Fundamental Soil Concepts and Soil Management in Hardwood Nurseries

3

L.A. Morris

Lawrence A. Morris is professor of forest soils in the Daniel B. Warnell School of Forestry and Natural Resources, University of Georgia, Athens, GA

Outline

Facing Page: *A nursery bed prepared for planting. (Photo by Chase Weatherly.)*

The Role of Soil in Nursery Management

Soils provide the foundation of nursery management and are a prime factor in site selection. Hardwood nursery site selection was described in detail by Stoeckeler and Jones (1957), and while many of the factors they describe remain important, some adjustment for the highly mechanized, technological nursery management in today's hardwood nurseries is necessary. These systems rely less on natural growth controls and place more emphasis on the ability to manipulate soils to control growth conditions. For example, while inherent soil fertility is important, inherent fertility must be weighed against the needs to manage nutrient availability and balance, control water availability, limit pathogens, till, plant, and manage root growth. Most nurseries induce hardiness by producing mild water and nutrient stress—a process made easier by coarser-textured surface soils that are more easily manipulated.

A well-sited nursery has soils that are well-drained, flat, and characterized by relatively deep surface horizons (A and E) over subsoil argillic horizons. Slope is a critical consideration and most nurseries are located on slopes of 2 percent or less, which minimizes surface runoff and erosion. The low slopes, however, increase the relative importance of good drainage because lateral subsurface flow is required to move water off site during heavy rainfall periods. Deep surfaces allow grading to be completed while providing enough depth above subsurface horizons for subsurface drainage. In the absence of sufficient surface soil depth, management becomes difficult. For example, in Florida, Phytophthora root rot of hardwood seedlings occurs only in fumigated soils that have shallow surface soils over clay subsoils (Barnard 1996). Loamy sand and sandy loam surface soils are generally preferred, as soils of this texture are relatively easily manipulated without physical degradation. In northern nurseries, they are also less prone to frost heaving (Briggs 2008). Boyer and South (1984) reported 21 of 51 southern nurseries (both pine and hardwood) were on sandy loam soils and only 13 were on clay loam or silt loam-textured soils. Elsewhere in the United States, nurseries on soils more finely textured than sandy loams are more common, but sandy loam textures are still preferred. Finally, a uniform site will tend to produce uniform seedlings. Although precision agricultural techniques enable adjustment for irrigation, fertilization, and pesticide applications within the nursery, uniform soil conditions allow management interventions to optimize seedling growth. Uniform soil conditions allow for more efficient management and lower costs for fertilization and other operations.

In this chapter we review basic soil characteristics and discuss how they affect nursery management.

Soil Physical Characteristics

The Soil Matrix

A handful of soil consists of inorganic minerals, organic debris left by decomposing plants and animals, water, air, and millions of living organisms. Together, these constitute the soil matrix (fig. 3.1). About 50 percent of the matrix consists of solid fragments of inorganic minerals with a small portion, usually 1 to 5 percent, consisting of particulate organic matter or organic coatings on inorganic minerals. The inorganic component of the matrix is stable. The organic fraction is less stable, varying over the course of a year or years depending on the balance between new inputs and loss through decomposition. The remaining 50 percent of the soil matrix is pore space that is filled with water and air. The proportion of the pores filled with water or air is dynamic and changes over the course of individual days.

Soil Particles. ***Texture.*** One important characteristic of the inorganic component of soil is the relative distribution of clay, silt, and sand-sized particles (table 3.1). Grouping by the relative proportions of these particle sizes into soils with similar characteristics is the basis of the textural triangle (fig. 3.2). Note that particles greater than sand-sized (greater than 2 millimeters [mm] diameter) are not included as part of soil texture determination. Loam- and silt loam-textured soils have the best combination of fertility, water retention and release characteristics, and workability for traditional agriculture. Generally, however, soils of these textural groups are difficult to manage in hardwood nurseries. Bed preparation and lifting are both more difficult

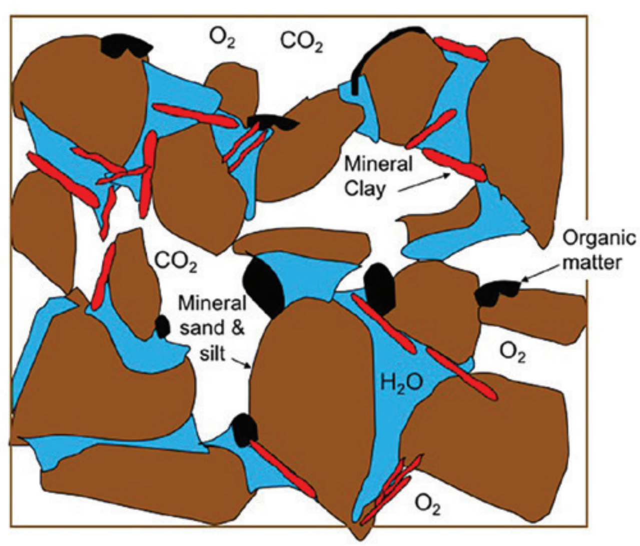

Figure 3.1*—Idealized soil matrix showing inorganic and organic particles and water and air-filled pores.*

Table 3.1—Size range of soil particles.

Particle	Size Ranges		
	Millimeters (mm)	Microns (µm)	Inches (in)
Sand	0.05 to 2.0	50 to 2000	0.002 to 0.08
Silt	0.002 to 0.05	2 to 50	0.00008 to 0.002
Clay	<0.002	< 2	< 0.00008

in these relatively fine-textured soils, and physical conditions are more likely to be adversely affected during tillage and lifting. Lifting can also be a problem when the soils are wet because the soil adheres to the roots (Bosch 1986). Several days of production can be lost after heavy rainfall on these soils in order to avoid compacting or puddling the soil (Hartmann 1970). Consequently, ideal nursery soils generally have sandy loam textures that retain less water and are more easily manipulated than loam-textured soils. Subsoil texture tends to be less of a concern than surface soil texture. Finer-textured subsoils are desirable in nurseries, particularly those with sandy surfaces (Boyer and South 1984).

Mineralogy. Clay has several meanings in soil science. As used above, it refers to the size class of a particle. "Clay" can also refer to the type of mineral. Clay minerals are composed of sheets of silica dioxide and aluminum hydroxide. Clays that have two sheets of silica dioxide for each sheet of aluminum hydroxide are termed 2:1 clays. Clays that have one sheet of silica dioxide for one sheet of aluminum hydroxide are termed 1:1 clays. This second type, 1:1 clays, are less prone to shrinking and swelling and associated problems of frost heaving and are the preferable clay mineralogy in nurseries (Stroup and Williams 1999).

