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Soils and Nutrition: A Forest Nursery Perspective

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ABSTRACT

A brief review of the published proceedings from meetings of nursery managers over the past 30 years reveals a high level of consistency with respect to topics of interest from year to year. Seedling quality, defined as seedling capacity to effectively compete after outplanting, has been the unifying theme. Production issues, including collection, storage, and sowing of seeds, planting density, irrigation, nutrition, pest control, and lifting, have been commonly featured. Soil management, with emphasis on organic matter and nutrition, occupies a prominent position among the individual titles. It seems that nursery production knowledge and practice have been maintained at a relatively high level; one would be hard pressed to identify the year of publication simply from a list of titles from any single proceedings. This paper focuses on soil and nutrition in nursery seedling production. One of the most recent additions is the topic of exponential nutrient loading. This practice is used to induce luxury consumption, producing loaded seedlings that are better able to compete in the outplanting environment. Performance of outplanted seedlings, followed for as long as 6 years, suggests that nutrient loading is an effective nursery practice; seedlings effectively compete in their outplanted environments. Nutrient loading papers are appearing with increasing frequency in the literature, reflecting a high degree of interest. Nutrient loading may become a standard practice as outplanted seedling success becomes more widely demonstrated.

KEY WORDS
analyses, fertility, management, organic matter

Introduction

I began preparing for this meeting by reviewing published proceedings of forest tree nursery workshops over the past 3 decades. A remarkable consistency among topics was readily apparent. The underlying theme of each meeting has been focused on production of disease-free, high quality seedlings. Although the specific morphological and physiological variables utilized to express seedling quality seem to be in a perpetual state of flux (Bunting 1980; South and Mexal 1984; Haase 2007), there appears to be general agreement that quality seedlings are those that will effectively compete in the outplanting environment.

Nursery production, at least in the northeast US, has gradually shifted emphasis from a primary focus on production of large numbers of conifer seedlings for planting by large industrial and government landowners to a more diffuse customer base with a wide array of smaller plantings. These plantings require a wide range in species for a variety of purposes, including stream bank stabilization, bioremediation of mildly contaminated sites, bioenergy plantations, wetland restoration, and so on. Many of these seedlings will face competition from existing vegetation and, perhaps, will be planted on sites that are less than ideal. Consequently, the need for high quality seedlings remains strong.

Production of high quality seedlings is a complex process that begins with seed selection and sowing, culminating with lifting and shipping. The diversity of species produced at individual nurseries, each with their individual nuances for successful growth and development, further challenges nursery management. The production process has been described using a chain as an analogy. Each component is required to get to the end point; a break of any single link introduces a discontinuity that reduces quality and quantity of the final product.

This paper focuses on the soil system as an integral component of the production chain, with particular emphasis on nutrition. The underlying theme of this paper is that monitoring soil and plant conditions is an important component of nursery production. Soil testing and plant analysis were common components of nursery management in the northeast US in past decades. This type of activity apparently has recently dropped off as part of an effort to reduce costs. The lack of information reduces the capacity to address occasional problems in seedling quality. As the number and severity of production problems increase, soil and plant analyses will likely become more common in nurseries in the northeast US.

The Soil System

The root system plays a critical role in uptake of water, nutrients, and oxygen (O_2). (Removal of CO_2 is implicit.) Delivery of those components to the roots in hydroponic systems is totally controlled by management of technology. Production of plants in soil (bareroot systems) or containers (media) adds a layer of complexity in delivery of water, nutrients, and O_2; the soil (or media) system plays a critical role. Root growth and development attain their maxima when fluxes of nutrients, water, and gas meet plant demand for growing tissue. When those fluxes are constrained, growth and development are necessarily reduced, having a negative impact on seedling capacity to effectively compete in a new environment. Management of the soil and media in the nursery is critical for maintenance of those fluxes.

