The Management of Seedling Nutrition

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Outline

Facing Page: *Field of pecan seedlings. (Photo by Greg Hoss.)*

General Considerations

Fertility management for the large-scale production of hardwood seedlings is a difficult and complex challenge. Research-based recommendations specific to the fertility management of individual species or even genera are lacking or very limited. As a result, hardwood fertility management tends to take a generalized approach, where many species are lumped together and managed in similar fashion (Stone 1980, Davey 1994, 2005), and a few general principles applicable to hardwood fertility management have developed.

First, it is generally accepted that hardwood crops require substantially more nutrients than do pine crops. Most eastern hardwood species are native to temperate deciduous forests. Natural temperate hardwood forests require substantially more nitrogen, phosphorus, potassium, calcium, and magnesium than do temperate conifer forests for tree growth (Cole and Rapp 1981). These higher nutritional requirements have implications for the amount and nature of fertilizer applications in nurseries. In addition, many hardwoods are deciduous and have evolved to efficiently recycle essential nutrients. A study conducted in a Tennessee hardwood nursery (dos Santos 2006) found that 19.5, 65.0, and 26.5 pounds per acre (lb/ac) (21.9, 73.2, and 29.8 kilograms per hectare [kg/ha]) of nitrogen was deposited through leaf litter in nursery beds during the growing season by Nuttall oak, yellow poplar, and green ash, respectively. This has implications for nutrient availability, the balance between nutrient removal and addition, and soil organic matter maintenance.

When compared to conifer forests, hardwood forests typically occur on soils with a higher pH. Hardwood physiological demand for base cations such as calcium and magnesium and subsequent nutrient recycling results in soils less acidic than conifer forests (Reich et al. 2005, Brady and Weil 2000). There is probably not an "ideal" soil pH for hardwood nurseries and there is still much research needed in this area, however, it seems likely that temperate hardwoods evolved within and contributed to ecosystems where soil pH was less acidic than temperate pine forests. Current nursery practice suggests nursery managers should maintain a soil pH between 5.0 and 6.0 when growing eastern hardwoods. This may or may not be the "ideal" pH for each of the many species grown across the Eastern United States, but this pH range both matches the general pH characteristics of soils in the eastern hardwood forest and provides a soil pH range where all soil nutrients are relatively available.

Finally, hardwood nursery crops require nearly twice as much water (rainfall plus irrigation) compared to pine crops. Faster growth, larger seedlings, increased transpiration potential as a result of different leaf structures, and more efficient water transpiration structures in stem xylem result in a higher water demand for hardwood crops than for pine. The difference is sufficient that nursery managers should physically separate hardwood crops from pine crops so the manager can water each crop differently.

While providing a helpful starting point, such generalized principles are limited in their applicability across the many hardwood species cultivated by nursery managers and the specific edaphic and climatic conditions encountered in individual nurseries. Appropriate fertility management should be based on the particular conditions of the nursery and the application of fertility recommendations as specific to the crop as information and experience allow. The following discussion is meant to assists managers to develop such an approach.

Macronutrients

Nitrogen

Hardwood seedling culture requires nitrogen fertilization. Not only do the seedlings require nitrogen for proper growth and development (table 6.1), nitrogen compounds tend to be easily lost through leaching and volatilization so that soil reserves must be replenished each growing season. Leaching losses (table 6.1) are increased by coarse-textured soils, low organic matter content, low cation exchange capacity, and heavy rainfall. As a general rule of thumb, a total of 225 lb/ac (252 kg/ha) of elemental nitrogen is needed each year to grow a crop of "1-0" hardwood seedlings. This is around 50 percent more nitrogen than required for pine crops.

Nitrogen fertilizers should be applied to hardwoods over the growing season to ensure a steady supply of elemental nitrogen, due to both the increased demand for nitrogen during the growing season and the loss of plant-available nitrogen compounds through leaching. For spring-sown species, application typically begins at 6 weeks after sowing. In the case of fall-sown species, application begins at the same time as seedling development, but depends on time of emergence and seasonal weather. Some fall-sown seed have nitrogen supplies that will support seedling development during the first few weeks after germination.

The total amount of recommended fertilizer nitrogen should be divided among several growing season applications until late August. To match seedling development, application equipment can be set to put out smaller amounts in greater frequency or larger amounts in less frequency. Soil texture also affects the frequency of application, with coarse-textured soils requiring more frequent applications. Nursery managers must learn to observe their trees for any change in color or development that might indicate a nitrogen deficiency, with the frequency and intensity of rainfall strongly

Table 6.1—*Characteristics of the nutrients essential for plant growth. (Sources: Tisdale et al. 1993, Brady and Weil 2000, Goldy 2013.)*

Element	Symbol	Uptake form	Use by plant	Plant mobility	Potential soil mobility
Nitrogen	N	NO_3^- NH_4^+	Formation of amino acids, proteins, chlorophyll, and multiple other plant components and processes	Yes Yes	High Low*
Phosphorus	P	$H_2PO_4^-$ HPO_4^{2-}	Energy storage and transfer for virtually all plant metabolic pathways	Yes Yes	Low Low
Potassium	K	K^+	Enzyme activation, water relations, transpiration, and multiple other plant activities	Yes	High in sandy soils with low CEC
Calcium	Ca	Ca^{2+}	Structure and permeability of cell membranes, plant growth	No	Medium
Magnesium	Mg	Mg^{2-}	Chlorophyll, several plant metabolic functions	Yes	Medium
Sulfur	S	SO_4^{2-}	Amino acid and protein syntheses and functionality	No	High
Iron	Fe	Fe^{2+} Fe^{3+}	Enzymatic activity and structure	No	Low
Manganese	Mn	Mn^{2+}	Reagent in various plant metabolic pathways	No	High in acidic soils
Zinc	Zn	Zn^{2+}	Enzymatic activity	No	Low
Boron	B	H_3BO_3	Meristematic cell development, other multiple metabolic functions	No	High in sandy soils
Copper	Cu	Cu^{2+}	Enzyme structure and functionality	No	Low
Chlorine	Cl	Cl-	Not clear, may be involved in water retention and movement	Yes	High
Molybdenum	Mo	MoO_4^{2-}	Essential component of the nitrate reductase enzyme, a component of the N fixing process in legume nodules	Yes	High in alkaline soils

CEC = cation exchange capacity.
* Compounds and elements may leach from very sandy soils regardless of their affinity for soil particles and low mobility.

influencing the movement of nitrogen down the soil profile. In the case of liquid fertilizers, the frequency of application may be as high as weekly. This provides an effective way of maintaining a stable nitrogen supply, which is important over the growing season.

