Fertilization of lodgepole pine in western Canada

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Introduction

Extensive research has been undertaken in British Columbia and Alberta to determine the nutritional status of lodgepole pine (Pinus contorta Dougl. var latifolia Engelm.) and to document the effectiveness of fertilization in improving the growth of immature and semi-mature stands. These studies have confirmed that nitrogen (N) deficiencies are widespread throughout the region and that N additions, often in combination with other nutrients, often have a substantial positive effect on tree and stand growth. In the interior of British Columbia, promising research results, combined with forecasted timber supply shortfalls, have resulted in several large-scale aerial fertilizer operations during the past 15 years. To date, approximately 44,000 hectares of forests (mostly lodgepole pine) have been operationally fertilized in the British Columbia interior (B.C. Min. For. 2000).

To varying degrees, several government agencies, universities, and forest companies have been engaged in lodgepole pine fertilizer research in Alberta and British Columbia. Research strategies have combined 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 required in support operational forest fertilization investments. The purpose of this paper is to review these lodgepole pine fertilization research studies and to summarize the results.

British Columbia

The earliest documented fertilization of lodgepole pine in British Columbia was in 1963, when S.M. Simpson Ltd. (acquired by Crown Zellerbach Canada Ltd. in 1965) established two fertilization trials in 30- to 40-year-old stands of thinned lodgepole pine near Kelowna. Of the nutrients applied (N, P, K, S, and B), only nitrogen had a significant effect on tree growth (Strand and Lin 1969; Boyd et al. 1975). A follow-up study was subsequently established to test the effects of N fertilization, chemical thinning, and fertilizer + thinning on the growth of 30- to 40-year-old and 70- to 80-year-old stands. Applications of 112 and 224 kg/ha increased four-year basal area (BA) growth of 40-year-old lodgepole pine by 22% and 44%, respectively. For 80-year-old stands, respective basal area increases were 11% and 22%. There was no significant interaction detected between thinning and fertilization (Boyd and Strand 1975).

Following these early trials, there was virtually no further interest in lodgepole pine forest nutrition or fertilization until 1979, when Dr. T.M. Ballard (UBC) began a series of fertilization-related contracts with the B.C. Ministry of Forests, Research Branch. Based on extensive foliar sampling, he completed a regional evaluation of lodgepole pine nutritional problems in the central and southern interior, reviewed and developed methodology for the collection and chemical analysis of foliage samples, and developed a computerized method for nutrient deficiency diagnosis (Ballard 1982, 1985, 1986a). In addition, Dr. Ballard and his graduate student, N. Mahid, established four “single tree” fertilizer trials in 1981 to determine the effects of foliar application of N, Cu and Fe on the growth and nutrient status of lodgepole pine. Fertilizer solutions of copper sulphate, ferrous sulphate and urea were applied at different rates and combinations to the crowns of lodgepole pine at the four sites. Highly significant positive responses in shoot growth and foliar biomass production were reported during the second growing season. Foliar applications of all three nutrients were highly effective in elevating foliar nutrient concentrations, but the effects were short-lived (Mahid 1984; Ballard and Mahid 1985).

In 1986, a manual specifying guidelines for collecting, preparing, and analyzing soil and conifer foliage samples and for interpreting analytical results was published by the Ministry of Forests (Ballard and Carter 1986). This publication is still a primary source of information for silviculturists assigned the task of collecting foliage samples and interpreting analytical data in British Columbia.

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UBC Fertilizer Screening Trials

Dr. Ballard's contract research in the interior of British Columbia coincided with the arrival to the province of Dr. G.F. Weetman, a renowned expert in forest fertilization from eastern Canada. In 1980, Dr. Weetman (UBC) was contracted by the B.C. Ministry of Forests, Research Branch to establish a series of fertilizer screening trials in young, thinned lodgepole pine stands in the interior of British Columbia. First-year increases in fascicle weight and foliar graphical vector analysis were used to assess the response potential of 17 stands to factorial combinations of N, P and K fertilizer. Each of 16 treatment combinations was applied to five circular, 0.01-ha miniplots. Results indicated there was considerable variation in the responsiveness of lodgepole pine to fertilization (Weetman and Fournier 1982). Eight of the 17 stands were moderately or very responsive to N additions; others were weakly or non-responsive. Most stands were unresponsive to nutrients other than nitrogen. For the responsive stands, increases in 1st year fascicle weight ranged from 8 to 60%, suggesting a strong likelihood of favorable stem volume responses. Subsequent remeasurement of 15 stands showed that 1st year shifts in fascicle weight generally corresponded with four-year BA response in 11 of the stands (Weetman et al. 1988). Nitrogen applied at rates of 50, 100, and 150 kg N/ha increased four-year basal area growth by 27, 41, and 46% over the control, respectively. Adding P significantly improved basal area growth in only two stands, while the effect of K was not significant.

Spillimacheen Experiments

A number of fertilization experiments were established in young (11- to 15-year-old), fire-origin lodgepole pine stands near Spillimacheen, B.C. in the early 1980s. The first of these experiments was a fertilizer x thinning experiment established by Dr. G.F. Weetman in the spring of 1980. Three levels of N (0, 50, 100 kg/ha as ammonium nitrate [AN; 34-0-0]) and three levels of thinning (unthinned, 800, 3000 stems/ha) were each replicated twice for a total of 18 fixed-area plots. In 1981, a similar experiment was established using ammonium sulphate (AS; 21-0-0) as the fertilizer source. Both fertilizer sources resulted in significant increases in fascicle weight in thinned plots (but not in unthinned plots) after one growing season, with AS showing the best response. However, the effects of fertilization on basal area increment were not significant after three years (Weetman and Fournier 1986).