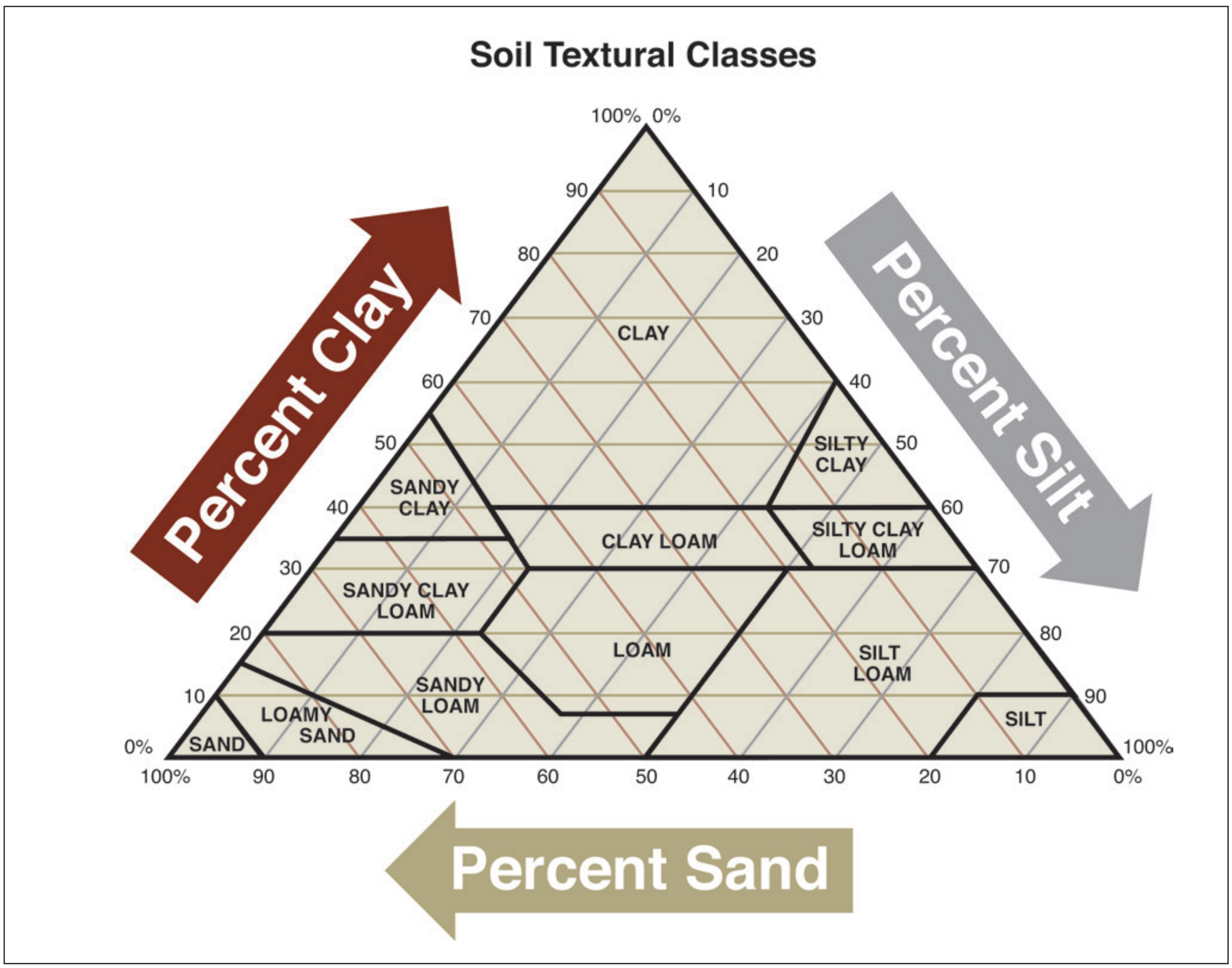

Figure 3.2—The soil texture triangle. Percentages of three soil particle sizes are plotted on the three axes. Texture class is determined from the percentage of any of the two groups.

Organic matter. Organic matter comprises the remaining component of the soil solids. Although it accounts for less than 5 percent, and is usually only 1 to 3 percent of the solid mass, it has a disproportional contribution to soil properties. Organic matter contributes to soil exchange, water-holding capacity, and soil structure. It buffers pesticide activity and is a source of nutrients. Organic matter is removed prior to texture analyses and does not contribute to the determination of soil texture.

Structure. In most soils, individual soil particles do not exist independently, rather, they are bound together by organic matter, metal oxides, and surface charges into groups of particles called aggregates. Soil aggregates are categorized by shape (fig. 3.3), size, and strength. Granular structure is typical of many surface soils, particularly for sandy loam and loamy sand-textured soils characteristic of nurseries. Blocky and sub-angular blocky structures are more common in finer-textured subsoils, but also characterize some surface soils of sandy clay loam and silt loam textures.

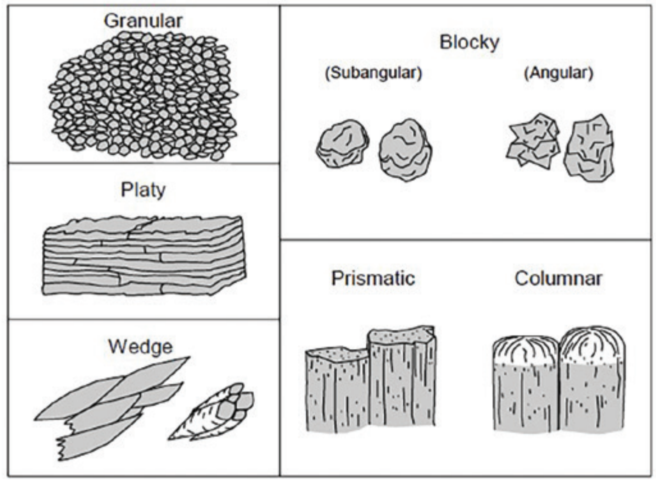

Figure 3.3*—Individual soil particles are organized into structural units. Single-grain and granular structure are common in sandy loam and loamy textured surface soils typical of most seedling nurseries. Block structure is common in subsoils and in some nurseries with finer-textured surface soil (Schoeneberger et al. 1998).*

Structure is particularly important to the development and maintenance of large soil pores that allow rapid infiltration and movement of water within the soil (see following section) and providing open pores that allow gas exchange between the soil and the atmosphere. Additionally, soils with good structure are less susceptible to physical degradation by equipment trafficking or tillage.

Pore space. Pore spaces within the soil are classified by size based on their interaction with water. Surfaces of soil particles contain electrical charge, and water has an affinity for soil surfaces due to its polar nature. The closer the water to the soil surface, the more tightly it is held. In the smallest micropores, the distance between soil surfaces are so short that water does not drain from these pores after the soil is saturated. Water is also held tightly enough that plant roots cannot generate enough tension to remove the water before they wilt. Mesopores are larger than micropores and distances between soil surfaces are greater. Mesopores are small enough that water is held so tightly that they do not drain after wetting but large enough that plants can generate sufficient tension to use this water for transpiration. Macropores are pores too large to hold water against gravitational forces. They drain after wetting and remain open to the atmosphere (fig. 3.1).

Soil Water

Retention and plant availability. The amount of water a soil can hold, expressed as a percent of total soil volume or inches per inch of soil depth, and the portion of this water available to support plant growth, is closely related to texture. This is illustrated in figure 3.4. The total amount of pore space in the soil, or the total porosity, is about 50 percent. When the soil is saturated, all of this pore space is filled with water. If the soil is allowed to drain under gravity, water will drain out of macropores. The amount of water remaining after this drainage is termed field capacity. Field capacity corresponds to water held at tensions (negative soil water potential) of about 0.3 bar (5.0 pounds per square inch [psi]). Plants grown in soil can use a portion of the water held at field capacity for transpiration because they can generate tensions greater than gravity. The lower limit of the water plants can use is termed "wilting point moisture." Below the wilting point, water cannot be withdrawn to supply transpirational needs because the water is held in micropores. This point corresponds to 15 bar (220 psi) tension. The water between field capacity and wilting point is termed "plant available water" and is the water held in mesopores. Sandy soils are dominated by macropores that drain after wetting. Because these soils have few micropores or mesopores that retain water, both the total and available water storage is low. Clay-textured soils retain large amounts of water, but a high percentage of this water is held in micropores and it is not available for transpiration.

While the concept of plant available water is useful, it is important to recognize that all plant available water is not, actually, equally available to plants. As water is removed from soils, the remaining water is held more tightly and moves to roots more slowly. For optimal growth, soil water content is maintained in the upper portion of available water and irrigation typically begins when available water is only 50 percent of the amount available at field capacity.

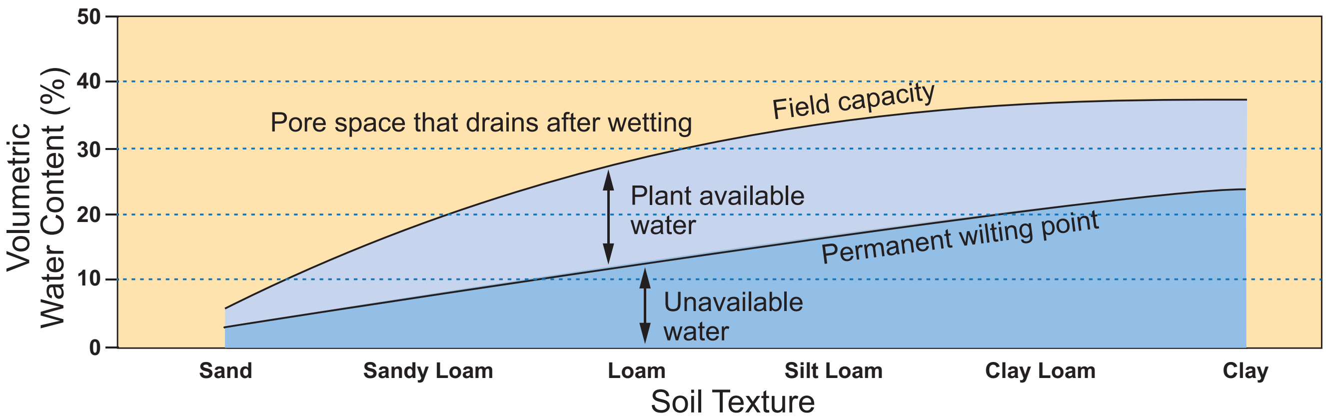

***Figure 3.4**—Water retention for noncompacted soils by soil texture class. About 50 percent of the soil is pore space. Macropores drain after rainfall and these air-filled pores are important for gas transfer. Water retained after these macropores drain is termed field capacity. Water held between field capacity and the permanent wilting point is considered plant available water.*

