Fertilization

11

Douglass F. Jacobs and Thomas D. Landis

Fertilization is one of the most critical components of producing high-quality nursery stock. Seedlings rapidly deplete mineral nutrients stored within seeds, and cuttings have limited nutrient reserves. Therefore, to achieve desired growth rates, nursery plants must rely on root uptake of nutrients from the growing medium. Plants require adequate quantities of mineral nutrients in the proper balance for basic physiological processes, such as photosynthesis, and to promote rapid growth and development. Without a good supply of mineral nutrients, growth is slowed and plant vigor reduced. Proper fertilization can promote growth rates three to five times greater than normal.

In this chapter, the importance of fertilization to plant growth development is briefly described and typical fertilization practices for producing native plants in small tribal nurseries are detailed.

BASIC PRINCIPLES OF PLANT NUTRITION

A common misconception is that fertilizer is "plant food" (figure 11.1A), but the basic nutrition of plants is very different from that of animals. Using the green chlorophyll in their leaves, plants make their own food, called "carbohydrates," from sunlight, water, and carbon dioxide in a process called "photosynthesis" (figure 11.1B). These carbohydrates provide energy to the plant, and when combined with mineral nutrients absorbed from the soil or growing medium, carbohydrates are used to synthesize proteins and other compounds necessary for basic metabolism and growth.

Adding controlled-release fertilizer to kinnikinnick by Tara Luna.

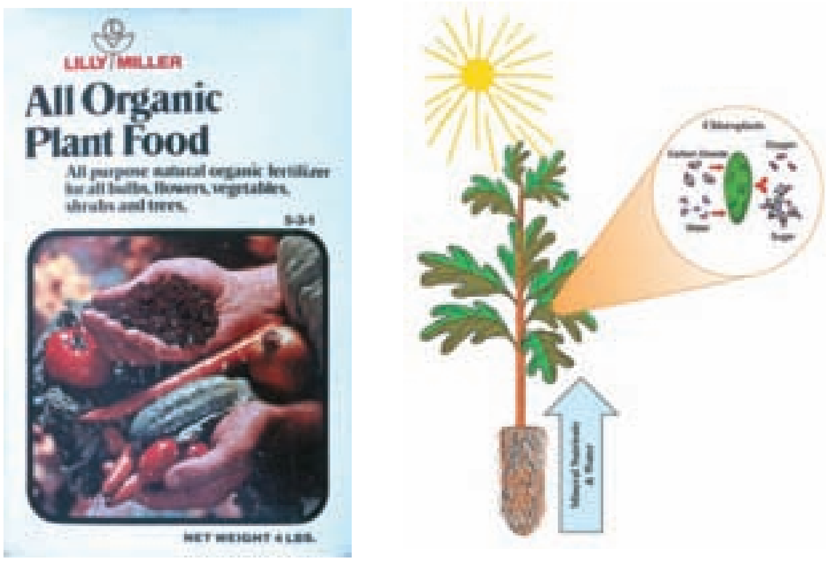

Figure 11.1—*(A) Although some fertilizers are advertised as "plant food," (B) plants create their own food through the process of photosynthesis in their green leaves.* Photo by Thomas D. Landis., illustration by Jim Marin.

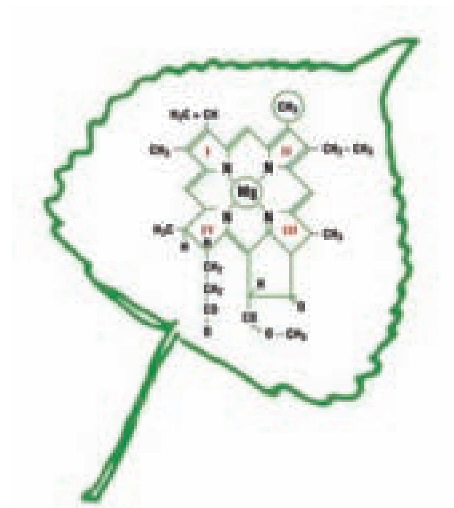

Figure 11.2—*Mineral nutrients such as nitrogen and magnesium are important components of chlorophyll molecules, which give leaves their green color and are essential for photosynthesis.* Illustration by Jim Marin.

Although many different factors influence plant growth, the growth rate and quality of nursery stock is largely dependent on mineral nutrient availability. When nutrients are supplied in proper amounts, in the proper ratio, and at the proper time, nursery plants can achieve growth rates many times faster than in nature. High-quality nursery stock can even be fortified with surplus nutrients that can accelerate growth after outplanting.

Thirteen mineral nutrients are considered essential to plant growth and development and are divided into macronutrients and micronutrients based on the amounts found in plant tissue (table 11.1). Mineral nutrients can have a structural function. For example, nitrogen is found in all proteins, and nitrogen and magnesium are structural components of chlorophyll molecules needed for photosynthesis (figure 11.2). Having knowledge of these functions is practical because a deficiency of either nutrient causes plants to be chlorotic (that is, yellowish in color). Other mineral nutrients, have no structural role, but potassium, for example, is critically important in the chemical reaction that causes stomata in leaves to open and close.

Nitrogen is almost always limiting to plant growth in nature, which is the reason why nitrogen fertilizer is applied frequently in nurseries. Nitrogen fertilization is one of the main reasons for the rapid growth and short production schedules of nurseries, and a nitrogen deficiency often shows up as stunted growth.

Many container nurseries that grow native plants use artificial growing media such as peat moss and vermiculite. Because media are essentially infertile, nurseries either incorporate a starter dose of fertilizer or start liquid fertigation (irrigation water containing liquid fertilizer) soon after germination.

An important concept to understand in regard to fertilization is Liebig's Law of the Minimum. This law states that plant growth is controlled by the mineral nutrient in shortest supply, even when sufficient quantities of other nutrients exist. See Chapter 4, *Propagation Environments*, for more discussion about limiting factors. Thus, a single nutrient element may be the only factor limiting to plant growth even if all other elements are supplied in sufficient quantity. A good way to visualize the concept of limiting factors is a wooden bucket with staves of different lengths. If water is poured into the bucket, it can be filled only to the height of the shortest stave—the limiting factor. As mentioned previously, nitrogen is almost always limiting in natural soils (figure 11.3).