Plants take up nitrogen primarily as the positively charged ammonium ion (NH_4^+) and the negatively charged nitrate ion (NO_3^-). The ammonium ion is often referred to as the "reduced" form of nitrogen, while the nitrate ion is an "oxidized" form. Studies have well established that pines thrive best on fertilizers that supply the reduced form of nitrogen, such as urea, diammonium phosphate, and ammonium sulfate. And, some studies have so far indicated that hardwoods also thrive best on fertilizers that provide a reduced form of nitrogen (Deines 1973, Villarrubia 1980). The research support is far from definitive, however, and it cannot be assumed that hardwoods will not do just as well with the oxidized forms of nitrogen. South (1975), for example, observed taller sweetgum seedlings when seedlings were fertilized with ammonium nitrate (vs. urea).

Other formulations of nitrogen fertilizer include ammonium thiosulfate (table 6.2) which is entirely a "reduced" form of nitrogen, and although containing sulfur, has limited, if any, effect on soil pH. Slow-release fertilizers are also available but are expensive and cost more than liquid forms of N. Furthermore, each has distinctive characteristics and fertilizer release curves. Unfortunately, the release curves for slow-release fertilizers have proven very difficult to match to the needs of hardwood seedlings over the typical seedling growing season.

Liquid nitrogen formulations are becoming a more popular source of fertilizer nitrogen in hardwood nurseries. Urea-ammonium nitrate (UAN) is one such fertilizer material that

The Mineralization of Organic Compounds

The soil is a dynamic matrix where chemical transformations constantly occur in both the organic and inorganic components. These transformations can have profound effects on the amount, nature, and availability of nutrients. The chemical transformations affecting soil nitrogen availability are especially important. In natural systems, organic matter is decomposed and nitrogen released through the process known as "mineralization" which transforms the nitrogen in organic compounds to the ammonium ion NH_4^+ then oxidizes it to NO_3^-. This process is mediated by soil microorganisms and as such the process is greatly affected by soil temperature and moisture conditions. The soil microbes associated with mineralization prefer warm temperatures, moist soil conditions, and abundant oxygen. These conditions are typically present in nursery soils during the growing season.

The mineralization process may be further stimulated when nitrogen fertilizer materials are added, resulting in important effects on soil properties. Because hydrogen ions are released during the chemical reactions associated with mineralization, the repetitive application of nitrogen fertilizers, particularly those containing ammonium sources, will lower soil pH over time (Tisdale et al. 1993, Darusman et al. 1991). Also, because NO_3^- is highly soluble and mobile in the soil, the loss of nitrogen through leaching will likely increase when conditions are optimal for microbial mediated mineralization. The potential for nitrogen loss through mineralization simultaneous to increased demand during the growing season requires that nursery managers remain especially vigilant to ensure plant requirements are being met.

Sulfur has a similar mineralization process where soil microbes transform organic sulfur-containing compounds to the plant available and highly leachable form SO_4^{2-}. These microbes thrive best in the same environmental conditions favored by nitrogen mineralization. Other essential plant nutrients such as phosphorus, potassium, and the micronutrients are also incorporated into the process of organic matter decomposition and released back into the soil environment. However, their chemical nature, movement, and plant availability are mostly affected by their complex interaction with the surfaces of soil colloids.

can be applied as a liquid. Ranging from 28- to 32-percent nitrogen content and applied over the top of seedlings during the growing season, UAN can quickly provide needed seedling fertilizer nitrogen requirements. UAN offers certain advantages, such as application uniformity, compatibility with many pesticides, and relative ease of handling and storage (Tisdale et al. 1993), but managers need to be aware of certain possible disadvantages, as well. Both the ammonium and urea components of UAN may volatilize, and the nitrate component is susceptible to leaching and denitrification (when microbes change the nitrate to nitrogen gas). Primarily because of the volatility issue, UAN should not be applied on hot, dry, and windy days. Leaf scorch can also be a problem, because high concentrations of ammonium may be toxic to seedlings. Younger seedlings will be most sensitive, but resistance should improve over the growing season as seedlings produce more mature leaves. The use of at least 1/2 inch (in) (12 millimeters [mm]) of irrigation, either during or immediately after application, can be particularly important for the effective use of UAN fertilizers. Not only can irrigation reduce the risk of leaf scorch, it can also help incorporate the fertilizer into the soil and reduce ammonium volatility. Finally, managers need to be aware that UAN fertilizers can "salt out" at low temperatures. The 32-percent formulation, for example, will begin to form fertilizer salt crystals at temperatures of 32 °F (0 °C). The 28-percent formulation begins to salt out at 1 °F (-18 °C).

Nitrogen-fixing trees, such as black locust, are the exception to the preceding general recommendations. Nursery managers should check seedling roots in early summer (June) to verify that nodulation is occurring. If so, and growth seems to appear on schedule, then further nitrogen fertilization is not usually required. On the other hand, if nodulation is not present or is weak, and the seedlings appear to lag behind the desired growth curve, then the seedlings should be put into the normal nitrogen fertilization regime with the other hardwoods. Some nitrogen-fixers can be sensitive to the presence of nitrogen in the soil, slowing nodulation, even when the nitrogen availability is not enough to maintain the desired growth curve.

