# Foliar Nutrient Analysis of Sugar Maple Decline: Retrospective Vector Diagnosis

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## Abstract

Accuracy of traditional foliar analysis of nutrient disorders in sugar maple (*Acer saccharum* Marsh) is limited by lack of validation and confounding by nutrient interactions. Vector nutrient diagnosis is relatively free of these problems. The technique is demonstrated retrospectively on four case studies. Diagnostic interpretations consistently suggest that decline incidence involves Ca and Mg deficiency induced by toxic accumulation of Mn.

## Introduction

The evaluation of nutrient sufficiency in trees is complex because there are many nutrients considered essential for vigorous tree growth. These nutrients are usually required in different amounts and balanced proportions, and their availability to trees may be affected by interactions occurring between different nutrients and also between nutrients and other elements in the soil or plant system. The interactions are difficult to detect and quantify, thus confounding interpretations of simple measures of deficiency and excess of nutrient supply. These problems are particularly pertinent to diagnosing nutritional symptoms of maple decline because of the widespread belief that multiple rather than single factors of stress may be contributing to the incidence of disorders (Cote and Oimet 1996). Thus reliable diagnostic techniques must have the capacity to cope effectively with multiple nutrients and their complex interactions.

Under such circumstances, foliar analysis rather than soil chemical analyses is the preferred method of assessing tree nutrient status since elemental composition of the leaf is considered a more direct index of nutrient availability to trees compared to measures of soil nutrient supply. It is also simpler to screen multiple element status (such as both macro- and micronutrients) by foliar analyses rather than by soil analysis because fewer and less complex laboratory procedures are involved. Traditionally, three major interpretive techniques have been applied to assess leaf chemistry of sugar maple: the critical concentration concept, the nutrient ratio approach and the DRIS norm system. Each technique has inherent limitations in terms of interpretive accuracy and reliability (Timmer 1991). This paper will introduce a fourth approach to foliar analysis interpretation, called vector nutrient diagnosis that has not been previously applied to sugar maple decline disorders. The technique is more comprehensive than the others, and has the potential to improve diagnostic power.

## Current Approaches

We reviewed recent studies relating sugar maple leaf chemistry to decline ratings or dieback symptoms in a range of stand conditions in eastern Canada and the United States (Bernier and Brazeau 1988; Bernier and Brazeau 1988; Cote and Camire 1995; Cote et al 1995; Cote and Ouimet 1996; Fyles et al 1994; Heisey 1995; Kolb and McCormick 1993; Liu et al 1997; Mader and Thompson 1969; McLaughlin 1992; Ouimet et al 1995; Ouimet et al 1996; Ouimet and Fortin 1992; Wilmot et al 1995; Wilmot et al 1996) to determine the most popular diagnostic technique used. We noted a clear reliance on pre-established "critical" or "threshold" concentrations of elements as indicators of nutrient sufficiency. Although simple in application, the diagnostic reliability and sensitivity of the critical level approach must be questioned. Published critical concentrations for mature sugar maple are highly variable and poorly defined (Kolb and McCormick 1993; van den Burg 1985), they are seldom verified and validated by controlled fertilization experiments (Timmer 1991), and may not account for nutrient interactions. Interpretations can be confounded by inconsistencies of leaf tissue concentration with age, season and development stage, and by possible dilution and accumulation effects when comparing plants or plant components of unequal size (Timmer 1991).

In general, diagnoses offered in these studies tended to be qualitative rather than quantitative, focusing more on nutrient deficiency rather than toxicity because of the lack of published critical toxicity levels, and the difficulty in distinguishing between luxury consumption and toxic uptake above sufficiency concentrations. All studies screened macronutrient status, only a few included micronutrients, which implies that the role of micronutrients and their interactions were not considered crucial in diagnosing this disorder. In three studies (Cote and Camire 1995; Cote et al 1995; Long et al 1997), diagnostic interpretations were supplemented by comparing leaf nutrient status of healthy and unhealthy trees, and using optimum nutrient ratios or DRIS norms to assess nutrient balance. This approach is more inclusive than that based solely on critical levels, but reliability suffers from similar problems of weak definition, calibration and validation. Vector diagnosis may avoid the interpretive problems associated with traditional foliar analyses because its application is independent on pre-established critical levels, nutrient ratios or DRIS indices, and the technique has been calibrated and validated by fertilization trials. We have applied this approach retrospectively to foliar chemistry data published in these studies to demonstrate its potential in evaluating nutritional problems associated with maple decline.

