ESTIMATING POTENTIAL RESPONSE TO FERTILIZER BASED ON TREE TISSUE AND LITTER ANALYSIS

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ABSTRACT

Foliar analysis is a valuable aid in identifying nutrient deficiencies in trees. It cannot be used to predict with certainty whether a growth response to fertilizer will be obtained under the conditions that prevail in the Pacific Northwest. Interpretation of analyses can be complicated by growth limitation by nonnutrient factors, growth dilution effects, seasonal and annual nutrient concentration variations, or provenance differences. Determination of internal nutrient ratios and of the form in which nutrients occur within the tree sometimes assists interpretation of foliar analysis. Analyses of inner bark, root tissues, and litter have received some attention because of the difficulty of sampling foliage from the top whorls of tall trees.

INTRODUCTION

Foliar analysis is a valuable aid in distinguishing between nutrient deficiency and sufficiency in trees. Information on foliar nutrient levels exists for some western species (Table 1). Probably all would agree that growth of Douglas-fir stand showing a mean N concentration of 1%, in current foliages samples removed from the upper crowns was limited at least by N. On the other hand, no one would expect to greatly improve the growth of a Douglas-fir stand showing a mean foliar N concentration of 1.8% by adding N. An idea of these extremes is useful but most stands are between the extremes, and predicting the likelihood of response to fertilizer on the basis of foliar analysis alone is unreliable.

As pointed out in an earlier review (van den Driessche 1974), foliar analysis has been found effective where acute deficiencies occur, as in parts of the southeastern United States, Queensland, and parts of New Zealand. In Queensland, P is deficient and exotic pine crops fail unless fertilized with P. The consumption of the added P fertilizer can be followed by determining foliar P concentration at 5-yr intervals. In New Zealand, P deficiencies are also quite common and deficiencies of B and other micronutrient occur. The deficiencies cause visible symptoms and reduced growth, and foliar analysis is used to determine which particular nutrient is likely to be causing the problem. Of course, this likelihood must be confirmed by alleviating the symptom through adding the necessary nutrient.

The situation is generally different in the Pacific Northwest, although acute deficiencies may exist locally. Usually growth is not drastically reduced and deficiency symptoms of discolored foliage and twisted or fused needles are not evident. On the other hand, in many instances addition of N fertilizer to the stand results in increased growth. Under these conditions tissue analysis does not consistently predict whether a growth response will be obtained by fertilization with a particular element, and much less does it predict the quantity of response.

It seems fairly clear from the long history of foliar analysis that its utility is limited. It does permit identification of deficient nutrients, however, and provides a general impression of the stand's nutrient status.

At first sight it seems that measurement of foliage nutrient concentration should be a quick and effective method of determining stand nutrient status and predicting the degree of response to added fertilizer. Why is the procedure so uncertain? In some instances other factors such as light or moisture supply may be more limiting. For example, N fertilization of Douglas-fir causes increased foliage production, but if the stand already has a high foliage area index (FAI) its photosynthetic rate is little increased. Thinned stands frequently respond well because their FAI is low (Brix and Ebell 1969).

It has been suggested that Douglas-fir stands in Washington and Oregon, which showed low foliar N concentrations, did not respond to N fertilizer because they were inadequately supplied with S (Turner et al. 1977). Sulfur deficiency can be detected by suitable analysis of foliage for inorganic S, but unfortunately the analytical procedure is difficult and not commonly done. This does not reflect adversely upon the foliar analysis method, of course, but upon the practitioners. Also the added fertilizer may not be taken up by the stand because of leaching, inactivation in the soil, or, even because of volatilization in the case of urea.

Table 1. Foliar[a] nutrient concentrations (as percentage of ovendry tissue) for five species native to the Pacific Northwest shown by three levels: (1) adequate, response to fertilization at this level unlikely; (2) low, response to fertilization at this level possible; (3) very low, response to fertilization at this level probable.

