71

Extension Note

March 2005

Sulphur Deficiencies in Lodgepole Pine: Occurrence, Diagnosis, and Treatment

Paul Sanborn
Ecosystem Science and Management Program
University of Northern British Columbia
3333 University Way
Prince George, BC V2N 4Z9

Rob Brockley
Research Branch
B.C. Ministry of Forests
3401 Reservoir Road
Vernon, BC V1B 2C7

Abstract

Sulphur (S) deficiencies are widespread in lodgepole pine stands in the British Columbia central interior. Low soil S availability can limit tree growth responses to nitrogen (N) fertilization. Refined diagnostic criteria and decision-making tools enable more reliable identification of stands that will respond to inclusion of S in fertilizer prescriptions. Most research and large-scale aerial fertilizer operations have used soluble sulphate-S sources, but evidence is accumulating that elemental-S provides equally satisfactory long-term amelioration of S deficiencies. New research is using stable isotope tracer methods to improve understanding of the fate and transformations of S fertilizers. For sites where fertilization may not be feasible, soil conservation is particularly important for preventing further losses of limited S.

Introduction

Forest fertilization research by the B.C. Ministry of Forests and its collaborators in the British Columbia interior initially addressed the widespread nitrogen (N) deficiencies in lodgepole pine (*Pinus contorta* Dougl. var. *latifolia* Engelm.), the leading commercial timber species. Investigation of inconsistent treatment responses led to the recognition that sulphur (S) deficiencies were likely limiting the tree growth responses to N fertilization on many sites. 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 additions of N alone (Brockley and Sheran 1994). Subsequently, Brockley (1996) reported that fertilization with N + S resulted in a larger mean 3-year stem diameter response than N alone (38 vs 23%, respectively) in 18 fertilizer trials.

This Extension Note provides silviculturists with an update on recent British Columbia research on the occurrence, diagnosis, and treatment of S deficiencies in British Columbia interior forests. We emphasize lodgepole pine, but the underlying ecological and geological causes of low S availability have also likely affected the nutrition and growth of other conifer species. However, detailed criteria for diagnosis and treatment of S deficiency in other species remain to be developed. Accordingly, silviculturists should be cautious in extrapolating these interim findings to other species.

British Columbia

Ministry of Forests Forest Science Program

Occurrence and Causes of Sulphur Deficiencies

Mineral horizons of soils in the British Columbia interior have S concentrations among the lowest reported (Kishchuk and Brockley 2002). Several factors contribute to this pattern, including:

- low atmospheric S inputs from industrial S emissions and natural sources,
- low S concentrations in soil parent materials and underlying bedrock, and
- S volatilization losses by combustion of biomass and forest floors in fire-prone forest types.

Forest soils in the British Columbia interior, like elsewhere in the temperate and boreal zones, contain most of their S in organic forms. Most soil organic S exists as carbon-bonded S, including defined compounds such as S-containing amino acids and sulpholipids, with much of the remainder consisting of ester sulphates (–C–O–S– linkages). These two broad classes of soil organic S forms appear to have differing roles in soil S cycling. Despite consistently low mineral soil total S concentrations (about 60 mg • kg^{-1}), Kishchuk and Brockley (2002) found a wide range in lodgepole pine growth responses to S fertilization at several British Columbia interior sites. In seeking an explanation for these differences, this study found empirical evidence that S cycling through the ester sulphate fraction was an important process in controlling soil S availability and stand response to fertilization. (For a more comprehensive review of S forms and behaviour in forest soils, see Sanborn et al. 2005.)

Only a small proportion (<5%) of soil S exists in inorganic forms, mostly as sulphate ions (SO_4^{2-}) that are adsorbed on soil solids or dissolved in soil water. Sulphate is the predominant S form taken up by plants, so the biological conversions of soil S between organic forms and sulphate are a major regulator of S supply to forest trees. Long-term forest nutrient cycling processes tend to concentrate soil S reserves in the upper, more organic matter–enriched soil horizons, particularly the forest floor. These surface organic S reserves then become more vulnerable to soil displacement, through site preparation and harvesting, and losses due to wildfire or prescribed burning.

