Plant Nutrient Testing and Analysis in Forest and Conservation Nurseries

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In: Dumroese, R. K.; Riley, L. E.; Landis, T. D., tech. coords. 2005. National proceedings: Forest and Conservation Nursery Associations—2004; 2004 July 12–15; Charleston, NC; and 2004 July 26–29; Medford, OR. Proc. RMRS-P-35. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station.

Abstract: Supplying mineral nutrients at the proper rate and in the proper balance has a major effect on seedling growth rate but, more importantly, on seedling quality. In addition, mounting concerns about fertilizer pollution are increasing awareness of the benefits of precision fertilization. Because they reflect actual mineral nutrient uptake, plant tissue tests are the best way to monitor a fertilization program. Analytical laboratories are able to accurately and precisely measure the levels of all 13 mineral nutrients in a small sample of plant tissue, and nursery managers can obtain results in as little as a week. While tentative guidelines for analyzing mineral nutrient levels exist, they are for general classes such as "conifer seedlings" and are of limited usefulness for precision monitoring of fertilizer programs. Most published test results are for commercial tree species, and almost nothing is known about other native plant species. Government nurseries can provide a real service by sharing their test results with other nurseries, and nursery cooperatives can serve as clearing houses for plant nutrient test results.

Keywords: nutrient content, nutrient concentration, nutrient deficiency

Introduction

For those working in forest and conservation nurseries, reforestation, or restoration, there is a logical connection between the mineral nutrient content of seedlings and their quality. Tree seedlings and other native plants use the 13 essential mineral nutrients for growth and development. While some mineral nutrients may become limiting in natural settings, nursery managers are able to supply nutrients through fertilization for optimal seedling growth. Nurseries, therefore, should be able to produce high quality seedlings that contain optimum levels of mineral nutrients when delivered for outplanting.

The purpose of this paper is twofold. First, we present an update on terminology and technology of plant nutrient testing and analysis. Second, we discuss how nursery managers can use results of these tests to produce the highest quality seedlings in forest and conservation nurseries. Foresters and restorationists will also be able to use this information when evaluating the quality of their nursery stock.

Basic Concepts of Mineral Nutrition for Nursery Seedlings

More than half the elements in the periodic table have been found in plant tissue (Kramer and Kozlowski 1979) because most chemical ions in the soil solution are passively absorbed in the large volume of water that is absorbed during transpirational uptake. However, only 16 elements have been proven to be required for plant growth. A mineral nutrient must meet 2 criteria if it is to be considered essential for plant growth. First, it must be required for the plant to complete its life cycle; and second, it must be part of some plant constituent or metabolite (Epstein 1972). Of these 16 essential nutrients, carbon, hydrogen, and

oxygen are obtained from water and carbon dioxide and together account for approximately 96% of the dry weight of plant tissue. The remaining 13 elements are of mineral origin, being absorbed as ions from the soil. These elements have been divided into 6 macronutrients and 7 micronutrients based on relative concentration (Table 1).

The functions of mineral elements vary from the structural components of plant cells to the physiological actions of molecules such as enzymes. All macronutrients, with the exception of potassium, are incorporated into cellular constituents (for example, nitrogen and magnesium in the chlorophyll molecule) but may also serve physiological functions as coenzymes or enzyme activators. Micronutrients primarily serve in a variety of metabolic functions in cells but do not constitute a significant part of any structural component.

Mineral Nutrient Uptake Patterns

The relationship between mineral nutrient uptake and plant growth follows a characteristic pattern (Figure 1). When a nutrient is present in relatively low concentrations in plant tissue, it is considered deficient and limiting to plant growth. At the lower ranges of this deficiency, the plant often exhibits certain observable characteristics, and these deficiency symptoms can be helpful in diagnosis of the deficiency. At slightly higher concentrations, however, the deficient nutrient is still low enough to limit plant growth but not low enough to produce deficiency symptoms. This condition is called "hidden hunger" because it is difficult to visually diagnose.

When supply of the nutrient is no longer limiting to growth, the plant growth rate increases rapidly until the critical point is reached (A in Figure 1). The critical point is the tissue nutrient concentration at which the growth rate declines significantly and is usually defined as 95% of the maximum growth or yield. The range of nutrient concentration at which maximum growth occurs has been defined as the optimum range. Plants may continue to take up mineral nutrients even though this additional uptake does not result in more growth (luxury consumption). When tissue nutrient concentrations reach extremely high levels, toxicity can occur with certain elements because plant growth begins to decrease with additional amounts of nutrient (B in Figure 1).