In the spring of 1981, another fertilizer experiment was established at Spillimacheen to document the effects of nitrogen source on growth of thinned lodgepole pine. Four N sources (at an application rate of 200 kg N/ha) were tested: 1) ammonium nitrate (AN); 2) ammonium sulphate (AS); 3) urea (U); and sulphur coated urea (SCU). Each treatment (plus an unfertilized control) was replicated three times for a total of 15, 0.05-ha plots. Basal area increments in three of the fertilizer treatments (U, AN, and AS) were 40% greater than the control after three years. The response to SCU was not significant. Height growth was unaffected by fertilization (Weetman and Fournier 1986).

The Canadian Forest Service established two fertilization experiments at Spillimacheen in the early 1980s. The first experiment was established in early 1981 to investigate the efficacy of winter application of nitrogenous fertilizer on snow. Two replicates of "single-tree" circular microplots were destructively sampled after one growing season to determine the recovery of 15N in trees, understory and soil from three 15N-labelled fertilizers ([^{15}N]urea, $^{15}NH_4NO_3$, and $NH_4{}^{15}NO_3$), each applied at rates of 100 kg N ha/1 (Preston et al. 1990). The remaining two replicates were destructively sampled in 1988 to document the long-term recovery and distribution of ^{15}N and to report on the tree growth response to the various fertilizer sources (Preston and Mead 1994). After one growing season, total recovery of [^{15}N]urea, $^{15}NH_4NO_3$ and $NH_4{}^{15}NO_3$ was 93.3, 95.2, and 44.4%, respectively. About two-thirds of this amount could still be accounted for in plant biomass and soil after eight years. The respective recovery in tree biomass after one year was 10.1, 5.3, and 1.9%, with little additional ^{15}N uptake by trees in subsequent years. The reported tree uptake of applied N from urea was within the range reported for urea in other studies. However, tree uptakes from the ammonium and nitrate sources were generally below reported levels. The large losses and poor uptake of $NH_4{}^{15}NO_3$ were attributed to leaching and denitrification of nitrate during snowmelt (Preston et al. 1990). For this reason, the authors recommended that the application of nitrate on snow not be considered for fertilizer operations. Ring measurements from the two replicate trees per treatment indicated a 34% increase in stem volume increment in fertilized versus control trees after eight years (Preston and Mead 1994). There was no apparent effect of fertilizer source on tree growth.

In 1983, the Canadian Forest Service established another experiment near Spillimacheen, B.C. to document the growth response of lodgepole pine to urea and ammonium nitrate (both applied at 300 kg N/ha) applied on bare ground and on snow across three stand densities (Marshall et al. 1992). Urea was applied on bare ground in October 1983 and on 70 cm of snow in February 1984, whereas ammonium nitrate was applied only on snow.

After three years, individual-tree volume increment was significantly increased by ammonium nitrate applied on snow in moderately thinned stands (2500 stems/ha) and dbh increment was significantly increased (up to 37%) by on-snow applications of ammonium nitrate and urea in heavily thinned stands (800 stems/ha). Height growth was not increased by fertilization and, in fact, may have been slightly depressed in the heavily thinned stand. The effectiveness of ammonium nitrate on snow relative to urea was surprising, given the poor recovery and uptake of $NH_4{}^{15}NO_3$ reported by Preston et al. (1990). The comparable, but relatively low, incremental tree growths from urea and ammonium nitrate were attributed to undetermined factors, including rapid fixation and microbial immobilization of ammonium N and other growth-limiting nutrients (e.g., B and S).

UBC Optimum Nutrition Trial

Sustained growth responses to repeated fertilization have been demonstrated in "optimum nutrition" experiments with Pinus species in eastern Canada and Europe (Weetman et al. 1995; Tamm et al. 1999). In 1982, Dr. G. Weetman (UBC) addressed the question of whether high growth rates of lodgepole pine can be sustained by repeated fertilization by establishing an optimum nutrition experiment near Okanagan Falls. Four levels of N (0, 50, 100, 150 kg N/ha as ammonium nitrate), applied alone and in combination with a "complete mix" fertilizer (P, K, Ca, Mg, S plus micronutrients), were applied to replicated treatment plots in a thinned, nine-year-old stand. Fertilizer treatments were applied four times between 1982 and 1988. After 14 years, mean tree volume in the treatment receiving the highest N application (525 kg N/ha over seven years) plus the "complete mix" fertilizer was 42% greater than in unfertilized plots. Conversely, tree growth was either unaffected, or slightly depressed, by repeated fertilization with N alone, likely due to induced S deficiency (Kishchuk et al. 2001).

Ministry of Forests (Forest Regions)

Several fertilizer screening trials have been established by MoF Regional staff during the past 15 years. Of these, only the results from a series of trials in 50- to 60-year old thinned, lodgepole pine in the Prince Rupert Forest Region have been reported (Yole et al. 1991; Trowbridge 1992). Based on dendrochronometer measurements, increases in six-year tree basal area increment averaged 64% following fertilization with a "complete blend" fertilizer. Average growth gains of 27% were obtained from fertilization with N alone.

In 1979, Les Herring (MoF, Prince George Forest Region) established two fixed-area experiments in an 18-year-old, severely repressed lodgepole pine stand at Fish Lake, near Prince George. A 2 x 2 factorial trial was designed to document the effects of mechanical row thinning (with and without selective hand thinning within rows) and two levels of N fertilization (0 and 150 kg N/ha) on the growth of the repressed stand. Another study tested a range of N application rates (200, 400 and 800 kg N/ha), broadcast and applied in concentrated strips, in an unthinned portion of the stand. Nineteen-year results from these studies are reported elsewhere in these proceedings (Farnden 2001).

In 1998, factorial combinations of thinning (unthinned and thinned) and fertilization (unfertilized and fertilized with a "complete blend") were applied to a 35-year-old, repressed lodgepole pine stand in the Rosita Fire, west of Williams Lake (T. Newsome, per. comm.). The results from this study have not yet been reported.

