fertilization research trials in the interior of British Columbia have been established in immature stands of lodgepole pine (Pinus contorta Dougl. var. latifolia Engelm.). The species is the most widespread conifer in British Columbia, occurring in all but the coldest (Alpine Tundra) and driest (Bunchgrass and Ponderosa Pine) of the 11 interior biogeoclimatic (BEC) zones. Lodgepole pine is especially widespread and abundant in the Sub-Boreal Spruce (SBS), Sub-Boreal Pine-Spruce (SBPS), and Montane Spruce (MS) biogeoclimatic zones, where seral stands commonly regenerate overabundantly following disturbance. Lodgepole pine plantations are also a common feature, especially on the SBS landscape. The MOF has made large silvicultural investments in thinning and fertilization during the past decade (FRDA I and II) to increase the yield and value of merchantable wood produced from this extensive immature lodgepole pine resource. Forest Renewal B.C. now provides forest licensees in the interior of British Columbia with a funding source for operational thinning and fertilization projects.

This report summarizes the results and interpretations from FRDA-funded lodgepole pine fertilization research, undertaken to date, by the FPDS Field Experiments group. The information will be of particular interest to field practitioners involved in the planning and implementation of lodgepole pine operational fertilization programs in the interior of British Columbia.

2 RESEARCH STRATEGY

Two different approaches have been adopted for planning and conducting lodgepole pine fertilization research in the interior of British Columbia (Brockley 1991b). The research strategy combines short-term fertilizer screening trials (to diagnose specific nutrient deficiencies and rapidly evaluate various fertilization regimes) with conventional, fixed-area plot experiments that provide the area-based response data (i.e., m$^3$/ha of "extra" wood produced) required to support and rank operational forest fertilization investments. Since 1981, the FPDS Field Experiments group has designed and undertaken seven lodgepole pine fertilization experimental projects (E.P.'s) in the interior of British Columbia. Fifteen fertilizer screening trials and 24 fixed-area trials have been established to date. The early trials (1981–1985) were established to document the response of lodgepole pine to nitrogen fertilization. Subsequent trials have been designed to test the effects of adding other nutrients (e.g., sulphur and boron) in conjunction with nitrogen.

At present, foliar nutrient data and growth response data are available for 33 of the 39 trials. These 33 trials are the subject of this report.

The distribution of the 33 trials by forest region, BEC zone, stand origin, and age is
FIGURE 1. The distribution of lodgepole pine fertilization research installations by (a) Forest Region, (b) BEC Zone, (c) stand origin, and (d) stand age (n=33).
shown in Figure 1a–d. The large proportion of trials in the SBS and MS reflects the abundance of immature lodgepole pine in these BGC zones and the importance of this resource in timber supply analyses. Most of the fertilization research to date has been conducted in fire-origin stands. The harvest and planting of lodgepole pine in the interior of British Columbia did not become widespread until the 1970's; consequently, few stands of these origins are old enough to be considered for operational fertilization. The highest fertilization research priority has been assigned to 15–35-year-old stands (Figure 1d). If not planted, all of these stands have been pre-commercially thinned to provide opportunities for crown expansion after fertilization. Post-thinning stand densities in research installations range from 1100 to 2100 stems per hectare. Unfortunately, virtually no early stand density control was undertaken in lodgepole pine stands that are now semi-mature. Therefore, existing semi-mature stands usually exhibit unfavourable stand structures and poor fertilization response potential. However, current pre-commercial thinning activities in young stands will certainly create good opportunities for fertilizing older stands in the future. Young stands (<15 years) may exhibit large relative responses to additions of fertilizer, but absolute stem volume gains will be small due to their small stem diameter. The site occupancy of such stands may also be too low to efficiently utilize the applied fertilizer, and noncrop vegetation may effectively compete for the added nutrients and overtake the crop trees.

3 FOLIAR NUTRIENT STATUS

3.1 Pre-fertilization

The average pre-treatment foliar nutrient concentrations by stand origin are shown in Table 1.

Initial foliar data indicate that nitrogen (N) deficiencies are widespread and serious throughout the interior of British Columbia. The low foliar N levels are typical of the levels commonly reported by the various agencies that conduct extensive foliar sampling throughout the region. Lodgepole pine forests have usually been perpetuated through repeated fire disturbance, and therefore often occupy sites of low-N status. Because N is present almost exclusively in organic materials and vaporizes at low fire temperature, it is the nutrient most at risk during burning. On some sites, inappropriate harvesting and site preparation practices may exacerbate existing nutritional problems. Figure 2 illustrates the cumulative distribution of pre-fertilization foliar N concentrations in the 33 trials. Fifteen percent of the stands have foliar N levels lower than 1.00%, indicating very severe N deficiency. Twenty (61%) of the stands have foliar N levels lower than 1.15%, indicating moderate to very severe N deficiency. Fire-origin stands have lower mean foliar N levels than either harvest-origin stands or plantations (Table 1). This may indicate lower soil-N status due to fire effects, but may also reflect differences in average stand age (24, 14, and 18 years, respectively). However, the relationship between stand age and foliar N concentration has not been studied. Of the 22 fire-origin stands, 17 (77%) have values less than 1.15%. Conversely, only one harvest-origin stand (25%) and two plantations (29%) have pre-treatment foliar N concentrations below this threshold.