## Vector Diagnosis

Graphical vector diagnosis is explained in detail (Timmer 1991), and has been reviewed by Weetman 1989 and Haase

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and Rose 1995, thus it will only be briefly described here. Initially developed by Timmer and Stone 1978, the technique has undergone periodic refinements to enhance reliability and flexibility. Interpretations of complex multi-vector responses were simplified by normalization procedures (Timmer and Morrow 1984). Identifying nutrient interactions was improved by comparing multiple nutrients in similar space (Teng and Timmer 1990a; Teng and Timmer 1990b; Timmer and Teng 1990). Concepts of steady-state nutrition were introduced by integrating dynamic or temporal parameters in the system (Imo and Timmer 1997). Recently, interspecific nutrient competition between species was identified by adopting a two-crop format of the technique (Imo and Timmer 1997).

Its application recognizes the biological principle that growth of plants is dependent on nutrient uptake, hence the nutrient concentration in the plant is a function of two fundamental processes: nutrient uptake and biomass accumulation. This relationship is examined by comparing growth and nutrient status of trees, or tree components, differing in health and/or productivity in a nomogram that plots biomass (accumulation) on the upper horizontal axis, nutrient (uptake or) content on the lower horizontal axes, and corresponding nutrient concentration (nutrient content divided by component biomass)on the vertical axis (Figure 1). When normalized to a specified reference sample (usually the control set to 100), differences are depicted as vectors because of shifts in both direction and magnitude. Diagnosis is based on vector direction of individual nutrients, identifying occurrence of deficiency (C), sufficiency (B), luxury consumption (D), toxicity (E), antagonism (F) and dilution (A). Each configuration corresponds to a specific phase in dose response curves relating changes [increasing (+), decreasing (-), or none (0)] in plant growth, nutrient content and nutrient concentration to increasing soil nutrient supply (Timmer 1991). Vector magnitude reflects the extent or severity of specific diagnoses, and facilitates relative ranking and prioritizing.

When only part of the tree is sampled (usually the case with large trees, not seedlings), the presumption is that biomass changes in plant components (such as shoots or foliage) accurately reflect growth changes of the sample trees (Timmer and Morrow 1984). In this exercise, it was assumed that routine measures of maple decline in stands, such as crown transparency, branch defoliation, canopy dieback, growth decline, etc. are closely correlated with tree productivity. Hence these measures served as surrogate estimates of foliar biomass in the nomograms. Accordingly, the upper and lower horizontal axes in Figures 2, 3 and 5 were labeled as indices of foliar biomass and nutrient content.

## Case Studies

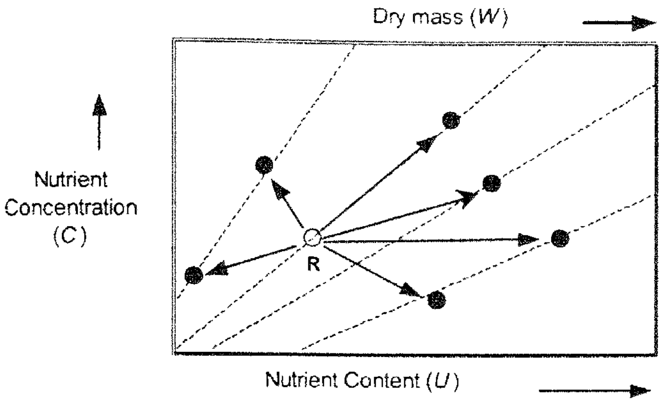
We present here data from studies that monitored both macronutrients and micronutrients in foliage in relation to a range of maple decline. The nomograms (Figure 2 and 3) show a common pattern of the largest downward, left-pointing vectors associated with Ca and Mg (Shift F, antagonism in Figure 1), and the largest, upward left-pointing vectors associated with Mn (Shift E, toxicity in Figure 1). Vector length increased with reduced foliar biomass or the severity of decline. Since the Mn vectors were larger than corresponding Ca or Mg vectors, diagnosis suggest that the disorder involved a toxic build up of Mn that inhibited uptake of Ca and Mg uptake, i.e., a case of Mn-induced Ca and Mg deficiency. Thus, as decline ratings increased, uptake (content) of base cations (mainly Ca and Mg) in foliage was severely depressed, while uptake (content) of Mn was slightly reduced in highly affected trees, or increased in less affected trees.

The mechanism could be explained by soil acidification increasing exchangeable Mn levels in the soil, which resulted in excess or toxic build up of this ion in trees (Marschner 1995). High levels of soluble Mn may in turn displace exchangeable Ca, Mg or K on the soil exchange complex inducing deficiencies of these nutrients for the trees. It is also well known in agriculture that within the plant high supplies of Mn may inhibit transport of Ca and Mg into fast growing tissues (Graham et al 1988).