	N	P	K	Ca	Mg	Total S	SO_4	References
Douglas-fir (coastal)								
Whole 1–0 seedlings								
Adequate	1.7	0.30	1.2	0.20	0.12			Gessel et al. 1950, Gessel et al. 1960, Heilman and Gessel 1963
Low	1.4	0.23	0.6					
Very low	0.8	0.17	0.4					
Needles of 1–0 seedlings								Beaton et al. 1965, Lavender and Carmichael 1966, Turner 1966, Kruger 1967
Adequate	2.0	0.40	1.2	0.20	0.12	0.20		
Low	1.5	0.25	0.6					
Very low	1.0	0.17	0.4					
Current needles of trees								van den Driessche 1969a, Everard 1973, Heilman and Gessel 1963, Turner et al. 1977
Adequate	1.8	0.22	0.8	0.20	0.12	0.18	0.008	
Low	1.2	0.16	0.6					
Very low	1.0	0.14	0.4					
Sitka spruce								
Whole 1–0 seedlings								
Adequate	2.1	0.25	1.2	0.50	0.10			Leyton 1958, Parker 1962, Beaton et al. 1965
Low	1.7	0.22	0.6	0.20	0.07			
Very low	1.0	0.16	0.4					
Needles of 1–0 seedlings								Binns and Atterson 1967, van den Driessche 1969a, Benzian and Smith 1973, Everard 1973
Adequate	2.3	0.33	1.2					
Low	1.9	0.24	0.6					
Very low	1.2	0.16	0.4					
Current needles of trees								
Adequate	1.8	0.25	1.2	0.50				Farr et al. 1977
Low	1.5	0.18	0.6	0.20				
Very low	1.0	0.14	0.4					
Western hemlock								
Whole 1–0 seedlings								
Adequate	1.8	0.33	1.4	0.18	0.12			Beaton et al. 1965, Baker 1969, Benzian and Smith 1973
Low	1.6	0.25	1.1	0.16				
Very low	1.1	0.15	0.6	0.10				
Needles of 1–0 seedlings								
Adequate	2.2	0.33	1.4	0.20	0.14			Everard 1973, Heilman and Ekuan 1973, van den Driessche 1976, Swan 1960
Low	1.8	0.25	1.1	0.18				
Very low	1.1	0.15	0.6	0.14				
Current needles of trees								
Adequate	1.8	0.33	0.8	0.20	0.14			
Low	1.2	0.26	0.6					
Very low	1.0	0.18	0.4					
White and Engelmann spruce								
Whole 1–0 seedlings								
Adequate	2.5	0.4	0.9	0.4	0.20			Armson and Carman 1961
Current needles of trees								
Adequate	1.9	0.30	0.8	0.25	0.15			Beaton et al. 1965, van den Driessche 1969b, 1977, Swan 1971, Landis 1976
Low	1.5	0.18	0.6	0.15	0.10			
Very low	1.3	0.14	0.3	0.10	0.06			
Lodgepole pine (interior: *Pinus contorta* var. *latifolia*)								
Whole 1–0 seedlings								
Adequate	2.2	0.30	1.10	0.40	0.15			Swan 1972
urrent needles of trees								
Adequate	1.7	0.20	0.70	0.12	0.10			Everard 1973, Landis 1976, van den Driessche 1977
Low	1.3	0.15	0.50					
Very low	1.0	0.12	0.35					

[a]These analyses apply to current foliage sampled from the upper crown during the dormant season (approximately October to March).

NUTRIENT INTERACTIONS AND DILUTION

One reason for difficulty in interpretation of foliar analysis may be interactions between nutrients and the diluting effect of growth. Increase in N supply level generally decreases foliar P and K concentrations, and increasing K supply usually reduces Mg concentration and vice versa. Low P supply may reduce foliar K concentration, but lack of K does not reduce P concentration. Many of these interactions are accounted for by the fact that the nutrient in greatest supply (often added as a fertilizer) promotes growth and tends to decrease (dilute) tissue concentrations of other nutrients.

