Foliar analysis as a planning tool for operational fertilization

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Introduction

Foliar analysis can be a convenient and cost-effective method for evaluating the nutrient status of forested sites. It provides an index of the amount of nutrients actually taken up by the tree and, as such, is based on the concept that the tree, not the soil, may be the best indicator of soil nutrient availability. By documenting foliar concentrations of individual nutrients, and overall foliar nutrient balance, foliar analysis reflects both soil nutrient availability and the degree to which trees require, or are capable of using, soil nutrients.

Lodgepole pine (*Pinus contorta* Dougl. var *latifolia* Engelm.) forests in the British Columbia's interior are commonly nutrient deficient, and foliar analysis is widely used by forest practitioners to evaluate their nutrient status as part of the stand selection process for large-scale fertilizer operations. Often with help from a forest nutrition specialist, foliar nutrient levels from collected samples are compared with published diagnostic criteria to confirm nitrogen (N) deficiencies, and to infer whether other nutrients will either limit growth response or become growth-limiting after N is added. Analytical results are often used to prescribe fertilizer formulations for candidate stands.

Foliar analysis is also used extensively by research scientists to interpret results from fertilization research experiments, the results from which are then used to refine foliar nutrient diagnostic criteria.

This paper reviews foliar analysis methodology and discusses ways in which foliar analysis can be effectively used as a planning tool in fertilizer operations.

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Foliar analysis as an operational tool

When used properly and efficiently, foliar analysis can be an effective tool for planning and monitoring operational fertilization projects. Foliar analysis information can be used to: 1) diagnose possible nutritional reasons for poor quality or rate of tree growth; 2) identify stands that will likely respond well to nutrient additions; 3) prescribe fertilizer formulations to correct inferred nutrient deficiencies and stimulate tree growth; and 4) assess post-fertilization uptake of applied nutrients and foliar nutrient balance. However, stand nutrient status is only one of several factors to be considered when assessing the suitability and priority of candidate stands for aerial fertilizer operations. Foliar sampling should only be undertaken on sites that satisfy other forest- and stand-level selection criteria. For example, foliar sampling is a wasted expense if stand structure or health indicate poor fertilization response potential or if there are serious non-nutritional constraints on site productivity.

Foliar sampling guidelines

Nutrient concentrations in conifer foliage can be strongly influenced by factors such as crown position, foliage age, time of year, and sample handling. It is essential, therefore, to use standardized procedures when sampling and processing foliage; otherwise, a reliable comparison of measured foliar values with published interpretative criteria may not be possible. A manual prepared by Ballard and Carter (1986) offered guidelines for collecting, preparing, and analyzing foliage samples and for interpreting analytical results. Although no longer readily available, this publication is still a primary source of information for silviculturists assigned the task of collecting foliage samples and interpreting analytical results. In recent years, extensive research has been undertaken by the British Columbia Ministry of Forests to determine the nutrient status of lodgepole pine and to document the effectiveness of fertilization in improving stand growth. These research results have been used to refine foliar interpretative criteria and update guidelines for the collection and handling of foliage samples (Brockley 2001*a*).

Fortunately, standardized foliar sampling guidelines have gained general acceptance in British Columbia. These guidelines, applicable to most conifer species, are summarized below:

1. Collect foliage during the dormant season, preferably between October 1 and December 31.
2. Confine sampling to current year's foliage.
3. Collect foliage from between the top one-quarter and the bottom one-half of the live crown.
4. Confine sampling to dominant and codominant trees.
5. Do not collect foliage from trees with heavy cone production, or with insect or disease problems.
6. Do not collect foliage from trees that are situated close to unpaved roads, where foliage may be contaminated by dust.

Some scientists have argued that sampling should be done during the active growing season, when trees are under their greatest nutrient demand. However, foliar levels of many nutrients fluctuate dramatically during the growing season, making it difficult to reconcile foliar results with interpretative criteria. Dormant season sampling is recommended due to the relative stability of nutrient levels throughout this period.

Reliable interpretations of foliar analytical data depend on the assumption that the data represent the forest stand (or stratum) in question. To evaluate the nutrient status of candidate stands for operational fertilization, foliage sampling of 15 to 20 trees per stand (or stratum) should provide adequate levels of precision and confidence for most macro- and micronutrients (Ballard 1985).

After foliage is collected, a decision must be made on whether the foliage from each tree will be analyzed separately or composited by amalgamating with foliage from other trees. Although composite analysis does not permit assessment of within-stand nutrient variability, it will, in most cases, provide reasonable estimates of mean foliar nutrient concentrations for the stand in question. For routine diagnostic purposes, composite sampling is desirable because it requires a smaller sample size per tree and greatly reduces the number, and hence the cost, of chemical analyses.