Our diagnosis was supported indirectly by growth and nutritional responses of trees in independent fertilization experiments testing soil base status and liming treatments. Response patterns of sugar maple seedlings raised on a gradient of soil base saturation and pH under greenhouse conditions (Figure 4) were similar to those of Figure 2 and 3. Biomass and uptake of Ca and Mg in foliage was markedly reduced (Shift F) as base saturation of the soil decreased (Figure 4). Since Mn uptake was little changed, and concentration increased appreciably (Shift E), interpretations suggest growth inhibition due to Mn-induced Ca and Mg deficiency. Logically, the problem could be alleviated by effective liming to increase pH and base status of the soil. Liming of mature sugar maple affected by decline raised soil pH and stimulated tree growth, while reducing crown dieback symptoms (Figure 5). The response was accompanied by increased uptake of Ca and Mg (Shift C, deficiency in Figure 1) and decreased uptake of Mn (Shift F) in foliage. Apparently, applications of dolomitic limestone corrected a deficiency of Ca and Mg, and antagonistically reduced Mn uptake thus counteracting possible Mn toxicity.

## Conclusion

We have limited our demonstration of retrospective vector nutrient diagnoses to four studies. Vector nomograms (not shown here) of other studies (Cote and Camire 1995; Liu et al 1997; Ouiumet et al 1995; Ouiumet and Fortin 1992; Wilmot et al 1995; Wilmot et al 1996) that monitored mostly macronutrient status in foliage, revealed similar patterns of reduced uptake of Ca and Mg (or K on some Quebec sites) in declining trees, supporting the diagnosis that base cation limitation may be associated with maple dieback. However, interactions with Mn could not be confirmed because of the lack of Mn data. We surmise from our combined results that sugar maple decline may be linked to induced base cation deficiency that is caused by toxic Mn accumulation in the rooting zone of soils. This preliminary diagnosis needs to be confirmed by field trials testing controlled additions of Mn to the soil in problem stands.




| Vector shift | Change in relative W | Change in relative U | Change in relative C | Nutritional effect | Nutrient status | Diagnosis |
|---|---|---|---|---|---|---|
| A | + | + | - | Dilution | Non-limiting | Growth dilution |
| B | + | + | 0 | Accumulation | Non-limiting | Sufficiency, steady-state |
| C | + | + | + | Accumulation | Limiting | Deficiency response |
| D | 0 | + | + | Accumulation | Non-limiting | Luxury consumption |
| E | - | -, + | + | Concentration | Excess | Toxic accumulation |
| F | - | - | - | Antagonism | Limiting | Induced deficiency by E |

Figure 1.—Interpretation of directional changes in relative dry mass and nutrient status of plants (or plant components) contrasting in growth and/or health. The reference condition (R) is usually normalized to 100. Diagnosis (A to F) is based on shifts (increase [+], decrease [-] or no change [0]) of individual nutrient characterized in dose response curves relating plant growth, nutrient concentration, and nutrient content to increasing soil nutrient supply. Vector magnitude reflects extend or severity of the diagnosis identified (modified from Timmer 1991). Note that results in this paper involve mostly vectors E and F, suggesting that the toxic accumulation of nutrient E antagonistically induced a deficiency of nutrient F.

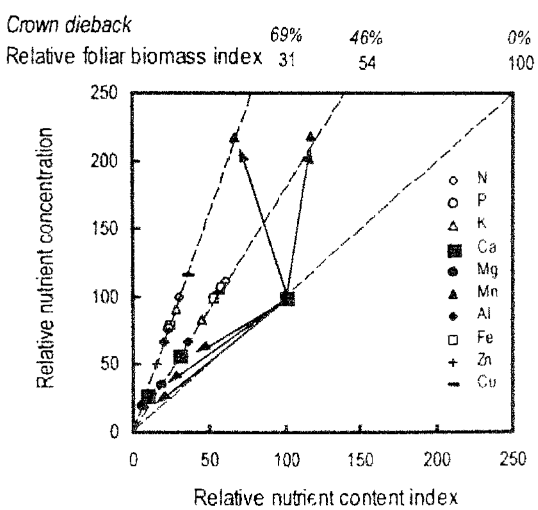



Figure 2.—Relative biomass index, nutrient concentration and nutrient content index of foliage of sugar maple stands of various degrees of crown dieback severity in Pennsylvania (Kolb and McCormick 1993). Crown dieback was defined as the proportion (percentage) of total crown volume containing dead branches with tips less than 2.5 cm in diameter. Rating was visually scored using the North American Maple Decline Project system. Relative foliar biomass index was calculated as 100 minus crown dieback rating. Foliar nutrient content index was the product of relative nutrient concentration and relative biomass index. Status of the healthy stand (with 0 to 5% crown dieback) was normalized to 100. Note that dieback severity increased with higher Mn uptake and lower Mg and Ca uptakes, suggesting a diagnosis of Ca and Mg deficiency induced by Mn toxicity.