Phosphorus

Unlike nitrogen, phosphorus tends to stay where it is placed. As an anion (negatively charged) it readily combines with many soil components such as organic matter, iron, and aluminum, to form stable compounds that resist leaching. Phosphorus compounds generally move only with the physical displacement of soil. Historically, in fact, solubility and plant availability presented a challenge for development of suitable phosphorus fertilizers. Unlike nitrogen, however, and similar to all other fertilizer elements, a soil test is useful for developing a phosphorus fertilizer recommendation.

Soil test results provide an estimate of "available" fertilizer nutrients in the soil. Unlike tissue samples, which are

Table 6.2—Nutrient content of various commercially available fertilizers (shown as percentage). (Source: Magdoff and Van Es 2009, Tisdale et al. 1993.)

Chemical	N	P_2O_5	K_2O	Ca	Mg	S	Cl
Nitrogen Materials							
Ammonium nitrate	34						
Ammonium sulfate	21					24	
Ammonium thiosulfate	12					26	
Calcium ammonium nitrate	27			4-8	4		
Urea	46						
Urea-Ammonium nitrate (UAN)	28-32						
Phosphorous and N+P Materials							
Superphosphate		20		20		12	
Triple superphosphate		46		14		1	
Diammonium phosphate (DAP)	18	46					
Monoammonium phosphate (MAP)	11-13	48-52					
Potassium Materials							
Potassium chloride (muriate of potash			60				47
Potassium-magnesium sulfate ("sul-po-mag")			22		11	23	2
Potassium sulfate			50		1	18	2
Other Materials							
Gypsum				23		18	
Limestone, calcitic				25-40	0.5-3		
Limestone, dolomitic				19-22	6-13		1
Magnesium sulfate				2	11	14	
Potassium nitrate							
Elemental sulfur						30-99	

chemically analyzed for total elemental content, soil test results provide an estimate of the amount of fertilizer element available for plant uptake, and not the total amount in the soil. This measure of availability greatly depends upon the chemical methodology employed to extract the element from the soil matrix. The Mehlich 3 extraction gives a reliable phosphorus and minor-element extraction for sandy acidic soil conditions—typical of most forest tree nurseries. Hardwood nursery crops need a little more phosphorus that do pine crops. Using a Mehlich 3 extraction, phosphorus fertilization is recommended when the level is less than 45 parts per million (ppm).

Phosphorus fertilizer compounds are often applied during the soil tillage phase and before bed shaping. In fact, once phosphorus soil levels are corrected, fertilizer phosphorus may not need to be further applied for 3 years or more. If a growing season addition of phosphorus fertilizer is needed, the most commonly used soluble formulation is diammonium phosphate ($(NH_4)_2HPO_4$), which may be used as a top dressing. Hardwood seedlings have been reported to respond faster to the application of liquid forms of phosphorus than granular DAP (Weatherly 2018). A growing season application of phosphorus might be needed when fumigation has decreased endomycorrhizae levels or, in the case of "new ground syndrome," where ectomycorrhizae have not had a chance to establish on species like oaks. Both endomycorrhizae and ectomycorrhizae may be found on hardwoods, depending upon species, and either may be affected by fumigation. (See accompanying discussion of Soil Fumigation and Hardwood Seedling Production.)

Potassium

Common fertilizer forms of potassium are potassium chloride (KCl) and potassium sulfate (K_2SO_4). Both are

Soil Fumigation and Hardwood Seedling Production

Scott Enebak

Mycorrhizae are beneficial soil-borne fungi associated with the roots of most forest nursery seedlings. These fungi have been shown to increase absorption of numerous macro- and micro-nutrients necessary for plant growth, particularly phosphorus. In fact, seedlings lacking in mycorrhizal fungi become purple due to the lack of available phosphorus. Because of the enhanced plant nutrition, seedlings with mycorrhizal fungi will grow more rapidly and appear healthier than non-mycorrhizal seedlings which often are stunted, with chlorotic foliage that becomes necrotic along the margins with corresponding sparse, limited and minimal root growth.

There are two types of soil mycorrhizae, ectomycorrhizae and endomycorrhizae, with the latter also known as Vesicular-Arbuscular (VAM). Ectomycorrhizae form and are found, on the outside of seedling roots and are commonly associated with conifer seedlings. These fungi produce spores on fruiting bodies that are easily dispersed in the wind and can quickly colonize and infest nursery soils. Two common nursery ectomycorrhizae are Telephora terrestris and Pisolithus tinctorius. These mycorrhizal fungi typically result in the formation of a mycelia around the seedling roots called a Hartig net that often results in root forks or bifurcations of the seedling roots. It is this Hartig net and multiple root forks that assist the tree in nutrient and water absorption, thereby increasing seedling growth. In contrast, endomycorrhizae (VAMs) form inside the root tissue cells, forming vesicles, thus the VAM designation. Endomycorrhizae are commonly associated with hardwood seedling root systems. These mycorrhizae do not produce fruiting bodies like the ectomycorrhizae and therefore do not spread by wind-blown spores, but rather by infected seedling root pieces. Therefore, endomycorrhizae do not spread and colonize nursery soils as effectively as ectomycorrhizae, and endomycorrhizal deficiencies in nursery soils are more pronounced and take longer to build up soil populations.

The production of conifer and hardwood seedlings without the use of soil fumigants is simply not possible in many bareroot nurseries. Weeds, nematodes, and damping-off fungi all take their toll on seed efficiency and seedling quality. The use of soil fumigants has long-been known to significantly reduce the levels and type of mycorrhizae in nursery soils resulting in the stunting and discoloration of both hardwood and conifer seedlings. Seedlings rarely die, but remain alive in a stunted condition, generally becoming culled in the lifting process and negatively affecting seedling densities and thereby seedling uniformity. Fortunately, conifer seedlings tend to be quickly colonized by ectomycorrhizae spores from surrounding, non-fumigated soils. However, the lack of spore production by endomycorrhizal fungi tends to result in hardwood seedlings being more susceptible to stunting due to soil fumigation.