SEASONAL AND PROVENANCE VARIATION

Other important problems include variation in nutrient concentrations with season and between different years (Leaf 1973, van den Driessche 1974, Morrison 1974). Part of the difficulty may arise because large trees are able to mobilize N reserves and maintain a sufficient concentration of N in current foliage. It has been suggested this effect could be partially overcome by sampling when growth is most rapid and redistribution of nutrients has not obscured deficiencies (Waring and Youngberg 1972). The idea has not been widely adopted, and it is still conventional to sample current foliage from the upper whorls of conifers in October at the end of the growing season (Leyton and Armson 1955). Provenance differences in nutrient concentrations have been demonstrated and probably affect interpretation of analyses (Walker and Hatcher 1965, Steinbeck 1966, van den Driessche 1973, Evers 1973, Burdon 1976, Pope 1979).

SAMPLING INTENSITY

Chemical analysis is relatively accurate if calibrated against generally accepted standards such as U.S. Bureau of Standards foliage samples, and is also relatively precise (i.e., repeatable). Foliage samples from a single stand can vary widely in their nutrient concentrations, however, and generalization from several studies suggests that sampling of 20 trees per stand is probably minimal for detecting a 5% difference from the mean, with 95% confidence limits (Heilman and Gessel 1963, Rennie 1966, Lowry and Avard 1969, Lavender 1970, van den Driessche 1974). The coefficient of variation of N is usually lowest and that of the cations K, Ca, and Mg highest, so that sample size depends both on the accuracy required and the nutrient of major interest. After collection it is perfectly acceptable to bulk samples and, after thorough mixing, conduct chemical analyses on one or two subsamples.

INNER BARK AND ROOT ANALYSIS

Foliage sampling is conventionally carried out from the upper third of the crown, and usually from the uppermost whorls on the tree. This is difficult even in relatively short trees (height 6 m) and no really cheap and safe method of sampling stands of tall trees has been developed. To overcome the difficulty in obtaining foliage samples it has been suggested that inner bark and even roots could be sampled instead (van den Driessche 1974). Good correlation between phloem N% and average N% analyses in needles over the previous 5 yr has been reported for spruce (*Picea abies* Karst; Alcubilla and Rehfuess 1975).

Inner bark samples may tend to integrate the annual variation of N concentration occurring in foliage (Moller 1978), suggesting that this type of sampling could actually have more predictive value than foliage. Certainly, increase in N concentration, resulting from N fertilizer application, persisted over 3 yr in inner bark of white spruce (*Picea glauca* Moench Voss), but was evident for only 2 yr in current needles (Timmer 1979). Concentrations of total and soluble N in foliage were more closely correlated with inner bark values than with root values in Douglas-fir (van den Driessche and Webber 1977a).

Root concentrations of N compounds, however, particularly the amino acid arginine, appeared more sensitive to fertilizer treatment than did inner bark (van den Driessche and Webber 1977a,b). Inner bark samples provide information about N and K concentrations closely similar to that of foliage samples in Sitka spruce (*Picea sitchensis* [Bong.] Carr.), but not about P (Hetherington and Owens 1979). About 50% more inner bark samples were necessary for the same measurement precision as obtained with foliage, but since bark sampling is easier this may not be a disadvantage.

NUTRIENT RATIOS

It has long been considered that nutrients must occur in plant tissue in relatively constant proportions, and, for example, plant growth has been considered a function of two nutritional variables, intensity and balance (Shear et al. 1946). These ideas have resulted in the examination of nutrient ratios in tissue, but ratios can vary widely (Table 2) and probably require almost as much care in interpretation as the actual concentration values, although probably reducing the problem of annual variation.

A slightly different approach is to express all nutrient concentrations as ratios in relation to N concentration (Ingestad 1966, 1967, 1979). This method has been done on the basis of careful sand culture experiments with seedlings of Norway spruce (*Picea abies* Karst.), Scots pine (*Pinus sylvestris* L.), and birch (*Betula verrucoas* L.). The ratios are referred to as "proportions" and it can be seen (Table 3) that nutrient concentrations in foliage of other species occur in the proposed proportions.

Table 2. Nitrogen:phosphorus ratios in conifer foliage.