The impacts of nutrients and moisture on seedling quality can be graphically illustrated in the conceptualization by Stone (1984), substituting seedling quality for site quality (Figure 1). High quality seedlings require an effective supply of water and nutrients; adequate aeration is implied in an effective water supply. Ultimately, maximization of root growth and development can be thought of as minimization of constraints for nutrients, moisture, and aeration. Unlike hydroponic systems, where delivery of moisture, nutrients, and dissolved O_2 are strictly controlled by management and technology, those fluxes in the soil system are constrained primarily by distribution of pore sizes and, secondarily, by management (that is, irrigation and fertilization). It follows that managing seedling quality requires management of pore size distribution.

Pore space occupies approximately 50% of the volume of the “ideal” soil. The distribution of pore sizes is even more important than the total pore volume (porosity). Pore size regulates movement and storage of water, which directly impacts aeration. Macropores, defined as those pores that do not hold water against the force of gravity, allow for drainage of water and consequent exchange of O_2 and CO_2 between plant roots and the soil atmosphere. Ideally, the pore volume would be evenly split between macro- and micropores, simultaneously providing aeration and moisture retention.

Pore size distribution is a function of soil physical properties. In managing nursery soils, it may be useful to think of these soil properties in the context of time scales.

The Soil Matrix

Texture: Long-term (10^3-year) Management

Soil texture, the relative proportion of sand-, silt-, and clay-sized particles, is the primary control of pore size distribution. Soil texture is stable over thousands of years. Altering soil texture is not feasible on the scale of bareroot production in forest nurseries, but is feasible on the scale of container media where various mixtures of organic substrates and perlite/vermiculite are used.

The macropores between sand particles (2 to 0.05 mm effective diameter) drain freely and promote aeration. In contrast, the very small pores between clay particles (< 0.002 mm), termed micropores, hold water against the force of gravity and aeration tends to be poor. This effect is strongly modified by soil organic matter (SOM), which has high pore space, low density, and contributes to formation of water stable aggregates.

One of the major decision criteria utilized for siting forest nurseries is soil texture (Wilde 1958; Armson and Sadreika 1979). Sandy loam and loamy sand textures with minimal coarse fragments (rocks) are considered most desirable because they provide rapid drainage, leading to good aeration and early warming in the spring. These textures, although not immune, are less prone to frost heaving.

Soil Organic Matter (SOM): Mid-term (10^0- to 10^1-year) Management

A sandy loam texture, recommended for nursery sites, provides excellent physical conditions for plant roots, minimizing the constraints of poor drainage and aeration. Lack of clay, however, limits soil capacity to retain water and nutrients. Addition of organic matter, which plays a crucial role in retention of water and nutrients in coarse textured soils, compensates for this deficiency. Coarse textured soils are well aerated, promoting rapid oxidation and decomposition of soil organic matter (SOM). In addition, periodic lifting of seedlings removes a significant quantity of SOM from nursery beds on a regular basis. Davey (1980) referred to this removal as "mining." It is easy to understand why maintenance of SOM is a key concern for tree seedling nurseries.

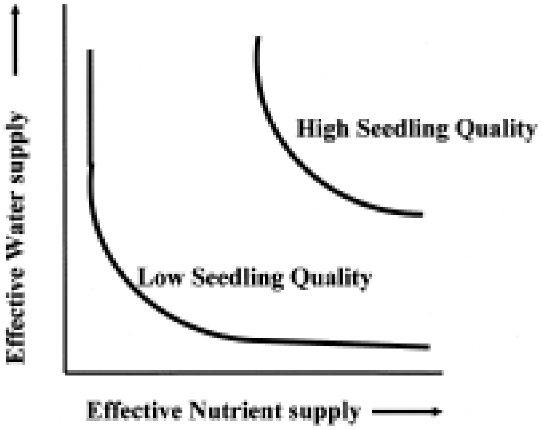

Figure 1. Seedling quality as a function of effective moisture and effective nutrient supply (after Stone 1984).