Fortunately, most nursery soils that are fumigated do not result in the elimination of 100% of the soil-borne fungi, and if stunting does occur, it does not appear on the entire field site. This is demonstrated by the patches of healthy seedlings scattered among the stunted seedlings which will serve as an inoculum source. VAM mycorrhizae will be embedded in the root materials that remain in the soil after lifting. In addition, studies have shown mycorrhizae surviving days of methyl bromide exposure at rates commonly used in soil fumigation. There is also some evidence that ectomycorrhizal fungi recolonization speed increases after the second and third soil fumigation, indicating that some populations resistant to fumigation were being selected. Numerous studies monitoring VAM recolonization after soil fumigation have shown that it takes at least 2 months for mycorrhizae to reappear in soil samples after fumigation and up to 13 months in some soils for populations to return to prefumigation levels. Endomycorrhizae are also spread and moved around by earthworms, small mammals, and insects. The roots of weeds also help recolonize the field prior to sowing the hardwood seedling crop. Therefore, cover crops that favor endomycorrhizae (winter wheat, for example) can also increase the levels of VAM's prior to soil fumigation.

Nursery managers have other options to minimize or eliminate the effect of fumigation on soil endomycorrhiza populations. Where possible, fall fumigation allows more time for the soil to become reinfected with mycorrhizae. When managers must fumigate in the spring they may want to consider lowering the rate of methyl bromide if they use totally impermeable film (TIF) during fumigation. When the stunting of pines occurs due to a lack of mycorrhiza, quickly adding P in one or two top-dressings (25 lb of P / acre) will mitigate the P deficiency. With endomycorrhizal hardwoods that often have problems with mycorrhiza such as yellow poplar and sweetgum, adding P in June with the first top-dressing of N is a rapid and inexpensive method to address mycorrhizae issues. Several types of P fertilizer can be used in this case. Diammonium phosphate (DAP) may be used for those preferring granular applications, while soluble monoammonium phosphate (MAP) may be used for those preferring liquids. Either granular or liquid materials are suitable if applied accurately and timely. Applying mycorrhizal spores at the time of sowing is not recommended because of the added expense of the fungal inoculum and the low probability of success.

highly soluble and subject to loss through leaching, particularly in coarse-textured soils with low cation exchange capacity and low organic matter. While nitrogen is critical to the growth of new foliage, potassium is essential to all growth and is therefore needed even after autumn leaf fall, when root and stem growth can be fueled by the photosynthesis of green branches. The demand for potassium may therefore extend beyond the summer growing season. The most common timing of potassium chloride (KCl) applications is preplant, at a maximum of 150 lb/ac (168 kg/ha).

A mid-summer application may be needed in some soils because of potential losses through leaching during the growing season.

Calcium

Hardwood seedling crops tend to take up more calcium (per unit of biomass) than pine species. When analyzed for total nutrient content, hardwood seedlings typically show a relatively high level of calcium in their tissue due to the formation of calcium pectate used in the lignification process, when forming woody branches and stems. Calcium must therefore be available as long as the seedling is growing woody tissue. Once incorporated into the stem structure, the calcium is trapped and is no longer mobile in the plant. Although relatively higher concentrations of calcium are required by hardwoods, it does not necessary follow that they need higher soil pH to supply that calcium. Adequate calcium can be provided by the appropriate application and balance of soil nutrients. Some nurseries may accumulate soil calcium, particularly if the nursery water source is a deep limestone well.

A soil test will provide an estimate of available soil calcium and indicate the need and amount of calcium necessary for application. A level of 300 ppm is appropriate for most hardwood nursery soils. However, the pH and buffering capacity determine the type and amount of soil amendment used to raise soil calcium levels. If the soil acidity is already at pH 5.5, then a form of calcium should be used that will not affect soil acidity when applied. In this case, gypsum, also known as calcium sulfate ($CaSO_4$-$2H_2O$), can be applied at a rate of 400 to 500 lb/ac (448 to 560 kg/ha). On the other hand, if the soil test indicates an acidic soil condition—for example pH 4.4—where decreasing soil acidity may benefit soil properties, then dolomitic lime (calcium magnesium carbonate ($CaMg(CO_3)^2$), should be used. On typical sandy nursery soils a common application rate is 1,000 pounds per acre (1,120 kg per ha). In some areas of the country, dolomitic lime has limited availability and calcitic lime ($CaCO_3$) may be substituted, although calcitic lime lacks the Mg component.

An important consideration in the application of any of the lime additives is that they be incorporated soon after application. Calcium does not readily leach in the soil and will have limited effect if left on the surface. To become available, it must be adequately mixed and incorporated into the root zone (i.e., the top 6 in [15 centimeters (cm)] of nursery soil). In addition, most lime products are fine powders that are easily moved by wind, causing uneven distribution over the area or even movement off the field, reducing application rates. Pelletized formulations greatly reduce wind-associated movement. Lime application is made during the soil tillage phase and before bed formation in the fall and spring. The time required for adequate soil reaction is around 3 weeks prior to sowing for dolomitic lime, while gypsum is faster acting and may be incorporated 2 days or even 1 day before sowing.

Magnesium

Magnesium is absorbed by plants as Mg^{2+} and is necessary for chlorophyll formation and therefore essential to photosynthesis and growth. Seedlings need magnesium as long as they are growing new foliage, but need little, if any, after leaf fall. Available soil magnesium should be 30 ppm. Magnesium is very similar to calcium in terms of reactivity in the soil and plant uptake. Both occur in the soil as positively charged divalent cations and may “compete” for sites on negatively charged soil colloids. Fortunately, hardwood seedlings tolerate calcium/magnesium ratios as high as 10 to 1 and as low as 1 to 1. The total amount of plant-available calcium and magnesium is substantially more important than their ratio (Koppitte and Menzies 2007, Schulte and Kelling 1985).