Foliar sulphate-sulphur (SO₄) has been used to diagnose sulphur (S) deficiencies and imbalances in other species. According to available diagnostic criteria (Ballard and Carter 1986), actual or inducible S deficiencies are common in immature lodgepole pine. For example, pre-treatment foliar SO₄ is less than 80 ppm in 18 of the 33 trials. This level indicates S deficiency in radiata pine (Pinus radiata D. Don). Foliar SO₄ levels are particularly low in harvest-origin stands and plantations (Table 1). Only in the MS biogeoclimatic zone do pre-treatment SO₄ levels indicate probable S sufficiency. Pre-treatment mean foliar boron (B) levels, shown in Table 1, indicate B sufficiency. However, low foliar B
TABLE 1. Mean initial foliar nutrient concentrations by stand origin

<table>
<thead>
<tr>
<th>Origin</th>
<th>N (% mm)</th>
<th>P (mm)</th>
<th>K (% mm)</th>
<th>Mg (% mm)</th>
<th>S (% mm)</th>
<th>SO₄ (ppm)</th>
<th>B (ppm)</th>
<th>N/S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire (n=22)</td>
<td>1.07 (0.02)</td>
<td>0.142 (0.003)</td>
<td>0.49 (0.01)</td>
<td>0.103 (0.002)</td>
<td>0.094 (0.002)</td>
<td>99.0 (1.6)</td>
<td>19.2 (1.5)</td>
<td>11.4 (0.3)</td>
</tr>
<tr>
<td>Harvest (n=4)</td>
<td>1.21 (0.04)</td>
<td>0.160 (0.005)</td>
<td>0.55 (0.01)</td>
<td>0.112 (0.004)</td>
<td>0.089 (0.003)</td>
<td>52.9 (7.2)</td>
<td>14.8 (3.1)</td>
<td>13.6 (0.8)</td>
</tr>
<tr>
<td>Plantation (n=7)</td>
<td>1.18 (0.05)</td>
<td>0.170 (0.008)</td>
<td>0.50 (0.02)</td>
<td>0.096 (0.004)</td>
<td>0.091 (0.002)</td>
<td>51.8 (3.1)</td>
<td>17.8 (1.6)</td>
<td>13.0 (0.4)</td>
</tr>
<tr>
<td>All (n=33)</td>
<td>1.11 (0.02)</td>
<td>0.150 (0.003)</td>
<td>0.50 (0.01)</td>
<td>0.103 (0.002)</td>
<td>0.093 (0.001)</td>
<td>81.6 (8.5)</td>
<td>18.4 (1.1)</td>
<td>11.9 (0.3)</td>
</tr>
</tbody>
</table>

NOTE: Numbers in parentheses indicate standard error.

TABLE 2. Mean foliar nutrient concentrations 1 year after fertilization with 200 kg N/ha, by stand origin

<table>
<thead>
<tr>
<th>Origin</th>
<th>N (% mm)</th>
<th>P (mm)</th>
<th>K (% mm)</th>
<th>M (% mm)</th>
<th>S (% mm)</th>
<th>SO₄ (ppm)</th>
<th>B (ppm)</th>
<th>N/S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire (n=22)</td>
<td>1.59 (0.04)</td>
<td>0.151 (0.002)</td>
<td>0.49 (0.01)</td>
<td>0.097 (0.002)</td>
<td>0.082 (0.002)</td>
<td>24.2 (1.6)</td>
<td>15.3 (1.4)</td>
<td>19.4 (0.8)</td>
</tr>
<tr>
<td>Harvest (n=4)</td>
<td>1.87 (0.03)</td>
<td>0.179 (0.001)</td>
<td>0.50 (0.03)</td>
<td>0.108 (0.006)</td>
<td>0.075 (0.004)</td>
<td>20.7 (3.5)</td>
<td>12.1 (2.1)</td>
<td>24.9 (1.6)</td>
</tr>
<tr>
<td>Plantation (n=7)</td>
<td>1.54 (0.07)</td>
<td>0.172 (0.003)</td>
<td>0.48 (0.02)</td>
<td>0.090 (0.004)</td>
<td>0.078 (0.004)</td>
<td>24.6 (3.4)</td>
<td>15.0 (1.5)</td>
<td>19.7 (0.9)</td>
</tr>
<tr>
<td>All (n=33)</td>
<td>1.61 (0.03)</td>
<td>0.159 (0.002)</td>
<td>0.49 (0.01)</td>
<td>0.097 (0.002)</td>
<td>0.080 (0.002)</td>
<td>23.9 (1.4)</td>
<td>14.8 (1.0)</td>
<td>20.1 (0.6)</td>
</tr>
</tbody>
</table>

NOTE: Numbers in parentheses indicate standard error.

Concentrations (<10 ppm) in a small number of installations indicate possible B deficiency, or a deficiency inducible by N fertilization. Most of these stands are located in the eastern portion of the Prince Rupert Forest Region and the western portion of the Prince George Forest Region.

According to published foliar diagnostic guidelines (Ballard and Carter 1986), other pre-treatment mean foliar nutrient levels indicate marginal to adequate nutrient status (Table 1). Sixty percent of the trials have adequate foliar phosphorus (P) concentrations (>0.15%), and the remainder are within the slightly deficient range (0.12–0.15%). Almost all of the pre-treatment foliar potassium (K) and magnesium (Mg) levels are within the slightly deficient to adequate range (>0.44% and >0.09%, respectively).

3.2 Post-fertilization

Mean foliar nutrient concentrations, by stand origin, 1 year following fertilization with 200 kg N/ha (as urea) are shown in Table 2.

Foliar N concentrations increase substantially during the first growing season after treatment. As shown in Figure 2, foliar levels are greater than the suggested deficiency threshold of 1.35% in virtually all of the stands 1 year after N fertilization. Nitrogen concentrations are particularly high in harvest-origin stands (Table 2), possibly due to their younger age (and smaller foliage crown mass).

A typical pattern of foliar N response following fertilization is illustrated in Figure 3. Foliar N levels peak in the first year, are significantly lower in the second year, and by years 3–4 are
FIGURE 2. The relative cumulative frequency distribution of foliar N concentration in research installations before and one year after fertilization with 200 kg N/ha.

FIGURE 3. Foliar nitrogen concentration of fertilized and unfertilized lodgepole pine.
FIGURE 4. The effects of N and N+S fertilization on mean foliar nitrogen/sulphur mass ratio.

generally the same as those found in unfertilized trees. The rapid decrease is mostly caused by a dilution effect, resulting from increased foliage production. Higher foliar N concentration has a positive effect on photosynthetic efficiency (i.e., rate of photosynthesis per unit foliage area), which is one of the factors controlling growth response following fertilization. However, because the duration of growth response far exceeds the short-term increase in foliage efficiency, the major factor controlling growth response is undoubtedly increased foliage production (i.e., increased photosynthetic surface area) (Brix 1991).