The topic of SOM in the context of forest nursery soil management has been treated extensively in the past decades. Papers dealing with SOM have been a prominent feature of nursery proceedings from 1980 (Abrahamson and Bickelhaupt 1980) to the present (Riley and others 2006). The topic's persistence over the past decades reflects the degree of attention and concern of nursery managers. The nature of that concern was articulately described by Davey (1984) in reviewing results from a nursery manager survey conducted by Oregon State University in the northwestern US. Eighty-six percent of 21 respondents intended to increase SOM levels; 62% listed SOM maintenance among their top 5 issues. A wide variety of amendments were applied to maintain or increase SOM, including cover crops or green manure (for example, peas, oats, lupines), peat, sawdust, bark, and sludge. The choice of amendment depends on a variety of local factors (not the least of which is availability). Davis and others (2007), summarizing a number of studies, pointed out that long-term application and continual monitoring are

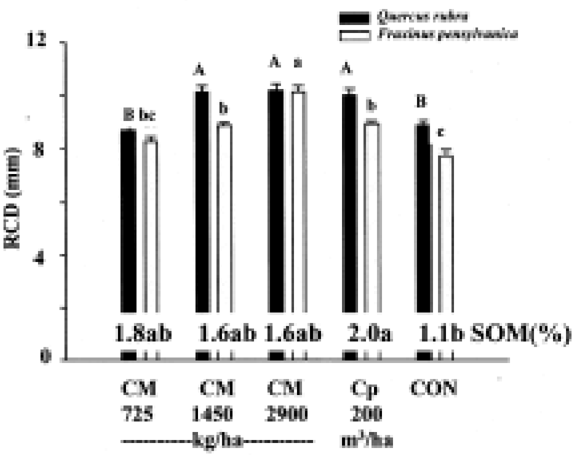

Figure 2. Influence of soil amendments (chicken manure [CM], compost [Cp]) relative to no amendments (CON), on soil organic matter (SOM) and root collar diameter for red oak and green ash seedlings prior to lifting. Different letters indicate significant differences at $P < 0.10$ (Davis and others 2006).

required in order to sustain SOM in forest nurseries.

Organic matter management practices continue to evolve, and research is ongoing. I selected 3 recently published papers to illustrate the nature of current scientific inquiry.

Davis and others (2006) incorporated the following organic amendments approximately 7.5 cm (3 in) deep in nursery beds at the Vallonia State Nursery, Indiana: chicken manure (following thermophilic decomposition) at 725, 1450, and 2900 kg/ha (650, 1300, 2590 lb/ac), and 2-year composted trimmings (leaf, tree, lawn) at 200 m^3/ha (106 yd^3/ac). Soil samples were collected for analysis immediately following amendment incorporation. Green ash (*Fraxinus pennsylvanica*) and red oak (*Quercus rubra*) seeds were sown in the beds. Seedlings were lifted and measured (root collar diameter [RCD], height, root volume) the following spring. All organic amendments increased SOM (Figure 2), as well as cation exchange capacity. All amendments increased seedling RCD above that of the control (no amendment) (Figure 2), with differences between the 2 species. Green ash seedling RCD attained the highest values on the highest level of chicken manure, while red oak seedlings attained equally high levels on all amendments except for chicken manure at 725 kg/ha (650 lb/ac), which did not differ from the control. Patterns of seedling root volume and height response were similar to those of RCD. Davis and others (2006) pointed out the need to continue this work to improve the integration of organic amendments with traditional inorganic fertilization practices.

Davis and others (2007) added an interesting twist by comparing the impacts of an array of organic amendments (incorporated as described in previous paragraph) on soil properties and sorghum (*Sorghum* spp.) cover crop production. Treatments evaluated were: a) 1450 kg/ha (1300 lb/ac) chicken manure (CM) alone; b) combination of 1200 kg/ha (1070 lb/ac) hardwood sawdust with 4350 kg/ha (3880 lb/ac) CM; c) combination of 1200 kg/ha (1070 lb/ac) hardwood sawdust with 8700 kg/ha (7770 lb/ac) CM; d) 2-year composted trimmings (leaf, tree, lawn) at 200 m^3/ha (2860 ft^3/ac); and e) 200m^3/ha (2860 ft^3/ac) uncomposted leaves. Sorghum was sown uniformly at 1.12 kg/ha (1 lb/ac), and soil samples were taken immediately after amendment incorporation. SOM and pH increased significantly above control levels (1.2% and 4.8%, respectively) for all treatments, with the exception of CM alone. All amendments had a positive effect on sorghum biomass production (Figure 3). The authors anticipate a long-term benefit from promotion of higher SOM from sorghum.