Just as important as the absolute quantities of nutrients in the growing media is the balance of one nutrient to another. The proper balance of nutrients to one another seems to be relatively consistent among plant species. A common reference is Ingestad's Ratios, which suggests a ratio of 100 parts nitrogen to 50 phosphorus, to 15 potassium, to 5 magnesium, to 5 sulfur.

Table 11.1—The 13 essential plant nutrients (divided into macronutrients and micronutrients), common percentages of these nutrients within plant tissues, and examples of physiological functions necessary to promote healthy plant development

Element	Percentage of Plant Tissue (ovendry weight)	Examples of Structural or Physiological Functions
Macronutrients		
Nitrogen (N)	1.5	Amino acid and protein formation
Phosphorus (P)	0.2	Energy transfer
Potassium (K)	1.0	Osmotic adjustment
Calcium (Ca)	0.5	Formation of cell walls
Magnesium (Mg)	0.2	Enzyme activation, constituent of chlorophyll
Sulfur (S)	0.1	Amino acid formation, protein synthesis
Micronutrients		
Iron (Fe)	0.01	Component of chloroplasts, RNA synthesis
Manganese (Mn)	0.005	Enzyme activation
Zinc (Zn)	0.002	Enzyme activation, component of chloroplasts
Copper (Cu)	0.0006	Component of chloroplasts, protein synthesis
Boron (B)	0.002	Transport of assimilates and cell growth
Chlorine (Cl)	0.01	Maintenance of cell turgor
Molybdenum (Mo)	0.00001	Component of enzymes

On a practical basis, most native plant nurseries use complete fertilizers that contain a balance of most mineral nutrients. Some nutrients, notably calcium and magnesium, are very insoluble in water and can even cause solubility problems in concentrated fertilizer solutions. So, if they are not present naturally in the irrigation water, they must be added to the growing medium as dolomite or in a separate fertilizer solution.

ACQUISITION OF MINERAL NUTRIENTS

Plants produced in container nurseries may acquire nutrients from several different sources, including the growing medium, irrigation water, beneficial microorganisms, and fertilizers. The inherent infertility of most commercial growing media was mentioned earlier and is discussed in detail in Chapter 5, *Growing Media*. Levels of mineral nutrients in peat-vermiculite media are generally very low, but native soils, including composts, may contain significantly higher nutrient concentrations than do commercial growing media. When using a good soil or compost-based medium, the substrate may contain enough nutrients for sufficient plant growth. These mixes, however, often tend to be nutrient deficient in some way and deficiencies of any single nutrient can significantly limit plant growth. Thus, if homemade growing media will be used, a soil test will reveal which nutrients may be lacking (see details on testing in a following section).

Figure 11.3— *The concept of limiting factors can be illustrated by a wooden bucket that can be filled only to the shortest stave.* Illustrated by Steve Morrison.

Another potential source of mineral nutrients in container nurseries is irrigation water. Usually only a few mineral macronutrients (sulfur, calcium, magne-

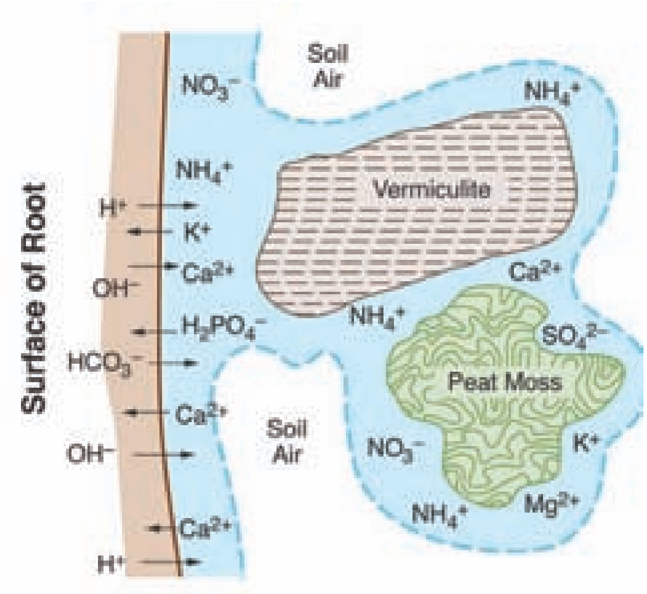

Figure 11.4—*Nutrients are extracted by plant roots through an exchange process with soil, compost, or artificial growing media.* Illustration by Jim Marin.

Figure 11.5—*Several different types of fertilizer products, including (A) organic fish emulsion, (B) inorganic granular ammonium nitrate, (C) and an inorganic water-soluble fertilizer. (D) A fertilizer label must show required description of fertilizer nutrient concentrations.* Photos by Thomas D. Landis.

sium) are found in nursery water supplies. Beneficial microorganisms may provide an important source of nitrogen for some species, such as legumes, as detailed in Chapter 14, *Beneficial Microorganisms*. To achieve the desired high growth rates, however, fertilizers are the most common source of mineral nutrients in native plant nurseries. Although fertilizers are powerful horticultural tools, nutrient interactions and the possibility of salt injury from excessive fertilization often occur. In the remainder of this chapter, some of the important considerations when applying fertilizers are discussed.

Mineral nutrients are absorbed by root hairs as two types of ions: cations and anions (figure 11.4). Cations have an electrically positive charge, while anions are negatively charged. Particles of soil, compost, and artificial growing medium are also charged, so nutrient ions can attach to organic matter or clay particles of an opposite charge. Ions may also be chemically bound to minerals, particularly under conditions of high or low media pH. Typically, roots exchange a cation (often H^+) or an anion (for instance, HCO_3^-) for a nutrient ion from the soil or growing media; see Chapter 5, *Growing Media*, for more information on this topic.