Foliar concentrations of P, K, Ca, Mg and most micronutrients remain relatively unchanged following N fertilization (Tables 1 and 2). As shown in Table 2, however, the marginal S status of the unfertilized lodgepole pine stands was exacerbated by N fertilization. Lower foliar S and SO$_4^-$ concentrations and higher N/S ratios indicate that S deficiencies may be induced on some sites following N additions, especially in the young harvest-origin stands. In some cases, induced S deficiencies may become serious enough to preclude or severely restrict growth response following N fertilization.

Sulphur deficiencies have been well documented in grasses and agricultural crops on Luvisolic and Brunisolic soils in the interior of British Columbia (Beaton and Soper 1986). On these soils, the use of nitrogenous fertilizers has caused serious N:S imbalances, and agricultural crops respond favourably to combined applications of N and S.

Because of the possibility of induced S deficiencies following N additions to lodgepole pine, a number of fertilization studies have been established since the late 1980's to evaluate the effect of various S sources and application rates on the S status and growth response of N-fertilized stands. Results from these trials indicate that applied S is readily taken up by trees, regardless of whether it is added in the sulphate form (e.g., ammonium
FIGURE 5. Boron deficiency symptoms following N fertilization of a lodgepole pine stand near Burns Lake, B.C.
FIGURE 6. The effects of N and N+B fertilization on mean foliar B concentration.

Foliar B concentrations in lodgepole pine usually decrease following N additions, thus increasing the likelihood of B deficiency (Table 2). Low B levels have resulted in reduced height increment and/or severe top dieback (Figure 5) in at least four of the trials (Brockley 1989a and 1990). Fortunately, fertilizer B is readily taken up by lodgepole pine, and the improved foliar B status is maintained for an extended period (i.e., >9 years) after additions of small amounts of B (Figure 6). Small B additions in conjunction with N have also been shown to prevent top die-back.

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2 also, Brockley, R.P. Unpubl. data (E.P.'s 886.01, 886.04, 886.05, 886.10, and E.P. 886.12).

3 also, Brockley, R.P. Unpubl. data (E.P.'s 886.01, 886.05, and 886.12).

4 Brockley, R.P. Unpubl. data (E.P. 886.05).

5 Brockley, R.P. Unpubl. data (E.P. 886.12).
4 FERTILIZATION EFFECTS ON TREE GROWTH

4.1 Nitrogen Fertilization

Results from previous studies in Scandinavia and North America clearly show that N is the nutrient that most limits the growth of northern temperate and boreal forests growing on mineral soils. Therefore, the initial series of fertilization trials established by the FPDS group were designed solely to document the growth response of lodgepole pine to N additions (Brockley 1989a, 1991a, and 1995). The recently established experiments to document the effects of other nutrients (e.g., S) also contain an N-only treatment (Mika et al. 1992; Brockley and Sheran 1994). In total, 3-year growth response information has been collected from 33 installations. Six- and 9-year growth response has been analyzed for a smaller number of trials.

Overall, lodgepole pine has responded quite well to N fertilizer applied at a rate of 200 kg/ha. A mean diameter (dbh) response of 31% relative to the growth of unfertilized trees has been obtained over a 3-year response period. Sixty-seven percent of the installations have responded significantly (p<0.05) to N additions. However, the coefficient of variation is high (57%), which indicates the response of lodgepole pine in the interior of British Columbia is quite variable. The relative cumulative frequency distribution of 3-year dbh response to N fertilization (200N) is shown in Figure 7. The vertical axis indicates the proportion of all installations that responded less than or equal to a particular response value shown on the horizontal axis. Growth response is expressed as a percentage of control plot dbh increment over the 3-year response period. For example, approximately one-quarter of the installations responded less than 15%, and about one-quarter responded more than 40%.

Additional information about response variation by BEC zone and stand origin is provided in Tables 3 and 4, respectively. The mean, minimum, and maximum 3-year dbh responses, expressed relative to control increment, are shown along with the median (50%) and the lower (25%) and upper (75%) quartiles. As shown in Table 3, the mean response to N was substantially higher within the MS zone than in other BEC zones. Overall, all eight of the MS installations were in the upper one-half of responsive stands; five of the them were in the upper (75%) quartile. The growth response to N fertilization within the SBS was highly variable. A small number of stands responded well to N additions. Overall, however, the entire lowest (25%) quartile of responding installations consisted of SBS stands.

As shown in Table 4, the mean 3-year dbh response of fire-origin stands to N fertilization was high relative to other stand origins. All of the installations within the upper (75%) quartile were fire-origin stands. Only one (9%) of the 11 nonfire-origin stands (i.e., plantations or harvest origin) were in the upper one-half of responding installations, and 9 of the 10 poorest-responding installations were nonfire-origin stands.

Six-year volume growth response has been analyzed for 15 fixed-area, lodgepole pine fertilization installations (Brockley 1991a). Eight of the 15 installations responded significantly to N fertilization (p<0.05) over the 6-year response period. Total volume gains above control averaged 7.4 (range—1.6–17.2) m³/ha for an application rate of 200 kg N/ha. In relative terms, these responses averaged 24% (range—7–54%). Unfortunately, the favourable effects of fertilization in four installations were partially negated by serious treatment-related damage and mortality. In two installations, the damage consisted of severe red squirrel feeding injuries to the stems of fertilized trees. Induced B deficiency in N-fertilized plots resulted in severe top die-back in one stand, and another installation was affected by snowpress (irreversible bending and breakage) of fertilized
FIGURE 7. The relative cumulative frequency distribution of mean 3-year dbh response in research installations after fertilization with 200 kg N/ha.