Riley and others (2006b) is an excellent illustration of the evolution of soil management practices, as well as many other aspects, for the J Herbert Stone Nursery in Central Point, Oregon. Their primary focus was on soil tilth and porosity rather than SOM *per se.* Addition of organic matter is one of several management practices used to maintain favorable soil tilth. In response to increasing costs of sawdust and N fertilizers, an alternative to sawdust was sought. Continuous monitoring and use of a variety of treatments (deep subsoiling, wrenching, organic amendments, and pumice) ultimately resulted in favorable soil tilth, although their goal of 50% soil porosity has not yet been attained.

Fertilization

Fertigation: Short-term (10^{-1} to 10^{-3} year) Management

Given a configuration of pores resulting from the combined effects of soil texture and organic matter, the delivery of water and nutrients to root systems is managed on a daily/weekly basis through irrigation and fertilization. The presence of soil in bareroot systems, or medium in the case of container stock, adds a degree of complexity in supplying water and nutrients to the roots.

This complexity is managed by monitoring soil moisture, armed with knowledge of the soil moisture characteristic (relationship between soil water concentration and soil water potential). A system of tensiometers is often utilized for irrigation management. When soil moisture tension falls somewhat below field capacity, irrigation is applied and moisture stress is avoided.

The situation for nutrients is a bit more daunting and somewhat indirect. Soil testing provides a snapshot in time of nutrient solubility. Soil nutrients are conceptually identified in a system consisting of 4 components: 1) very slowly available (structural framework of primary minerals and organic matter); 2) slowly available colloidal fraction (structural framework of clay and humus); 3) adsorbed fraction (ions attracted to colloidal surfaces); and 4) readily available (soil solution fraction) (Brady and Weil 2002). Soil testing involves leaching soil samples with one of many extracting solutions varying in composition and ionic strength, extracting soluble nutrients (pool 4 described above) and a small portion of those in pool (3) and perhaps (2). The actual results are strongly dependent on the extractant and procedure used. In the past, these were often referred to as "available" nutrients, but there is no clear indication that those extracted fractions are equivalent to what plant roots absorb. Consequently, they are more appropriately referred to as extractable nutrients.

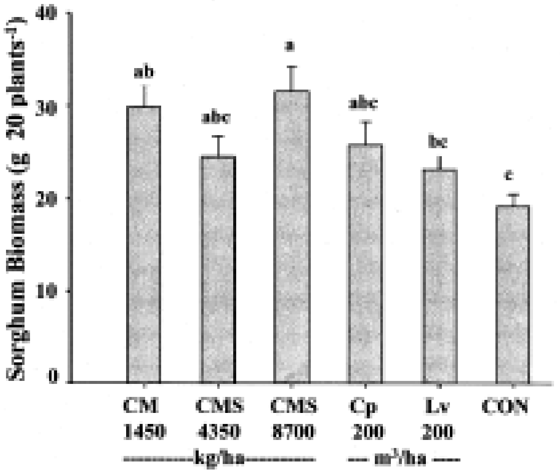

Figure 3. Influence of soil amendments (chicken manure alone at 1450 kg/ha [1300 lb/ac] [CM], chicken manure at 4350 and 8700 kg/ha [3880 and 7770 lb/ac] in combination with 1200 kg/ha [1070 lb/ac] sawdust [CMS], compost [Cp], and leaves [Lv]) relative to no amendments (CON) on sorghum cover crop biomass. Different letters indicate significant differences at $P < 0.05$ (Davis and others 2007).

Soil tests, in and of themselves, are only of use when a relationship has been established between some measure of seedling quality (that is, height, biomass, root volume, and so on) and soil test values. During the late 1970s and early 1980s, a considerable effort to develop such as relationship was expended by the Forest Soils Analytical Lab at the State University of New York College of Environmental Science and Forestry (SUNY ESF) in cooperation with 18 nurseries (Table 1) distributed across the US. Soil test recommendations developed on the basis of that work are summarized in Table 2. It is important to keep in mind that those recommendations are method specific. Armson and Sadreika (1979), for example, recommend minimum extractable P as 300 mg/kg, using the Bray-Kurtz (another common method) extraction.