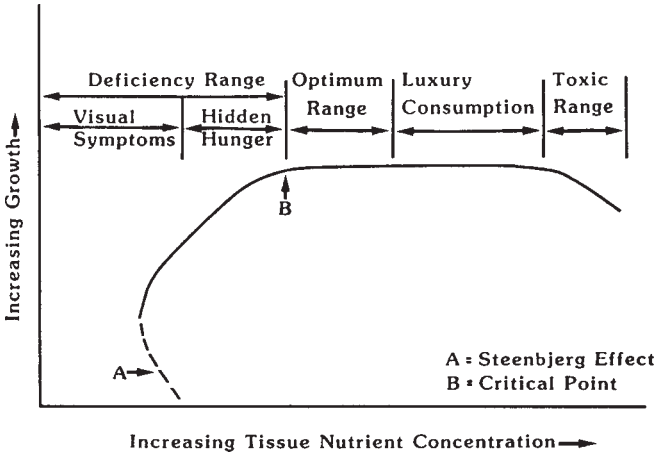

Figure 1—Hypothetical relationship between mineral nutrient concentration in seedling tissue and growth (modified from Chapman 1967).

Plant Nutrient Analysis Methodology

Sample Collection and Handling

Correct interpretations of nutrient test results cannot be made unless proper sampling methods have been used. Samples submitted for plant nutrient analyses should be collected in a consistent manner for optimum data quality. For example, the age of the tissue can have a significant

Table 1—Standard range of values for mineral nutrient concentrations in conifer needle tissue of container and bareroot nursery stock (Landis 1985).

Nutrient	Symbol	Adequate range		Mobility in plant tissue
		Bareroot	Container	
Macronutrients as percent				
Nitrogen	N	1.20 to 2.00	1.30 to 3.50	Mobile
Phosphorus	P	0.10 to 0.20	0.20 to 0.60	Mobile
Potassium	K	0.30 to 0.80	0.70 to 2.50	Mobile
Calcium	Ca	0.20 to 0.50	0.30 to 1.00	Immobile
Magnesium	Mg	0.10 to 0.15	0.10 to 0.30	Mobile
Sulfur	S	0.10 to 0.20	0.10 to 0.20	Mobile
Micronutrients as ppm				
Iron	Fe	50 to 100	40 to 200	Immobile
Manganese	Mn	100 to 5,000	100 to 250	Immobile
Zinc	Zn	10 to 125	30 to 150	Immobile
Copper	Cu	4 to 12	4 to 20	Immobile
Boron	B	10 to 100	20 to 100	Immobile
Molybdenum	Mo	0.05 to 0.25	0.25 to 5.00	Immobile
Chloride	Cl	10 to 3,000	10 to 3,000	Mobile

influence on nutrient levels. Mobile nutrients are often found in higher concentrations in the younger, actively growing foliage, whereas immobile nutrients tend to concentrate in older parts of the plant (Table 1). Therefore, it is imperative to select tissue so that variation due to age is minimized. This can be done by sampling the entire plant in young non-woody seedlings, or by sampling the oldest or newest foliar tissue in older plants. Usually, nurseries tend to look at total foliar nutrition or at the tissue that has most recently matured. Analyses of older tissue are useful for diagnosing problems associated with immobile elements, especially micronutrients such as boron (Table 1).

The best type of tissue sample will also depend on whether you want to measure nutrient concentration or content. Because nutrient concentration is a proportional measure, either foliage or whole plants may be used. Nutrient content, however, is reported as weight per plant. Therefore, it is necessary to know the over-dry weight of the sample.

Sampling intensity is another important factor to consider. Too often, a nursery will send just one composite sample for analyses once or twice a year; these do not accurately assess crop nutrition. For example, if seedlings with a deficiency problem are combined with seedlings that do not have a deficiency, then the true problem will be diluted in the composite sample. While the nursery manager may be pleased to save money on laboratory analyses, what has really happened is that the money was wasted on meaningless data. Management decisions based on conclusions made from such data can be risky and costly.

The frequency of taking samples will also be influenced by the crop's growing cycle and the nursery's cultural practices. It is best to sample at several times during the growing season rather than to focus on samples taken at one time only. Regular, replicated sampling on randomly selected representative seedlings results in credible information, which can be confidently used for monitoring seedling nutrition.

Laboratory Analysis Methods and Costs

Most laboratories use standard methodology to assess plant tissue. In general, foliar tissue is digested to remove the carbon component and then examined with inductively coupled plasma emission spectrometry (ICP) to determine concentrations of individual nutrients. For a better understanding of ICP and the other analytical procedures used by laboratories, the reader is referred to Mills and Jones (1996).