TABLE 3. Selected percentiles of 3-year relative dbh response (%) by biogeoclimatic zone

<table>
<thead>
<tr>
<th>BEC zone</th>
<th>Mean</th>
<th>Min.</th>
<th>25%</th>
<th>50%</th>
<th>75%</th>
<th>Max.</th>
<th>CVa</th>
</tr>
</thead>
<tbody>
<tr>
<td>SBS (n=21)</td>
<td>7</td>
<td>9</td>
<td>20</td>
<td>43</td>
<td>55</td>
<td>56</td>
<td></td>
</tr>
<tr>
<td>MS (n=8)</td>
<td>51</td>
<td>28</td>
<td>30</td>
<td>53</td>
<td>70</td>
<td>70</td>
<td>31</td>
</tr>
<tr>
<td>Other (n=4)</td>
<td>24</td>
<td>22</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>27</td>
<td>9</td>
</tr>
<tr>
<td>All (n=33)</td>
<td>31</td>
<td>7</td>
<td>17</td>
<td>26</td>
<td>42</td>
<td>70</td>
<td>57</td>
</tr>
</tbody>
</table>

a coefficient of variation
b not applicable

TABLE 4. Selected percentiles of 3-year relative dbh response (%) by stand origin

<table>
<thead>
<tr>
<th>BEC zone</th>
<th>Mean</th>
<th>Min.</th>
<th>25%</th>
<th>50%</th>
<th>75%</th>
<th>Max.</th>
<th>CVa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire (n=22)</td>
<td>38</td>
<td>17</td>
<td>23</td>
<td>32</td>
<td>55</td>
<td>70</td>
<td>42</td>
</tr>
<tr>
<td>Other (n=11)</td>
<td>15</td>
<td>7</td>
<td>9</td>
<td>12</td>
<td>20</td>
<td>34</td>
<td>53</td>
</tr>
</tbody>
</table>

a coefficient of variation
trees. The resulting mortality and reduced growth increment all but wiped out per-hectare volume gains in damaged installations. The 6-year volume response averaged 9.6 m³/ha (32%) in the 11 installations with small amounts of damage or mortality.

4.2 Nitrogen and Sulphur Fertilization

Foliar analysis data indicate that the S status of many lodgepole pine stands is marginal before fertilization, and that N additions result in further deterioration of S nutrition. Foliar N:S ratios often increase dramatically, and sulphate-S reserves are often depleted to extremely low levels—an indication that the added N may not be fully utilized in protein synthesis. A number of single-tree and fixed-area installations have been established to document whether combined applications of N and S will improve the growth response in stands with inferred S deficiencies. In total, 3-year growth response information for N and N+S treatments has been collected from 18 installations. Six-year growth response has been analyzed for a smaller number of installations.

Overall, combined N+S application has resulted in a larger 3-year relative dbh response than N alone (38% versus 23%, respectively). Seventeen of the 18 installations (94%) responded significantly (p<0.05) to N+S fertilization; 61% (11 of 18) responded significantly to N alone. The relative cumulative frequency shown in Figure 8 indicates that a dbh response of more than 30% was obtained in two-thirds of the installations fertilized with N+S. A similar response was achieved by less than one-fifth of the stands fertilized with N only. Growth response to N and N+S by stand origin is shown in Table 5. Fire-origin stands responded well to N fertilization, relative to other stand types. However, even better growth was achieved when S was added in combination with N. Sulphur was especially effective in fire-origin stands within the SBS and IDF biogeoclimatic zones, where mean 3-year dbh responses to N and N+S were 24% and 53%, respectively. The corresponding gains in the MS and ICH were 39 and 48%. Sulphur additions also had a large positive effect on growth in harvest-origin stands (Table 5), all of which were in the SBS. In addition to

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7 Brockley, R.P. Unpubl. data (S.P.'s 886.01, 886.04, 886.09, 886.10, and 886.12).
producing larger mean growth responses, N+S additions also reduced response variability in fire- and harvest-origin stands (Table 5).

**TABLE 5.** Mean 3-year relative dbh response (%) to N and N+S fertilization by stand origin (n=18)

<table>
<thead>
<tr>
<th>Origin</th>
<th>N</th>
<th>N+S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fire (n=8)</td>
<td>31 (54)</td>
<td>50 (29)</td>
</tr>
<tr>
<td>Harvest (n=3)</td>
<td>19 (70)</td>
<td>35 (42)</td>
</tr>
<tr>
<td>Plantation (n=7)</td>
<td>15 (42)</td>
<td>25 (40)</td>
</tr>
<tr>
<td>All (n=18)</td>
<td>23 (64)</td>
<td>38 (45)</td>
</tr>
</tbody>
</table>

Note: Numbers in parentheses indicate coefficient of variation

Three-year area-based volume growth response (i.e., m³/ha of "extra" wood) has been analyzed for six fixed-area, lodgepole pine installations. However, one installation was severely damaged by top die-back caused by induced B deficiency. Of the five undamaged installations, three responded significantly (p<0.05) to N fertilization, and all five responded significantly to N+S. The incremental gain between N and N+S was statistically significant in three of the five installations. Two of the installations are in the SBS zone; the others are in the MS, IDF, and SBPS. The MS stand responded well to N fertilization (10.1 m³/ha; 47%), and did not respond incrementally to S. For the other installations, the 3-year volume gains above control averaged 2.9 (range 0.3–5.1) m³/ha and 6.0 (range 4.6–8.4) m³/ha for N and N+S, respectively. In relative terms, these respective responses averaged 20% (range 3–37%) and 42% (range 32–60%).

Six-year volume growth response has been analyzed for three of the five fixed-area installations (2 SBS, 1 MS). The MS stand responded well to N fertilization (17.2 m³/ha; 34%), and did not respond incrementally to S additions. For the two SBS installations, 6-year volume gains above control averaged 8.1 m³/ha and 14.7 m³/ha for N and N+S, respectively. In relative terms, these responses averaged 21 and 38%.