Ministry of Forests (Research Branch)

The widespread and serious N deficiencies reported by Ballard's contract research, combined with the likelihood of growth responses following N fertilization indicated by Weetman's screening trials, encouraged the Ministry of Forests, Research Branch to implement a large-scale lodgepole pine fertilization research program in 1981. Since that time, a large number of fertilizer "screening" trials, using various replicated "single-tree" or "mini" research plot designs, have been established by the Research Branch to diagnose specific nutrient deficiencies and rapidly evaluate fertilization response potential and the efficacy of different fertilization regimes (Brockley 1990, 1995; Brockley and Sheran 1994). In addition, 38 fixed-area plot experiments have been established to provide the area-based response data (m^3/ha of "extra" wood produced) required in support of operational forest fertilization investments. The results from fixed-area experiments have been extensively reported (Brockley 1989, 1991, 1996, 2000*a*; Mika *et al*. 1992).

Most of these trials have been established in 20- to 30-year-old stands. If not planted, all of these stands were pre-commercially thinned prior to, or at the time of, fertilization. Post-thinning stand densities range from 1100 to 2100 stems per hectare. The Research Branch has not conducted fertilization research in unthinned stands, where opportunities for crown expansion following fertilization are often limited and where competition mortality will likely reduce harvest gains. To date, there has been relatively little fertilization research activity in mid- to late rotation lodgepole pine stands. Because early stand density control was not undertaken, these stands are often in relatively poor biological condition (e.g., small live crown, high incidence of stem disease) and thus may have relatively poor fertilization response potential. However, current pre-commercial thinning activities in young stands, combined with extensive planting, will certainly create good opportunities for fertilizing older stands in the future. A small number of fertilizer trials have been established in young stands (10 to 15 years old). These are mainly short-term fertilizer screening trials and "maximum productivity" trials, where the effects of repeatedly fertilizing throughout the rotation are being documented.

Nitrogen fertilization

Foliar analytical data reported by Ballard (1982) and Weetman and Fournier (1982) indicated that nitrogen (N) deficiencies were widespread and serious throughout the interior of British Columbia. These findings were in agreement with previous studies in Scandinavia and North America where N had been clearly shown to be the nutrient most limiting the growth of northern temperate and boreal forests growing on mineral soils. Therefore, the initial series of fertilization trials established by the Ministry of Forests, Research Branch were designed solely to document the growth response of lodgepole pine to N additions (Brockley 1989, 1991). Figure 1 illustrates the cumulative distribution of pre-fertilization foliar N concentrations in the 52 fertilization research trials from which foliar information has been collected. The vertical axis indicates the proportion of all installations that have foliar N levels less than or equal to a particular foliar concentration shown on the horizontal axis. For example, 75% of the stands have foliar N levels lower than 1.15%, indicating moderate to severe N deficiency (Ballard and Carter 1986; Brockley 2001). Approximately one-quarter of the stands have foliar N levels lower than 1.00%, indicating severe N deficiency.

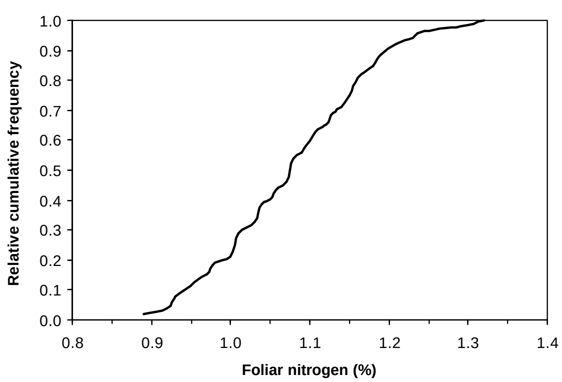

Figure 1. The relative cumulative frequency distribution of pre-fertilization foliar N concentration in lodgepole pine fertilization research installations (n=52) (Brockley unpubl. data).

Six-year growth response information is currently available for 31 research trials. Overall, lodgepole pine has responded quite well to N fertilizer applied at a rate of 200 kg N/ha. Basal area response was statistically significant ($p<0.05$) in 17 (55%) of the 31 installations (Brockley 2000). However, growth response following N fertilization was quite variable, with relative BA responses ranging from 5 to 77%. The relative cumulative frequency distribution of six-year BA response to N fertilization is shown in Figure 2. Growth response is expressed as a percentage of control plot BA increment over the six-year response period. For example, approximately one-quarter of the installations responded less than 15%, and about one-quarter responded more than 40%.

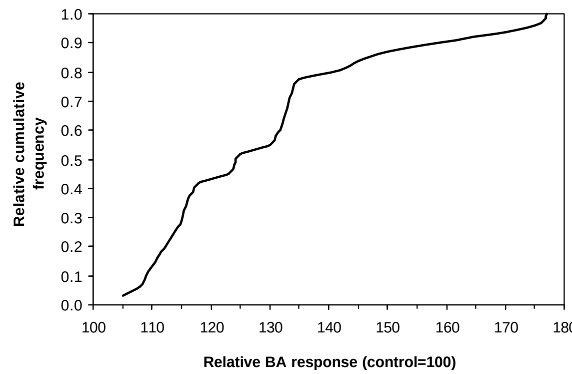

Figure 2. The relative cumulative frequency distrubution of mean 6-year basal area response in lodgepole pine research installations after fertilization with 200 kg N/ha (n=31).

Six-year area-based growth response (m^3/ha of "extra" wood produced) has been analyzed for 17 fixed-area, lodgepole pine installations, of which three have been abandoned due to serious mortality and damage to crop trees (i.e., small mammal damage, snowpress) that all but wiped out per-hectare volume gains. Ten of the 14 undamaged trials responded significantly to N fertilization ($p < 0.05$) over the six-year response period (Brockley unpubl. data). Total volume gains above control averaged 9.2 (range –0.5 to 20.4) m^3/ha for an application rate of 200 kg N/ha. In relative terms these responses averaged 29% (range –2 to 50%).