Besides dolomitic lime, there are two other sources for magnesium soil amendments. The first is magnesium sulfate, or Epsom salts, $MgSO_4$. (CAUTION: Magnesium sulfate is a strong purgative and applicators should conscientiously minimize respiratory inhalation and oral ingestion.) The second compound is a mixture of magnesium sulfate and potassium sulfate, and may be sold as either “sul-po-mag,” “Kmag,” or “sulfate of potash magnesia.” Application rates depend upon the objectives and are typically 200 to 250 lb/ac (224 to 280 kg/ha), depending on the soil test.

Sulfur

Sulfur is a macronutrient used primarily in the formation of essential amino acids required for building proteins and is essential to virtually all plant metabolic activities. Although sulfur can be found in the soil in a large variety of reduced and oxidized states, it is taken up by seedlings in the sulfate form, SO_4. The process of oxidation, which produces the form taken up by plants, is regulated by soil microbes and affected by oxygen availability. Sulfur uptake may be limited in conditions of low soil oxygen.

The required amount of available soil sulfur is 10 ppm. When sulfur amendments are necessary, two commonly used fertilizer materials are elemental sulfur and ammonium sulfate. Elemental sulfur is a finely ground powder that must be evenly and accurately applied, then incorporated into the root zone for maximum effectiveness and speed of reaction. In a well-aerated soil, microbial activity changes the sulfur to SO_4, which reacts with water to form sulfuric acid ($H_2SO_4^{2-}$), which lowers the pH value. This reaction is relatively quick and effective. Both plant-available sulfates and pH-modifying acids are formed quickly. (Avoid applying elemental sulfur immediately before sowing to reduce any chance of an acid burn to the roots or cotyledons of germinating seedlings.) On the other hand, the addition of ammonium sulfate occurs at a slower pace, with the SO_4 being released as the plant takes up the NH_4. Bacteria are not required for this activity. Elemental sulfur application produces a measurable effect after only 3 weeks, while the addition of ammonium sulfate may take an entire season.

Micronutrients

Micronutrients are necessary for plant growth and development but are required in relatively small amounts. These small amounts do not indicate small importance. Micronutrient deficiencies can and will impact plant growth as surely as will macronutrient deficiencies, so managing micronutrient fertility is essential to proper hardwood seedling production.

Iron

Any hardwood species can show iron deficiencies, although hardwoods seem to be more effective at absorbing iron from the soil compared to pines. Iron deficiencies in hardwoods seem to be most common in green ash and the oaks. Deficiencies show up as a foliage chlorosis and because iron does not translocate, deficiencies are seen in the new shoots of growing plants. This is different from nitrogen chlorosis, as nitrogen is highly mobile and may move from older leaves to younger leaves, leaving a chlorotic condition in the older leaves, or in severe cases the entire plant. A soil test of 20 ppm using the Mehlich 3 extraction is considered the threshold for deficiency, although such a low value is rarely encountered. Interpreting soil test results and correcting iron deficiency therefore depends on other factors.

Iron mobility in the soil results from a complex interaction between inorganic soil chemistry and the activity of soil microbes. Iron is one of the most abundant soil minerals but is not readily available for plant uptake. Plants absorb iron as both the Fe^{3+} (ferric) and the Fe^{2+} (ferrous) forms, but iron is often present in the soil as unavailable insoluble precipitates, particularly at high pH. The chemistry of iron solubility, transport, and absorption is complex and not entirely understood, however iron chelation by soil microbes has been shown to be closely associated with increased mobility and availability to plant roots. Plants have developed specific mechanisms to remove the iron from chelates present in the soil solution, actively transport the Fe^{2+} ion across root cell membranes, and then rechelate it for internal plant transport. Summer temperatures can be high enough to kill soil microbes and slow the process of chelation, making iron even less available to plant roots than it normally would be and resulting in chlorosis. On the other hand, cooler periods of the growing season may not have visible signs of iron deficiency. Obviously, a soil test is limited because a test may indicate adequate soil iron content only to have iron moved from available to unavailable forms during the high temperatures of summer.

Iron deficiency may be corrected through foliar application of iron fertilizer. Direct application to the soil solely on the results of a soil test may or may not prevent deficiency symptoms from appearing once microbial activities decrease in the summer. A direct foliar application of 2 lb/ac (2.24 kg/ha) of elemental iron in late June or early July is directly absorbed into the plant and will normally resolve iron deficiency problems. Irrigate the seedlings within 8 to 12 hours after application to wash off any residual salts found in the fertilizer that might “burn” the leaves. Much of the iron in the fertilizer should have been absorbed into the leaves within 8 hours after application.

Boron

Boron is used in cell wall formation, and deficiencies are seen primarily in a chocolate-colored pith of small branches, weak stems, and apical meristem death, although different species may show different symptoms. It is taken up by the plant in the form of borate H_3BO_3. Boron is an anion (negatively charged) while most other micronutrients are cations (positively charged). As such, boron is more easily leached from the soil, particularly coarse soils, where deficiency symptoms may occur. Much of the boron available to seedlings comes from the organic matter fraction of the soil and is made available through microbial activity. A minimum soil test level should be considered 0.4 ppm (0.8 lb/ac, 0.9 kg/ha).

Correction of boron deficiency in hardwood nurseries can be made through a foliar application of 2 lb/ac (2.24 kg/ha) of elemental boron in the form of sodium borate ($Na_2B_3O_7$-$10H_2O$) in late June or early July. In this case, an irrigation rinse should be applied 8 to 12 hours after application to wash off any salts that may have been present in the fertilizer. Boron may also be applied directly to the soil using 2.25 lb/ac (2.52 kg/ha) of elemental boron in the form of sodium borate during the soil preparation phase prior to sowing. Foliar applications tend to resolve deficiency symptoms relatively quickly, producing an effect on seedling appearance within weeks, sometimes even days. Presowing soil applications, on the other hand, are intended to prevent any deficiency from occurring.