Interpretation of foliar nutrient data

Interpretation of foliar nutrient data generally involves an assessment of the foliar concentration of individual nutrients relative to published "critical levels", in combination with an evaluation of overall foliar nutrient balance. This combined approach is based on the premise that the relative proportions of nutrients in the foliage are as important (or more so) than absolute amounts.

The critical level for a particular nutrient (or nutrient ratio) is generally defined as the foliar nutrient concentration (or ratio) below which a significant decline in growth occurs, assuming all other nutrients are adequately supplied. Published interpretative criteria, indicating deficiency and sufficiency ranges for individual species, nutrients, and nutrient ratios, are based on a wide range of field or greenhouse experiments. Brockley (2001) recently published updated foliar interpretative criteria for lodgepole pine.

Unfortunately, the interpretation of foliar nutrient data is not particularly straightforward, even when interpretative criteria are available. Foliar nutrient interpretations are subject to serious shortcomings when foliage is collected using non-standardized methodology, and when data are reviewed without knowledge, or consideration of, site and stand conditions. The current growth performance of the stand, environmental characteristics of the site, and other factors (e.g., insect or disease problems) affecting foliar nutrient status should always be considered when interpreting foliar nutrient data. Foliar analysis results can also be affected by differences in analytical methodology used for the extraction or determination of foliar nutrients. For most nutrients, methodological differences are likely too small to affect interpretation of nutrient sufficiency or deficiency. However, inter-laboratory comparisons have shown that differences between foliar N levels obtained from combustion and wet digestion methods are relatively large (Figure 1). For inorganic sulphate-S (SO_4), results with ion chromatography compare favourably with the hydriodic acid (HI) reduction-bismuth colorimetric method. However, results obtained with an inductively coupled plasma (ICP) spectrophotometer are generally much higher than those obtained with the other two methods (Figure 2). Fortunately, these inter-laboratory comparisons indicate that relationships between the results obtained with different analytical methods are relatively strong.

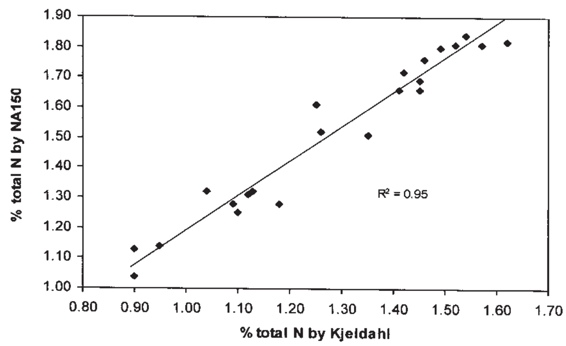

Figure 1. Relationship between foliar N concentration determined by combustion (NA1500) and wet digestion (modified Kjeldahl) methods.

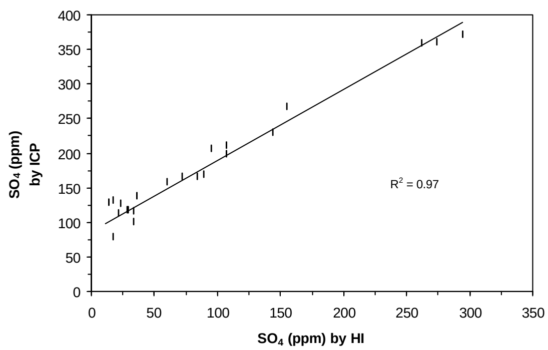

Figure 2. Relationship between foliar sulphate-S concentration determined by inductively coupled plasma (ICP) spectrophotometer and HI-deduction - bismuth colorimetric methods.

Even when the above complexities are adequately dealt with, intangible knowledge accumulated from years of foliar analysis and fertilization research experience can be an important part of diagnosing probable nutrient deficiencies and formulating fertilizer prescriptions. Because field practitioners often lack this experience, the Canadian Forestry Service and the B.C. Ministry of Forests have jointly developed a Web-based "Lodgepole Pine Foliar Nutrient Diagnosis and Fertilizer Advisory System" (Thomson *et al.* 2001). This interactive, knowledge based system was developed specifically for forest practitioners to facilitate reliable diagnosis of lodgepole pine nutrient status and formulation of appropriate fertilizer prescriptions for large-scale fertilizer operations. An advantage of a Web-based system is that it is accessible to most personal computers and can be easily updated to broaden its scientific and practical applications. Users of the system are prompted for various input information, some of which is used for diagnostic purposes and some of which is simply reformatted and printed to provide complete documentation of the foliar sampling project. The system uses the input data to generate five types of output:

1. administrative information (name, organization, analytical laboratory, foliar sampling date) and pertinent site/stand documentation (latitude, longitude, BEC subzone, site series, elevation, mapsheet, stand age, origin, site index);
2. tabulated foliar concentrations of individual nutrients and calculated nutrient ratios;
3. comments on input information that may affect nutrient diagnosis or fertilization response potential (e.g., age and crown position of sampled foliage, stand health);
4. complete foliar nutrient diagnosis for all macro- and micronutrients for which data are provided; and
5. recommended fertilizer prescription to correct inferred nutrient deficiencies.