Species	Type of sample	Ratio	Authority
Japanese larch	seedlings	9–12	van Goor 1953
Japanese larch	young trees	12.6–14.7	Leyton 1958
Sitka spruce	young trees	10	Leyton 1958
Scots pine	seedlings	5–16	Boszormenyi 1958
Douglas-fir	trees unfertilized	2.6–3.6	Heilman and Gessel 1963
Douglas-fir	trees fertilized	5–10	
Dougals-fir	trees unfertilized	3.3–6.9	Beaton et al. 1964
	trees unfertilized	12.7–17.9	

Table 3. Optimum proportions of macronutrients with N set at 100.

Source of proportions	N	P	K	Ca	Mg	S	Fe
Ingestad's optimum	100	13	65	6	8.5	9	0.7
Ingestad's range	100	8–15	50–100	5–10	5–10		
Black spruce[a]							
Unfertilized	100	20	56	15	38		
Fertilized	100	15	41	9	20		
Western hemlock seedlings[b]	100	14	65	11	6		

[a]Data of Weetman 1968. [b]Data of van den Driessche 1976.

The black spruce data were interpreted as indicating N deficiency before fertilization, followed by a possible shortage of K induced by N fertilization. The proportions for western hemlock were averages for rapidly growing seedlings in three different sand culture experiments. Clearly there is some consistency in nutrient ratios when seedlings are growing under favorable nutrient conditions, but considerable variation can occur with relatively little evident adverse effect on growth.

MEASURING SOLUBLE NITROGEN COMPOUNDS

Besides examining the ratios of nutrient concentrations it is also possible to consider in what condition proportions of a single element exist within the plant. Determination of the forms in which N occurs within the plant may be particularly rewarding, and this approach may also be useful for other elements such as S, where inorganic sulfate is a more sensitive measure of tree and site S status than is analysis of total S in foliage (Kelly and Lambert 1972).

Work on fruit trees has shown that during the growing season N is stored largely in soluble form with the amino acid arginine, often the predominant compound (Oland 1959, Taylor 1967, Taylor and May 1967, Tromp 1970, Tromp and Ovaa 1973, O'Kennedy et al. 1975). The same appears true for Douglas-fir (van den Driessche and Webber 1975, 1977a,b) since fertilization results in increased soluble N and arginine concentrations. It has recently been pointed out that arginine is S-free and possibly accumulates as a result of N fertilization only when S supply is inadequate (Turner this volume). Analysis of Douglas-fir foliage, inner bark, and root samples has shown that measurements of arginine or total soluble N compounds indicate the effect of N fertilizer treatment on tree N status more sensitively than analysis of total N% (Table 4).

Table 4. Sensitivity of tissues and analyses for detecting the effect of N fertilization (van den Driessche and Webber 1977a,b).

N treatments (kg/ha) shown by organs and tissue	Nitrogen analysis		
	N%	soluble N%	Arginine (μmol/g)
	Experiment 1		
Current needles			
0	1.11 a[a]		0.1 a
224	1.26 a		3.9 ab
448	1.44 a		21.3 b
Inner bark			
0	0.44 a		0.2 a
224	0.54 a		1.4 a
448	0.56 a		2.3 a
Roots			
0	0.27 a		0.4 a
224	0.35 a		3.3 b
448	0.41 a		5.5 b
	Experiment 2		
Inner bark			
0	0.22 a	0.025 a	0.032 a
224	0.22 a	0.026 ab	0.024 a
448	0.24 a	0.028 b	0.032 a
Roots			
0	0.16 a	0.017 a	0.16 a
224	0.18 a	0.021 b	0.29 a
448	0.19 a	0.025 c	0.74 b

[a]Within tissues and N analyses, N treatments followed by the same letter are not significantly different at p = 0.05.

Possibly this type of analysis would be a way to improve the effectiveness of foliar analysis in determining tree N status, and even the status of other nutrients. Variations in the supply of mineral nutrients have some pronounced effects on the free amino acid composition of plants (Hewitt 1963, Steward et al. 1959) so that study of the free amino acids in tissue might be most informative. A drawback to this approach is that tissue for amino acid analysis should be frozen at sampling and freeze-dried prior to analysis.