Unlike other micronutrients, the range from boron deficiency to toxicity is relatively narrow. Boron toxicity can be produced by improper calibration or excessive application of fertilizer materials. In the case of boron, follow application recommendations as closely as possible. Calcium levels affect boron toxicity. Seedlings growing in soils with high calcium levels seem to tolerate higher levels of boron than would otherwise be toxic.

Manganese

Manganese is used by plants in enzyme functionality and is important in a variety of metabolic processes, but does not seem to be necessary for plant structure formation. Manganese deficiency usually produces a plant with “bronze” colored leaves, sometimes greenish grey, and smaller than normal. Manganese is similar to iron in that it is not mobile in the plant and deficiency symptoms appear in new shoots. Plants take up available soil manganese in the manganous form (Mg^{2+}), with soil availability increased in acidic soils. The soil test threshold level for available (Mehlich 3 extraction) manganese is 5 ppm (10 lb/ac, 11.2 kg/ha). Seedling deficiencies can be treated by a foliar application of manganese sulfate ($MnSO_4[H_2O]$) at 20 lb/ac (22.4 kg/ha) in late June or July (followed by an irrigation rinse 8 to 12 hours after application), or using a presowing incorporated soil application of 40 lb/ac (44.8 kg/ha). Plants tolerate a high level of manganese seemingly without any adverse effect and toxicity symptoms have not been reported for hardwood nurseries.

Zinc

Zinc (Zn^{2+}) is used by plants as a catalytic and structural component of enzymes and is taken up from soil as the Zn^{2+} divalent cation. Zinc deficiencies seem to be more common in large seeded hardwood species such as hickory (including pecan) and the oaks. A minimum threshold level for available soil zinc (Mehlich 3 extraction) is 1 ppm or 2 pounds per acre (2.24 kg per ha). Deficiency symptoms may be treated through a presowing incorporated soil application of 40 pounds per acre (44.8 kg per ha) of zinc sulfate ($ZnSO_4$) or a late June, early July foliar application of 20 pounds per acre (22.4 kg per ha) followed by an irrigation washing at eight to twelve hours after application. Toxicity problems have not been reported for hardwood nurseries.

Copper

Copper is essential to several enzymatic reactions and lignification, and is taken up from the soil as the cupric form (Cu^{2+}). Seedling copper deficiencies show up as “droopy” foliage and weak branch formation. The soil test threshold level (Mehlich 3 extraction) for available soil copper is 0.8 ppm or 1.6 lb/ac (1.8 kg/ha). Deficiencies may be treated using a foliar application of 12 lb/ac (13.4 kg/ha) of copper sulfate ($CuSO_4$)—also known as blue vitriol—in late June or early July (followed by a foliar rinse at 8 to 12 hours after application), or a presowing soil incorporation of 15 lb/ac (16.8 kg/ha) of copper sulfate.

Molybdenum

Molybdenum (Mo) is necessary for enzymatic functionality, particularly for nitrogen fixation and is considered essential for plant growth. A deficiency of molybdenum in forest tree nurseries of the Eastern United States has not yet been reported.

Chlorine

Along with boron and molybdenum, chlorine (Cl^-) is one of the three micronutrients that is an anion. While considered essential to plant growth, its metabolic function is not clearly understood. A deficiency in nursery soils has not yet been reported.

Soil Acidity

Soil acidity, which is measured in units of pH, profoundly affects the availability of all plant nutrients. First, acidity has strong influence on the movement of nutritional elements from the surface of soil particles into the surrounding soil solution. Since nutrients must be in the soil solution to move to the plant root where it might be taken up, the interchange between soil particle surfaces and the soil solution is fundamental to nutrient availability. Secondly, soil acidity greatly influences the oxidation/reduction state of individual elements, not only through the direct chemical reaction caused by available H^+, but also through the activity of microbes that may be positively or negatively impacted by soil acidity. These reactions determine if the nutrient exists in the soil solution in a form the plant can use. The understanding and management of soil acidity is fundamental to proper plant nutrition.

The hardwood species produced in nurseries of the Eastern United States are native to a wide range of soil conditions (Burns and Honkala 1990), but for the most part evolved over time on moderately acidic soils. It is a challenge, however, to specify an ideal pH value for hardwood nursery culture. Not only must hardwood nursery managers work with a large number of species and genera native to a variety of soil types with a wide range of characteristics, but those species also may vary in their sensitivity to pH. Londo et al. (2006), for example, indicated that black cherry (*Prunus serotina* Ehrh.) will grow best on a site with a soil pH between 3.0 to 5.0, while dogwood (*Cornus florida* L.) prefers a rage of 5.0 to 8.0, with sweetgum (*Liquidambar styraciflua* L.) doing well on a pH range of 3.6 to 7.5. Soil pH ranges applicable to silvicultural decisions, however, may or may not be applicable to the more artificial and intensely managed conditions of the hardwood nursery, but until better and more complete research and field trials show the way, managers must do their best with the experiences they have shared. A good target for hardwood nursery management, therefore, would be a pH range of somewhere between 5.0 and 6.0. This range generally matches the moderately acidic conditions favored by most hardwoods in their native habitat and provides optimal nutrient availability, including N and the cations K, Ca, and Mg, which hardwoods require in large amounts compared to pine. While some nutrients may become more available in more acid soils, and other nutrients may become more available under more alkaline conditions, the availability of both macro- and micronutrients is maximized around pH 5.5. Soils with pH values below 5 and above 6 are candidates for corrective soil amendments.

Measures To Raise Soil pH

With pH values below 5, adding lime can raise soil pH values nearer to the target range (i.e., decrease soil acidity). This can be done by adding either dolomitic or calcitic lime. The choice of compound depends on the ratio of available calcium to magnesium. Dolomitic lime contains magnesium, while calcitic lime does not. A desirable calcium to magnesium ratio is around 4 to 1, and if the current soil test indicates this to be the case, then a lime application to adjust soil acidity should use dolomitic lime, as it would tend to maintain this desirable ratio. If, on the other hand, the ratio is considerably lower, say around 1 or 2 parts calcium to 1 part magnesium, then calcite should be used to adjust soil acidity. In many locations, calcitic lime is also the cheaper alternative. However, the ratio of calcium to magnesium should be considered when weighing the two options.