Reporting Units

Most analytical labs report their results in concentration units, although nutrient content is often reported in research studies. For day-to-day nursery work, concentration units are the most common.

Concentration—Plant nutrient levels are traditionally reported in proportional units of tissue dry weight: macronutrients in percent and micronutrients in parts per million (ppm). Proportional units describe how concentrated the nutrients are in the tissue. Conversion between percent and ppm is sometimes necessary and is very simple. To convert percent to ppm, multiply by 10,000. To convert ppm to %, divide by 10,000.

You may see published concentration units using the international standard (SI) of grams per kilogram (g/kg) for macronutrients. To convert from SI units to percent, just divide by 10. The SI units for micronutrients are milligrams per kilogram (mg/kg), which is the same as parts per million. Another unit of nutrient concentration is micrograms per gram (g/g), which is the same as ppm.

Content—Content is the actual amount (g or mg) of a nutrient in a given amount of plant tissue (for example, total foliage or 100 needles). This is calculated by multiplying tissue dry weight by concentration. Although this measure requires additional effort to attain, it can yield useful information. When nutrients are diluted in rapidly growing seedlings, content can provide useful information about the plant's nutrient status that is not apparent in nutrient concentration data. Nutrient content can also allow data interpretation via vector analysis (Haase and Rose 1995) and is usual for comparisons among seedlings in fertilization studies where treatments cause seedlings to be different sizes.

It is important to carefully distinguish between nutrient concentration and nutrient content when comparing data. The terms are often confused in the literature, which has confounded interpretation. Both concentration and content units have limitations. Data reported in concentration units are subject to the dilution effect resulting from new growth; data reported in content units vary by plant size.

Variation Between Laboratories

Laboratory analyses can vary within and between labs, as well as costs, and turnaround times (Table 2). In a study conducted by the Oregon State Nursery Technology Cooperative (NTC), identical tissue samples were sent to several labs. The resulting data revealed notable variation. So, it is advisable for a nursery to investigate a lab's reputation prior to submitting samples and to consult other local nurseries about their experiences. Once a lab has been selected, it is crucial to stick with that lab throughout the season (and even for many years) in order to generate data that is not influenced by lab-to-lab variation. Furthermore, it is a good idea to "test" the lab by including identical samples every now and then.

Table 2—Analytical costs and turnaround times from laboratories used by Western nurseries.

Laboratory and location	Complete plant tissue analysis	Turnaround time[a]
	U.S. $	*days*
JR Peters (PA)	36	10
Quality Analytical (FL)	25	7
A & L Western (OR)	26	10
Micro Macro (GA)	30	7
Soil & Plant (CA)	50	21
MDS Harris (NE)	16 to 30	7

[a]Web site or e-mail service is necessary for the shortest times.

Interpreting Plant Nutrient Test Results

Most of us have struggled over laboratory reports of seedling nutrient analyses and attempted to make some sense out of them by comparing the reported nutrient values to ranges of values published in some nursery manual. The interpretation of seedling nutrient analyses requires an appreciation of the variation that can be expected. Skill in interpretation is only acquired through practice and experience, and so professional help should be sought when considering nutrient analysis for the first time.

Types of Variation in Plant Nutrient Data

Genetic: Genus, Species, or Ecotype—Plant nutrient test results have been shown to vary between different species or even between different ecotypes of the same species—interior and coastal Douglas-fir (*Pseudotsuga menziesii*) (van den Driessche 1984b). Research trials using controlled fertilizer solutions in sand cultures have shown that even closely related plant species take up mineral nutrients at different concentrations—for example, sugar maple (*Acer saccharum*) and red maple (*Acer rubrum*). Some species, such as balsam poplar (*Populus balsamifera*), are very efficient at nutrient uptake and are able to accumulate very high levels of most macronutrients when compared to normal ranges (Table 3).

Seasonal: Changes During Growing Season—The amount of mineral nutrients in plant tissue can change dramatically during the growing season, primarily due to the growth dilution effect. Tests taken throughout the season show that nutrient levels are high early in the year when plants are small, but decrease steadily as the growth rate increases.

Between Nurseries—Nursery environment may also affect the nutrient status of tree seedlings because of differences in soil fertility, cultural practices, and climate. In a study of Douglas-fir seedlings, both macro- and micronutrients were shown to vary not only between nurseries but between sections in the same nursery (Krueger 1967). In an NTC study, nutrients of healthy Douglas-fir seedlings were monitored regularly at 3 nurseries for 1 growing season. Results showed considerable variation between the nurseries as well as seasonally (Nursery Technology Cooperative 2004).