Soluble fertilizers are chemical salts that dissolve in water into mineral nutrients. Plant roots are very sensitive to high salinity, so growers must be careful not to apply too much fertilizer. Because all salts are electrically charged, growers may easily monitor levels of fertilizer nutrients in irrigation water or in the growing medium by measuring electrical conductivity (EC). This process is discussed in detail in Chapter 10, *Water Quality and Irrigation,* and in the monitoring and testing section later in this chapter.

TYPES OF COMMERCIAL FERTILIZERS

Many different types of fertilizers are available for use in native plant nurseries (figures 11.5A–C) and vary according to their source materials, nutrient quantities, and mechanisms of nutrient release. All commercial fertilizers are required by law to show the ratio of nitrogen to phosphorus to potassium (actually to the oxides of phosphorus and potassium; $N:P_2O_5:K_2O$) on the package (figure 11.5B). In addition, most show a complete nutrient analysis on the label (figure 11.5D).

Some fertilizers contain only one mineral nutrient whereas others contain several. Examples of single-nutrient fertilizers include ammonium nitrate (34-0-0)

Figure 11.6—*Many tribal nurseries use organic fertilizers to reduce environmental impacts.* Photo by Thomas D. Landis.

(figure 11.5B), urea (46-0-0), and concentrated superphosphate (0-45-0). Multiple-nutrient fertilizers may be blended or reacted to provide two or more essential nutrients. An example of a blended fertilizer is a 12-10-8 + 4 percent magnesium + 8 percent sulfur + 2 percent calcium product, which was formed by adding triple superphosphate (0-46-0), potassium magnesium sulfate (0-0-22 plus Mg and S), and ammonium nitrate (34-0-0). An example of a reacted multiple nutrient fertilizer is potassium nitrate (13-0-44).

Organic Fertilizers

Historically, all fertilizers were organic and applied manually. Organic fertilizers are often not well balanced and the release of nutrients can be unpredictable—either too fast or too slow. Some tribes, however, are using organic materials with great success in native plant nurseries (figure 11.6), showing that experience may lead to the successful identification of organic fertilizer options. Examples of organic fertilizers include animal manure, sewage sludge, compost, fish emulsion (figure 11.5A), and other animal wastes. Because plants take up all their mineral nutrients as ions, it does not matter whether the ions came from an organic or an inorganic (synthetic) source. Many people are concerned about the higher energy input to create inorganic fertilizers and therefore prefer to use organic sources.

An obvious advantage of inorganic fertilizers is that they are widely available and relatively inexpensive. A disadvantage is that many are bulky, heavy, or unpleasant to handle. In many cases, however, organics such as manure may be free if the nursery provides labor and transport. Most organic fertilizers have relatively low nutrient analyses (table 11.2), although actual concentrations may vary considerably depending on the type of material and stage of decomposition. On the one hand, an advantage of the low-nutrient concentrations of organic fertilizers, such as compost, is that it is more difficult to apply excessive amounts of fertilizer, to "overfertilize," but other organic fertilizers, such as fresh chicken manure, could damage plants. On the other hand, the low levels of nutrients provided by organic materials may be insufficient to achieve the rapid plant growth expected of nursery stock and to have plants reach an acceptable size for outplanting within a desired time frame. Anyone considering the use of bulk organic fertilizers should have them tested first to establish the need for composting, determine

Table 11.2—Mineral nutrients supplied by a variety of organic materials (from Jaenicke 1999)

Source	Nitrogen (% N)	Phosphorus (% P_2O_5)	Potassium (% K_2O)
Manures			
Cow	0.35	0.2	0.1 – 0.5
Goat/sheep	0.5 – 0.8	0.2 – 0.6	0.3 – 0.7
Pig	0.55	0.4 – 0.75	0.1 – 0.5
Chicken	1.7	1.6	0.6 – 1.0
Horse	0.3 – 0.6	0.3	0.5
Compost	0.2 – 3.5	0.2 – 1.0	0.2 – 2.0
Fish emulsion	5.0	2.0	2.0
Kelp	1.0	0.2	2.0

Table 11.3—Advantages and disadvantages of controlled-release fertilizers compared with immediately available fertilizers

Advantages

— Better suited to the longer term nutrient requirements of perennial species
— Extended nutrient availability with single applications
— Potential improvement in efficiency of fertilizer use, leading to decreased leaching of nitrogen and other nutrients from the nursery
— Potential reduction in salt damage to root systems
—More conducive to beneficial microorganisms

Disadvantages

— Cost is higher (this may be alleviated somewhat by labor and machine application savings)
— Availability may be limited in some locales
— Nutrient release rates can be unpredictable in nurseries
— More difficult to adjust nutrient inputs to match needs based on growing cycle

proper application rates, and identify potential nutrient toxicities or deficiencies.

Inorganic Fertilizers

With the advent of inorganic (synthetic) fertilizers, the use of organic fertilizers has declined over the years. Nutrients in synthetic materials are derived either from mine extraction or by chemical reaction to capture nitrogen from the atmosphere. These products are readily available at most garden supply shops and through horticultural dealers.

Although these fertilizers work consistently well, it should be noted that some organic options can provide significant nutrition to plants, as described previously. Sometimes, growers of native plants tend to favor organic over inorganic fertilizers due to simple preference. Experimentation and experience will help to determine the best fertilizer type for your nursery.

Immediately Available versus Controlled-Release Inorganic Fertilizers

Two general categories of inorganic fertilizer materials are those with immediately available forms of nutrients and those that release nutrients slowly over time ("slow-release" or "controlled-release" fertilizers). These two forms have several notable advantages and disadvantages (table 11.3).

Fertilizers immediately available to plants include water-soluble fertilizers commonly used in container nurseries (figure 11.5C). Other immediately available fertilizers, such as urea, are seldom used in native plant nurseries. Soluble fertilizers are typically injected into the irrigation system, a process known as fertigation (see the discussion in the following section). Their popularity stems from the fact that the application rates can be easily calculated, distribution is as uniform as the irrigation system, the nutrients are readily available, and, if properly formulated and applied, the chance of fertilizer burn is very low.