Application rate depends on the buffering capacity of the soil, which is mostly controlled by texture. The typical application rate for lime for sandy soils is 1,000 lb/ac (1,120 kg/ha). The lime is applied in the spring, during soil tillage and before bed formation. It must be incorporated to a depth of 4 to 6 in in order to activate the lime, which is a simple chemical interaction with soil particles and is not mediated by microbial activity. In the case of finer textured (10-percent clay) or high organic matter soils (4 percent), the rate may be raised to 1,500 or 2,000 lb/ac (1,680 or 2,240 kg/ha). Nursery managers should take a conservative approach in their acidity correction measures. It is better to apply a small amount twice than to over-correct in a single application.

Measures To Lower Soil pH

If soil pH values are above 6, then the addition of elemental sulfur can bring pH values down closer to the targeted range (increase soil acidity). Typical application rates for sandy nursery soils range between 400 to 800 lb/ac (448 to 896 kg/ha) of elemental sulfur applied during soil tillage and several weeks, if not months, before bed formation in the spring. Elemental S needs to be incorporated to a depth of 4 to 6 in. Generally, 2,000 lb/ac (2,240 kg/ha) of lime has approximately the same degree of change on soil pH as does 800 lb/ac (896 kg/ha) of elemental sulfur. As in the case of lime application, soil buffering capacity has a strong effect on application rates. Organic matter content is particularly important because the reaction producing the acidifying affect is mediated by soil microbes.

$$S \rightarrow \text{microbial activity} \rightarrow H_2SO_4 \rightarrow \text{microbial activity} \rightarrow \mathbf{2H^+} \text{ plus } SO_4$$

Environmental conditions that increase microbial activity will hasten this process. On the other hand, environmental conditions that decrease microbial activity (such as dry weather) will slow the process.

Soil Sampling

Proper management depends on obtaining an accurate assessment of soil fertility conditions. Reliable analytic laboratories can generally provide an accurate and replicable soil analysis report. However, the accuracy of their results is only as valid as the samples they analyze. If the soil sampling technique does not accurately reflect soil conditions in the nursery, then any nutrition management prescription based on those samples will most likely be erroneous, a waste of time and resources, and possibly damaging to the crop. A suitable soil sampling procedure is essential to proper nursery fertility management.

There is no hard and fast rule dictating a specific number of soil samples per unit of area. Sampling intensity depends on the variability of the units to be sampled; the objective is to provide enough detail in the soil fertility report to achieve crop production goals across the area of production. Differences in soil texture and cropping history should be reflected in the sampling protocols. Cover crop areas should also be sampled if time and resources allow. Then any needed corrective action (sulfur or lime) can be taken before the field returns to seedling production. Once the sample units have been determined, take 30 to 50 subsamples in a representable pattern across each unit using a standard 1-in soil probe

The Interpretation of Soil Tests

David B. South

Once soil test reports arrive, the next step is interpreting the numbers. By themselves, numbers have no meaning, so an interpreter can help to develop an operational fertilizer regime. This individual should have knowledge of soil testing procedures, an understanding of how hardwoods respond to various soil conditions and which fertilizers are available from the dealer at reasonable prices. Professionals with different backgrounds, training and experience will interpret soil and foliage test results differently, and nursery managers should expect different recommendations when identical reports are sent to various interpreters. Soil agronomists rely on scientific studies to make fertilizer prescriptions for various agronomic crops and this helps explain why yields from genetically improved row-crops are typically high. However, an experienced hardwood nursery manager once said that although soil testing laboratories make good cover-crop recommendations, they do not know the best rates for hardwood seedlings. Unfortunately, useful fertilizer trials for hardwood nurseries are rare in the eastern United States.

Hardwood nursery manuals may provide estimates of desired foliar nutrient values for growing hardwood seedlings, but most do not provide information on when managers should apply fertilizers to nursery soils. In the absence of fertilizer rate trials, experience and intuition are used to set "trigger values" for hardwood seedbeds. If the soil test is below the "trigger value" for a certain nutrient, then a fertilizer is recommended. Typically, the "trigger value" is at the low end of what is considered an adequate nutrient range for growing hardwoods. Some call this minimum value a "target value" while others may set a higher level for the desired fertility level (e.g. trigger = 75 ppm K; target = 100 ppm K). There are many factors to consider when determining if the "trigger value" has been met and how much fertilizer should be applied to achieve the target soil fertility level. Some professionals take soil texture into account when setting a "trigger value" while others use the same values for all soil textures and all hardwood species. The buffering capacity of a particular soil can strongly influence the amount of sulfur or lime necessary to reach the target soil acidity level.

The laboratory test methodology used to determine soil nutrient levels must be taken into account when interpreting soil test results. Different laboratories may use different chemical extractants when conducting their tests. A good soil test interpreter must take into account the methodologies used to produce the values on the soil test result. Likewise, when reviewing a foliar nutrient test, the timing of the test is an important consideration. Was the foliage sampled in July to make a growing season correction because leaves appeared purple or yellow? If so, then the interpretation of the results may be very different than for an analysis made in the fall, just before leaves are about to drop from the seedling. Also, the interpreter should be able to identify obvious typographical errors that occasionally occur in results.

The interpreter should consider the individual history of the nursery fertilization program and previous soil amendments that have been applied. Row-crop fertilization recommendations are made based on research specific to individual soil series. No such specific soil series information exists for hardwood seedling culture. Site familiarity, soil tests and nursery records are often the best information available.