Infiltration rate/hydraulic conductivity. Two other important concepts of soil water are infiltration rate and hydraulic conductivity. Infiltration rate is a measure, usually in inches per hour, that the soil is able to absorb rainfall or irrigation. If rainfall exceeds infiltration rate, runoff will occur. Hydraulic conductivity is a measure of the ease that water can pass through soil. Typically, dry soils have a high infiltration rate but low hydraulic conductivity. As the soil wets, the infiltration rate is reduced and the hydraulic conductivity is increased until the saturated hydraulic conductivity of soil beneath the surface is controlling the infiltration rate (fig. 3.5). In nurseries with fine-textured argillic horizons and shallow surfaces, the saturated hydraulic conductivity may be too low to drain adequately, even with addition of drain tiles (Hartman 1970).

Drainage. Infiltration and hydraulic conductivity depend on intrinsic properties of the soil matrix and the arrangement of soil horizons of different texture and structure. In contrast, drainage is a property related to the natural condition of soils within the landscape. It is an indication of the degree, frequency, and duration of wetness and is inferred from observations of landscape position and soil morphology. A sandy-textured soil with high infiltration capacity and high saturated hydraulic conductivity can be poorly drained if it is located in low landscape position with a high water table. Conversely, a clay-textured soil with poor infiltration and low hydraulic conductivity can be well-drained if it occurs on a ridge.

Eight drainage classes are recognized in the U.S. system of soil taxonomy:

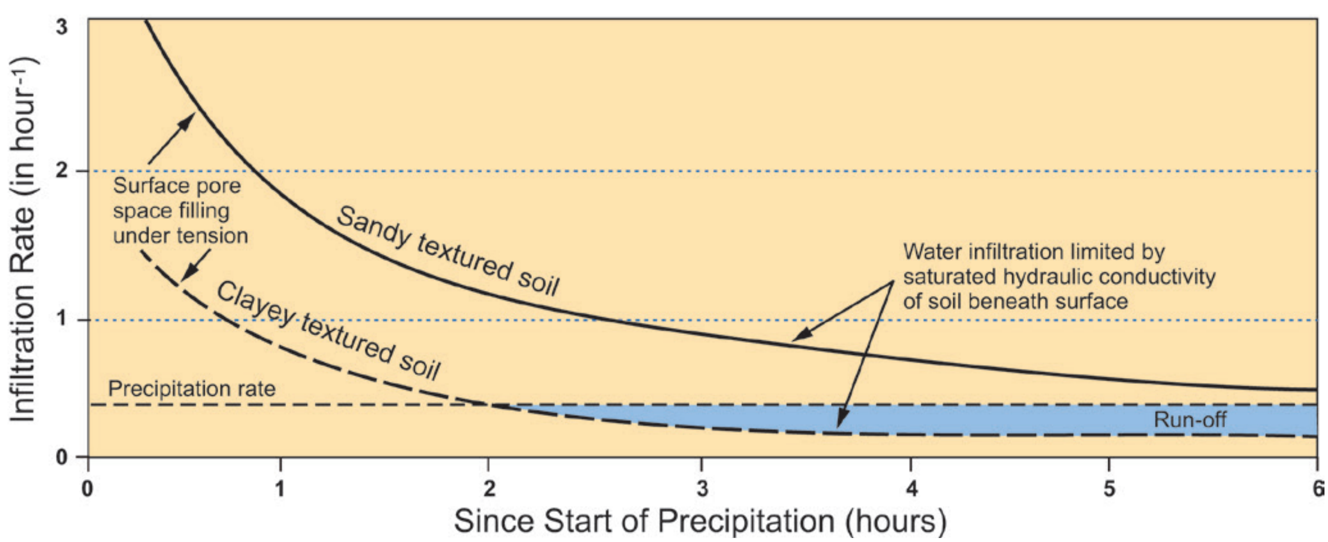

***Figure 3.5**—Response of a dry soil to precipitation. Initially, infiltration rate is high and water rapidly enters a soil under tension and fills the air-filled pore space. As the soil continues to wet and air-filled pores fill with water, the ability of the saturated soils to transmit water deeper into the profile begins to control infiltration rate.*

1. Excessively drained
2. Somewhat excessively drained
3. Well-drained
4. Moderately well-drained
5. Somewhat poorly drained
6. Poorly drained
7. Very poorly drained
8. Subaqueous

May (1995) suggests that nursery sites have a minimum depth to the seasonal high water table of 5 feet (ft) (1.5 meters [m]). Excessively drained, somewhat excessively drained, and well-drained soils all meet this criterion. Water moves through excessively drained soils and somewhat excessively drained soils rapidly; they have very low to low available water-holding capacity and a water table seldom occurs within the soil profile. Water movement is slower through well-drained soils and they have higher available waterholding capacity than excessively and somewhat excessively drained soils, but like these soils, they seldom have a water table within the soil profile. Most nurseries are located on well- and somewhat-excessively well-drained soils because they pose little limitation to operations during wet seasons. Moderately well-drained soils typically have a layer of low saturated hydraulic conductivity within 3 ft (0.9 m) of the soil surfaces and are characterized by a water table within the profile during parts of the year. Nurseries located on soils of this drainage class must modify operations to accommodate the periodic wet conditions that occur (Peevy 1976).

Soil Mechanical Properties

Bulk density. Soil bulk density (g/cm3) is defined as the mass (weight) of soil per unit volume. In the United States, SI units of g cm^3 (grams per cubic centimeter) are most often used to express soil bulk density, but English units of lb ft^3 (pounds per cubic foot) are also used. The conversion from grams per cubic centimeter to pounds per cubic inch is: 1 g per cm^3 equals 0.036 lb per in^3. Total porosity can be estimated from soil bulk density using equation 1 (where 2.65 g cm^3 is the assumed particle density).

Porosity % = (1-(Bulk Density/2.65))*100 [Equation 1]

Soil bulk density is easy to measure and is often correlated to other soil physical conditions. Bulk density increases when soils are physically damaged by trafficking, loss of organic matter, and, in many instances, degradation of structure. Because of this, bulk density is often used as an index of soil physical conditions. However, bulk density has little value for assessing soil physical condition unless soil texture is also considered, as the bulk density associated with adverse soil physical conditions varies depending on soil texture. The relationship between soil texture and the bulk densities considered to be restrictive to root growth are provided in table 3.2. For sandy-textured soils, bulk densities of up to 1.69 g cm^3 can occur without root growth restrictions developing. For clay-textured soils with clay contents greater than 45 percent, root growth restriction begins at bulk densities as low as 1.39 g cm^3.

Soil strength. Roots grow through soils by either exploiting pores large enough to accommodate them or by growing into and enlarging small pores. There is a general relationship between the ability of roots to expand pores and grow into soil and soil strength. Root growth is at a maximum when soil strength is low and decreases with increasing soil strength. Root growth essentially stops when soil strength exceeds 20 bars (290 psi). For any given soil, soil strength is lowest when the soil is wet and increases as the soil dries because increased tension of the remaining water tends to hold particles together. Low bulk density is associated with the lowest soil strength and the smallest increase in strength as soils dry (da Silva et al. 1994). The same soil at a higher bulk density has greater strength, and the increase in soil strength under dry conditions tends to be relatively greater than the same soil at a lower bulk density.