Despite generally favorable stem radial response, height response of lodgepole pine following N fertilization is relatively small. For thinned, fixed-area plot research installations, six-year height responses following fertilization with 200N averaged only 20 cm (range –23 to 60 cm) greater than thinned but unfertilized trees. In relative terms, average height response was 10% (range – 8 to 54%). For thinned stands, the timing of fertilization in relation to thinning affects the magnitude of height response following N fertilization. Comparison of installations thinned at the time of fertilization (Type 1) with adjacent installations thinned at least two years before fertilization (Type 2) indicates that Type 1 stands are generally more responsive to fertilization in both relative and absolute terms (Figure 3). These results indicate fertilization may help offset the short-term negative effects of thinning on height increment (i.e., thinning shock).

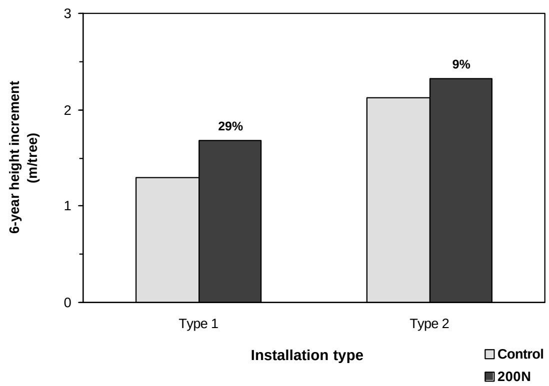

Figure 3. The effect of nitrogen fertilization on mean height increment in stands thinned at the time of fertization (Type 1; n=4) and adjacent stands thinned 2-3 years before fertilization (Type 2;n=4).

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 – and indication that the added N may not be fully utilized in protein synthesis. The effects of N and N+S fertilization on the first-year fascicle weight and foliar nutrient status of young, thinned lodgepole pine were reported by Brockley and Sheran (1994). These screening trial results indicated that S deficiencies, either aggravated or induced by N fertilization, limited the responsiveness of some lodgepole pine stands to N additions. At four of seven locations, combined N and S additions improved the S status of fertilized trees and significantly increased the weight of fascicles produced during the first year after treatment compared with that achieved with N alone. In 1990, another screening trial was established to test the effects of N application rate, with and without added S, on the growth of lodgepole pine. Factorial combinations of N (0, 200, 400 kg N/ha as urea) and S (0, 50 and 100 kg/ha as S^o and as ammonium sulphate[AS]) were applied to a thinned, 15-year-old lodgepole pine stand. When added alone, applications of 200 and 400 kg N/ha both had significant positive effects on tree BA increment after three years (39% and 24% above control, respectively) (Figure 4). Although 400N was apparently less effective than 200N (likely due to induced S deficiency), the difference between the two application rates was not statistically significant. Addition of S (100 kg/ha as ammonium sulphate) in combination with N resulted in significantly larger BA responses at both N application rates (66 and 60%, respectively).

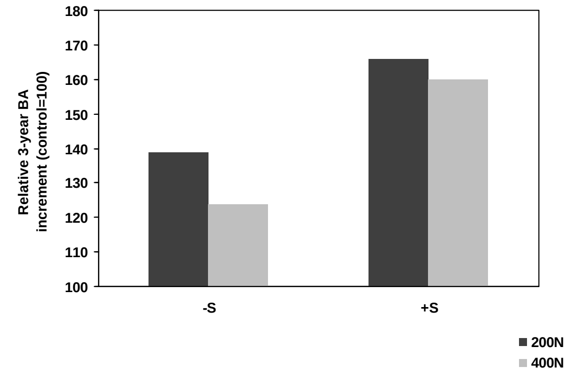

Figure 4. The effects of N application rate, with and without added S (100 kg S/ha as ammonium sulphate), on 3-year relative tree volume increment (control=100) (Brockley unpubl. data).

Six-year BA response information has been collected from a total of 17 “single-tree” and fixed-area plot trials in which the effects of N vs. N+S have been tested. In these 17 installations, the combined N+S application resulted in a larger mean six-year BA response than N alone (28 vs. 19%, respectively). Six (35%) of the 17 installations responded significantly to N alone; 88% (15 of 17) responded significantly to combined N+S fertilization (Brockley 2000a). As shown in Figure 5, a BA response of more than 30% was obtained in approximately one-half of the installations fertilized with N+S. A similar response was achieved by less than one-fifth of the stands fertilized with N alone.

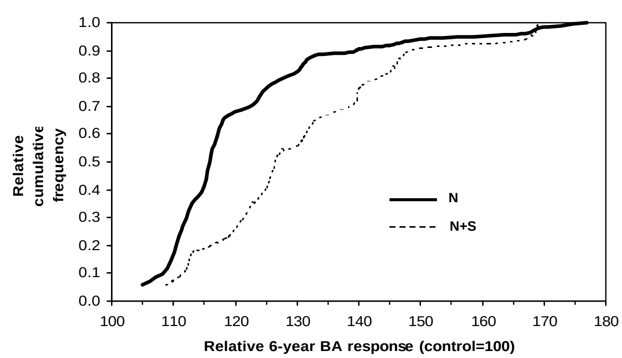

Figure 5. The relative cumulative frequency distribution of mean 6-year basal area response in research installations fertilized with N and N+S (from Brockley (2000)).