The accuracy, hence utility, of soil test results depends on quality control in the laboratory.

Table 1. List of 18 nurseries (identified by location) involved with soil testing program at SUNY ESF (identified from MEMO to participating nurseries).

Carbondale, Colorado
Magalia, California
Coeur d'Alene, Idano
Topeka, Illinois
Fryeburg, Maine
Passadumkeag, Maine
Harmans, Maryland
Freesoil, Michigan
Manistique, Michigan
Licking, Missouri
Bismark, North Dakota
Boscawen, New Hampshire
Concord, New Hampshire
Saratoga Springs, New York
Bonanza, Oregon
Swansea, South Carolina
Draper, Utah
Lakin, West Virginia

Table 2. Recommended levels for chemical values for nursery soils based on research at SUNY ESF Forest Soils Analytical Lab.

Variable	**Conifer**	**Hardwood**
Organic matter^z	2.5%	2.5%
pH^y	5 to 6	6 to 7
P (mg/kg)^x	100	150
K (mg/kg)^w	100	150
Ca (mg/kg)^w	500	1000
Mg (mg/kg)^w	150	250
CEC (cmol$_c$/kg)^w	8	11
EC (dS/m)^v	< 2	< 2

[z] Organic matter determined by loss-on-ignition or Walkley-Black wet oxidation.

[y] Measured in1:2 soil:water slurry.

[x] P extracted with 0.002 *N* sulfuric acid (Truog procedure).

[w] Cations and CEC determined from extracts using neutral 1 *N* ammonium acetate.

[v] Electrical conductivity determined from saturated soil paste vacuum filtered 2 hours after mixing.

Credible labs have systems in place to insure accuracy and repeatability of their results. For example, our quality control program consists of several components:

1) Periodic analysis of "standard" soil and plant tissue samples (obtained from commercial sources or collected by us from a single location, homogenized, and stored);

2) Participation with US Geological Survey (USGS) round-robin analysis of water samples from a group of laboratories;

3) Inclusion of blank (distilled deionized water) and spiked (known concentrations) samples in every sample run.

Finally, dedication to a single laboratory is implicit. An excellent working example is provided by the Auburn Nursery Cooperative, which utilizes a single commercial lab for all of their analyses (Davey 1995). This allows comparison of results across nurseries, immensely increasing the value of the program for all of the nurseries involved.

As government support for state and USDA Forest Service nurseries has diminished, so has routine soil testing. It has been almost a decade since the SUNY ESF Forest Soils Analytical Lab received a soil sample from a nursery. I suspect that this trend will be reversed. Monitoring soil conditions is an important component of nursery management and becomes more critical as problems with seedling quality develop. One of the most memorable examples of the utility of soil monitoring in identifying seedling quality problems is drawn from our cooperative work with the state nursery at Saratoga, New York. During the late 1970s, several conifer beds exhibited unusually high chlorosis and mortality. Laboratory analysis revealed soil pH well in excess of 7.0, which was traced to overzealous application of an organic amendment. The ample supply of horse manure (routinely treated with lime to control odor) from the adjacent harness track invited excessive application. The high buffering capacity of the added organic matter prevented rapid recovery; pH remained elevated for at least 4 years following application. Negative impacts on seedlings were documented by Bickelhaupt and others (1987). Amelioration required substantial applications of acid coupled with deep plowing over a lengthy time period.

In addition to its obvious utility as a tool for ensuring seedling quality, soil monitoring is becoming more important from an environmental perspective. Application of nutrients in excess of seedling uptake capacity is costly, both financially and environmentally. Excess nutrients dissolved in water move below the root zone and are delivered to surface water, degrading water quality. State and federal agencies are focusing more attention on water quality in efforts to control eutrophication. Eutrophication, a result of increased delivery of nitrogen (N) and phosphorus (P) to surface water systems, is a serious problem that has directly contributed to hypoxia and anoxia across the globe (Diaz 2001). Soil monitoring can be a useful tool in minimizing unnecessary or excessive nutrient amendments.