Stock Type: Bareroot Versus Container—The same species of plant will typically show much higher levels of mineral nutrients when grown in container nurseries compared to those grown at bareroot facilities. As shown in Table 1, container nursery stock have higher ranges for almost all nutrients. Container stock is grown in individual containers so that competition between seedlings is lacking. More importantly, artificial growing media have very high cation exchange capacities, and mineral nutrients are not chemically fixed like they are in many field soils. This is particularly true for micronutrients, like iron. As a result, the width of recommended nutrient ranges must be necessarily broad for bareroot stock due to soil variations. Because of the uniformity of commercial growing media, however, it should be possible to develop narrower guidelines for container seedlings.

Comparison to Standard Values

For plant nutrient values to be meaningful, they must be compared to some ideal or "standard" values. Most sources present standard nutrient values as ranges instead of discrete values to accommodate natural variation. Nutrient standards for conifer foliage tissue are presented in Table 1. The problem with these "generic" nutrient standards is that they may not be sensitive enough to reveal significant differences. Until more specific data can be accumulated, however, these general nutrient standards are the best available. Some nurseries are beginning to gather specific mineral nutrient values for their species and environments. Loblolly pine seedlings were collected from 33 Southeastern United States nurseries by the Auburn Nursery Cooperative and analyzed at the same laboratory for seedling nutrients to provide base data for soil management decisions (Boyer and South 1984). Likewise, the NTC at Oregon State University monitored bareroot seedling nutrition from 3 nurseries to determine expected ranges for Pacific Northwest Douglas-fir seedlings with target morphological characteristics (Nursery Technology Cooperative 2004).

Ideal values are provided for bareroot commercial conifers in the Pacific Northwest (Krueger 1967; van den Driessche 1984a; Youngberg 1984) and some hardwood species from the Northeastern States (Erdmann and others 1979). Unfortunately, some very good information has been published in rather obscure nursery proceedings and is not accessible to most nurseries (for example, Hallett 1985). Be wary of plant nutrient results in general horticultural publications. For

Table 3—Mineral nutrients can vary considerably between plant species or even within a genus.

Mineral nutrient	Sugar maple[a]	Red maple[a]	Paper birch[a]	Balsam poplar[b]
			percent	
Nitrogen	2.24	1.43	1.12	3.44
Phosphorus	0.16	0.17	0.51	0.35
Potassium	0.90	0.78	1.46	2.71
Calcium	2.38	2.24	1.87	0.99
Magnesium	0.43	0.63	1.17	0.33
Sulfur	0.19	0.21	0.22	0.48

[a]Grown in same fertilizer solution (Erdmann and others 1979).
[b]Grown at low nitrogen rate of 50 ppm (Wood 2004).

example, Mills and Jones (1996) report nutrient data for a wide variety of plants including sections on conifers and forest trees. However, many of these are from cultivars and the season of collection is simply listed as "summer."

Unfortunately, published mineral nutrient values for most native plant species just don't exist. Native plant nurseries are doing plant tissue analysis, but do not share their results. Although many laboratories provide recommended general mineral nutrient ranges with their test results, they do not have experience with minor crops like most native plants. Also, it is important to be aware that general guidelines are typically based on values at the end of the year after growth has stopped and so are of little value during the growing season. Therefore, the best and most useful data must be developed on a nursery by nursery basis. By using the same laboratory season after season, nurseries can quickly generate enough data to develop reasonable guidelines.

Mathematical Analysis

Several different types of mathematical analysis have been published. Ingestad (1979) recommended using nutrient ratios as a way to compare the levels of different nutrients. The Diagnosis and Recommendation Integrated System (DRIS) technique has been advocated for agronomic crops (Mills and Jones 1996). Vector analysis has been used to examine nutrient concentration, nutrient content, and plant dry weight in an integrated graphical format (Haase and Rose 1995). These types of mathematical analysis are rarely used in operational nurseries. For those interested in a comprehensive explanation of the various techniques, the authors recommend Bigg and Schalau (1990).

Uses of Plant Nutrient Analyses

Testing nursery plants for nutrient concentration can have several practical applications: adjusting fertilization, comparing growth curves, diagnosing nutritional problems, establishing seedling quality, and resulting outplanting performance.

Adjusting Fertilization

Using plant nutrient analysis to establish and adjust fertilization schedules is the most common application in forest and conservation nurseries. Determining the type and amount of fertilizer to apply and the proper application times can be bewildering to the novice grower. Even for the experienced nursery manager, the concentration of essential mineral nutrients in seedling tissue is the best way to determine the effectiveness of a fertilization program.