Six-year area-based volume growth response following N and N+S fertilization has been analyzed for seven fixed-area, lodgepole pine installations. However, one installation was severely damaged by top die-back caused by induced B deficiency. Five of the six undamaged installations responded significantly ($p<0.05$) to N fertilization and all six responded significantly to N+S (Brockley unpubl. data). The incremental gain between N and N+S was statistically significant in three of the six installations. The two installations in the ICH and MS biogeoclimatic zones responded well to N fertilization (13 and 20 m^3/ha of "extra" wood over six years, respectively), and did not respond incrementally to added S. For the other installations in the SBS, SPBS, and IDF biogeoclimatic zones, the six-year volume gains above control averaged 5.2 (range -0.5 to 11.9) and 11.4 (range 7.3 to 19.2) m^3/ha for N and N+S, respectively. In relative terms, these respective responses averaged 16% and 35%, respectively.

Examination of S properties of unfertilized soils and foliage from S-deficient and S-sufficient sites in the interior of British Columbia revealed that cycling of soluble-SO4 through organic-SO4 is likely the process limiting S availability on S-deficient sites (Kishchuk 1998). These results indicate that organic-SO4 is more actively cycling in soils and contributes more to S uptake than C-bonded-S. Total soil S levels did not differ between S-deficient and S-sufficient sites. Results also indicated that soil organic C may play an important role in the cycling of organic-SO4 and S availability. Organic matter losses resulting from repeated wildfires might explain low levels of soil organic C on S-deficient sites.

Other nutrient additions

Low foliar B concentrations are quite common in lodgepole pine stands throughout north-central British Columbia. Nitrogen fertilization further depletes foliar B levels, and has resulted in visible B deficiency symptoms (i.e., top die-back) in at least one fertilization research trial near Burns Lake (Brockley 1989) and in a nearby stand that was previously operationally fertilized (Brockley and Yole 1985). In another research trial in the southern interior, a combination of high rainfall and coarse-textured soil apparently depleted soil-available B and caused severe top die-back three years following N fertilization (Brockley, unpubl. data). Boron deficiency symptoms can develop very rapidly, and the resulting damage reduces stem volume increment and adversely affects stem quality and value. A small amount of B (e.g., 3 kg B/ha) added in combination with N (or N+S) has proven effective in preventing top die-back in lodgepole pine (Figure 6).

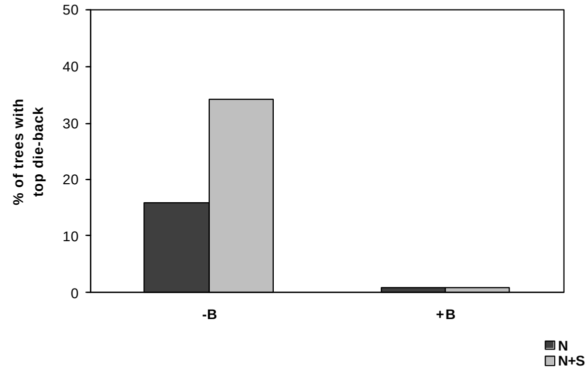

Figure 6. The effects of N and N+S fertilization, with and without added B, on the incidence of top dieback in a lodgepole pine stand near Golden, BC (Brockley unpubl. data).

Although dramatic, visual symptoms of B deficiency are relatively rare in the interior of British Columbia. However, subacute B deficiency (without visible growth disturbance symptoms) has been shown to reduce growth response following N fertilization. Results from a "single-tree" fertilization trial near Burns Lake showed that combined N and B application significantly improved growth response over that achieved with N fertilization alone (Brockley 1990). Average six-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.

The occurrence of nutrient deficiencies other than N, S and B in lodgepole pine has not been systematically tested. A "complete mix" treatment has been applied in addition to N and N+S treatments in two fixed-area plot fertilization trials. In both trials, the "complete mix" fertilizer contained (kg/ha): 200N, 100P, 100K, 75S, 37Mg, 3B. After six years, there were incremental differences between the N+S and "complete mix" treatments in both trials, but the difference was statistically significant in only one trial (Figure 7). It is doubtful whether the additional growth gains are large enough to justify the higher cost of purchasing and applying a "complete mix" fertilizer.

Nitrogen source

The effects of urea and ammonium nitrate [AN] fertilizer on the nutrition and growth of lodgepole pine were evaluated at three locations in the interior of British Columbia over a six-year period (Brockley 1995). Because their effectiveness may be influenced by season of application, both spring and fall applications of these two sources were also 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 differences in 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 AN consistently gives larger growth responses than urea (Moller 1992). 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 is often more effective than urea in increasing foliar N concentration, it is more likely to create a N:S imbalance and S deficiency, at least over the short term. An experiment was recently established near Prince George to test whether AN is better than urea at stimulating tree growth when accompanied by S additions.

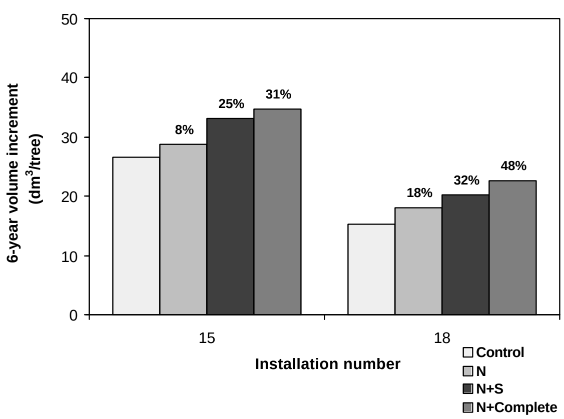

Figure 7. The effects of N, with and without the additions of S and a "complete mix" fertilizer, on 6-year tree volume increment in two fertilizer trials in central BC (Brockley unpubl. data).

Effects of post-thinning density

In view of the dramatic effects that thinning has on stand structure and subsequent development, it is likely that the intensity of thinning will also influence growth responses to fertilizer application. The effects of density on stand development and competition mortality following fertilization, and on the volume of "extra" fertilized wood available at harvest, are important issues. It is also important to document the effects of thinning and fertilization on wood quality factors such as specific gravity, branch size and stem taper. Although a number of different post-thinning densities have been used in lodgepole pine fertilizer research trials, they have not been tested at the same location. Therefore, given the confounding effects of site, pre-thinning density and stand age, definitive conclusions about the effects of fertilizer x thinning interactions cannot be made.