Nutrient Loading

One of the most exciting new areas of research and practice in seedling nursery management is nutrient loading, or the application of relative addition rate concept in nursery seedling production (Ingstead and Lund 1986). The efforts have been documented in a series of papers over the past 15 years.

Timmer (1996) provides a concise history of the development and application of exponential nutrient loading in greenhouse production. Seedlings are produced with nutrient reserves that promote maximum growth upon outplanting. Nutrients are concentrated (stored) in seedlings by inducing luxury consumption, matching nutrient supply with plant growth (biomass). Exponential loading is illustrated relative to conventional single dose and periodic application of a single rate in Figure 4, which also depicts an adjustment for incomplete root exploitation of the medium early in the seedling growth period.

Field performance of nutrient-loaded seedlings has been documented for a variety of species. Timmer (1999) found that 6-year biomass and height of nutrient-loaded black spruce (*Picea mariana*) seedlings outplanted on sites where competition had not been controlled were equivalent to conventionally fertilized seedlings planted on herbicide treated sites; nutrient loading compensated for lack of competition control (Figure 5). These results, which are based on the longest term data currently available, demonstrate the capacity of nutrient-loaded seedlings to overcome the negative effects of competition, a tremendous advantage as herbicide costs increase and application becomes more restricted.

Interest in exponential fertilization is increasing, and the technique is being expanded for application to hardwood species. Birge and others (2006) reported positive results of nutrient loading to induce luxury consumption of N for red

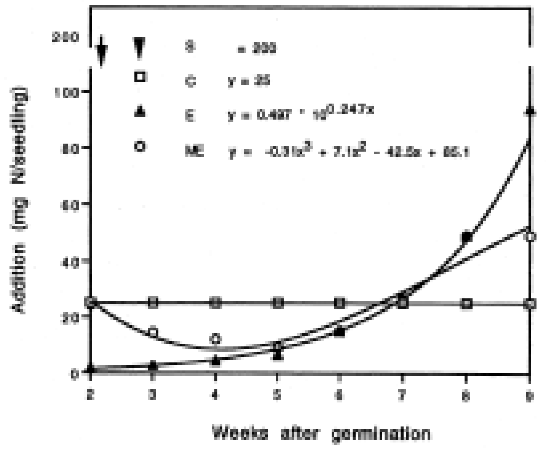

Figure 4. Scheduling of fertilizer additions by seedling age applied as single dose (S), constant top dressing (C), exponential (E), and modified exponential (ME) during greenhouse culture. (Initial exponential rate was reduced to account for incomplete root exploitation, but later balanced by increased exponential rate following complete root exploitation.) Note scale break in y-axis (from Timmer 1996).

(*Quercus rubra*) and white oak (*Q. alba*) at the Vallonia State Nursery, Indiana. Seedling biomass and tissue N concentrations of nutrient-loaded seedlings exceeded those of conventionally fertilized seedlings. As the exponential nutrient loading technique comes into greater use, additional long term data tracking outplanting performance will likely become more widely dissipated.

Slow-Release Fertilizer

Use of slow-release fertilizer (SRF) in nursery seedling production represents somewhat of a middle ground between exponential loading and conventional fertilization. Dissolution of polymer coatings over time allows nutrients to move outward over a period of months. Unlike exponential loading, where plant nutrient additions are estimated on a weekly or shorter term basis, nutrient release from SRF is not precisely quantified on such a fine time scale. Huett and Gogel (2000) showed that SRF nutrient release is uneven. Highest rates occur early in the release period, which is not well timed with steadily increasing seedling nutrient demand. Actual SRF nutrient-release periods were considerably shorter than nominal rates. In spite of these shortcomings, slow-release fertilizers have been used successfully in nursery production.