In the British Columbia interior, positive responses to S fertilization had been noted for agricultural soils by the 1960s (Sanborn et al. 2005). The lodgepole pine fertilization research program of the Ministry of Forests began in the early 1980s, and initially focused on treatments involving only N. By the mid-1990s, widespread evidence showed superior growth responses to treatments that included both N and S. Responses to added S were particularly strong in the Sub-Boreal Spruce and Interior Douglas-fir biogeoclimatic zones, where 3-year diameter growth relative to the control was 53% higher with N + S, compared with 24% higher with N-only treatments (Brockley 1996). These findings reflected basic processes of tree nutrition—all plants contain N and S primarily in amino acid and protein forms, so the relative availability of these elements in soils is important in controlling nutrient balance during growth. On soils with naturally low S supplies, addition of N alone can create a nutritional imbalance that is expressed as a fertilization-induced S deficiency. Conversely, when soil S supplies are relatively more available than those of N, excess S tends to accumulate in tree foliage as inorganic sulphate.

Diagnosis

Analysis of foliar nutrient concentrations and ratios is a cost-effective approach for identifying nutritional problems and predicting responses to fertilizer treatments. The initial guidelines for interpreting lodgepole pine foliar analyses (Ballard and Carter 1986) have been refined by an extensive program of fertilizer trials that has combined assessment of tree growth responses with pre- and post-treatment foliar sampling and analysis. A significant result of this program has been the downward adjustment of deficiency thresholds for foliar total S and sulphate-S concentrations. Fuller accounts elsewhere explain the rationale for revised interpretive criteria, and only key points will be reviewed here (Brockley 2000a, 2000b, 2001).

The physiological linkages between N and S transformations in trees require that both elements be considered in interpreting foliar analyses. Taken together, the concentrations and ratios of both elements provide an improved basis for identifying stands that respond to additions of N alone, or respond better if both N and S are added. Based on analysis of 31 interior lodgepole pine stands, Brockley (2000b) reported that stands with pre-fertilization foliar sulphate-S concentrations less than or equal to 60 mg • kg^{-1} and N/S ratios greater than or equal to 13 did not respond significantly to N alone but always responded significantly to N + S. With foliar sulphate-S levels greater than 60 mg • kg^{-1} and an N/S ratio less than or equal to 12, there was always a favourable response to N and no additional benefit from adding S. Users of foliar analysis data must also be aware of differences resulting from different analytical procedures for measuring foliar S and sulphate-S concentrations (Brockley 2000a, 2000b).

These and other considerations mean that interpretation of foliar analysis results is complex. It is increasingly difficult to present these nutritional relationships in simple tabular form. To give silviculturists a more sophisticated tool for exploiting our improved understanding of tree nutrition, the Canadian Forest Service and the B.C. Ministry of Forests recently developed the Lodgepole Pine Foliar Nutrient Diagnosis and Fertilizer Advisory System. This interactive diagnostic system uses not only interpretive criteria, but also analytical methods and the knowledge gained through long experience in interpreting foliar analyses and making fertilizer recommendations (see "Web Resources" box).

Treatment

By the 1990s, S deficiencies were recognized in lodgepole pine stands across much of the interior, and a blend of urea and ammonium sulphate (10% S) became widely used in large-scale fertilizer operations. Research trials demonstrated rapid S uptake when soluble sulphate-S was applied in combination with N, though little additional growth response was obtained when S additions were increased from 50 to 100 kg • ha^{-1} (Brockley and Sheran 1994; Brockley 2004). Although sulphate-S fertilizers are readily available to plants, evidence from agricultural experiments suggests that long-term soil retention of S added in this form may be limited (Sanborn et al. 2005). Moreover, in forest fertilization the cost of aerial application is a large proportion of treatment costs, so the low S concentration (<25%) of sulphate-based fertilizers is a disadvantage.