### 4.3 Other Nutrient Additions

Low foliar B concentrations in lodgepole pine are quite common in north-central British Columbia. The lowest foliar B levels are often associated with soils derived from igneous rocks that are subject to periods of soil water deficit during the growing season. Nitrogen fertilization further depletes foliar B levels, and has resulted in visible B deficiency symptoms (i.e., top die-back) in at least one lodgepole pine fertilization installation near Burns Lake (Brockley 1989a). In the ICH near Golden, British Columbia, a combination of high rainfall and coarse-textured soil apparently depleted soil-available B, which also led to severe top die-back in a N fertilization research installation. Boron deficiency symptoms developed very rapidly, and the resulting damage reduced stand volume increment and adversely affected stem quality and value. In this same stand, the addition of a small amount of B in combination with N completely prevented top die-back.

Visible B deficiencies, although dramatic, are rare in the interior of British Columbia. However, subacute B deficiency (without visible growth disturbance symptoms) may also reduce the N fertilization response potential of lodgepole pine. Results from a single-tree fertilization trial near Burns Lake showed that combined N and B application in the absence of any visible B deficiency symptoms significantly (p<0.05) improved growth response over that obtained with N fertilization alone (Brockley 1990). Average 6-year stem volume gains were 20 and 34% for N and N+B treatments, respectively. The difference was largely due to reduced height increment (but no top die-back) of trees fertilized with N alone.

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8 Brockley, R.P. Unpubl. data (E.P. 886.01).

9 Brockley, R.P. Unpubl. data (E.P. 886.12).

10 Brockley, R.P. Unpubl. data (E.P. 886.05).
The occurrence of nutrient deficiencies other than S and B in lodgepole pine have not been systematically tested. In four lodgepole pine installations (2 fixed-area; 2 single-tree), a "complete mix" treatment has been applied in addition to N and N+S treatments. The "complete" fertilizer used in both single-tree trials and in one fixed-area trial was custom blended to deliver (kg/ha) 200N, 100P, 100K, 116Ca, 50Mg, 50S, 13Fe, 52Zn, 5.5Mn, 2.2Cu, 2.2B and 1.5Mo. In the other fixed-area installation, the complete fertilizer contained (kg/ha) 200N, 100P, 100K, 37Mg, 75S, and 3B.

The "complete" fertilizer resulted in a slightly greater 3-year dbh response than the N+S treatment in all four of the installations. The responses to N, N+S, and "complete" treatments averaged 14, 26, and 33%, respectively. However, the difference between the N+S and "complete" treatments was not statistically significant (p<0.05) in any of the installations. Consequently, there is no clear indication that the growth of lodgepole pine in the interior of British Columbia is seriously affected by deficiencies other than N, S, and B. However, additional research is required before the possibility of other nutrient deficiencies can be dismissed.

4.4 Duration of Response

Growth response data for 11 fixed-area installations are available for three remeasurements conducted at 3-year intervals. As shown in Figure 9, average relative growth gains were largest in the 1–3-year growth period, and declined in each of the following periods. Although similar in the 1–3- and 4–6-year response periods, absolute volume gains declined in the 7–9-year period.

Fertilization growth response is made up of two distinct components: a direct effect and an indirect effect. The direct effect represents the increase in tree or stand growth due solely to improved nutrition (which results in greater photosynthetic efficiency and larger photosynthetic surface area). The difference in growth between fertilized and unfertilized trees in the period immediately after fertilization (i.e., 2–3 years) is generally considered wholly a direct effect. Assuming there is a positive fertilizer effect on tree growth, however, some of the subsequent differences in growth between fertilized and unfertilized trees will be due to the progressively larger size of the fertilized trees, brought on by the direct effect in previous growing seasons. This is commonly referred to as the indirect fertilizer effect. When calculating total growth response beyond the initial (i.e., 1–3-year) response period, the response can be partitioned into one portion directly attributable to the fertilizer (a direct effect) and another portion resulting from tree size differences at the start of the response period (an indirect effect). The indirect effect accumulates so that, as the time since treatment lengthens, an increasing portion of the difference between treated and untreated tree growth can be attributed to past growth increases.

The individual-tree volume responses in 11 lodgepole pine fixed-area installations have been partitioned into direct and indirect components. On average, approximately 70% of the 0–9-year individual-tree volume response to 200N in lodgepole pine fixed-area installations was due to improved nutrition (i.e., direct effect). However, indirect effects accounted for approximately 40 and 70% of the total growth response during the 4–6- and 7–9-year response periods, respectively. Based on these results, the direct effects of fertilization are generally not expected to last much beyond 9 years; additional volume gains beyond this period can be attributed almost entirely to indirect effects.

4.5 Effects of Nitrogen Application Rate

The initial series of 11 fixed-area installations was designed to compare the effects of fertilizing with 100 and 200 kg N/ha. Average 6-year individual-tree relative volume response for an application of 100N was 25%

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11 Brockley, R.P. Unpubl. data (E.P. 886.01 and E.P. 886.04).
12 Brockley, R.P. Unpubl. data (E.P. 886.01).
13 Ibid.
FIGURE 9. The effect of N fertilization on mean individual-tree volume increment in research installations, by response period.

FIGURE 10. The effect of N application rate with and without S additions on mean 3-year dbh response.
The effects of urea and AN fertilizer on the nutrition and growth of lodgepole pine have been evaluated at three locations in the interior of British Columbia over a 6-year period (Brockley 1989b and 1995). Because their effectiveness may be influenced by season of application, both spring and fall applications of these two sources have been tested. Lodgepole pine showed no clear preference for a particular N source or season of application in this study. Despite the superiority of AN over urea in improving foliar N status (especially when applied in the spring), the stem growth response of fertilized trees in the three trials was not affected by N source. In fact, spring-applied AN produced the smallest diameter and height increments at two of the study locations. These results clearly differ from Scandinavian experiments, in which spring-applied AN has consistently resulted in the largest stemwood growth responses. These conflicting results may be partially explained by the negative effect of spring-applied AN on lodgepole pine foliar S status in the interior of British Columbia. Because spring-applied AN more effectively increases foliar N concentration, it is most likely to create a N:S imbalance and S deficiency, at least over the short term. Additional field trials over a range of sites are needed to fully evaluate the relative merits of the different N sources and seasons of application. Also, studies are needed to test whether AN is better than urea at stimulating tree growth when accompanied by S additions. Meanwhile, there appears to be no reason for changing the current operational practice of fertilizing with urea in the fall. Fall operations are preferred because road access to fertilized blocks is more predictable than in the spring, and fall weather conditions are usually more favourable for urea application. Also, other silvicultural tasks (e.g., planting) have significant priority in the spring.