Compaction and puddling. Compaction is the reduction of soil volume under pressure. By definition, soil bulk den-

***Table 3.2**—Bulk density range associated with initial root growth restriction and full root growth limitation (Adapted from USDA NRCS 2011.)*

Particle	Bulk density of initial root growth restriction	Bulk density above which root growth is limited
	g cm^3	
Sand and loamy sand	1.69	1.85
Sandy loam, loam	1.63	1.80
Sandy clay loam, clay loam	1.60	1.78
Silt loam, silty clay loam, silt	1.54	1.65
Sandy clay, silty clay and clay with clay < 45%	1.49	1.58
Sandy clay, silty clay and clay with clay > 45%	1.39	1.47

cm = centimeter. g = grams.

sity increases when a soil is compacted. Problems created by excessive soil compaction are: (1) increased soil strength and mechanical restriction to root growth, (2) reduced infiltration rate and saturated hydraulic conductivity resulting in reduced drainage, and (3) reduced macropore volume and decreased gas diffusion. Compaction in nursery soils may result from wheel traffic (particularly when soils are moist and strength is low) as well as tillage operations such as disking, undercutting, and lifting (Allmaras et al. 1993). The formation of a compacted zone between 20 and 30 cm (8 to12 in) depth is a predictable consequence of repeated tillage without ameliorative treatment.

Soil puddling is the destruction of soil structure. It occurs when shear force (e.g., spinning wheels, disk harrowing) is applied to wet soils. Although puddling can occur without compaction, typically they occur together. The loss of structure by puddling contributes to the reduced infiltration, water flow, and air exchange essential to root growth observed in compacted soils.

Soil Temperature

Soil temperature is a function of air temperature, incoming radiation, surface albedo (the amount of radiation reflected versus adsorbed), the thermal capacity of the soil, and the thermal conductivity of the soil. Dark-colored surfaces adsorb more radiation than light-colored surfaces (lower albedo). Wet soils transmit heat energy to deeper layers more rapidly and also require more radiation to increase temperature than do dry soils. Thus, dark wet soils will warm to depth more quickly than light-colored wet soils. The surface of dark dry soils will become hotter than the surface of light-colored soils when the soil is dry because the heat energy absorbed at the soil surface is not transferred to deeper in the soil and collects at the surface.

Soil temperature affects root growth both directly and indirectly. Each tree species has an optimum range for root growth. Below this temperature optimum, root growth slows until a minimum temperature is reached (usually 3 to 7 °C; 37 to 45 °F) and growth stops. Above the optimum, respiration increases faster than carbohydrates are made available and net growth is reduced. Lethal temperatures are reached from 40 to 50 °C (105 to 122 °F), again, depending on the species. Lethal temperatures can be reached at the ground line and may kill newly germinated seedlings when high temperatures are combined with low soil moisture and seedbeds covered with dark-colored mulch (Barnard 1990).

Temperature has a profound effect on decomposition and availability of nutrients and on the use of nutrients by trees. Biological zero for decomposition and mineralization processes is about 4 °C (39 °F). Above this temperature, mineralization increases, approximately doubling for each 10 °C (18 °F) increase in temperature to a maximum temperature of about 40 °C (105 °F). Low temperatures reduce mineralization and nutrient availability and, as Dong et al. (2001) showed, may also limit uptake of nitrogen applied as fertilizer. Soil temperature also affects activity of damping-off pathogens. Soils with high clay contents tend to retain more water and warm more slowly in the spring. This increases the period over which seed germination occurs and increases the potential for damping-off (Barnard 1996).

Soil Chemical Characteristics

Nature of Soil Surfaces and Interactions With Soil Solution

Cation and anion exchange. The surfaces of soil particles are electrically charged. Both positively and negatively charged sites occur (fig. 3.6). The total amount of negative charge for a given mass of soil is termed cation exchange capacity (CEC). CEC is expressed in terms of the number of charges in a given mass of soil. In the United States, it is customary to express CEC as milliequivalents (0.001of a mole) per 100 g soil (meq 100 g^{-1}). The amount of positive charge for a given mass of soil is termed the anion exchange capacity (AEC) in a manner analogous to the cation exchange capacity. Positively charged sites that contribute to AEC occur when H+ is added to neutral hydroxyl groups of

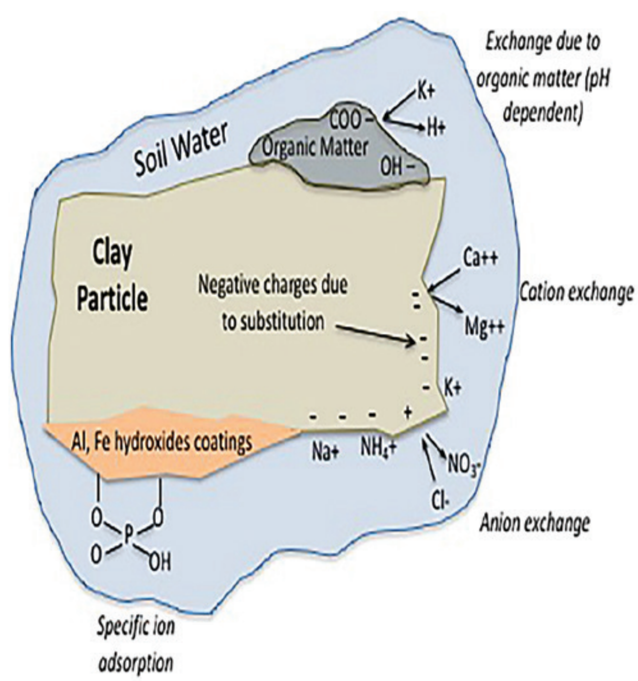

***Figure 3.6**—Adsorption and release of cations and anions on mineral and organic soil surfaces is the primary mechanism controlling availability of most essential elements.*

humus or metal oxides. The anion exchange capacity is typically much smaller than the cation exchange capacity. Although small, AEC contributes to the retention of anions (e.g., Cl^-, NO^{3-}) in soils.

The adsorption of ions to soil surfaces by negative and positive charges of the CEC and AEC is weak and easily reversed. Ions of different types can be replaced by other ions, and the concentrations of exchangeable nutrients in solution are governed by exchange reactions that describe the equilibrium between surface adsorbed cations and cations in solution. Soils with coarser textures, such as loamy sands and sandy loams have lower CECs than finer-textured soils. When fertilizers are added that have an abundance of one cation, it may be preferentially adsorbed to surfaces and displace other cations. This can cause an imbalance and lead to nutritional problems or problems with soil structure.

Potassium (K^+), calcium (Ca^{++}), magnesium (Mg^{++}), and sodium (Na^+) are termed base cations because they are cations of strong bases such as sodium hydroxide (NaOH) and do not contribute protons (H^+) to the soil. H^+ is obviously an acid cation. Additionally, Al^{3+} is considered an acid cation because it combines with water to form $AlOH_3$ and similar compounds that release H^+ and lower soil pH. The balance between basic and acid cations is measured by base saturation (eq. 2), which is the percentage of the CEC occupied by the sum of K, Ca, Mg and Na.

$$BS\% = 100 \sum (K,Ca,Mg,Na)/CEC \quad \text{[Equation 2]}$$

Soils with a high base saturation tend to be more fertile while soils with a low base saturation are acidic and of lower fertility.

Specific ion adsorption. In addition to the weak adsorption of ions to soil surfaces by the electrostatic charge of the exchange complex, ions can also be adsorbed to surfaces of soil particles through the process of specific ion adsorption. In this type of adsorption, ions form chemical bonds at one or more locations on the surface of metal oxides or with organic matter (fig. 3.6). As its name implies, sites for this type of adsorption are unique to the compound and the adsorption is much stronger. This type of adsorption tends to be very important for elements that form anionic compounds with oxygen (e.g., $H_2PO_4^-$).

Solubility. The most abundant form of many soil micronutrients, and under some conditions soil P (Phosphorus), is as a component of a compound with low solubility. The concentration of these elements in the soil solution, and hence their availability, is a function of a solubility reaction. The lower the solubility, the less likely an ion will move into the soil solution. The factors affecting solubility, therefore, become increasingly important to manage nutrient availability. For example, a common source of plant-available phosphorus is calcium phosphate, $Ca_3(PO_4)_2$. If the soil pH is high (above 7) then a large amount of Ca^{++} will be available in the soil solution. This makes it difficult for the calcium in calcium phosphate to move into the soil solution. Therefore, the phosphorus remains tied up in a form unavailable to plants.