In 1992, factorial combinations of post-thinning densities (600, 1100, 1600 stems per hectare) and fertilization (unfertilized, fertilized) were applied to a 13-year-old, harvest-origin lodgepole pine stand near Williams Lake. After five years, the main effects of density and fertilization were highly significant for both individual-tree and area-based analyses (Figures 8 and 9). The fertilizer x thinning interaction was not statistically significant. In both relative and absolute terms, the effects of fertilization on tree and stand BA increment were greatest at higher densities after five years. This trial will be periodically refertilized and remeasured throughout the rotation.

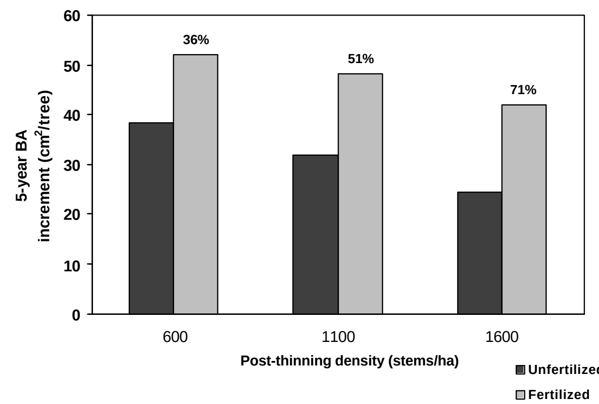

Figure 8. Effects of post-thinning stand density on 5-year tree basal area increment (cm²/tree) following fertilization (Brockley unpubl. data).

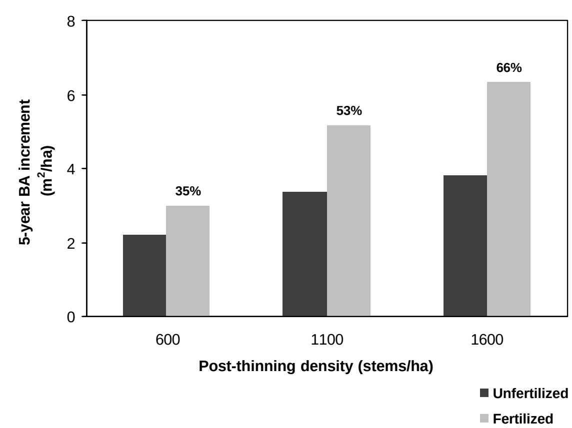

Figure 9. Effects of post-thinning density on 5-year stand basal area increment (m²/ha) following fertilization (Brockley unpubl. data).

Predictive relationships

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 identify stands where the response can be significantly improved by adding other growth-limiting nutrients in combination with N. Previous studies in

British Columbia have suggested that nutrient limitations and fertilization response potential can be estimated with reasonable accuracy from first-year increases in the fascicle mass of fertilized trees (Weetman and Fournier 1982; Weetman et al. 1988; Brockley 1989). The positive relationship between fascicle mass response and subsequent stemwood response is the basis of the "screening" approach to fertilizer response prediction. On the basis of statistical significance, fascicle mass response correctly predicted six-year BA response (or lack of it) to fertilization with N alone in 21 of 31 lodgepole pine research trials (Brockley 2000a). Overall, fascicle mass explained 34% of the variation in six-year BA response. However, approximately one-third of the installations in which fertilization with N alone significantly increased first-year fascicle mass did not show a significant BA response to added N. Also, fascicle mass differences between N and N+S were, on average, considerably higher than the differential BA responses, thereby over-estimating the long-term positive effects of S additions on tree growth. In fact, significant BA responses to added S did not materialize in more than one-half of the installations in which S significantly increased first-year fascicle mass over that achieved with N alone. Clearly, there is some risk of not recouping fertilization investment costs when the screening technique is used to select candidate sites for fertilizer operations or to make fertilizer prescriptions based on the statistical significance of fascicle mass response.

Brockley (2000*a*, 2000*b*) reported that pre-fertilization levels of foliar N or inorganic sulphate-S may be more reliable than the fascicle mass screening method for predicting whether or not a significant stemwood response will occur following N fertilization. In an analysis of 31 trials, an overall trend of declining BA response was observed with increasing N concentration in the foliage of unfertilized trees. Conversely, there was clearly a positive relationship between relative BA response and foliar sulphate-S. Individually, each of these foliar variables explained approximately one half of the observed variance in relative BA response between installations. When combined, N and sulphate-S levels in unfertilized foliage explained 68% of the variation in relative BA response to fertilization with N alone. Foliar nutrients were also useful for determining whether or not lodgepole pine would respond incrementally to S when added in combination with N. Stands in which pre-fertilization foliar sulphate-S was < 60 mg/kg and N/S ratio was > 13 did not respond significantly to N alone but always responded significantly to N+S. Conversely, a foliar sulphate-S level > 60 mg/kg combined with a N/S ratio of < 12 always resulted in a favorable response to N with no incremental benefit of added S. These results, combined with the fact that the screening method is more expensive and requires at least one year of lead time prior to operational fertilization, indicate that foliar nutrient assessment using pre-fertilization foliar levels of N, sulphate-S and N/S ratios may have greater utility than first-year increases in fascicle mass for assessing fertilization response potential and for making appropriate fertilization prescriptions.