Compare to Seedling Growth Curves or Fertilizer Data—Collecting and analyzing seedling samples at regular intervals during the growing season and comparing the results to growth curves or correlating them with fertilization trials can be a powerful management tool. Accumulating test results in a spreadsheet program along with seedling growth data allows easy analysis and creates a permanent database that only gets better with time. When growth versus nutrient curves are developed, it is easy to identify the critical point in the curve when growth begins to flatten out (Figure 2A). Applying more fertilizer will only lead to luxury consumption and, in the case of nitrogen and phosphorus, may cause environmental pollution. Be sure to consider the lag time between fertilizer application and uptake. In bareroot nurseries, this can take 2 to 4 weeks depending on the type of fertilizer, frequency of irrigation, and soil characteristics. Uptake is much faster in container nurseries where artificial growing media allow quick penetration and easy availability of mineral nutrients.

Unless specific nutritional problems have been identified, the most attention should be give to the "fertilizer elements"—nitrogen, phosphorus, and potassium. Of these, nitrogen is by far the most important, as it controls so many aspects of seedling growth. The tendency in nurseries is to overfertilize "just to make sure," and because fertilizer is relatively inexpensive. A good example can be seen from phosphorus fertilizer trials (van den Driessche 1984b, 1990) with Douglas-fir and white spruce (*Picea glauca*). Growth curves show that seedling biomass increases rapidly with more phosphorus fertilizer, but quickly peaks at around 0.2% (Figure 2B). This response is further confirmed by a photograph of an experiment testing seedling height versus fertilization level (Figure 2C), demonstrating that only 10 to 15 ppm of available phosphorus are necessary when applied early in the growing season.

Diagnosing Seedling Problems

Many growers test plant tissue in order to diagnose a growth problem. It's important to send paired samples (the more the better for calculation of an accurate mean) of seedling tissue (healthy versus symptomatic) so that comparisons can be made. Some problems, like nitrogen chlorosis, are relatively easy to identify (Figure 3). Unfortunately, by the time the problem is diagnosed, severe growth loss has already occurred.

Most nutritional problems are not that simple, and iron chlorosis is a good example. Because it is immobile in plants, a lack of iron availability induces chlorosis in the younger foliage, which quickly causes severe metabolic problems and subsequent stunting. Once chlorosis and stunting occur, the plants are so "physiologically confused" that they continue to uptake iron, but in a form that is unavailable (Landis 1985). The result is an accumulation of iron in the plants and, typically, concentrations are greater in the chlorotic foliage (Table 4). So, without considerable background knowledge and experience, tissue tests by themselves are of dubious value in diagnosing iron chlorosis and generally just confuse the issue.

Correlating with Outplanting Performance

The final application of plant nutrient testing in forest and conservation nurseries is for the determination of seedling quality and outplanting success. Nitrogen is the only nutrient that has been statistically correlated to outplanting performance and, even at that, there are only a few published research trials that show good correlation (Figure 4). This is one instance in which nutrient content is more useful than concentration.