Soil reaction (pH) and acidity. When pure water disassociates into H^+ and OH^- ions, neither ion occurs in greater concentration and the water is neither acid nor basic. If greater concentrations of H+ ions occur, the water is acidic. If greater concentrations of OH- occur, the water is basic or alkaline. The relative acidity or alkalinity of a solution is its pH. It is determined by measuring the concentration of H^+ in soil solution and expressing it as the negative log of the H^+ ion concentration (eq. 3).

$$pH = - \log10 [H^+] \quad \text{[Equation 3]}$$

Many soil processes are pH-dependent. The disassociation of H^+ from soil organic matter results in a negative charge that contributes to CEC (known as pH-dependent charge). The activity of microorganisms responsible for organic matter decomposition and nutrient mineralization and the formation and stability of compounds that contain and control the availability of some essential nutrients are all affected by soil solution pH.

Soil pH must be kept within an appropriate range to maintain nutrient availability and to control disease. The best balance in nutrient availability occurs when pH is between 5.5 and 6.5. Under more acid conditions, nutrients that occur in solution as anions form low-solubility compounds and are removed from solution. This includes the micronutrient anions boron (B), chlorine (Cl^-) and molybdenum (Mo) as well as the macronutrient phosphorus (P). Under more alkaline conditions, insoluble compounds with copper (Cu), iron (Fe), magnesium (Mg), manganese (Mn), and zinc (Zn) form. For example, Altland (2006) showed that foliar chlorosis of red maple (*Acer rubrum* L.) seedlings in a commercial nursery was due to Mn deficiency in areas of high soil pH. Soil pH also affects disease. The effect of soil pH on damping off (*Fusarium, Rhizoctonia,* and *Phytopthora*) is well known in conifer and hardwood nurseries, and it is standard practice to maintain pH below 6.0 to control this fungal problem (Sutherland and Anderson 1980).

Buffering capacity. Control of pH depends on changing the proportion of the cation exchange complex comprised of H and Al cations. To raise soil pH, elements that can replace (exchange for) H and Al are added to the soil. Typically, Ca and Mg sources are added. To lower soil pH, materials that supply H and Al are added. These are typically elemental S or Al compounds. The amounts added depend not only on the desired pH change, but also the exchange capacity of the soil—its buffering capacity. Soils with a high cation exchange capacity will require more material to be added to effect the same change in pH than soils with a low cation exchange capacity. Thus, sandy soils with low CEC are poorly buffered and relatively small additions of base or acid-forming compounds will change the pH. Soils with greater clay content such as a clay-loam are well buffered and greater additions are required to alter soil pH to the same extent (fig. 3.7). Generally, a soil pH that is too high would only occur in hardwood nurseries when alkaline organic materials (such as some composts) have been inadvertently added in an effort to increase soil organic matter content.

Salinity and Sodicity. Any compound that is made up of positively and negatively charged components is a salt. Examples of salts with high solubility include sodium chloride (NaCl), sodium sulfate (Na_2SO_4), and calcium sulfate ($CaSO_4$). In water, these salts disassociate to their component ions, some of which are essential elements absorbed and used by plants. The sum of the concentration of all of these dissolved ions is termed "soil salinity" and is expressed as total dissolved solids (TDS) expressed as mass per unit volume such as milligrams per liter (mg L^{-1}). Saline soils occur when salt concentrations are so great that plants cannot draw water into the roots. Saline soils develop when salt in low-moderate salt concentration irrigation water builds up in the surface soil because of evaporation and transpiration without adequate leaching. Typically, excess salinity is only a problem for nurseries located in drier climatic regions or with poor-quality irrigation water.

Because charged ions of salts conduct electricity, and it is easy to measure the charge carrying capacity of a soil-water mix, salt concentrations are typically assessed by measuring electrical conductivity. Water is added to soil until the point that the soil is completely saturated and begins to flow and measurements are taken using a conductivity probe. These "saturated paste extracts" can be correlated with TDS. Conductivities greater than 2.0 dS m^{-1} (decisiemens per meter) are considered saline and nursery soils must be maintained below this conductivity. Ideally, the conductivity of nursery soils should be much lower, less than 0.5 dS m^{-1}.

Sodicity refers to the amount of the specific cation, Na, relative to other cations on the cation exchange complex. It is expressed as the exchangeable sodium percentage (ESP). Generally, when more than 15 percent of the cation exchange complex is Na, degradation of soil structure can occur. This is seldom a problem in tree nurseries.

Essential Elements

Thirteen mineral nutrients are recognized as being required for tree growth: the macronutrients nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sulfur (S), and the micronutrients iron (Fe), zinc (Zn), copper (Cu), manganese (Mn), boron (B), chlorine (Cl), and molybdenum (Mo). Several other elements have been shown to be beneficial for growth, but not essential. These include sodium (Na), cobalt (Co), nickel (Ni), selenium (Se), and silicon (Si). The macronutrients are constituents of proteins, components of cell

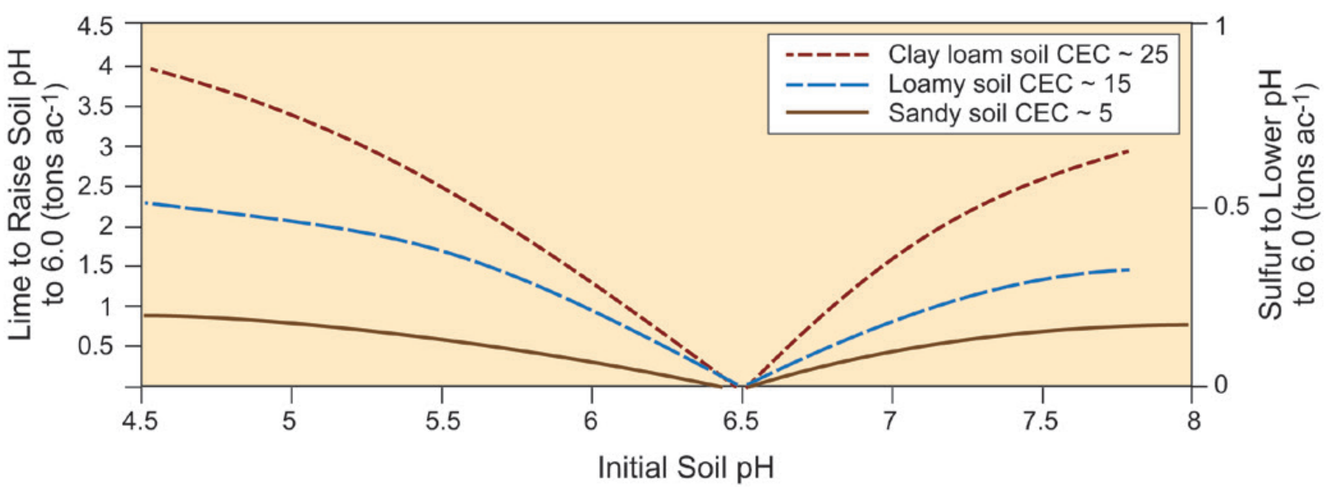

***Figure 3.7**—Approximate amounts of lime required to raise pH and sulfur required to lower pH to a target pH of 6.5 for soils of different texture. Note the differences in the axes. (Adapted from Havlin et al. 2005, Himelrick 2008.)*

walls and are involved in metabolic pathways and occur in plant tissue in high concentrations, normally from several hundredths to more than a percent of plant tissue by mass. The micronutrients occur in low concentrations from a few parts per million to several hundred parts per million.

Essential elements occur in the soil in a variety of chemical forms. The greatest quantity of essential elements is found bound within organic matter, adsorbed to soil surfaces, or in low-solubility compounds. Elements in these solid phases are not available for uptake and utilization by plants until they enter soil solution. Thus, nutrient availability depends on the mechanisms that release elements from solid forms into solution. Although each essential element is unique, it is possible to group elements with similar behaviors.

Nitrogen. Soil organic matter is important in the storage and release of all nutrients, but is always the dominant source of N in soils. When considered relative to annual requirements, little N occurs in plant-available forms at any one time and conversion of organic nitrogen to inorganic forms (mineralization) of NH_4^- (ammonification) and NO_3^- (nitrification), largely controls the quantity of N in soil solution. Factors that affect rates of decomposition such as soil moisture, temperature, and fertility affect mineralization of N.

An understanding of carbon to nitrogen ratio (C:N ratio) is important to understanding the effects of organic matter addition on N availability as it provides a rough estimate of the relative need for N by decomposing organisms involved in decomposition. When the amount of carbon is high and nitrogen low in organic materials (high C:N ratio), there is abundant energy and all available N is used by the decomposer community. Little N is released to soil solution, where it is available for plant uptake. When the C:N ratio is low, energy availability limits decomposer activity and excess N is leaked to the soil solution and can be absorbed by plants (fig. 3.8). Generally, N starts becoming available to the plant when about 35 percent of the original organic matter remains or when the C:N ratio is about 35:1.