4.7 Effects of Post-Thinning Density

The different post-thinning densities (i.e., 1100, 1600, and 2100 stems per hectare) that have been used in lodgepole pine fertilization research studies have not been tested at the same location. Therefore, definitive conclusions about the effect of post-thinning density on the
magnitude of fertilization growth response cannot be made, given the confounding effects of site and stand age. Research with coastal Douglas-fir indicates that, on an individual-tree basis, fertilization growth response is inversely related to post-thinning density (Gardner 1990). Because their smaller crowns afford greater room for crown expansion, however, this inverse relationship will probably be less pronounced for lodgepole pine within the density range tested (1100–2100 stems per hectare). Therefore, for a given lodgepole pine stand and fertilizer treatment, the magnitude of area-based growth response (m³/ha) following a single fertilizer treatment will probably be larger at 2100 stems per hectare than at 1100 stems per hectare. However, the higher-density stand will spend the latter portion of the rotation within the upper zone of imminent competition-mortality. Consequently, a portion of the fertilized volume may be unavailable at final harvest unless a commercial thinning is undertaken. Also, there are fewer opportunities for repeated fertilization in higher-density stands because of the negative effects of crown competition on fertilization response. Consequently, the potential for increasing lodgepole pine harvest volume (or reducing rotation length) by fertilization is probably greater at lower post-thinning densities.

Factorial combinations of post-thinning densities and fertilization have recently been established on the same site to more fully explore the effect of stand density on lodgepole pine fertilization growth response.

Managed stand yield tables produced by WinTYP SY,¹⁵ and lodgepole pine stand density management diagrams (Farnden 1996), can be used to track stand development at various site indices and stand densities. By using these tools, the timing and frequency of fertilization treatments can be scheduled to maximize fertilization response potential and the utilization of the "extra" wood produced. Fertilization after pre-commercial and commercial thinning are logical scheduling choices, since thinning creates room for crown expansion and increases the likelihood that fertilization volume gains will be harvested. Fertilization will shorten the time required to reach the operability target of the thinned stand while minimizing the sacrifice in volume production caused by thinning. Also, combining fertilization with pruning will accelerate the production of clear wood on pruned stems. However, the position on the stand density management diagram and the projected trajectory of the stand between the time of fertilization and the next cut should be plotted when scheduling fertilization treatments at other times during the rotation. For example, fertilization 10–15 years before harvest is probably not a logical treatment choice for stands with a pre-commercial thinning regime of 1600 stems per hectare and no subsequent thinning, since there will be limited potential for crown expansion within the Zone of Imminent Competition Mortality. However, provided that stand health and crown conditions are favourable, pre-harvest fertilization of the same stand might be scheduled immediately following commercial thinning (Figure 11).

4.8 Effects of Timing of Fertilization and Thinning

The initial series of fixed-area N fertilization installations was designed so that the effects of timing of fertilization in relation to thinning could be evaluated. Installations thinned at the time of fertilization (Type 1) were established immediately adjacent to installations that were thinned 2–4 years before fertilization (Type 2). Results indicate that the relative volume growth response was considerably greater for Type 1 than for Type 2 installations in both the 1–3- and 4–6-year response periods (Brockley 1989a and 1991a) (Figure 12). Absolute volume gains for the 4–6-year response period were considerably greater for Type 1 than for Type 2 installations, despite the larger trees in previously thinning installations. As a result, "direct" fertilizer effects generally accounted for a greater portion

¹⁵ WinTYP SY is a computer program which accesses a data base of managed stand yield tables produced by the TASS growth model. It is available from the B.C. Ministry of Forests, Forest Productivity and Decision Support Section, Victoria.
FIGURE 11. Crop planning for fertilization using a stand density management diagram.
FIGURE 12. The effect of N fertilization on mean individual-tree volume increment in research installations thinned at the time of fertilization and installations thinned at least 2 years before fertilization, by response period.

of the 4–6-year total growth response in Type 1 than in Type 2 installations. The distribution of volume growth response among crop trees is apparently different for Type 1 and Type 2 installations. Larger trees respond to fertilization better than smaller trees in installations thinned at the time of fertilization. Conversely, large and small trees appear to respond equally to fertilizer when it is applied to previously thinned stands.

The timing of fertilization in relation to thinning also had a significant effect on the magnitude of height response to N fertilization. Average 6-year relative height responses were 29 and 9% for Type 1 and Type 2 installations, respectively. These results indicate that fertilization may alleviate the effects of thinning shock (a temporary decline in the height growth of crop trees immediately after thinning) if undertaken at the time of thinning.

4.9 Effects of Site Productivity

Research studies with coastal Douglas-fir have shown that relative fertilization growth response—the percentage difference in growth between fertilized and unfertilized trees—is inversely related to site productivity, as measured by site index (the average height of selected ‘top height’ trees at a specified age—usually 50 years). In coastal areas, highly productive sites are unlikely to have N deficiencies, and nutritional factors may be more important than non-nutritional factors, such as soil moisture, in controlling the growth of Douglas-fir on lower-productivity sites. However, because tree size on good sites is often larger, compared to lower quality sites, absolute volume gains on the former may be quite large.

Fertilization studies with lodgepole pine indicate that there is no relationship between relative 3-year dbh response and site index (r = -0.08). This is not really surprising, since the growth of many lower-productivity interior forests is probably controlled primarily by non-nutritional factors such as low soil moisture and short growing season. On sites where non-nutritional factors are playing the dominant

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16 Brockley, R.F. Unpubl. data (E.P.'s 886.01, 886.04, 886.05, 886.09, 886.10, 886.12).
role in determining site productivity, fertilization growth response may be small, even though soil N may be in short supply. Also, site productivity may be strongly influenced by nutrient deficiencies other than N (e.g., S) on some lodgepole pine sites. Correlations between fertilizer N response and site index are probably low for those sites where multiple nutrient deficiencies exist. Finally, even though extremely productive Interior sites may be unresponsive to N additions, lodgepole pine rarely regenerates or is planted on such sites.