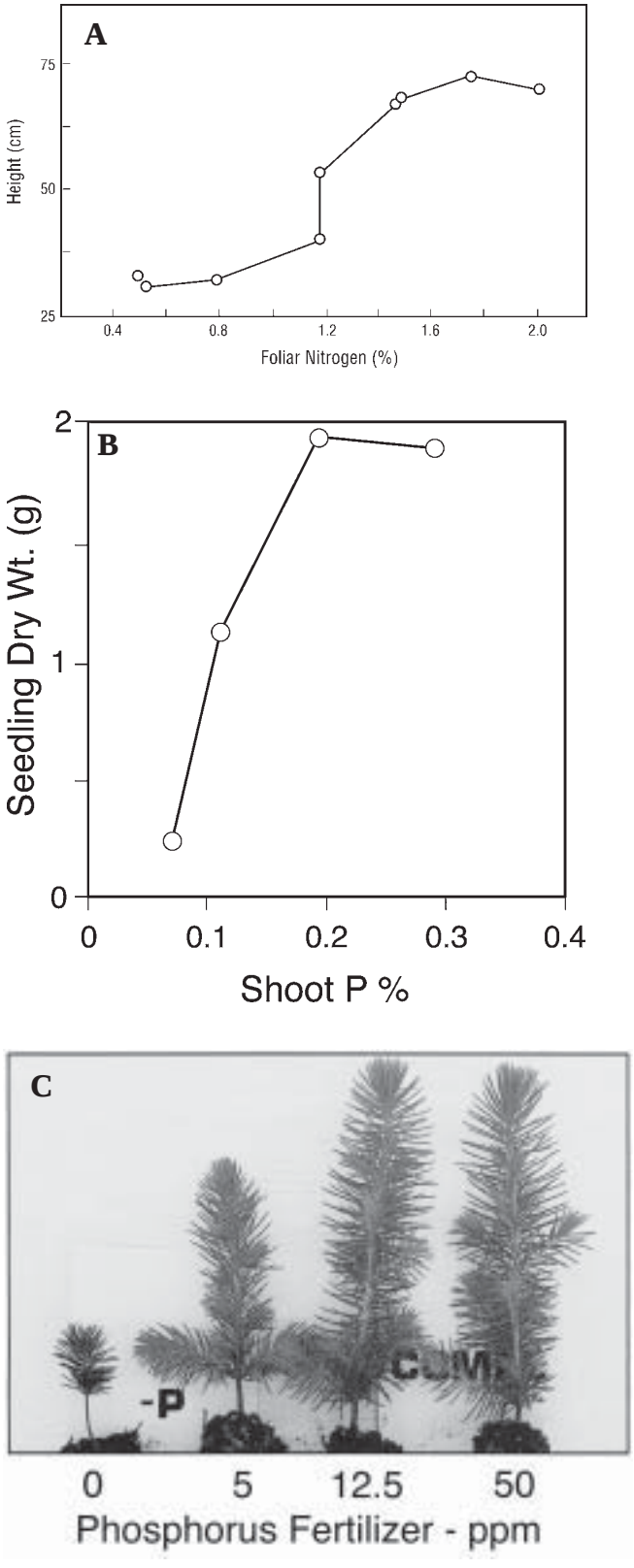

Figure 2—Foliar nutrient levels should be compared against growth curves and fertilizer trials: (A) nitrogen concentration and growth of eastern redcedar (Henry and others 1992); (B) shoot growth versus foliar phosphorus in white spruce (van den Driessche 1984b); (C) phosphorus fertilizer trials with white spruce (van den Driessche 1990).

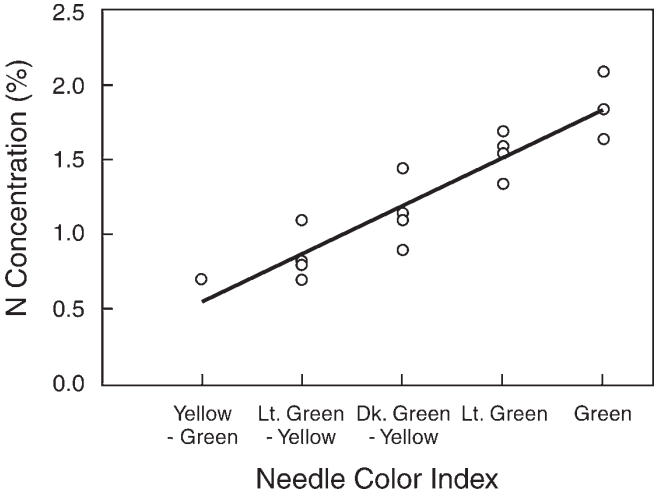

Figure 3—The relationship between nitrogen concentration and green color of Norway spruce needles in Southern Sweden (adapted from Bergquist and Orlander 1988).

The latest research into the relationship between seedling nutrient levels and outplanting performance involves a concept called "nutrient loading" with nitrogen. The idea is that "supercharging" a seedling with nitrogen will help it survive and grow better on the outplanting site where mineral nutrients are usually limiting. Nutrient loading involves fertilizing seedlings during the hardening phase until their nitrogen content is in the luxury consumption area of the growth curves (Figure 5). This process has been successful with black spruce (*Picea mariana*) on sites with heavy plant competition, as chronicled by Timmer and his associates (for example, Timmer 1997).

Nutrient loading is certainly attractive and it is hoped that this technique will be tested with more species and on more outplanting sites. Nutrient loading, however, should not be viewed as a panacea because other factors may be more limiting to survival and growth on specific sites. Water, in particular, is often the most limiting factor after planting regardless of soil nutrient levels. In addition, animal damage may be a problem because nursery seedlings are often preferentially browsed because of their higher nutrient content (Bergquist and Olander 1998).

Table 4—A comparison of foliar iron levels of healthy and chlorotic seedlings at three Intermountain nurseries (modified from Landis 1985).

Nursery and location	Iron concentration in seedling foliage[a]	
	Healthy seedlings	Chlorotic seedlings
	- - - - - - - *ppm* - - - - - - - -	
Mt. Sopris Nursery, CO	302	422
Colorado State Nursery, CO	217	346
Albuquerque Nursery, NM	303	624

[a]Recommended range = 50 to 100 ppm.