Damaging Agents

Red squirrels (*Tamiasciurus hudsonicus Erxleben*) have been clearly implicated as significant damaging agents in young, fire-origin stands of fertilized lodgepole pine stands in the interior of British Columbia (Sullivan and Sullivan 1982; Brockley and Sullivan 1988; Brockley 1991). Feeding injuries are caused by the peeling and removal of bark from the basal (and sometimes upper) sections of trees. Although damaged trees are usually not completely girdled, sub-lethal injuries reduce growth response following fertilization, and damaged stems may be more susceptible to snow or wind breakage at the point of injury. In heavily damaged fertilizer research trials, the incidence and severity of damage is significantly higher in fertilized plots than in unfertilized plots, especially in stands that are thinned at the time of fertilization (Brockley 1991). Squirrel feeding injuries can be minimized by delaying fertilization for at least two years after thinning. Also, stands that have a low incidence of damage before fertilization will likely not suffer significant feeding injuries after fertilization.

The accumulation of snow in the fuller crowns of fertilized lodgepole pine may increase the likelihood of irreversible bending and breakage of trees in stands thinned at the time of fertilization, especially where average height/dbh ratio is high (>90). Snowpress damage rarely occurs in stands where fertilization has been delayed for two to three years after thinning (Brockley 1991).

"Maximum Productivity" Trials

A single fertilizer application typically produces only a temporary increase in growth (usually six to nine years). To what extent intensive, repeated fertilization can increase productivity and thus mitigate reductions in AAC that may result from a shrinking working forest land base is a question of some importance to forest managers. Beginning in 1993, a network of six "maximum productivity" research installations has been established on benchmark lodgepole pine sites in the interior of British Columbia. These installations will provide valuable information on the effects of repeated fertilization on harvest volumes and on various ecosystem processes and non-timber resources. Each of the plantations or juvenile-spaced, harvest-origin stands was 9-15 years old at the time of installation establishment. Each of six treatments is replicated three times for a total of 18, 0.164-ha treatment plots. The treatments are as follows:

1. Control (i.e., not fertilized)
2. NB – fertilized every six years with (kg/ha): 200N, 1.5B
3. NSB – fertilized every six years with (kg/ha): 200N, 50S, 1.5B
4. Complete – fertilized every six years with (kg/ha): 200N, 100P, 100K, 50S, 25 Mg, 1.5B
5. ON_1 – fertilized yearly to maintain foliar N concentration at 1.3% and other nutrients and nutrient ratios at "optimum" levels
6. ON_2 – fertilized yearly to maintain foliar N concentration at 1.6% and other nutrients and nutrient ratios at "optimum" levels

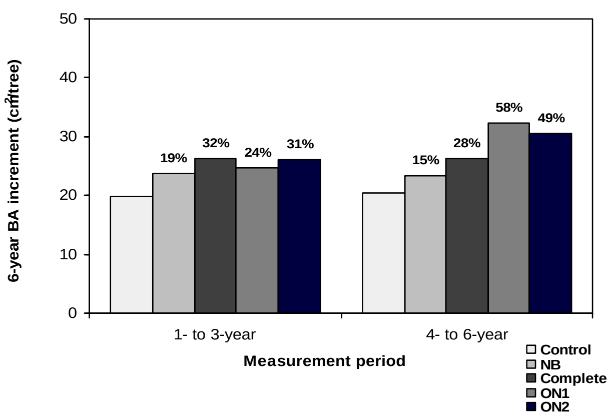

Figure 10. Effects of single and repeated fertilization on 6-year basal area increment in a lodgepole pine "maximum productivity" trial near Williams Lake, BC (Brockley unpubl. data).

Six-year basal area response in an installation near Williams Lake is illustrated in Figure 10. Over six years, the ON1 and ON2 treatments received 450 and 900 kg N/ha, respectively. Large quantities of other essential nutrients (350P, 350K, 225 Mg, 216S, 3B) were also added during this period. Results indicate that all fertilizer treatments were more-or-less equally effective in increasing growth during the initial three-year response period. However, the ON1 and ON2 treatments were significantly more effective than the other treatments in stimulating BA growth during the four- to six-year period. Interestingly, repeated fertilization at the ON2 level had a significant negative effect on height increment after six years (Figure 11). A number of ancillary studies are also being undertaken at selected trial locations to document the effects of repeated fertilization on understory vegetation biomass and diversity, litterfall quality and quantity, litter decomposition, fine root activity, and soil biota activity and diversity.

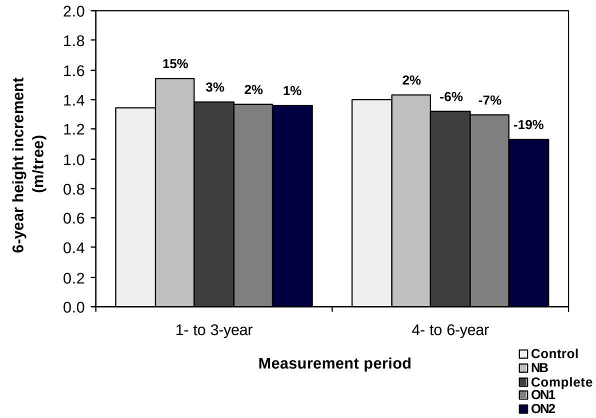

Figure 11. Effects of single and repeated fertilization on a 6-year height increment in a lodgepole pine "maximum productivity" trial mear Williams Lake, BC (Brockley unpubl. data).

Alberta

Canadian Forest Service

The earliest documented lodgepole pine fertilization research in Alberta was in 1968, when the Canadian Forestry Service established a fertilization trial in a thinned, 72-year-old lodgepole pine stand near Rocky Mountain House. Three levels of N (0, 112, and 673 kg N/ha), three levels of P (0, 56, and 168 kg P/ha), and three levels of S (0, 28, and 84 kg S/ha) were tested in a randomized, incomplete factorial experiment. Fourteen treatments were replicated three times, for a total of 42, 0.04-ha plots. Bella (1978) reported a significant growth response to N but no additional response to P or S after seven years. The gain in merchantable volume averaged about seven m^3/ha (30%) over the seven-year period.