Results from Interior Douglas-fir fertilization research in the Intermountain region support these findings of a low, simple correlation between growth response and site index (Moore et al. 1991).

4.10 Predictive Relationships

Stand nutrition and fertilization response potential are the result of complex interactions between site factors (e.g., temperature, moisture, nutrient supply), stand factors (e.g., age, stocking), and management factors (e.g., stand density control, site preparation). These interactions, combined with large climatic and geologic diversity, result in substantial variability in the responsiveness of lodgepole pine to N fertilization in the interior of British Columbia. The uncertainty and lack of site specificity regarding growth response potential are major factors in the reluctance of Interior forest managers to invest in large-scale fertilization programs. Reliable predictors of fertilization response are needed so that forest managers can identify those stands that have the greatest growth response potential to N additions, as well as stands where the response can be significantly improved by adding other growth-limiting nutrients in combination with N.

Many previous fertilization studies, with various tree species, have documented a strong positive correlation between the mass of needles produced during the first year after fertilization and subsequent stemwood response (Timmer and Morrow 1984). Consequently, first-year increases in needle weight are often used to provide a "quick index" for evaluating the long-term growth response potential of fertilized stands (Brockley 1986).

Results from the 33 lodgepole pine fertilization research trials indicate that the method is usually able to predict whether or not a significant (p<0.05) 3-year dbh response will occur. Nineteen (83%) of the 23 trials that showed a significant dbh response also had significant (p<0.05) increases in first-year fascicle weight. There were only three cases in which a significant increase in fascicle weight did not result in significant dbh response. The method was slightly less successful in identifying unresponsive stands: fascicle weight correctly predicted insignificant dbh response in 6 of 10 installations. First-year increase in fascicle weight was also usually an effective predictor of whether or not dbh response would be greater with combined applications of N and S than with N alone; the prediction was correct in 14 of the 18 installations (78%). The method correctly identified 5 of the 6 stands that were significantly more responsive to N+S additions than to N alone.

Although first-year fascicle weight is a fairly reliable predictor of whether or not a significant stemwood response will occur, it does not reliably rank stands according to their expected stemwood response. In other words, sites with the largest first-year fascicle weight response do not necessarily have the largest dbh response. First-year relative fascicle weight response explained only 25% (r=0.50) of the variation in 3-year relative dbh response after N fertilization.

A significant positive correlation was found between 3-year relative dbh response and pre-fertilization foliar SO4-S (r=0.79). This relationship is illustrated graphically in Figure 13. Installations with more than 60 ppm foliar SO4 before fertilization had a mean 3-year dbh response of 47%. In fact, only two of the installations with more than 60 ppm SO4 had a 3-year dbh response of less than 40%. None of the 18 installations with less than 60 ppm SO4 achieved a 3-year dbh response of more than 40%, and the installations with less than 40 ppm SO4 all responded less than 15%.

A strong negative correlation was found between relative dbh response and pre-fertilization foliar N concentration (r= -0.74). The average 3-year dbh response was 46% for
FIGURE 13. The relationship between mean 3-year dbh response to N fertilization and pre-fertilization foliar SO₄

installations with pre-fertilization foliar N levels less than 1.05%. The average dbh response was only 13% for installations with more than 1.20% foliar N prior to fertilization.

A strong negative correlation ($r = -0.74$) was also found between relative dbh response and pre-fertilization N/S ratio. The average 3-year dbh response was 47% for installations with N/S ratios of less than 11.5. The average dbh response was only 16% for those installations with N/S ratios greater than 13.

The strong correlations between relative dbh response and pre-treatment foliar N and S levels adds considerable strength to the argument that these two nutrients are the major nutritional factors influencing the productivity of Interior lodgepole pine forests. Consequently, pre-treatment N and S levels may be valuable predictive tools for identifying which stands will be responsive or unresponsive to N fertilization. A multiple regression model using pre-fertilization N and SO₄ levels as independent variables produced the following equation:

$$3\text{-year dbh response (}) = 91.8 + 0.34(\text{SO}_4 \text{ ppm}) - 75.6(\%\text{N})$$

$R^2 = 0.79$ Standard error = 8.6%

This model explained 79% of the variation in 3-year relative dbh response.
FIGURE 14. Severe feeding injuries to fertilized lodgepole pine caused by red squirrel.
5 DAMAGING AGENTS

5.1 Feeding Injuries Caused by Red Squirrel

The higher nutritive quality of fertilized lodgepole pine may make it more palatable to red squirrels, significantly increasing susceptibility to feeding damage. Feeding injuries are caused by the peeling and removal of bark from the basal (and sometimes upper) sections of trees (Figure 14). Although damaged trees are usually not completely girdled, sub-lethal injuries reduce growth response following fertilization, and damaged stems appear to be susceptible to snow or wind breakage at the point of injury.

About 25% of the lodgepole pine research trials have sustained some red squirrel damage after fertilization. Although these stands had all experienced some squirrel damage before fertilization, the incidence and severity of damage is significantly higher in fertilized plots than in unfertilized plots (Brockley 1986 and 1989a; Brockley and Sullivan 1988). All of the damage has occurred in fire-origin stands. Within fire-origin stands, the incidence and severity of squirrel damage is higher in trials that were thinned at the time of fertilization than in trials thinned 2–4 years before fertilization. This may be due to the smaller average tree size in the former, and the presence of fresh thinning debris that provides effective cover and protection for the squirrels.

Red squirrel feeding injuries have also been reported from some large-scale lodgepole pine fertilizer operations in the interior of British Columbia. The aerial distribution of sunflower seeds in susceptible stands has been shown to reduce red squirrel feeding damage in some operational fertilization projects. However, the risk of squirrel damage is probably minimal if no evidence of damage is found during the pre-fertilization stand selection survey.