Phosphorus. Phosphorus chemistry is complex and not easily grouped with other essential elements. It forms low-solubility compounds with Al and Fe at low soil pH (see below) and with Ca and Mg at high pH. It can be adsorbed on metal oxides and soil humus and its concentration in plant tissue and organic debris is high. In weathered soils of the South, particularly those with finer texture, P storage and availability is dominated by inorganic solubility reactions. However, organic matter decomposition and P mineralization may dominate storage and availability in sandy-textured nursery soils.

Sulfur. Like N, organic matter is usually the dominant source of S in surface soils. This is particularly true in the sandy-textured surface soils characteristic of most tree seedling nurseries. Consequently, S availability in surface soils is affected by factors impacting decomposition rate. Sulfur can be specifically adsorbed on surfaces of Fe and Al oxides coating clay particles, and specific ion adsorption is the dominant storage and availability-controlling mechanism in subsoils.

Base nutrients. The macronutrients K, Ca, and Mg are stored in large amounts in soil on the cation exchange

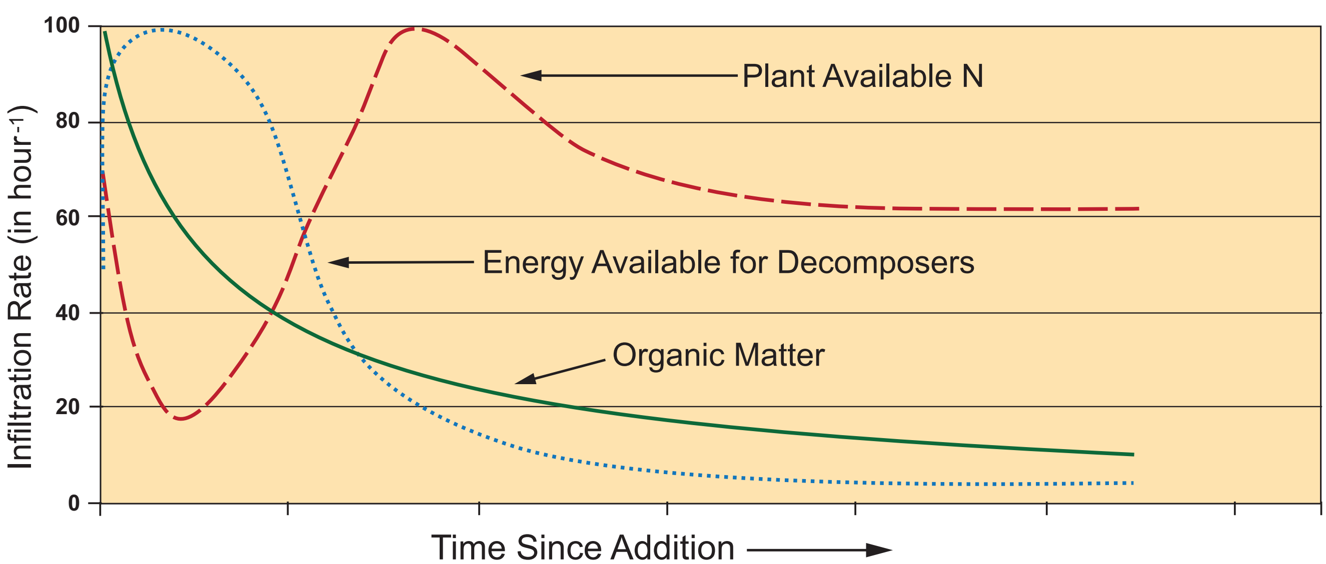

Figure 3.8—*Relationship among organic matter remaining, energy available for the decomposing community, and plant-available N after the addition of high C:N ratio organics to soil.*

complex; and the CEC is the primary available source of these nutrients. Weathering of primary minerals and mineralization of organic matter also releases these nutrients to solution, but these released nutrients quickly establish equilibrium with the CEC through exchange reactions. Hardwoods have a higher base nutrient demand than conifers and the fertilization of hardwood nurseries will result in the greater incorporation of base nutrients. For example, at high rates of N fertilization, P and K can become growth-limiting in hardwood nurseries (Birge et al. 2006).

Micronutrient cations. Micronutrient cations (Cu^{2+}, Fe^{3+}, Fe^{2+}, Mn^{2+}, Mn^{4+}, Zn^{2+}) can be adsorbed to the exchange complex in a manner similar to K, Ca, and Mg, but this is not the dominant source in soil. Instead, specific ion adsorption to soil organic matter is the major solid-phase storage of these nutrients at typical nursery soil pH. At high soil pH, micronutrient cations form low solubility compounds by combining with hydroxide (OH^-), which greatly reduces concentrations in soil solution. Thus, at high pH, solubility reactions will control plant availability of micronutrient cations. Deficiencies in micronutrient cations can become problematic at soil pH > 7.0.

Micronutrient anions. (B, Cl^-, Mo). The availability of the micronutrient anions is the reverse of the micronutrient cations. Boron and molybdenum both occur as oxyanions in solution. These oxyanions adsorb to metal oxides and form low-solubility compounds under acid conditions. These reactions control soil solution concentrations and plant availability in fine-textured, weathered soils. However, the primary storage and source of B in sandy soils is organic matter and B deficiencies have been reported in Florida, where organic matter concentration of a nursery on sandy soil with few primary minerals was allowed to fall to 1 percent (Stone et al. 1982).

Organic Matter

Contributions of Organic Matter to Healthy Soil

Organic matter concentration of undisturbed upland forest soils typical of the sites where tree nurseries are located could contain anywhere from 2- to 10-percent organic matter on a weight basis, depending on the location. These concentrations reflect the balance between inputs from fallen leaves, branches and bark, root exudates, and root production and mortality. However, organic matter content in forest nurseries is generally at the low end of this range. Undisturbed forest soils in the Southern United States may contain 5-percent organic matter, while tree nurseries will routinely use 1.5 to 3.0 percent as target organic matter content. In the cooler climates of the Pacific Northwest, forest soils can contain over 10-percent organic matter and nurseries may target 5 to 8 percent as a reasonable content (Davey 1996). Target ranges for organic matter depend on soil texture. Nurseries in the Southern United States with sandy-textured surfaces should contain 1.5- to 2.0-percent organic matter, and soils with loam-textured surfaces should contain 2.0- to 3.0-percent organic matter (May 1964).

The organic matter included in these percentages range from recently dead organic debris of obvious origin to amorphous black material that is a mix of fine particulate and colloids with origins that are not possible to determine. Fresh organic matter (corresponding to the Oi horizon of soil taxonomy) contains abundant energy and C and is the food that drives the decomposer community. It is nutrient-poor in relation to its energy content and, in the short-term, can be a sink rather than a source of nutrients. Humus, which is thoroughly decomposed amorphous organic matter, is at the opposite end of the spectrum. It is composed of complex molecules with numerous cross bonds that provide little energy for decomposers and is relatively stable. It contributes to a number of soil properties, but is relatively unimportant as an energy and C source to the decomposer community. Between these two end points exist a range of partially decomposed organic matter that have adequate energy and C to support a thriving decomposer community but that also release mineral nutrients to support plant growth.

Organic matter affects many soil characteristics and processes, and several of these have been previously discussed. Soil organic matter:

- is a primary storage site of N and is an important site for storing other essential elements,
- provides energy and carbon to heterotrophic organisms, including those microorganisms, responsible for nutrient mineralization and transformation and meso- and macrofauna whose activities create soil pores,
- helps bind individual soil articles into aggregates responsible for soil structure,
- influences the chemical activity of important essential elements,
- contributes to soil cation exchange,
- increases soil water-holding capacity,

- partially controls thermal characteristics of soils,
- affects activity and recommended rates of soil-applied pesticides.

Organic Matter Maintenance

The essential role of organic matter in soil processes makes its maintenance a critical goal of nursery soil management. Several factors contribute to the low-organic-matter content typical of nurseries. First, organic matter decomposition is at a maximum when soils are near-field-capacity moisture content and fertility is high. Nurseries are irrigated and fertilized precisely to maintain these conditions. Second, rapid decomposition of organic matter is supported by warmer temperatures. Exposure to the sun and raised beds contribute to more rapid warming of nursery beds in the spring. Third, the frequent tillage that occurs in nursery production breaks up the soil and exposes organic matter protected within structural aggregates to microbial populations. Under these conditions, frequent additions are necessary to maintain soil organic matter with optimal ranges.