In contrast, elemental-S–based fertilizers provide S concentrations approaching 100%, but must be microbially oxidized to sulphate to become plant-available. When appropriately formulated to enhance oxidation rates, elemental-S has satisfactorily enhanced S availability in agricultural soils (Hu et al. 2002). Some of the lodgepole pine fertilizer trials in the British Columbia interior have included treatments that allow comparison of responses to sulphate-S and elemental-S fertilizers. Longer-term results suggest that both S sources are likely equally effective for treating S deficiencies and improving tree growth in S-deficient stands (Brockley 2004).

New results from a central interior lodgepole pine trial established at Cluculz Creek (Figure 1) in 1990 offer additional evidence of lasting benefits from elemental-S applications (Sanborn et al. 2004). Forest floor samples collected more than a decade after treatment with 100 kg S • ha^{-1} as elemental-S showed significantly higher total S concentrations than those from either control or ammonium sulphate–treated plots (Figure 2). A similar pattern occurred for foliar sulphate-S concentrations (Figure 3). In an accompanying laboratory experiment, rates of sulphate-S production from forest floors treated with elemental-S were dramatically higher than in these other two treatments (Figure 4). In contrast, the underlying mineral soil (0–20 cm) showed no elevation of total S concentrations in either of the fertilization treatments studied. This may indicate that much of the S added in elemental form has remained in the forest floor, while S added as ammonium sulphate has leached deeper into the soils. Taken together, these tree growth and soil data suggest that elemental-S additions can considerably improve long-term soil S availability.

Current Research Initiatives

The extensive network of interior fertilization trials established by the B.C. Ministry of Forests between 1981 and 2000 continues to provide quantitative data on growth responses by lodgepole pine to N, S, and other nutrients. To better understand S fertilizer behaviour in these forest types, we began a new research project (E.P. 886.15) in 2001 to use stable isotope methods to trace the fate and transformations of S applied in various fertilizer forms (see "Using Stable Isotopes to Trace Sulphur Fertilizers" box). In collaboration with Dr. Bernhard Mayer of the Isotope Science Laboratory at the University of Calgary, we established two new installations: Holy Cross, south of Fraser Lake, and Kenneth Creek, in the Bowron River valley (Figure 1).

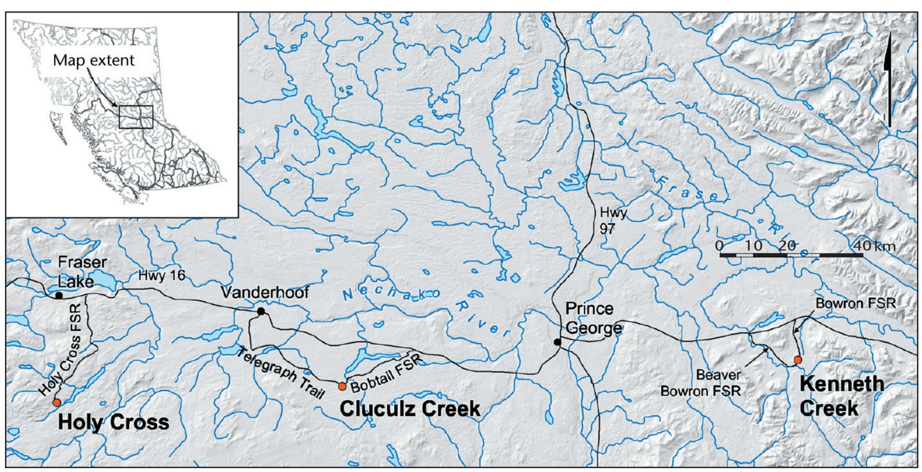


FIGURE 1 *Study site locations.*

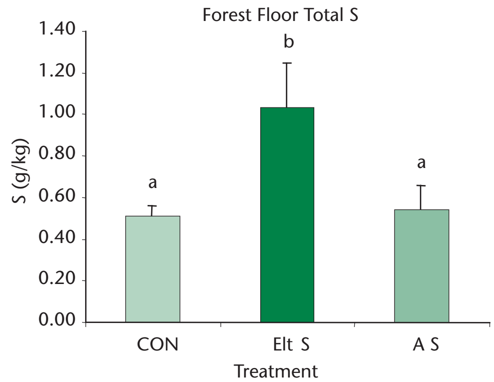


FIGURE 2 *Total S concentrations in forest floors sampled in 2003 from selected 1990 treatments at Cluculz Creek (CON = control; Elt S = 100 kg S • ha^{-1} (elemental-S) + 400 kg N • ha^{-1} (urea); AS = 100 kg S • ha^{-1} + 400 kg N • ha^{-1} ($(NH_4)_2SO_4$)). Error bars indicate standard deviations. Values for treatments labelled with the same letter are not significantly different (Fisher's LSD, $P < 0.05$).*