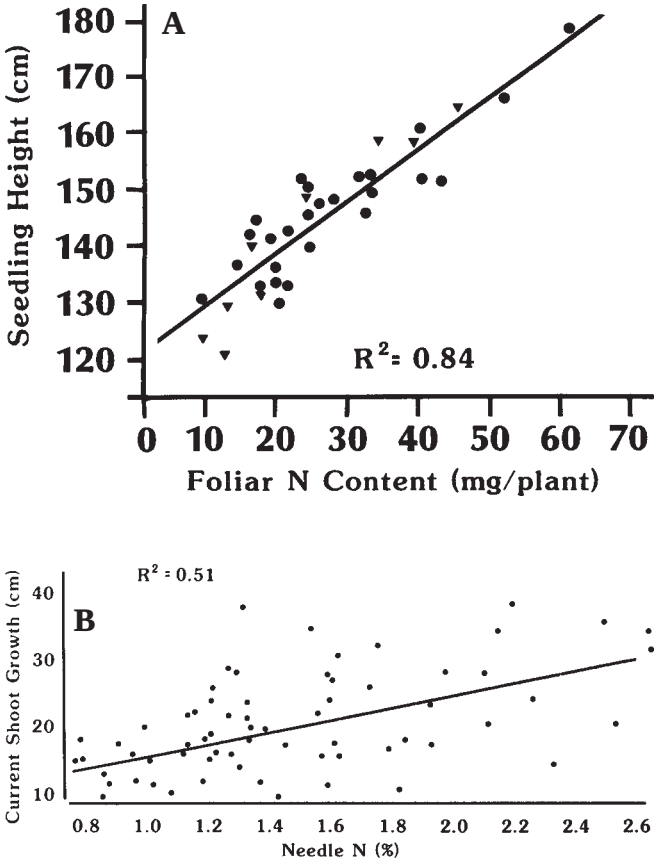

Figure 4— When correlating foliar nitrogen to outplanting performance, nitrogen content (A) has more predictive value than concentration (B) (A—modified from Switzer and Nelson 1963; B—modified from van den Driessche 1984b).

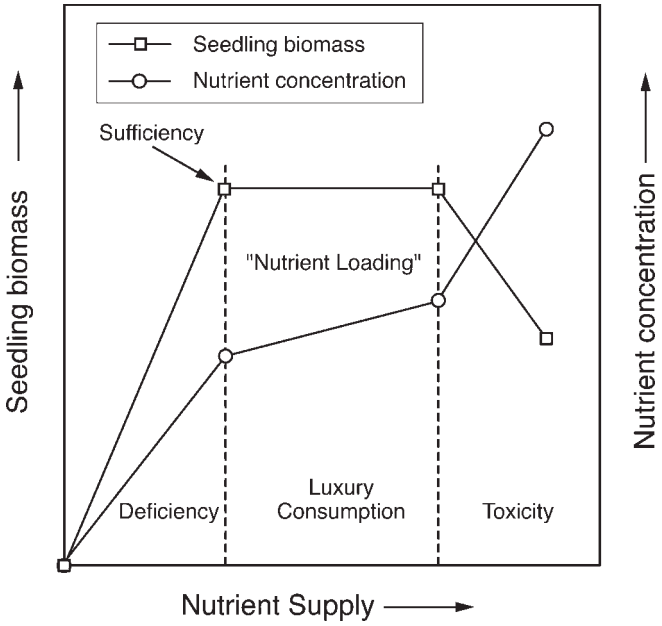

Figure 5—Nutrient loading involves building up nitrogen reserves in the foliage by adding nitrogen fertilizer to induce luxury consumption without changing maximum growth or inducing toxicity (Timmer 1997).

Conclusions and Recommendations

- Plant nutrient analysis during the growing season is an effective and relatively inexpensive way to monitor fertilization effectiveness.
- It's best to develop your own standards using growth response curves or fertilizer trials.
- Plant nutrient analysis can be useful in diagnosing nursery problems, but results are often difficult to interpret.
- By itself, plant nutrition has limited use as a predictor of outplanting performance because water availability is often the most limiting factor on a site.

References

Bergquist J, Orlander G. 1998. Browsing damage by roe deer on Norway spruce seedlings planted on clearcuts of different ages. 2. Effect of seedling vigour. Forest Ecology and Management 105(1-3):295-302.