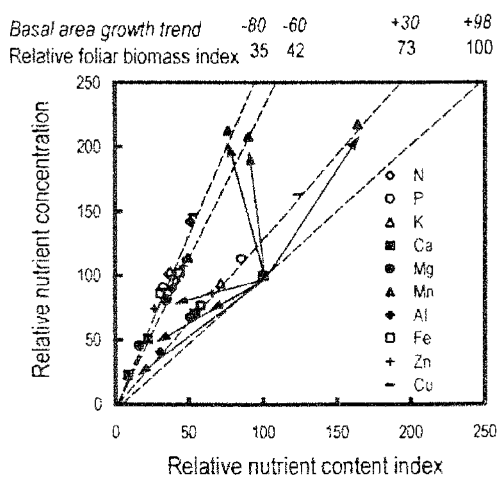



Figure 3.—Relative foliar biomass index, nutrient concentration and nutrient content index of sugar maple stands of similar age, but varying in relative basal area growth (RAG) compared to a 60-yr growth period (1928-1987) in Pennsylvania (Heisey 1995). The trend is positive if RAG increased and negative if it declined. Relative foliar biomass index was estimated as a linear function of RAG for the 1978-87 period. Foliar nutrient content index was the product of nutrient concentration and biomass index. Nutrient status of the stand with the highest RAG difference (+98) was normalized to 100. Note that basal area growth trends decreased with higher Mn uptake and lower Mg and Ca uptake, suggesting Ca and Mg deficiency induced by Mn toxicity.

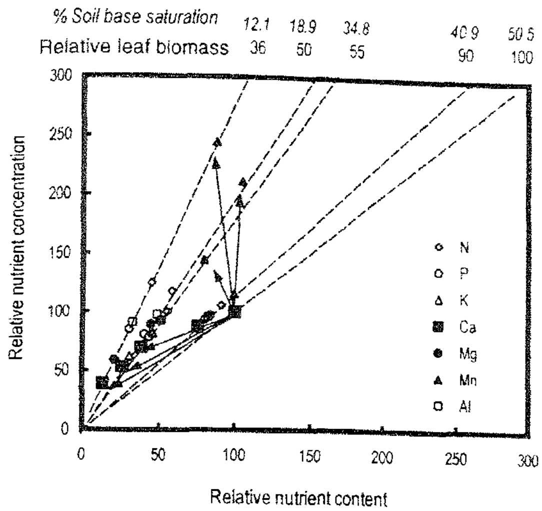



Figure 4.—Effect of soil base saturation on relative leaf biomass, nutrient concentration, and nutrient content of sugar maple seedling in a greenhouse pot trial in Quebec (Ouimet et al. 1996). The soil was a strongly acidic (pH = 4.1) sandy loam podzol with low base saturation (5%). A gradient of increasing soil base saturation was created by adding base cation solutions. The seedlings were transplanted to the pots at cotyledon stage and grown for three months. Note that low soil base saturation inhibited leaf biomass and depressed uptake of Ca and Mg most, and Mn least.

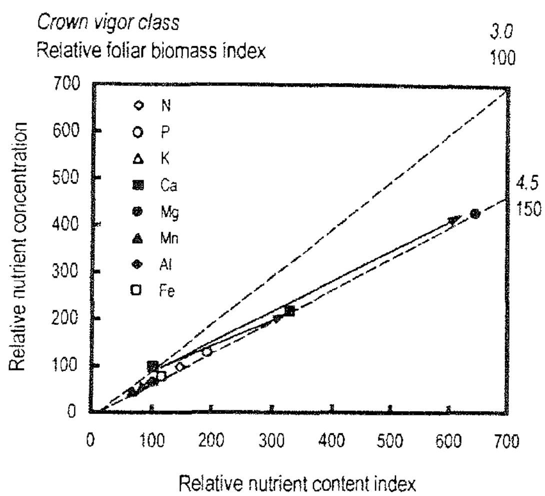



Figure 5.—Response of declining maple trees to liming in Pennsylvania (Long et al. 1997). The liming treatment was a single application of commercial pulverized dolomitic limestone (Ca = 21%, Mg = 12%, CaO equivalent = 58.8) at 22.4 Mg.ha$^{-1}$. Foliar biomass index was estimated as a linear function of total basal area. Nutrient status of the unlimed plots was normalized to 100. Foliar nutrient content index was the product of nutrient concentration and biomass index. Note that the positive biomass response was associated with depressed Mn uptake (-65%), and enhanced Ca (+330%) and Mg (+640%) uptake, suggesting that liming alleviated Ca and Mg deficiency, and countered Mn toxicity by reducing Mn availability.

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