Familiarity with operational hardwood seedling production can be an important component of soil test interpretation and fertilizer program development. For example, when growing certain endomycorrhizal species on fumigated soil, a nursery manager may apply monoammonium phosphate to young seedlings even when the soil contains more than 60 ppm of extractable phosphorus. This "insurance" application allows non-mycorrhizal seedlings access to readily available phosphorus and sometimes produces a more uniform crop (especially after newer, more effective soil fumigation has been accomplished).

In summary, there are many considerations to making appropriate soil and foliage test interpretations, and many times it is more of an "art" than "science." While test results are presented as a series of numbers, the exact meaning of those numbers and the management actions they may initiate, are subject to a great deal of interpretation.

to a depth of 4 to 6 in. The sampling often takes the form of a crisscross or "W"-shaped pattern across the unit (May 1984). Place the subsamples in a plastic (NOT galvanized or metal) bucket and mix thoroughly. If field conditions are suitably dry, place a sample of the thoroughly mixed soil directly into the laboratory-provided sample boxes for shipment. Label each box with enough detail so that same specific area could be located for a second sample if needed. If soil conditions are wet, place the samples in well-labeled open plastic bags and spread them out in the packing shed or other building to air dry. When dry, place them in the boxes for shipping to the laboratory.

Carefully selecting the areas to be sampled can help avoid sampling problems. For example, do not take a subsample from the end of a riser line area where agricultural lime was stored the previous year because this material could strongly bias the sample and result in an erroneous recommendation for the entire management unit. The objective is to obtain soil analysis values that are representative of the entire sample unit.

Finally, the importance of careful recordkeeping cannot be overemphasized. As May (1984) suggests: "Nursery managers should have a map showing the location of samples, crops, and fertilizers since the last analysis and any other relevant information such as deficiencies observed, quality of last crop and unusual summer rainfall."

Diagnosis of Nutrition Problems

Under ideal conditions, a nursery fertility program is based on representative soil sampling, accurate analysis, well-conceived fertility recommendations, and proper application procedures. Invariably, however, the unexpected happens and problems occur. Hardwood seedlings may show signs of inadequate nutrition anytime between 4 weeks after sowing up to leaf fall. Nursery managers should be inspecting their crop at least weekly for signs of anything negatively affecting proper seedling morphological developments, such as inadequate coloration, leaf shape, and stem development. A proper and timely diagnosis of the problem is essential to corrective action. Insect damage is usually easy to spot and diagnose, either by seeing the insect, signs of feeding on leaves or stems, or the presence of frass. Disease is typically found as irregular patches in seedling production areas, as opposed to a general impact caused by a fertility issue. And drought effects, while possibly difficult to see in conifers, causes wilting in hardwoods and the observant nursery manager can quickly alleviate the problem. But, not all growth problems can be quickly diagnosed or resolved.

The possibility of herbicide toxicity must be considered when morphological abnormalities appear in hardwood seedling crops. Herbicide damage can cause discoloration, leaf and stem deformation, and stunted growth. These same characteristics can be caused by nutrient deficiencies and, without check plots (areas not sprayed with the herbicide), it can be challenging to tell them apart. The manager could consider several factors when assessing the possibility of herbicide damage. First, does the area of damage match that of a recent herbicide application or, if not, does the damage occur in a manner that might indicate the influence of wind-associated drift or water-associated flooding that could have brought herbicide into the area? Second, does the timing of the injury match an earlier preemergent or postemergent herbicide application? For example, if the damage shows up in late July, but the last herbicide application was a preemergent application before sowing, then herbicide damage is unlikely. Third, do the physical symptoms match possible herbicide effects? Individual herbicides and classes of herbicides affect plants in different ways. Associating plant symptoms with the mode of action of a class of chemicals or a specific compound can be instrumental in diagnosis. Finally, does the intensity of the damage seem to vary by soil characteristics? Damage from postemergent herbicides like glyphosate, for example, are typically found across an entire application area and not related to changes in soil moisture, fertility, or organic matter content. In summary, diagnosing herbicide damage can be a complex matching of plant symptoms, application timing, product, site characteristics, crop species, application method, and other factors. The services of an expert may be required.

Table 6.3*—Midsummer foliar nutrient levels in hardwood seedlings.*

Element	Unit	Low	Medium	High
N	%	1.0	2.0	3.0
P	%	0.12	0.2	0.3
K	%	0.6	1.2	2.4
Ca	%	0.3	0.5	0.8
Mg	%	0.1	0.15	0.3
S	%	0.06	0.1	0.2
Na	%	0.01	<0.05	0.15
Al	ppm	200	<400	2,000
Fe	ppm	100	400	2,000
Mn	ppm	100	300	1,000
Zn	ppm	30	60	100
B	ppm	15	25	60
Cu	ppm	2	8	15

ppm = parts per million.

Once it is apparent that the crop is showing signs of nutrient deficiency, a tissue analysis will help achieve proper diagnosis. Previous soil analyses may be used or current soil samples may help in diagnosis, but at this point a tissue sample will more accurately indicate which nutrient is deficient. The sample should be WHOLE leaves taken from individual seedlings in the affected area, about 2 ounces (56 grams) of green sample per tree. The number of leaves will vary depending upon size.

Select leaf samples from affected parts of the seedling. The location of the leaf sample is important, as some elements are not mobile in the plant: Iron is a good example, where older leaves may contain low but adequate levels of iron, while new leaves may be deficient. A general leaf sample from all parts of the individual seedling may indicate adequate average iron levels, leading to an inaccurate diagnosis. If, on the other hand, the entire seedling seems to be affected, then leaf samples should be taken using "typical" leaves.

Table 6.3 provides general guidelines for hardwood leaf nutrient contents. While providing estimated values for low, medium, and high nutrient levels, these values should be used in conjunction with previous or current soil tests and seedling morphological development to make an assessment of seedling nutrition. Good photographs of nutrient deficiency symptoms in nursery-grown hardwood seedlings are generally not available. Erdmann et al. (1979) and Hacskaylo et al. (1969) have photographs derived from nutrient omission studies with seedlings of a variety of hardwood species.

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