The system uses functions developed from inter-laboratory comparisons to automatically adjust foliar levels of some nutrients to a standard from which interpretations are made using criteria suggested by (Brockley 2001*a*). Foliar nutrient interpretations are then used to develop customized fertilizer prescriptions to correct inferred nutrient deficiencies.

A link to the "Lodgepole Pine Foliar Nutrient Diagnosis and Fertilizer Advisory System" can be found at the Canadian Forestry Service, Pacific Forestry Centre Web site at http://www.pfc.cfs.nrcan.gc.ca/silviculture/.

Foliar N and S as predictors of growth response

Extensive foliar analysis and fertilization research has been undertaken by the B.C. Ministry of Forests to determine the nutrient status of lodgepole pine and to document the effectiveness of fertilization in improving stand growth. These studies have confirmed that N deficiencies are widespread throughout the region and that N additions often have a substantial positive effect on tree and stand growth (Brockley 1989, 1991, 1995, 1996, 2000*a*, 2000*b*). Elsewhere in these proceedings, Brockley (2001*b*) reported that seventy-five percent of stands from which foliar nutrient information has been collected have foliar N levels lower than 1.15%, indicating moderate to severe N deficiency. Approximately one-quarter of the stands have foliar N levels lower than 1.00%, indicating severe N deficiency (Ballard and Carter 1986; Brockley 2001*a*). In an analysis of 31 fertilization research trials, an overall trend of declining basal area response to fertilization with N alone was observed with increasing concentration of this nutrient in the foliage of unfertilized trees (Brockley 2000*a*). Pre-fertilization foliar N explained approximately one-half of the observed variation in relative basal area response among installations. Six-year basal area response to fertilization with N alone averaged 42% in installations with less than 1.1% foliar N. However, the average growth response in installations with greater than 1.2% foliar N was only 13%. By setting the critical level at 1.2%, foliar N correctly predicted statistically significant 6-year basal area response (or lack of it) to N fertilization in approximately two-thirds of the installations in this analysis. Studies with Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) and Scots pine (*Pinus sylvestris* L.) have also reported strong negative relationships between stemwood responses to N fertilizer and pre-treatment levels of N in foliage (Turner *et al.* 1988; Hopmans and Chappell 1994; Sikstrom *et al.* 1998).

In the interior of British Columbia, sulphur (S) deficiencies, either induced or aggravated by N fertilization, have been implicated in limiting the effectiveness of added N in some lodgepole pine stands. Growth responses have been enhanced on some sites by combining S with N in fertilizer prescriptions (Mika *et al.* 1992; Brockley 1996, 2000; Brockley and Sheran 1994). Studies with radiata pine (*Pinus radiata* D. Don) and Douglas-fir have used pre-fertilization foliar SO_4 to predict whether or not stands will respond to N additions (Turner *et al.* 1977, 1979). The usefulness of foliar SO_4 in predicting fertilization response is based on the constant ratio between total N and organic S in the foliage of conifers (Kelly and Lambert 1972). Any S in excess of that required to balance foliar N in protein formation accumulates in the foliage as inorganic SO_4. Therefore, in the absence of other nutritional or non-nutritional constraints, stands with inadequate foliar N and large reserves of foliar SO_4 (indicating S sufficiency) will likely respond well to N fertilization. Conversely, stands with low pre-fertilization SO_4 reserves (indicating S deficiency) will likely not respond to N additions even if foliar N levels indicate N deficiency. Brockley (2000*a*) reported a positive relationship between relative basal area response to fertilization with N alone and foliar SO_4 concentration in lodgepole pine. Pre-fertilization foliar SO_4 explained 55% of the observed variation in relative growth response among 31 installations. Six-year basal area response to fertilization with N alone averaged 47% in installations with more than 80 ppm SO_4 in unfertilized foliage. The average response for installations with less than 60 ppm of SO_4 was only 15%. By setting the critical level at 60 ppm, the amount of SO_4 in unfertilized foliage was 87% effective in predicting whether a significant basal area response would occur following fertilization with N alone. Elsewhere in these proceedings, Brockley (2001*b*) reported that sixty percent of lodgepole pine research trials from which pre-fertilization foliar nutrient information has been collected have foliar SO_4 levels less than 60 ppm. These data indicate that S deficiencies are relatively common in the interior of British Columbia and that foliar analysis can be readily used as an operational tool to identify lodgepole pine candidate stands that will be likely be unresponsive to fertilization unless S is added to the fertilizer prescription.