Two approaches to organic matter addition are available. The first is to grow a green manure crop that can be tilled into the soil. The second is to add organic soil amendments.

Green manure crops. Crops are grown between seedling rotations for four basic purposes: (1) to protect against erosion, (2) to control weeds, (3) to serve as a "living mulch" to protect sown seeds from injury by wind, rain, or frost, and (4) to act as a green manure that can be tilled into the soil and increase organic matter content. Many combinations of crops and crop rotations are used—almost as many as the number of tree nurseries—and, in most cases, two or more of these four purposes are combined in crop selection.

Grains, such as rye (*Secale cereale* L.), *sorghum-sudangrass* (*Sorghum x drummondi* (Nees ex. Steud.) Millsp. & Chase), and wheat (*Triticum aestivum* L.), are commonly used in hardwood nurseries (Stauder 1993, Ensminger 2002) as both a living mulch and as a green manure. When used as a green manure, however, these crops are tilled into the soil rather than left on the surface. Corn (*Zea mays* L.) is also used as a summer cover crop. Legumes and buckwheat (*Fagopyrum esculentum* Moench.) are less frequently used because they have been associated with increased root disease (Davey 1996). When a 2-year cover crop rotation is used, woodier crops, such as pigeon pea (*Cajanus cajan* (L.) Millsp.), may be used in the first year (Davey 1996). Nurseries in the Pacific Northwest typically use rye and oats (*Avena sativa* L.) as green manures. Use of sorghum sudan grass, which is common in the Midwest and South, is associated with seedling mortality in the Pacific Northwest (Iyer 1979).

The impact that cover crops have on soil organic matter content is limited because the fresh organic matter added by these crops decomposes rapidly. A good cover crop produces 5 to 8 tons/acre (11.2 to 17.9 metric tons per hectare [ha]) of organic matter. If incorporated into the top 6 in (15.2 cm) of soil, this would increase organic matter by a maximum of 0.5 to 0.6 percent, but most of it decomposes rapidly. This is demonstrated by the results of Sumner and Bouton (1981) in their study of organic matter content change in a Georgia nursery following a two-year crop rotation. Summer crops of corn, sorghum (*Sorgum bicolor* L. Moench) and millet (*Pennisetum* spp.) increased organic matter content with the greatest increase—from 1.12 to 1.64 percent—observed for sorghum after the first crop. There was no additional increase after the second summer crop and winter cover crops had little effect on soil organic matter. These authors concluded that the increased organic matter content would be unlikely to persist, a conclusion reiterated by Davey (1996).

Organic amendments. In most nurseries, the use of green manure crops is not enough to maintain sufficient soil organic matter. Consequently, most nurseries also add organic amendments to the soil. Wood wastes such as sawdust and bark, peat moss, agricultural residues and manures are all potential sources of organic amendments (Rose et al. 1995, Davis et al. 2006, Koll et al. 2010).

It is important to distinguish between the two main uses of organic amendments: amendments spread on the soil and left on the surface as a mulch, and amendments tilled into the soil to improve organic matter content. While organic mulches will eventually decompose and be incorporated into soil organic matter, the immediate effects of mulches in nurseries are to protect the surface from erosion, conserve water, moderate surface soil temperature extremes, and reduce weed growth. Mulches have relatively little immediate impact on soil chemistry. In contrast, organic matter tilled into the soil decomposes rapidly and has both immediate and long-term effects on soil chemistry and nutrient availability.

Fresh woody materials such as sawdust or bark have high C:N ratios, typically greater than 100:1 and as high as 300:1. When these materials are incorporated into soil, microbial populations increase because of the abundance of C and energy to support growth and metabolism. However, because of the low amount of N, available N is quickly incorporated into the community of decomposing organisms. Little is available to support plant growth and N deficiency develops due to low plant availability (fig. 3.8). To a lesser extent this microbial demand also reduces availability of other nutrients. Under nursery conditions, the immobilization period that results from the addition of high C:N ratio woody materials ranges from 20 to 80 days, depending on the source of material (Davey 1996). Planting immediately after amendment with sawdust will reduce seedling growth (Koll et al. 2010). Thus, the use of sawdust or bark usually results in the need to either fertilize with N or to leave amended areas out of production until the material is partially decomposed and normal nutrient availability returns. As an alternative to inorganic fertilization, some nurseries mix high C:N ratio organic amendments with manures that have a low C:N ratio and can supply N.

The addition of composted materials will avoid some of the difficulties associated with the use of bark and sawdust amendments. Typically, composts are produced using a mix of organic materials with different C:N ratios, such as sawdust with municipal wastewater treatment plant biosolids or animal manures. Decomposition is promoted by maintaining proper moisture and providing adequate aeration, so oxygen does not limit aerobic decomposition. After a relatively short period of several weeks to several months, a compost is produced that can be incorporated into the soil and immediately planted. Gouin et al. (1978) reported both yellow poplar (*Liriodendron tulipifera* L.) and red maple stem length increased following addition of a compost of wood chips and municipal sludge (fig. 3.9).

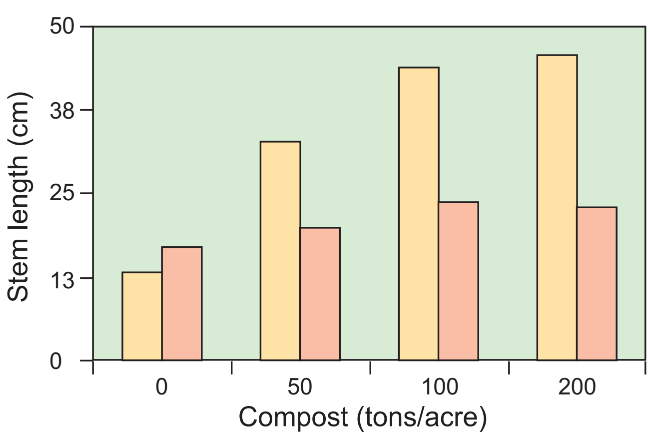

***Figure 3.9**—Effect of compost made from a 3:1 mixture of wood chips and municipal sludge on the growth of yellow poplar (yellow bars) and red maple (red bars) in a nursery (Gouin et al. 1978).*

Composts are characterized by "stability" and "maturity." Stable composts have completed the rapid phase of decomposition and no longer have high nutrient demands and are, instead, slowly releasing N available for plant uptake. "Mature" composts have undergone sufficient decomposition that few volatile compounds or potentially toxic fatty acids or phenols remain. Soil incorporation of unstable or immature composts can result in N deficiency and introduction of weeds to the nursery. Similarly, insufficiently composted materials (immature composts) may introduce allelopathic chemicals. Composts made with cedar (*Juniperus virginiana* L.), eucalyptus (*Eucalyptus* spp.), pecan (*Carya illinoensis* Wangenh. K. Koch), and walnut (*Juglans nigr*a L.) are all potentially allelopathic and must be composted before use.

Composts used in nurseries should have a pH between 5.5 and 6.5. Many composts made using biosolids from wastewater treatment facilities or animal manures have a high pH because of the use of lime for pathogen or odor control. Use of such composts as a soil amendment can result in long-term problems due to elevated pH, such as occurred at the Saratoga Tree Nursery in New York (Bicklehaupt 1989).

There is consensus among nursery managers that soil organic matter maintenance is important in tree nurseries and increases in soil organic matter can increase tree growth. If measured immediately after addition, soil organic matter content increases about 0.1 percent for each dry ton of organic amendment added. However, the effects of a one-time addition of organic matter are short-lived. For example, Mexal and Fisher (1987) studied the effects of a single application of sewage sludge, peat moss, pine bark and sawdust on the organic matter content of a nursery soil in New Mexico. Regardless of the amendment or rate applied, nursery soil organic matter contents returned to preapplication levels within 2 years of application. Similarly, Munson (1982) reported that the addition of 245 tons per acre (550 metric tons per ha) of sawdust raised soil organic matter to almost 5 percent in a sandy textured Florida nursery, but in less than 3 years, soil organic matter contents had fallen to pretreatment levels of 1.3 percent. In contrast to these studies, May and Gilmore (1985) showed that increases in organic matter content could be sustained with repeated additions. Thus, it appears that a combination of green manure crops and repeated applications of organic amendments are necessary to maintain nursery soil organic matter content at desired levels.