5.2 Snowpress

Stands thinned at the time of fertilization (Type 1 stands) are usually more responsive to fertilizer additions than previously thinned (Type 2) stands (Brockley 1989a and 1991a). Unfortunately, the accumulation of snow in the fuller crowns of fertilized trees may increase the likelihood of irreversible bending and breakage of boles in Type 1 stands, especially where average height/dbh ratio is high (e.g., >90). These conditions are common in high-density, unthinned fire- and harvest-origin lodgepole pine stands. Snowpress damage rarely occurs in stands where fertilization has been delayed for 2–3 years after thinning (Brockley 1989a and 1991a). Therefore, it is probably wise to delay fertilization for a short period, even though a slightly smaller growth response may be achieved. In addition to eliminating snowpress, a short delay after thinning will enable a better evaluation of the potential for red squirrel damage before operational fertilization investment decisions are made.

17 J. Wearing, B.C. Min. For., Vernon, and J. Perry, B.C. Min. For., Williams Lake. Pers. comm.
18 T. Sullivan, Faculty of Forestry, University of British Columbia. Pers. comm.
6 CONCLUSIONS

Substantial progress has been made evaluating the nutrition and fertilization response potential of lodgepole pine in the interior of British Columbia. The original hypothesis that N is the most important growth-limiting nutrient in Interior forests has been supported. However, other nutrient deficiencies—most notably S and B—have been documented, and may exert strong control over the growth response to N additions on many Interior sites. First approximations of site-specific decision-making tools for operational use have been developed using pre-fertilization foliar N and S levels. However, additional research is required, especially in the SBS biogeoclimatic zone where the growth response to fertilization has been extremely variable. This will enable further development of these, and other, site-specific decision-making tools to guide fertilizer operations in north-central British Columbia.

Most lodgepole pine fertilization research to date has been conducted in 15–35-year-old stands. From an economic perspective, however, mid- to late-rotation lodgepole pine stands are better candidates for operational fertilization, since the cost of fertilizing is carried for fewer years before harvest. Because the amount of "extra" wood produced following fertilization depends in part on the amount of standing volume at the time of treatment, semi-mature stands with favourable stand structure should also result in attractive volume gains. Unfortunately, there may be few opportunities over the short-term for fertilizing older lodgepole pine in the interior of British Columbia. Many older stands have poor live crown ratios and marginal stand health due to the absence of early stand density control. Also, thinning is usually required before fertilization to create sufficient room for crown expansion. Yield implications should be carefully evaluated before older stands are thinned to provide fertilization opportunities. Fortunately, early stand density control in fire- and harvest-origin stands during the past two decades, combined with extensive planting of lodgepole pine, will create many future opportunities for mid- to late-rotation fertilization.

In spite of the higher risks associated with red squirrel feeding damage, 25–35-year-old, thinned, fire-origin stands presently exhibit the greatest area-based fertilization growth response potential (i.e., m³/ha of "extra" wood). At present, there are not enough data available to fully evaluate the responsiveness of harvest-origin stands and plantations. Although they may provide excellent opportunities for future fertilizer operations, most of these stand types are still too young to maximize fertilization volume gains.

Lodgepole pine stands within the MS biogeoclimatic zone respond particularly well to fertilization. Also, available evidence indicates that S additions are not necessary when fertilizing in the MS zone. Within the SBS zone, foliar SO₄ and B levels should be carefully evaluated before fertilization: deficiencies of either of these two nutrients will limit the responsiveness of lodgepole pine to N additions.

Despite the small incremental gains often detected between N application rates of 100 and 200 kg/ha, there is probably no need to adjust the N prescriptions currently used in large-scale aerial fertilizer operations. Fixed costs associated with operational fertilization are high compared to the cost of the additional N. Also, the effectiveness of higher N application rates may be improved when N is added in combination with S.
7 RECOMMENDATIONS

Based on results to date, the following guidelines are suggested for lodgepole pine fertilization operations:

1. Candidate stands with pre-fertilization foliar N levels below 1.10% should be assigned the highest fertilization priority. Fertilization response is usually low for stands with more than 1.20% foliar N.

2. Operational fertilizer prescriptions for lodgepole pine should include both N and S where pre-fertilization foliar SO₄ levels are below 60 ppm. Recommended application rates are 175–200 kg N/ha and 50–75 kg S/ha.

3. Although apparently not as widespread as N-induced S deficiencies, inadequate B nutrition may have an adverse effect on lodgepole pine health and vigour in the interior of British Columbia. Because even a single die-back episode leaves persistent stem defects, the economic consequences of B deficiency may be far greater than the actual volume losses. Therefore, in stands with marginal B status (i.e., <10 ppm) the addition of a small amount of B in the fertilizer prescription (1–3 kg/ha) may be a wise "insurance policy" in large-scale operational fertilization programs. Alternatively, and probably more cost effective, stands with low foliar B levels should be excluded from fertilization projects.

4. Despite favourable relative growth responses, the absolute stand volume gains and piece size on low-productivity sites may be too small to make fertilization profitable. Therefore, where nutrient deficiencies are indicated, preference should be given to fertilizing medium to good lodgepole pine sites in the interior of British Columbia.

5. A low priority should be assigned to lodgepole pine stands in which red squirrel feeding injuries are detected during the field survey of candidate stands. In such stands, the incidence and severity of squirrel damage will probably increase after fertilization. The potential for post-fertilization damage is minimal in stands where damage is not observed before fertilization.

6. To reduce the risk of snowpress damage, fertilizer operations should be delayed for at least 1 year after thinning in stands where pre-thinning stand density was high and the height/dbh ratio is higher than 90.
REFERENCES


_____. 1989b. The response of young lodgepole pine to spring and fall applications of urea and ammonium nitrate fertilizer. B.C. Min. For., Victoria, B.C. FRDA Res. Memo No. 120.


FURTHER READING