Brockley (2000*a*) presented a multiple regression model, using two independent variables (foliar N and SO_4), that explained 68% of the variation in relative 6-year basal area response of lodgepole pine to fertilization with N alone. Pre-fertilization foliar N and SO_4 levels, as well as N:S ratios, were also useful in predicting whether growth response can be increased by combining S with the added N. Lodgepole pine stands with less than 60 ppm of foliar SO_4, or N:S ratios greater than 13, generally responded poorly to fertilization with N alone, but almost always responded well to combined applications of N and S. On the other hand, stands with greater than 60 ppm of foliar SO_4, or N:S ratios less than 12, rarely showed large incremental S response. Brockley (2000*b*) presented tables in which pre-fertilization levels of foliar N, SO_4, and N:S ratios can be used to determine the likelihood of obtaining growth responses to fertilization with N alone, or N in combination with S. Clearly, pre-fertilization foliar analysis is a useful way to confirm the presence, and severity, of N and S deficiencies in lodgepole pine and to predict growth response potential following N additions.

Foliar analysis to document boron status

Foliar analysis has been useful in documenting the boron (B) status of lodgepole pine in the interior of British Columbia. Low foliar B levels are most commonly associated with morrainal soils derived from igneous rocks and subject to periods of soil moisture deficit during the growing season. These soil conditions have been described as being especially susceptible to B deficiencies (Wikner 1983; Stone 1990). Low foliar B levels have also been documented on coarse-textured, glacial outwash soils with low organic matter in the B.C. interior, where high rainfall may deplete soil-available B. On both these soil types, acute B deficiency symptoms (i.e., top dieback) have been induced by N fertilization (Brockley 1989, 1996) with resulting negative impact on stem volume response. Similar symptoms have been reported following N fertilization of Scots pine in Scandinavia (Braekke 1983) and radiata pine in New Zealand (Will 1985). In the absence of visual growth disturbance symptoms, subacute B deficiency has also been shown to reduce the N fertilization response potential of lodgepole pine. Combined N and B application significantly improved height (and thus volume) response over that obtained with N fertilization alone (Brockley 1990).

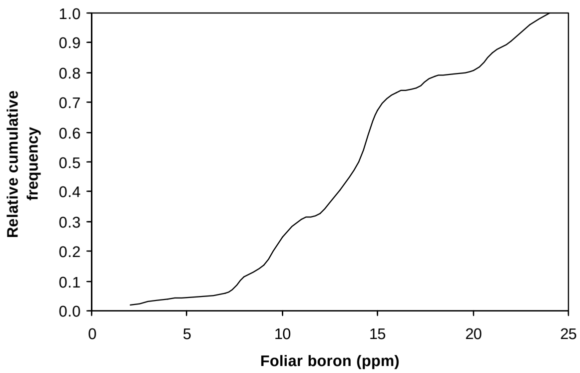

Figure 3. The relative cumulative frequency distribution of pre-fertilization foliar B concentration in lodgepole pole pine fertilization research trials (n=52) (Brockley unpubl. data).

Foliar analysis has proven to be an effective tool for identifying stands that are either B deficient or at risk from N-induced B deficiencies following operational fertilization. Where foliar B status is low or marginal stands can either be eliminated as candidates for operational fertilization, or a small amount of B (i.e., 2-3 kg B/ha) can easily be added to the fertilizer prescription. Figure 3 illustrates the cumulative distribution of pre-fertilization foliar B concentrations in 52 fertilization research trials in the interior of British Columbia. The vertical axis indicates the proportion of all installations that have foliar B levels less than or equal to a particular foliar concentration shown on the horizontal axis. Approximately one-third of the stands have foliar B less than 12 ppm, indicating the possibility of B deficiency, or deficiency induced by N fertilization.

Conclusions

Foliar analysis can be a reliable and cost-effective planning tool for fertilizer operations. In British Columbia, it is currently being used effectively to confirm N deficiencies and to identify stands in which other nutrients, most notably S and B, may have to be added to the fertilizer prescription in order to maximize growth response. A Web-based foliar interpretative system has recently been developed for lodgepole pine that diagnoses specific nutrient deficiencies and formulates fertilizer prescription to correct inferred deficiencies.

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