References

Allmaras, R.R.; Juzwik, J.; Overton, R.P.; Copeland, S.M. 1993. Soil compaction: causes, effects and management in bareroot nurseries. In: Landis, T.D., tech coord. National Nursery Proceedings, Proceedings Northeastern and Intermountain Forest and Conservation Nursery Association. Gen. Tech. Rep. RM-243. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station: 19–32

Altland, J. 2006. Foliar chlorosis in field-grown red maples. Hortscience: 41(5): 1347–1350.

Barnard, E.L. 1990. Ground line heat lesions on tree seedlings. Florida Department of Agriculture & Consumer Services, Division of Plant Industry. Plant Pathology Circular 338. 2 p.

Barnard, E.L. 1996. Diseases of seedlings in forest tree nurseries in Florida: history and status. In: Third meeting of IUFRO Working Party S7.03-04 (Diseases and Insects in Forest Nurseries). Orlando-Gainesville, FL.

Bickelhaupt, D. 1989. The long-term effect of a single application of horse manure on soil pH. Tree Planters' Notes. 40(1): 31–33.

Birge, Z.K.; Salifu, D.K.F.; Jacobs, D.F. 2006. Modified exponential nitrogen loading to promote morphological quality and nutrient storage of bareroot-cultured *Quercus rubra* and *Quercus alba* seedlings. Scandinavian Journal of Forest Research. 21: 306–316.

Bosch, L. 1986. Site preparation and soil management in a high silt nursery. National Nursery Proceedings, Southern Forest Nursery Association. Pensacola, FL: 16–17.

Boyer, J.N; South, D.B. 1984. Forest nursery practices in the South. Southern Journal of Applied Forestry. 8(2): 67-75.

Briggs, R.D. 2008. Soil and nutrition: a forest nursery perspective. In: Dumroese, R.K.; Riley, L.E., tech. coords. National Proceedings Forest and Conservation Nursery Associations; 2007. RMRS-P-57. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 55–64.

Da Silva, A.P.; Kay, B.D.; Perfect, E. 1994. Characterization of the least limiting water range of soils. Soil Science Society of America Journal. 58: 1775–1781.

Davey, C.B. 1996. Nursery soil management-organic amendments. In: Landis T.D.; South, D.B., tech. coords. National Proceedings, Forest and Conservation Nursery Associations. Southern Forest Nursery Association. PNW-GTR-389. Portland, OR: U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station: 6–18.

Davis, A.S.; Jacobs, D.F.; Wightman, K.E.; Birge, Z.K.D. 2006. Organic matter added to bareroot nursery beds influences soil properties and morphology of *Fraxinus pennsylvanica* and *Quercus rubra* seedlings. New Forests. 31: 293–303.

Dong, S.; Scagel, C.F.; Cheng, L. [et al.]. 2001. Interactions between soil temperature and plant growth stage on nitrogen uptake and amino acid content of apple nursery stock during early spring growth. Tree Physiology. 21: 541–547.

Ensminger, P. 2002. Nursery practices in Tennessee. In: Dumroese, R.K.; Riley, L.E.; Landis, T.D., tech. coords. National Proceedings Forest and Conservation Nursery Associations; 1999, 2000 and 2001, Western Forest and Conservation Nursery Association Conference. RMRS-P-24. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station: 281–283.

Gouin, F.R.; Link, C.B.N.; Kundt, J.F. 1978. Forest tree seedlings thrive on composted sludge. Compost Science. 19(4): 28–30.

Hartmann, H.R. 1970. Results of nursery management on a heavy-textured soil. National Nursery Proceedings, Southeastern Nurseryman's Conference: 69–72.

Havlin. J.L.; Beaton, J.D.; Tisdale, J.D.; Nelson, W.L. 2005. Soil fertility and fertilizers: an introduction to nutrient management. 7th ed. Upper Saddle River, NJ: Pearson-Prentice Hall. p. 63.

Himelrick, D.G. 2008. Home blueberry production in Louisiana. Louisiana State University AgCenter Research and Extension. 7p. (http://www.lsuagcenter.com/NR/rdonlyres/D30270C0-F2DC-4B33-8AB7-036865AB6AAE/43116/pub1978HomeBlueberryProductionHIGHRES.pdf). (March 20, 2018).

Iyer, J.G. 1979. Sorghum-sudan grass manure: its effect on nursery stock. University of Wisconsin Short Communication 4082, Madison, WI. 4 p.

Koll, P.; Jurgensen, M.F.; Dumroese, R.K. 2010. Effects of pine sawdust, hardwood sawdust and peat on bareroot soil properties. In: Riley, L.E.; Pinto, J.R.; Dumroese, R.K., tech. coords. National Proceedings Forest and Conservation Nursery Associations. RMRS-P-62. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station: 71–75.

May, J.T. 1995. Chapter 2: Site selection. In: Landis, T.; Tinus, R.; McDonald S.; Barnett, J. eds. The Container Tree Nursery Manual—Volume 1: Nursery Planning, Development and Management. Agric. Handb. 674. Washington, DC: U.S. Department of Agriculture, Forest Service: 27–46.

May, J.T. 1964. The forest nursery and its soils. National Nursery Proceedings, Proceedings Region 8 Forest Nurseryman's Conference: 3–9.

May, J.T.; Gilmore A.R. 1985. Continuous cropping at the Stauffer nursery in Alabama. In: South, D.B. ed. Proceedings of Symposium on Nursery Management Practices for Southern Pines: 213–221.

Mexal, J.G.; Fisher, J.T. 1987. Organic matter amendments to a calcareous forest nursery soil. New Forests. 4: 311–323.

Munson, K.R. 1982. Decomposition and effect on pH of various organic soil amendments. In: Proceedings of Southern Nursery Conference. R8-TP4. U.S. Department of Agriculture, Forest Service: 121–130.

Peevy, C.E. 1976. Hardwood nursery management: problems that can and do occur in the nursery and how these problems can be avoided and solved. National Nursery Proceedings, Southeastern Area Nurserymen's Conference: 4–7.

Rose, R.; Haase, D.L.; Boyer, D. 1995. Organic matter management in forest nurseries: theory and practice. Corvallis, OR: Oregon State University, Nursery Technical Cooperative. 655 p.

Schoeneberger, P.J.; Wysocki, D.A.; Benham, E.C.; Broderson, W.D. 1998. Field book for describing and sampling soils. Lincoln, NE: U.S. Department of Agriculture, Natural Resources Conservation Service. 182 p.

Stauder, A.F. 1993. The use of green over winter mulch in the Illinois State Nursery program. In: Landis, T.D., tech coord. National Nursery Proceedings, Proceedings Northeastern and Intermountain Forest and Conservation Nursery Association. Gen. Tech. Rep. RM-243. Fort Collins, CO: U.S. Department of Agricultures Forest Service, Rocky Mountain Forest and Range Experiment Station: 51–53.

Stoeckeler, J.H.; Jones, G.W. 1957. Forestry nursery practice in the Lake States. Agric. Handb. 110. Washington, DC: U.S. Department of Agriculture, Forest Service. 124 p.

Stone, E.L.; Hollis, C.A.; Barnard, E.L. 1982. Boron deficiency in a southern pine nursery. Southern Journal of Applied Forestry. 6(2): 108–112.

Stroup, M.C.; Williams, H.M. 1999. Frost heaving of container hardwood seedlings planted in an abandoned agricultural field in Sharkey County, Mississippi. In: Haywood, J.D., ed. Proceedings Tenth Biennial Southern Silviculture Research Conference. Gen. Tech. Rep. SRS 30. Asheville, NC: U.S. Department of Agriculture, Forest Service: 148–150.

Sumner, M.E.; Bouton, J.H. 1981. Organic matter maintenance in forestry nurseries. Georgia Forest Research Paper 24. Macon, GA: Georgia Forestry Commission. 6 p.

Sutherland, J.R.; Anderson, R.L. 1980. Seedling disease and insect problems related to nursery soil conditions in North America. Proceedings, North American Forest Tree Nursery Soils Workshop: 182-190.

U.S. Department of Agriculture (USDA), National Resources Conservation Service (NRCS). 2011. Technical Soil Services Handbook. http://soils.usda.gov/technical/tssh/. (August 3).


INTERNATIONAL