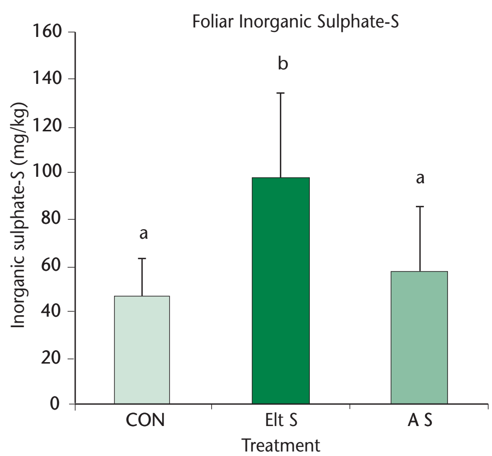


FIGURE 3 *Sulphate-S concentrations in 2002 current-year foliage from selected 1990 treatments at Cluculz Creek (legend as for Figure 2).*

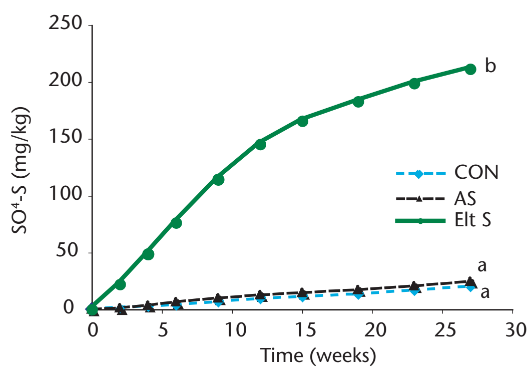


FIGURE 4 *Cumulative sulphate-S production during a 27-week aerobic incubation of forest floors sampled in 2003 from selected 1990 treatments at Cluculz Creek (legend as for Figure 2).*

This project seeks to answer three questions:

1) How much of the S added as fertilizer is actually taken up by the crop trees, retained in the soil (and in which forms), and (or) lost from the site?
2) For single-dose applications, does a slow-release form of S, such as elemental-S, give more or less long-term improvement in S nutrition than a more readily available form, such as a soluble sulphate salt?
3) What is the size of the tree growth responses to these treatments on a land area basis?

The principal innovation of this study is its coupling of a traditional fertilization response methodology, using fixed-area plots, with stable isotope tracing of S uptake and fate after fertilizer application. Pilot studies in 1997 demonstrated the feasibility of this approach. With the very low background S levels and the availability of fertilizers naturally enriched in the stable isotope ^{34}S, we are confident that operationally realistic rates of S addition (100 kg • ha^{-1}) will produce a detectable tracer effect. These installations are designed to allow longer-term assessment of growth and yield, as well as stand nutrient dynamics, beyond the initial 3 years of the study. The experimental design and pre-treatment soil and stand conditions are fully described in the project establishment report (Sanborn et al. 2005).

Options for Silviculturists

Refined criteria for diagnosing deficiencies of N, S, and other nutrients, along with new decision-making tools, have greatly improved the ability of silviculturists to design fertilizer prescriptions for interior lodgepole pine stands. These advances are timely, given the looming imbalance of age classes created by the mountain pine beetle (*Dendroctonus ponderosae* Hopk.) outbreak. Fertilization is likely one of the few methods available for accelerating the growth of the remaining younger lodgepole pine stands.