All controlled-release fertilizers are synthetic, including plastic-coated fertilizers and those manufactured from nitrogen reactions. Coated fertilizers consist of a water-soluble fertilizer core covered with a less-insoluble barrier, which affects the nutrient release rate. Coatings must be thin and free of imperfections, which is challenging because fertilizer granules are relatively porous, rough, and irregularly surfaced.

The most common coatings for controlled-release fertilizers are sulfur or a polymer material. With sulfur-coated products, nutrients are released by water penetration through micropores or incomplete sulfur coverage. These materials are typically less expensive than polymer-coated fertilizers. Nutrient release rates, however, are less consistent than those with polymer-coated fertilizers. For example, with sulfur-coated urea, a rapid initial release of nutrients is followed by a rapidly decreasing release rate.

Polymer-coated fertilizers (figure 11.7) are considered the "state of the art" controlled-release fertilizer for horticultural plant production and are widely used in native plant nurseries. The round, polymer-coated "prills" have a more uniform nutrient release than sulfur-coated products. In addition, the prills can be formulated to contain the proper balance of both macronutrients and micronutrients, whereas sulfur-coated products generally release only nitrogen. Note that calcium is the only nutrient missing from a popular controlled-release fertilizer (table 11.4).

Nutrient release from polymer-coated fertilizer is a multistep process. During the first irrigation, water vapor is absorbed through microscopic pores in the coating. This process creates an osmotic pressure gradient within the prill, causing the flexible polymer coating to expand. This expansion enlarges the tiny pores and the mineral nutrients are released into the soil or growing medium (figure 11.8). Besides water, temperature is the primary factor affecting the speed of this process, so nutrient release generally increases with rising temperature. Release rates of polymer-coated products are adjusted by the manufacturer by altering the thickness and nature of the polymer material, and longevities vary from about 3 to 16 months. Popular brands of polymer-coated fertilizers include Osmocote®, Nutricote®, and Polyon®.

Another category of controlled-release fertilizers are the nitrogen-reaction products, such as ureaform and IBDU Micro Grade Fertilizer. These fertilizers are created through a chemical reaction of water-soluble nitrogen compounds, which results in a more complex molecular structure with very limited water solubility. The rate of nutrient release of ureaform is controlled by many factors, including soil temperature, moisture, pH, and aeration, while IBDU becomes available primarily through hydrolysis. These materials are rarely used in native plant container production but are more commonly applied at outplanting.

FERTILIZER APPLICATION

Fertigation

Most forest and conservation nurseries apply soluble fertilizers through their irrigation systems, a process known as fertigation. The fertigation method varies depending on the type of irrigation and the size and sophistication of the nursery. The simplest method is to combine soluble fertilizers (figure 11.9A) in a watering container or use a hose injector (figure 11.9B), and water plants by hand. This method can be tedious and time consuming, however, when fertigat-

Figure 11.7—*Polymer-coated fertilizers occur as round "prills" in which nutrients are encapsulated by a plastic coating that controls the rate of nutrient release.* Photo by Douglass F. Jacobs.

Table 11.4—Nutrient analysis of 15-9-12 Osmocote® Plus controlled release fertilizer (from The Scotts Company 2006)

Mineral Nutrient	Percentage
Macronutrients	
Nitrogen (7% ammonium; 8% nitrate)	15.0
Phosphorus (P_2O_5)	9.0
Potassium (K_2O)	12.0
Calcium	0.0
Magnesium	1.0
Sulfur	2.3
Micronutrients	
Iron (chelated 0.23%)	0.45
Manganese	0.06
Zinc	0.05
Copper	0.05
Boron	0.02
Molybdenum	0.02

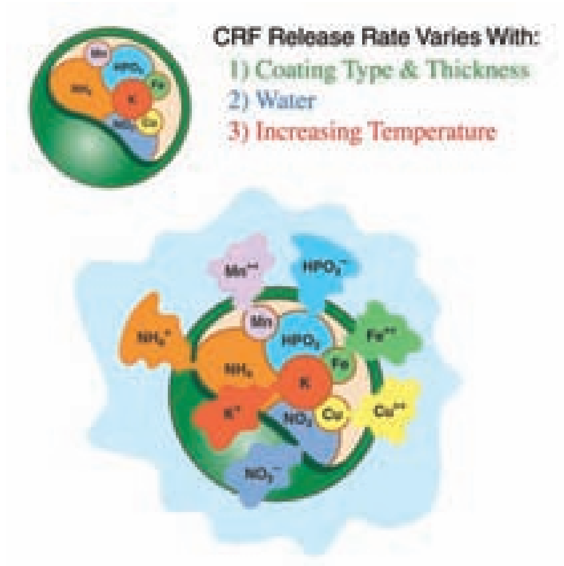

Figure 11.8—*Nutrient release from polymer-coated fertilizers occurs after water is absorbed through the prill membrane, creating an osmotic pressure gradient that expands the pores within the coating and allows fertilizer nutrients to pass through to the growing medium.* Illustration by Jim Marin.

ing a large quantity of plants. Nonetheless, this method may be best when growing a variety of species with different fertilizer needs in small areas.

Fertilizer injectors are used when growing large numbers of plants with the same fertilizer requirements. The simplest injectors are called siphon mixers and the HOZ Hozon™ and EZ-FLO® are common brands. Siphon injectors are attached to the water faucet and have a piece of rubber tubing that is inserted into a concentrated fertilizer solution (figure 11.9C). When an irrigation hose is attached to the other end and the water is turned on, the flow through the hose causes suction that pulls the fertilizer stock solution up and mixes it with the water at a fixed ratio. For example, the Hozon™ injects 1 part of soluble fertilizer to 16 parts of water, which is a 1:16 injection ratio. Note that this injector requires a water pressure of at least 30 pounds per square inch (psi) to work properly whereas the EZ-FLO® functions at water pressures as low as 5 psi.