LITTER ANALYSIS

A further alternative to sampling living foliage from the tree may be to analyze litter, which may be recently fallen material trapped in trays (Miller and Miller 1976) or an accumulation of several years (Evers 1967, Adams 1974, van den Driessche and Webber 1977b).

In Corsican pine (*Pinus nigra* var. *maritima* [Ait.] Melv.) stands on the Culbin sands, the concentration of N in freshly fallen needle litter follows the changes of N concentration in top whorl foliage (Miller and Miller 1976). Since there is a good correlation between growth and top whorl foliage N concentration (Miller and Cooper 1973), it follows that growth and needle litter N concentration should be correlated. Evidently such a relation exists, and Miller and Miller (1976) conclude that, "analysis of October needle fall can usefully diagnose N deficiency, predict growth and hence be used to estimate the response to N fertilizer."

In a study of 119 Sitka spruce (*Picea sitchensis* Carr.) stands in northern Ireland, growth of 64 was classified as good and growth of 55 as unsatisfactory. Chemical analysis of the litter showed significant differences between the two sets of stands, with good stands having higher N concentrations and lower C/N ratios (Adams 1974).

Analysis of the top 4 cm of the soil (i.e., mainly F and H layers) in spruce (*Picea abies* Karst.) stands in Baden-Wurttemburg is suggested as the basis for fertilizer recommendations (Evers 1967). This is because C/N and C/P ratios, and the like, of this layer were better related to growth than any other analyses.

Analysis of litter total N in a Douglas-fir stand, which had been fertilized 4 yr previously, clearly distinguished between fertilizer treatments although there were no differences in soil total N between treatments (van den Driessche and Webber 1977b). This study also showed apparent seasonal changes in litter total N, so that certain times of the year may be more satisfactory for sampling than others. Mineralizable N in litter, which also fluctuated seasonally, seemed no better than total N for measurements to differentiate between previous fertilizer treatments.

Estimates of litterfall and nutrient content of litter for tree species native to the Pacific Northwest are available (e.g., Tarrant et al. 1951, Cole et al. 1968, Carey and Farrell 1978). A study of litterfall in Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco) stands showed that annual needle litterfall increases up to about age 40 and then becomes fairly constant (Gessel and Turner 1976). In western Washington there is a peak of litterfall in early autumn. Furthermore, the annual leaf litter weight is very similar to the weight of current needle production. Using this fact it is possible to estimate stand foliage biomass. In three unfertilized Sitka spruce stands the amount of litterfall was also related to stand basal area rather than to site productivity (Carey and Farrell 1978), as would be expected if leaf litter weight corresponds to current needle production.

Nitrogen fertilizer application usually results in increased needle retention and a decrease in litterfall for the first few years after treatment. Gessel and Turner (1976) cite a 68% decrease in litterfall a year after fertilization with 220 kg/ha. About 5 yr after fertilizer treatment, however, litter production in fertilized stands starts to increase (Heilman and Gessel 1963).

Thus, besides measuring the nutrient concentration of litter and examining the C:nutrient ratios, measurement of the annual rate of litterfall may provide additional information about the condition of the stand and its possible response to fertilizer. Annual litterfall apparently can be used to estimate foliage biomass or FAI, which may be an important factor in determining whether response to N fertilizer is likely. In addition, measurements of annual litterfall and nutrient concentration allow the quantitative estimation of an important part of the stand nutrient cycle.

In summary, analysis of foliage and other tissue is valuable in diagnosing the likely cause where acute nutrient deficiency symptoms are evident. It can also be used as an aid in understanding response or lack of response to fertilization and other silvicultural treatments. The value of tissue analysis for predicting response to fertilization is likely to be greater when considered in conjunction with other possible nonnutritional limiting factors. It is of restricted value when used in isolation. Recent research suggests some improvements and alternative approaches are also possible with the technique itself.

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