However, a significant proportion of the interior land base may never be suitable for operational fertilization treatments. Although S and other nutrients may be deficient on many sites, climatic and other inherent limitations to productivity could make fertilizer responses uneconomic. On sites where nutrient management via fertilization is impractical or uneconomic, the implications of basic silvicultural practices for long-term nutrient availability must be considered. For example, conservative management of soil organic matter on sites with relatively infertile coarse-textured soils would be prudent, given the particular concentration of soil S and N reserves in forest floors.

There may also be opportunities for innovative modifications of stand-tending regimes that combine more than one approach to nutrient management. For example, Sitka alder (*Alnus viridis* spp. *sinuata* (Regel) Á. Löve & D. Löve) is an important N-fixing shrub component of many interior lodgepole pine stands. Recent work has shown that N inputs from alder in such stands can be large enough to induce imbalances with other nutrients, particularly S (Brockley and Sanborn 2003). With the evidence presented previously that elemental S provides a lasting improvement in S availability, it may be possible to achieve long-term amelioration of N and S deficiencies by combining symbiotic N-fixation with a single application of elemental S fertilizer. This combination has not yet been field tested, but we present it as a possible component of experimental stand-tending regimes that could be applied to lodgepole pine in the British Columbia central interior.

Using Stable Isotopes to Trace Sulphur Fertilizers

To follow fertilizer S movement in a forest ecosystem, we need to distinguish between the added S and the S that is already in the soil and vegetation. Isotopic tracer methods allow this, and use different instrumentation and experimental approaches, depending on whether radioactive or stable isotopes are involved. Tracer studies with radioactive ^{35}S have given important insights into the biological transformations of S in soil–plant systems. However, in addition to safety issues, ^{35}S has a major limitation for forest fertilization studies—a short half-life of 88 days.

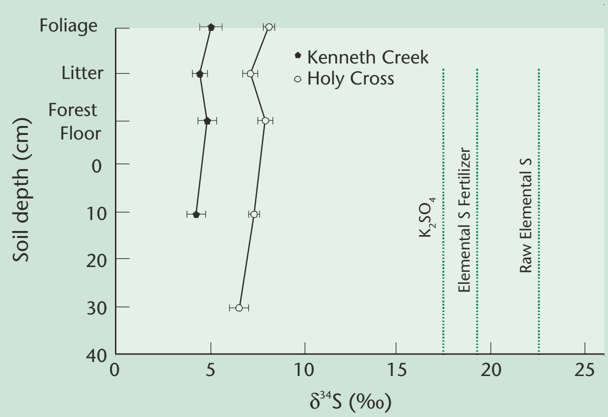
For longer-term field research, the stable isotope ^{34}S is potentially much more useful, and raises no radioactive safety concerns. About 95% of the S in the environment occurs as the stable isotope ^{32}S, while 4.22% occurs as the heavier stable isotope ^{34}S. If an artificial source of S, such as a fertilizer, differs even slightly from natural background levels in the relative amounts of these two isotopes, then it produces a distinctive fingerprint for this source. This method requires that both isotopes behave in the same way during biological processes, a condition that generally holds in aerated soils. Very small differences in isotopic ratios of only a few parts per thousand (‰)[1] can be readily detected, even in soils and plant materials containing low concentrations of S. For this reason, we are able to use commercially available S fertilizers in our work, providing that they have isotopic signatures that are sufficiently different from natural background levels in the ecosystem.

For the Holy Cross and Kenneth Creek sites, pre-treatment S isotope analyses showed that background values differed by 10–15‰ from our sulphate-S and elemental-S sources, making a tracer experiment feasible (see following diagram). Isotope analyses of foliage collected 1 year after fertilization indicated that sulphate-S had been taken up from the K_2SO_4 + N treatment during the first growing season post-treatment.

1 $\delta^{34}S$ is the scale used for expressing the difference in the relative abundances of ^{34}S and ^{32}S between a sample and a standard reference material, in parts per mil (thousand) (‰):

$$\delta^{34}S\ (‰) = \frac{R_{sample} - R_{standard}}{R_{standard}} \times 1000$$

where R is the relative number of ^{34}S and ^{32}S atoms. Positive $\delta^{34}S$ values indicate enrichment relative to the standard, while negative values indicate depletion.