More complicated but more accurate fertilizer injectors cost from around $300 to more than $3,000. For example, the Dosatron® is a water pump type of injector that installs directly into the irrigation line and pumps the fertilizer solution into the irrigation pipe at a range of injection ratios (figure 11.9D).

Any injector must be calibrated after it is installed to verify the fertilizer injection ratio and then must be

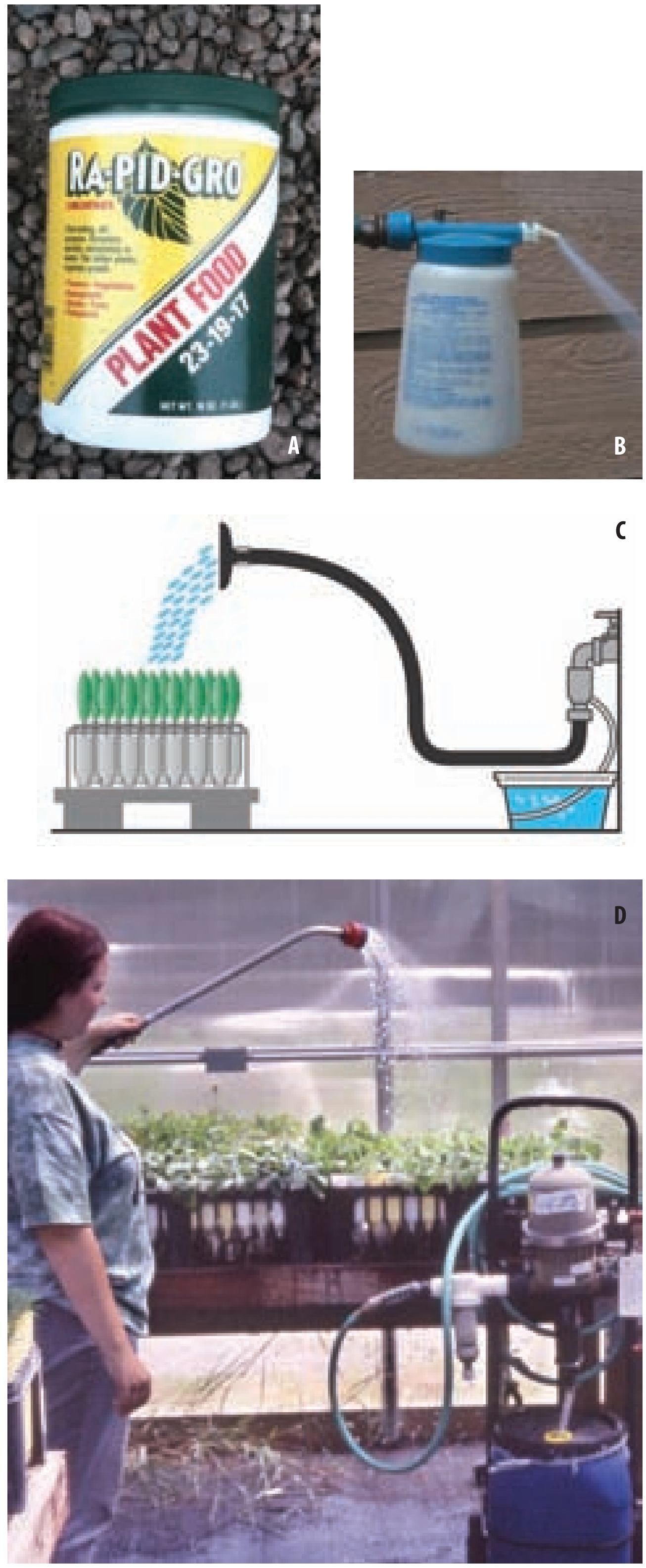

Figure 11.9—*(A) Soluble fertilizers can be mixed with water and applied to the crop, a process called "fertigation." (B) The liquid fertilizer solution can be applied in a watering can or through a hose-end sprayer. (C) A siphon injector sucks up concentrated soluble fertilizer solutions and mixes it with irrigation water that can be applied with a hose. (D) The Dosatron® injector allows more precise control of injection ratios.* Photos A and B by Thomas D. Landis, D by Tara Luna, illustration from Dumroese and others (1998).

checked monthly to make sure that it is still working properly. Among the most technologically advanced fertigation systems is the automated hydraulic boom, which provides very consistent and uniform coverage of water and fertilizer to the crop. The relatively high price of irrigation booms makes them cost prohibitive for many small native plant nurseries.

Special types of water-soluble fertilizers are sometimes applied directly to the crop to stimulate uptake through the foliage ("foliar feeding"). Although this method seems to be a good way to fertilize, remember that all leaves are covered with a water-repelling cuticle, so foliar feeding is very inefficient. More nutrient uptake actually occurs through the roots as a result of the fertilizer solution washing down into the soil or growing medium rather than through the foliage itself. Special care must be taken to prevent salt damage to foliage, so we do not recommend foliar feeding for smaller nurseries.

Applying Granular or Controlled-Release Fertilizers

Applying dry fertilizers directly to the tops of the containers ("topdressing"), should never be attempted with granular dry fertilizers because of the possibility of "burning" plants with succulent tissue. Controlled-release fertilizers can be topdressed, however, if care is taken to make sure that each container or cell receives an equal number of prills (figure 11.10A). A special drop-type application wand can be used to topdress larger (> 1-gal [4-L]) containers because a measured dose of fertilizer can be applied to the base of each plant. This method avoids the potential of fertilizer granules being lodged in foliage and burning it as soon as the crop is watered.