In 1971, four fertilizer trials were established by the Canadian Forestry Service southeast of Hinton. The trials were located in unthinned stands of two stand ages (30 and 70 years old) on Coalspur (Orthic Gray Luvisol) and Mercoal (Podzolic Gray Luvisol) soil types. Incomplete factorial combinations of each of five levels of N, P, and S were tested in a central composite rotatable second-order design to provide a general predictive relationship between tree and stand responses and fertilizer levels. In addition to the 20 composite design treatments, four extra treatments were added to allow the analysis of results by two 23 factorials arranged in a randomized complete block design. All of the fertilizers were applied to circular treatment plots prior to the 1972 growing season. After 10 years, all tagged, living trees within treatment plots were remeasured. Three of the 10 tagged trees within each plot were felled to accurately determine tree volume increment.

Because of the inadequacy of the central composite design in evaluating tree and stand responses to fertilization (Yang 1983a), only the analysis of the factorial combinations were reported (Yang 1983b, 1985a, 1985b; Yang and Bella 1986; Weetman et al. 1985). Factorial analysis of 10-year volume increments of dominant and codominant trees showed different response on the two soil types to N, P, and S fertilization. Fertilization with N dosages of at least 188 kg N/ha resulted in significant tree volume growth responses in both 30- and 70-year-old stands on Coalspur soils. Little additional growth was obtained when P and/or S were added alone or in combination with N. On Mercoal soils, a combined application of 188N and 56S consistently gave larger 10-year tree volume responses than N alone in both 30- and 70-year-old stands. The effect of P on volume growth was not statistically significant. Fertilization improved 10-year total stand volume growth by as much as 31 and 34 m^3/ha in 70-year-old Mercoal and Coalspur stands, respectively. These represent increases of up to 50% in periodic stand volume increment. However, net stand volume responses were less consistent than individual-tree responses because of mortality following fertilization in unthinned stands, especially in 30-year-old stands. Yang (1985b) suggested that thinning should precede fertilization in younger, unthinned stands.

In 1984, the Canadian Forestry Service established a fertilizer x thinning trial in a densely stocked, 40-year-old lodgepole pine stand southwest of Hinton. Factorial combinations of thinning (unthinned, thinned to 2100 stems/ha) and fertilization (0, 180, 360, and 540 kg N/ha, as ammonium nitrate) were applied to 72, 0.03-ha circular plots (i.e., eight treatments x nine plots per treatment). In addition to N, fertilized plots received 40 kg/ha of P and 40 kg/ha of S. Thinning and initial measurements were completed in the summer of 1994 and fertilizer was applied in the fall of 1995.

Applications of N at 360 kg/ha to thinned and unthinned plots, respectively, improved 10-year periodic height increment by 20 and 19%, and diameter at breast height by 29 and 34% (Yang 1998). Fertilization at 540N had a negative impact on height increment in thinned plots. Fertilization with 360N produced the largest stand BA responses in both thinned and unthinned stands after 10 years. Relative BA responses in thinned and unthinned stands were 21 and 36%, respectively. Relative 10-year stand volume responses to 360N were 25 and 29% in thinned and unthinned stands, respectively. In absolute terms, fertilization produced up to 23.0 and 17.1 m^3/ha of "extra" wood on unthinned and thinned plots after 10 years. Yang (1998) indicated that fertilization at this level was optimal based on foliar and mensurational responses.

Alberta Land and Forest Service

In 1989, two fertilizer x thinning experiments were established in a 23-year-old, fire-origin lodgepole pine stand near Edson. In one study, factorial combinations of three thinning methods and three fertilization regimes were replicated four times, for a total of 36 fixed-area treatment plots. The thinning methods were: 1) no thinning; 2) selective tree thinning (1600 stems per hectare); and 3) simulated machine row thinning. The fertilizer regimes were (kg/ha): 1) 0N:0P:0K; 2) 250N:150P:200K; and 3) 500N:300P:400K. The second large fixed-area-plot trial tested three thinning methods and six fertilizer treatments. The three thinning treatments were the same as used in the first study. The six fertilizer treatments were (kg/ha): 1) 0N:0P:0K; 2) 0N:150P:200K; 3) 200N (as urea):150P:200K; 4) 200N (as ammonium nitrate):150P:200K; 5) 400N (as urea):150P:200K; and 6) 400N (as AN):150P:200K. Each of the 18 factorial combinations was replicated four times for a total of 72 fixed-area treatment plots.

The results from these two well-designed experiments have never been formally reported. In an unpublished report, however, the fertilizer main effects indicated about 50% increases in dbh increment over unfertilized treatments after three growing seasons. There was little difference between N application rates and N source[2]. These trials were recently remeasured by Weldwood of Canada Ltd. (Hinton).

Forest Licensees

Since 1997, Weldwood of Canada Ltd. (Hinton) and Miller Western Forest Products Ltd. have established approximately 50 fertilizer screening trials in mid- and late-rotation lodgepole pine stands within their respective operating areas. Urea and ammonium nitrate, alone and in combination with other nutrients, have been tested in both thinned and unthinned stands. Preliminary results from some of the Weldwood trials

[2] Takyi, S. Undated. Some trends in the response of a 26-year-old lodgepole pine stand to fertilization and thinning. Alberta Environment, Land and Forest Service, Edmonton. Unpubl. report.

are reported elsewhere in these proceedings (Braun and Navratil 2001).

Weldwood of Canada Ltd. has also recently established nine fixed-area plot fertilization trials. Seven trials have been established in older, unthinned stands; the others in row thinned, 35-year-old stands. The following fertilizer treatments are being tested: 1) unfertilized; 2) 200N + boron; and 3) 200N + "complete blend". In addition, Weldwood has recently established 14 "paired-plot" fertilizer trials to document the effects of fertilization on mortality and stand differentiation in 40- to 60-year-old, repressed lodgepole pine (T. Braun, per. comm.).

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