Bigg WL, Schalau JW. 1990. Mineral nutrition and the target seedling. In: Rose R, Campbell SJ, Landis TD, editors. Target seedling symposium: proceedings, combined meeting of the Western Forest Nursery Associations; 1990 August 13-17; Roseburg, OR. Fort Collins (CO): USDA Forest Service, Rocky Mountain Forest and Range Experiment Station. General Technical Report RM-200. p 139-160.

Boyer JN, South DB. 1984. Nutrient content of nursery-grown loblolly pine seedlings. Auburn (AL): Auburn University, Southern Forest Nursery Management Cooperative. No. 14. 33 p.

Chapman HD. 1967. Plant analysis values suggestive of nutrient status of selected crops. In: Soil testing and plant analysis. II. Madison (WI): Soil Science Society of America. Special Publication Series No. 2. p 77-92.

Epstein E. 1972. Mineral nutrition of plants: principles and perspectives. New York (NY): John Wiley and Sons. 412 p.

Erdmann GG, Metzger FT, Oberg RR. 1979. Macronutrient deficiency symptoms in seedlings of four northern hardwoods. St Paul (MN): USDA Forest Service, North Central Forest Experiment Station. General Technical Report NC-53. 36 p.

Haase DL, Rose R. 1995. Vector analysis and its use for interpreting plant nutrient shifts in response to silvicultural treatments. Forest Science. 41:54-66.

Hallett RD. 1985. Forest nursery practices in the Maritimes. In: Hallett RD, Cameron MD, Murray TS, editors. Reforestation in the Maritimes, 1984 symposium, proceedings. Fredericton (NB): Maritimes Forest Research Centre, New Brunswick Department of Natural Resources, Nova Scotia Department of Lands and Forests and Prince Edward Island Department of Energy and Forestry. p 81-107.

Henry PH, Blazich FA, Hinesley LE, Wright RD. 1992. Nitrogen nutrition of containerized eastern redcedar. I. Growth, mineral nutrient concentrations, and carbohydrate status. Journal of the American Society for Horticultural Science 117(4):563-567.

Ingestad T. 1979. Mineral nutrient requirement of *Pinus silvestris* and *Picea abies* seedlings. Physiologia Plantarum 45:373-380.

Kramer PJ, Kozlowski TT. 1979. Physiology of woody plants. New York (NY): Academic Press. 811 p.

Krueger KW. 1967. Foliar mineral content of forest- and nursery-grown Douglas-fir seedlings. Portland (OR): USDA Forest Service, Pacific Northwest Station. Research Paper PNW-45. 12 p.

Landis TD. 1985. Mineral nutrition as an index of seedling quality. In: Duryea ML, editor. Proceedings: evaluating seedling quality: principles, procedures, and predictive abilities of major tests; 1984 Oct. 16-18; Corvallis, OR. Corvallis (OR): Forest Research Laboratory, Oregon State University. p 29-48

Mills HA, Jones JB Jr. 1996. Plant analysis handbook. II: a practical sample, preparation, analysis and interpretation guide. Athens (GA): Micromacro Publishing. 422 p.

Nursery Technology Cooperative. 2004. Evaluation of seedling foliar nutrients in PNW bareroot forest nurseries. In: Haase D, editor. Nursery Technology Cooperative annual report 2003-04. Corvallis (OR): Department of Forest Science, Oregon State University. p 36-39.

Switzer GL, Nelson LE. 1963. Effects of nursery fertility and density on seedling characteristics, yield, and field performance of loblolly pine (*Pinus taeda* L.). Soil Science Society of America Proceedings 27(4):461-464.

Timmer VR. 1997. Exponential nutrient loading: a new fertilization technique to improved seedling performance on competitive sites. New Forests 13:279-299.

van den Driessche R. 1984a. Soil fertility in forest nurseries. In: Duryea ML, Landis TD, editors. Forest nursery manual: production of bareroot seedlings. Boston (MA): Martinus Nijhoff/Dr W Junk Publishers. p 63-74.

van den Driessche R. 1984b. Relationship between spacing and nitrogen fertilization of seedlings in the nursery, seedling mineral nutrition, and outplanting performance. Canadian Journal of Forest Research 14:431-436.

van den Driessche R. 1990. Mineral nutrition of conifer seedlings. Boston (MA): CRC Press. 274 p.

Wood E. 2004. Personal communication. Beaverlodge (AB): PRT Nursery.

Youngberg CT. 1984. Soil and tissue analysis: tools for maintaining soil fertility. In: Duryea ML, Landis TD, editors. Forest nursery manual: production of bareroot seedlings. Boston (MA): Martinus Nijhoff/Dr W Junk Publishers. p 75-80.