Pre-treatment depth profiles of S stable isotope ratios, expressed as $\delta^{34}S$, at the Holy Cross and Kenneth Creek installations (B. Mayer, unpublished data).

References

Ballard, T.M. and R.E. Carter. 1986. Evaluating forest stand nutrient status. B.C. Min. For., Victoria, B.C. Land Manage. Rep. 20.

Brockley, R.P. 1996. Lodgepole pine nutrition and fertilization: a summary of B.C. Ministry of Forests research results. For. Can. and B.C. Min. For., Victoria, B.C. FRDA Rep. 266.

———. 2000a. Using foliar nutrient levels to predict lodgepole pine fertilization response. B.C. Min. For., Victoria, B.C. Exten. Note 44.

———. 2000b. Using foliar variables to predict the response of lodgepole pine to nitrogen and sulphur fertilization. Can. J. For. Res. 30:1389–99.

———. 2001. Foliar sampling guidelines and nutrient interpretative criteria for lodgepole pine. B.C. Min. For., Victoria, B.C. Exten. Note No. 52.

———. 2004. Effects of different sources and rates of sulphur on the growth and foliar nutrition of nitrogen-fertilized lodgepole pine. Can. J. For. Res. 34:728–43.

Brockley, R. and P. Sanborn. 2003. Effects of Sitka alder on the growth and foliar nutrition of young lodgepole pine in the central Interior of British Columbia. Can. J. For. Res. 33:1761–71.

Brockley, R.P. and F.J. Sheran. 1994. Foliar nutrient status and fascicle weight of lodgepole pine after nitrogen and sulphur fertilization in the interior of British Columbia. Can. J. For. Res. 24:792–803.

Hu, Z.Y., J.D. Beaton, Z.H. Cao, and A. Henderson. 2002. Sulfate formation and extraction from red soil treated with micronized elemental sulfur fertilizer and incubated in closed and open systems. Commun. Soil Sci. Plant. Anal. 33:1779–97.

Kishchuk, B.E. and R.P. Brockley. 2002. Sulfur availability on lodgepole pine sites in British Columbia. Soil Sci. Soc. Am. J. 66:1325–33.

Sanborn, P., R. Brockley, B. Mayer, M. Yun, and J. Prietzel. 2005. Sulphur fertilization of lodgepole pine: a stable isotope tracer study (E.P. 886.15). Establishment report. B.C. Min. For., Victoria, B.C. Tech. Rep. 020.

Sanborn, P., J. Prietzel, and R.P. Brockley. [2004]. Long-term soil and lodgepole pine foliar responses to sulphate-S and elemental-S fertilization, Sub-Boreal Spruce zone, central interior British Columbia. Can. J. For. Res. Submitted.

Web Resources

All cited B.C. Ministry of Forests publications are available as PDF files from: <http://www.for.gov.bc.ca/scripts/hfd/pubs/hfdcatalog/index.asp>.

Additional information on British Columbia fertilization research, including project descriptions and links to additional publications, is available from: <http://www.for.gov.bc.ca/hre/standman/trtfert.htm>.

The Lodgepole Pine Foliar Nutrient Diagnosis and Fertilizer Advisory System, developed jointly by the Canadian Forest Service and the B.C. Ministry of Forests is available from: <http://www.pfc.forestry.ca/silviculture/lodgepole/index_e.html>.

The National Research Council of Canada grants permission to individuals to download or print single copies of articles published by the NRC Research Press. Canadian Journal of Forest Research articles (starting with vol. 27) can be downloaded from the following website: <http://pubs.nrc-cnrc.gc.ca/cgi-bin/rp/rp2_vols_e?cjfr>.

Citation

Sanborn, P. and R.P. Brockley. 2005. Sulphur deficiencies in lodgepole pine: occurrence, diagnosis, and treatment. B.C. Min. For., Res. Br., Victoria, B.C. Exten. Note 71. <http://www.for.gov.bc.ca/hfd/pubs/Docs/En/En71.htm>