A better option for applying dry granular fertilizers or controlled-release prills is to incorporate them into the growing medium (figure 11.10B). The only time dry granular fertilizers are used is when a "starter dose" is incorporated into the growing medium by the manufacturer. The incorporation of controlled-release fertilizers, however, is the method of choice. If nurseries decide to mix their own growing medium, controlled-release fertilizers can be incorporated, but special care must be taken to ensure even distribution (figure 11.10C) and prevent damage to the prill coating. If the coating is fractured, then the soluble fertilizer releases immediately, which may cause severe salt injury. We recommend that nurseries purchase their growing media with controlled-release fertilizers already incorporated with more accurate commercial mixing equipment.

> **!** **Caution:** Every fertilizer injector must be installed with a backflow preventer to eliminate the possibility that soluble fertilizer could be sucked back into the water line and contaminate drinking water.

Calculating Fertilizer Application Rates

Fertilizer application rates depend on the growing environment and other cultural factors such as container volume, type of growing media, and irrigation frequency. In particular, the size of the growth container has a profound effect on the best application rate and timing. Very small containers require lower rates, but more frequent application, whereas larger containers can tolerate higher application rates applied less frequently.

Soluble Fertilizers

For most fertilizer products, manufacturers provide general recommended application rates for container nursery plants on package labels. Few recommendations can be found, however, for most native plants. Experimentation, consultation with other growers, and propagation protocols (see Chapter 3, *Crop Planning and Developing Propagation Protocols*) will help develop better fertilizer application rates for native plants (table 11.5). Note that species with wide geographic distribution, such as Douglas-fir, have different nutrient requirements based on their source. Seedlings of coastal sources can be produced with 100 parts per million (ppm) nitrogen, whereas high-elevation sources and those from the Intermountain Region require much more nitrogen (200 ppm) to grow plants of the same size (Thompson 1995).

Detailed descriptions of liquid fertilizer calculations for commercial conifer crops and adjustments for fertilizer injector ratios can be found in Landis and others (1989). These calculations can be confusing at first but get easier with practice and growing experience.

Controlled-Release Fertilizers

Much less has been published about how much controlled-release fertilizer to apply to native plants in containers. Growers can use the general recommenda-

Figure 11.10—*(A) Controlled-release fertilizers can be applied directly to containers ("top-dressing") if care is taken to achieve uniform application. (B) Incorporating controlled-release fertilizers when the growing medium is mixed (C) is a better to achieve even distribution of prills in small containers.* Photos A and C by Tara Luna, B by Thomas D. Landis.

tions if they classify their crops by relative nutrient uses: low, medium, or high (table 11.6). Of course, these applications rates should be used conservatively until their effect on individual plant growth and performance can be evaluated.

DETERMINING WHEN TO FERTILIZE

How do you determine when to fertilize? Because artificial growing media such as peat-vermiculite media are infertile, fertilization should begin as soon as the seedlings or cuttings become established. Some brands of growing media contain a starter dose of fertilizer, so fertilization can be delayed. Native soil mixes that have been amended with compost or other organic fertilizers may not need fertilization right away.

In nurseries, plant growth rates can be controlled by fertilization rates, especially nitrogen rates. As plants take up more nutrients, growth rate increases rapidly until it reaches the critical point (A in figure 11.11A). After this point, adding more fertilizer does not increase plant growth but can be used to "load" nursery stock with extra nutrients for use after outplanting. Overfertilization can cause plant growth to decrease (B in figure 11.11A) and eventually results in toxicity.

Much depends, however, on the species of plant. Some natives require very little fertilizer but others must be "pushed" with nitrogen to achieve good growth rates and reach target specifications. Small-seeded species (for example, quaking aspen) expend their stored nutrients soon after germination whereas those with large seeds (for example, oak) contain greater nutrient reserves and do not need to be fertilized right away. Some native plants require minimal fertilization whereas others need relatively large fertilizer inputs to sustain rapid growth. Experience in growing a particular species is the best course of action to develop species-specific fertilizer prescriptions.

Native plant growers should never wait for their crops to show deficiency symptoms before fertilizing. Plant growth rate will slow down first and, even after fertilization, it can take weeks before growth will resume. Evaluating symptoms of nutrient deficiencies based on foliar characteristics can be challenging even for experts. Many different nutrient deficiencies may result in similar characteristic symptoms and considerable variation in these symptoms may occur among species. In addition, typical foliar symptoms such as chlorosis may

Table 11.5—Examples of liquid fertilizer application rates for a variety of native plants, applied once or twice per week during the rapid growth phase

Low Rate: 25–50 ppm N	buffaloberry[a]
	ceanothus[a]
	dogbane
	fourwing saltbush
	hawthorn
	sagebrush
Medium Rate: 50–100 ppm N	chokecherry
	cottonwood
	cow parsnip
	elderberry
	redoiser dogwood
	serviceberry
	wild hollyhock
	willow
High Rate: 100–200 ppm N	blue spruce
	Douglas-fir [b]
	limber pine
	western white pine
	whitebark pine

ppm = parts per million
[a] = Plants that fix nitrogen (see Chapter 14, *Beneficial Microorganisms*).
[b] = Coastal sources require low N levels but high elevation and interior sources require very high N levels.

Table 11.6—Manufacturer's recommendations for applying 5-9-12 Osmocote® Plus controlled-release fertilizer (from The Scotts Company 2006)

Nutrient Release Rate (months)	**Incorporation: Ounces per Cubic Foot of Growing Medium[a]**		
	Low	**Medium**	**High**
3–4	1.8	3.6	7.1
5–6	2.4	4.7	7.1
8–9	4.1	5.9	8.3
12–14	2.0 – 4.0	5.0 – 7.0	8.0 – 12.0
14–16	8.0	12.0	16.0
	Topdressing: Ounces per 5-inch Diameter Container[b]		
3–4	0.07	0.10	0.25
5–6	0.07	0.18	0.25
8–9	0.14	0.21	0.28
12–14	0.07–0.14	0.18–0.25	0.25–0.39
14–16	0.25	0.39	0.53

[a] Multiply ounces by 1,000 to obtain grams per cubic meter or multiply ounces by 1 to obtain grams per cubic liter.
[b] Multiply ounces by 28.35 to obtain grams. Multiply inches by 2.54 to obtain centimeters.

sometimes be a result of an environmental response unrelated to nutrient stress, such as heat damage or root disease. The position of the symptomatic foliage can also be diagnostic. For instance, nitrogen is very mobile within the plant and will be translocated to new foliage when nitrogen is limiting (figure 11.11B). Therefore, nitrogen deficient plants will show yellowing in the older rather than newer foliage. Compare this condition to the symptoms of iron deficiency; iron is very immobile in plants, so deficiency symptoms first appear in newer rather than older foliage (figure 11.11C). *Deficiency symptoms are visible only after a severe nutrient deficiency has developed, so they should never be used as a guide to fertilization.* Keep in mind that excessive fertilization can cause toxicity symptoms (figure 11.11D).