Haase and others (2006) supplemented conventional fertilization of container Douglas-fir (*Pseudotsuga menziesii*) seedlings with 4 SRF treatments: Apex 1®, Apex 2®, Forestcote®, and Osmocote®. Seedling growth and nutrient concentrations were monitored immediately after outplanting and over 4 growing seasons at 2 sites in Oregon. Only results from the Powers site in western Oregon are presented below. Luxury consumption was successfully induced by SRF. At the time of planting, seedlings grown with SRF in the medium treatment had higher concentrations of N and P relative to conventional fertilization; seedlings grown with Forestcote® were larger than those grown with Apex 1®, Apex 2®, or conventional fertilization (Table 3).

Height growth of all SRF-treated seedlings exceeded that of conventionally fertilized seedlings at the end of the first and second field seasons after planting (Table 3). Although no differences were observed in height growth among the 5 treatments following the third and fourth seasons after planting (data not shown), the initial SRF effect persisted, carrying through 4 years after planting. Height in 2001 (4 growing seasons after planting) of SRF-treated seedlings was significantly greater than conventionally fertilized seedlings.

Closing Comments

Seedling quality continues to be a unifying theme among nursery managers, as indicated in the papers that have appeared in proceedings published over the past 30 years. Soil management is critical to maintain production of high quality seedlings. Nursery soil management practices appear to be keeping pace with scientific knowledge through effective technology transfer; the contents of published proceedings provide ample evidence that this is the case. Soil and plant tissue analysis is an important tool that can be effectively used in producing quality seedlings. Increasing pressure to reduce costs, while improving efficiency at many nurseries, seems to have reduced routine use of soil and plant analyses as a management tool for many nurseries in the northeast US. As seedling quality issues and environmental concerns increase, greater use of soil and plant tissue nutrient monitoring is likely.

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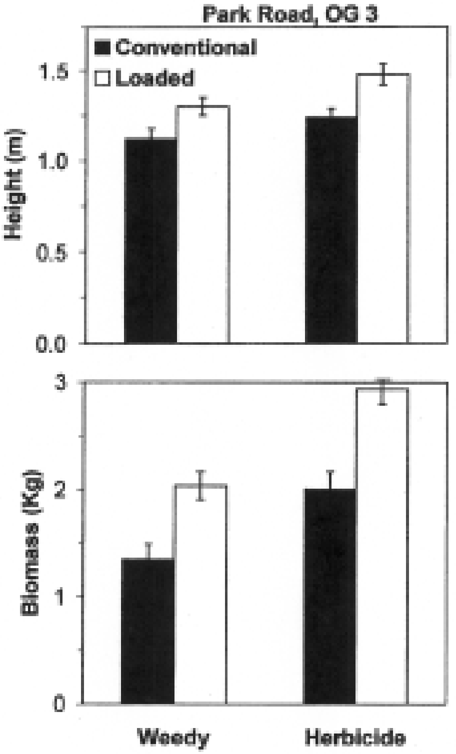

Figure 5. Comparison of 6-year height and biomass response of conventional and nutrient-loaded black spruce seedlings growing in untreated (Weedy) versus herbicide-treated (Herbicide) plots at time of planting (Timmer 1999).

Table 3. Initial height and annual growth (cm) for Douglas-fir seedlings produced in the nursery with conventional fertilization alone and supplemented with slow-release fertilizers prior to outplanting at the Powers site (after Haase and others 2006).

Treatment	Initial Height [x]	1998 Height Growth [x]	1999 Height Growth [x]	Σ4-year Growth [x]	2001 Height [x]
Conventional [z]	33.5 bc	9.3 b	18.1 b	128	162 b
Apex 1® [y]	33.5 bc	13.5 a	20.6 ab	144	177 a
Apex 2® [y]	32.1 c	14.1 a	21.8 a	136	168 ab
Forestcote® [y]	36.9 a	13.4 a	22.2 a	136	174 a
Osmocote® [y]	34.3 b	14.2 a	22.3 a	141	176 a

[Z] Conventional fertilization consisted of regular application of soluble nutrients via overhead irrigation system.

[Y] SRF treatments applied at 30 kg/m^3 (1.9 lb/ft^3) in addition to conventional fertilization.

[X] Different letters associated with means within a column denote statistically significant differences at $P < 0.05$.

(1 cm = 0.39 in)

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