MONITORING AND TESTING

What is the best way to monitor fertilization during the growing season? As previously discussed, by the time deficiency symptoms appear, plant growth has already seriously slowed. Instead, the EC of fertilizer solutions and chemical analysis of plant foliage can determine if fertilization is sufficient and prevent problems from developing.

EC Testing

Remember that all fertilizers are taken up as electrically charged ions, so the ability of a water solution to conduct electricity is an indication of how much fertilizer is present. Growers who fertigate should periodically check the EC of the applied fertigation water and the growing medium solution. Note that this practice is much more useful for artificial growing media than native soil mixes.

Simple handheld EC meters (figure 11.12) are fairly inexpensive and are very useful for monitoring fertigation. Measuring the EC of fertigation water as it is applied to the crop can confirm that the fertilizer solution has been correctly calculated and that the injector is functioning. Remember that the total EC reading is a combination of fertilizer salts and natural salts present in the water source. Normal readings in applied ferti-

Figure 11.11—*(A) Fertilization is one of the major ways to increase plant growth, which follows a characteristic pattern. Deficiency symptoms such as chlorosis (yellowing) are common but can be caused by several different nutrients. (B) Nitrogen chlorosis is seen first in newer foliage, whereas (C) iron chlorosis occurs in older foliage. (D) Excessive fertilization can cause toxicity symptoms, such as the chlorosis and leaf margin scorch of boron toxicity.* Photo B from Erdmann and others (1979), C and D by Thomas D. Landis, illustration by Jim Marin.

gation should range from 0.75 to 2.0 µS/cm. See Chapter 10, *Water Quality and Irrigation*, for information about units of measure for EC. Measuring the EC of water leached from containers can also help pinpoint problems of improper leaching and salt buildup within the growing medium. Measurements of the EC of the solution in the growing medium, however, provide the best estimate of how much fertilizer is available to plant roots. In the growing medium, the typical range of acceptable EC values for most native plant species is about 1.2 to 2.5 µS/cm. If the EC is much over 2.5, it is probably a good idea to leach out the salts with clean irrigation water.

Foliar Testing

The best way to monitor fertilization is to test plant foliage. This test shows the exact level of nutrients that the plant has acquired. By examining tissue nutrient concentrations and simultaneously monitoring plant growth, it is possible to identify when nutrients are limiting to growth, if they are in optimal supply, or if they are creating growth toxicities (figure 11.11A).

Foliar samples must be collected in a systematic manner and be sent to a reputable laboratory for processing (recommendations are often available through local county extension agents). The analyzed nutrient concentration values are then compared to some known set of adequate nutrient values to determine which specific elements are deficient. The cost to analyze these samples is relatively inexpensive considering the potential improvement in crop quality that may result from conducting the tests.

Growth Trials

Small growth trials are another good way to monitor fertilization. This concept is especially true for native plants because so little published information is available. Detailed documentation of growing conditions, fertilizer inputs, and resulting plant response can help to formulate future fertilizer prescriptions for a specific species within a nursery. See Chapter 17, *Discovering Ways to Improve Crop Production and Plant Quality*, for more information on how to make these discoveries through trials and experiments.

Figure 11.12—*An electrical conductivity meter used to estimate fertilizer salt concentrations in irrigation water, fertigation water, or saturated media extract.* Photo by Douglass F. Jacobs.

FERTILIZATION DURING PLANT GROWTH PHASES

As discussed in Chapter 3, *Crop Planning and Developing Propagation Protocols*, plants go through three growth phases during their nursery tenure. Growers should be aware of the different nutrient requirements during each of these phases and adjust fertilizer prescriptions accordingly (table 11.7). These adjustments are particularly important for nitrogen (especially the ammonium form of nitrogen), which tends to be a primary driver of plant growth and development (figure 11.13).

Establishment Phase

Soon after germination, we want to stimulate plant growth. Small plants, however, are particularly vulnerable to root damage from high salt concentrations. In addition, high nitrogen at this time results in succulent tissue at the root collar that can cause plants to be vulnerable to damping-off fungi and other pest problems. Thus, it is recommended to use moderate nitrogen applications during this period.

Rapid Growth Phase

This phase is the period when plants attain most of their shoot development; high levels of nitrogen tend to promote this growth. Growers must closely monitor plant growth and development, however, to ensure that shoots do not become excessively large. A good rule of thumb for conifer seedlings (and a good starting point for many native plants) is that hardening should begin and nitrogen fertilization should be reduced when shoots have reached 75 to 80 percent of the target size. Plants take several weeks to respond to this change in fertilization and will continue to grow even though nitrogen fertilization has been reduced. Leaching the growing medium with several irrigations of plain water is a good way to make certain that all excess nitrogen is eliminated.

Hardening Phase

Adjusting fertilizer inputs during the hardening phase is perhaps one of the most critical procedures to follow in plant fertilization. See Chapter 12, *Hardening*, for a complete description of this topic. The objective of the hardening phase is to prepare plants for the stresses of shipping, storage, and outplanting by slowing shoot growth while simultaneously promoting stem and root growth. It is recommended to use low nitrogen applications during this period. Typically, a lower ratio of nitrogen to that of phosphorus and potassium is helpful (table 11.7). In addition, changing

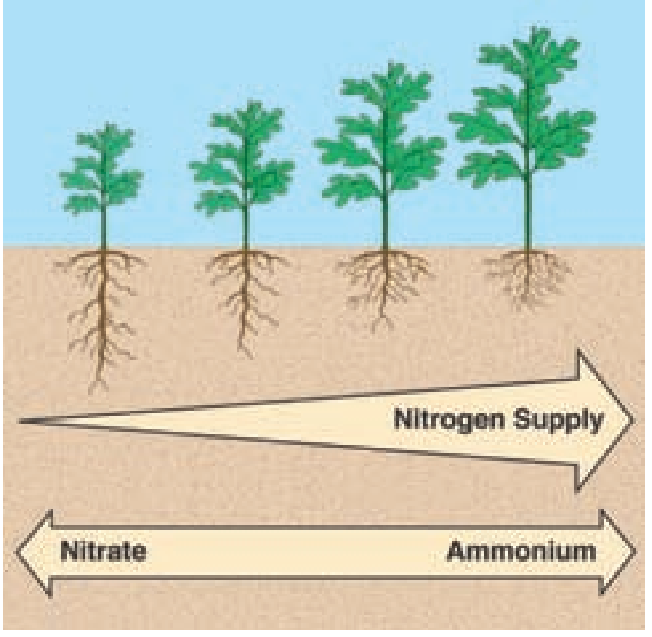

Figure 11.13—*Because nitrogen is so critical ot seedling physiology, nitrogen fertilization can be used to speed up or slow down plant growth and to control the shoot-to-root ratio.* Illustration by Jim Marin.

Table 11.7—Examples of fertilization regimes adjusted for plant growth phases

Growth phase	Nitrogen Inputs[a]	Proportion of Nitrogen	Proportion of Phosphorus	Proportion of Potassium
Establishment	Half-strength	Medium	High	Low
Rapid growth	Full-strength	High	Medium	Medium
Hardening	Quarter-strength	Low	Low	High

[a]An example of a "full-strength" solution might be 100 ppm nitrogen

to fertilizers containing the nitrate form of nitrogen (as opposed to ammonium) is helpful because nitrate-nitrogen does not promote shoot growth. Calcium nitrate is an ideal fertilizer for hardening because it provides the only soluble form of calcium, which has the added benefit of helping to promote strong cell wall development. It is important to distinguish granular calcium nitrate from liquid calcium ammonium nitrate, which does contain ammonium.

ENVIRONMENTAL IMPACT OF FERTILIZATION

Regardless of the method of fertilizer application, a major concern is the impact that the application of fertilizers has on the water quality of the natural environment outside of the nursery. Nutrient ions, such as nitrate and phosphate, which easily leach from container nurseries, may potentially enter adjacent water supplies and degrade water quality. Thus, as growers of native plants for ecological restoration, do everything you can to minimize environmental impacts associated with fertilization. From an economic standpoint as well, as much applied fertilizer as possible should be taken up by plants (as opposed to leached away from roots). Fertilizer applications should be carefully calculated and applied only as necessary in pursuit of high-quality plant production. Continued investigation of options such as organic materials, controlled-release fertilizer, and self-contained systems (for example, subirrigation) that may minimize resulting nutrient leaching would be a logical future direction to reduce the impact of fertilization in native plant nurseries on the environment.

LITERATURE CITED

Dumroese, R.K.; Landis, T.D.; Wenny, D.L. 1998. Raising forest tree seedlings at home: simple methods for growing conifers of the Pacific Northwest from seeds. Moscow, ID: Idaho Forest, Wildlife and Range Experiment Station. Contribution 860. 56 p.

Erdmann, G.G.; Metzger, F.T.; Oberg, R.R. 1979. Macronutrient deficiency symptoms in plants of four northern hardwoods. General Technical Report. NC-53. Washington, DC: U.S. Department of Agriculture, Forest Service. 36 p.

Jaenicke, H. 1999. Good tree nursery practices: practical guidelines for research nurseries. International Centre for Research in Agroforestry. Nairobi, Kenya: Majestic Printing Works. 93 p.

Landis, T.D.; Tinus, R.W.; McDonald, S.E.; Barnett, J.P. 1989. The container tree nursery manual: volume 4, plant nutrition and irrigation. Agriculture Handbook 674. Washington, DC: U.S. Department of Agriculture, Forest Service. 119.

The Scotts Company. 2006. Scotts fertilizer tech sheet. http://www.scottsprohort.com/products/fertilizers/osmocote_plus.cfm (19 Jan 2006).

Thompson, G. 1995. Nitrogen fertilization requirements of Douglas-fir container seedlings vary by seed source. Tree Planters' Notes 46(1): 15-18.

ADDITIONAL READINGS

Bunt, A.C. 1988. Media and mixes for container grown plants. London: Unwin Hyman, Ltd. 309 p.

Marschner, H. 1995. Mineral nutrition of higher plants. 2nd ed. London: Academic Press. 889 p.

APPENDIX 11.A. PLANTS MENTIONED IN THIS CHAPTER

blue spruce, *Picea pungens*
buffaloberry, *Shepherdia* species
ceanothus, *Ceanothus* species
chokecherry, *Prunus virginiana*
cottonwood, *Populus* species
cowparsnip, *Heracleum* species
dogbane, *Apocynum* species
Douglas-fir, *Pseudotsuga menziesii*
elderberry, *Sambucus* species
fourwing saltbush, *Atriplex canescens*
hawthorn, *Crataegus* species
kinnikinnick, *Arctostaphylos* species
limber pine, *Pinus flexilis*
oak, *Quercus* species
quaking aspen, *Populus tremuloides*
redoiser dogwood, *Cornus sericea*
sagebrush, *Artemisia* species
serviceberry, *Amelanchier* species
western white pine, *Pinus monticola*
whitebark pine, *Pinus albicaulis*
wild hollyhock, *Iliamna* species
willow, *Salix* species