The Container Tree Nursery Manual

Volume Four
Seedling Nutrition and Irrigation

Chapter 1
Mineral Nutrients and Fertilization

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Contents

4.1.1 Essential Mineral Nutrients

The importance of mineral nutrition on both the quality and quantity of growth of container tree seedlings cannot be overemphasized. Probably more than any other cultural practice, with the possible exception of irrigation, fertilization controls both the rate and type of growth in container tree seedling nurseries.

The terminology of plant nutrition contains several terms that are technically inaccurate. In the jargon of plant science, "mineral" nutrients are the essential elements that plants obtain from the soil. Under the strict chemical definition, however, the term mineral refers to a compound, rather than a group of single elements. The term "nutrient" is also commonly used to refer to an essential element although this is not the exact scientific definition of the term (Jones 1983). Although they may not be etymologically correct, we will use established conventional plant nutrition terms, such as mineral nutrient, in this text.

The beneficial effects of adding "mineral" substances, such as wood ash or lime, to the soil to improve plant growth have been known for more than 2,000 years. It was not until the 19th century that the observations and speculations of Justus von Liebig lead to the "mineral element theory;" which stated that elements such as nitrogen, sulfur, phosphorus, and others are "essential" for plant growth (Marschner 1986). The terms *essential mineral element* and *mineral nutrient* were proposed by two University of California plant physiologists in 1939. In this landmark paper, Amon and Stout (1939) established three criteria for essentiality (Jones 1983, Marschner 1986):

1. Omission of the element must result in abnormal growth, failure to complete all phases of the life cycle, or premature death of the plant.

2. The function of this element must be specific and not replaceable by another element.

3. The element must exert a direct effect on plant growth and metabolism; be a component of a plant constituent, such as an enzyme; or be required for a distinct metabolic process, such as an enzyme reaction. According to this definition, mineral elements that have indirect effects on plant growth are not considered essential.

Thirteen elements have been identified as being essential for the growth of higher plants, although chlorine has been proven to be essential for only a limited number of species (Marschner 1986). For convenience' sake, the thirteen elements are classified as six macronutrients, which are used by plants in relatively large amounts, and seven micronutrients, which are required in very small quantities (table 4.1.1). Macronutrients are either constituents of organic compounds, such as proteins or nucleic acids, or act in osmotic regulation and are therefore found in relatively large amounts in plant tissue. Micronutrients, on the other hand, are primarily constituents of enzymes and are found in relatively minor proportions in plant tissue (tables 4.1.1 and 4.1.2).

Table 4.1.1—*Chemical information about the thirteen essential mineral nutrients*

Element or ion	Chemical symbol	% of plant tissue (ovendry wt)	Atomic weight	Equivalent weight[b]
Macronutrients				
Nitrogen	N	1.5	14.0	4.7
Nitrate[a]	NO_3^-	—	62.0	62.0
Ammonium[a]	NH_4^+	—	18.0	18.0
Phosphorus	P	0.2	31.0	10.3
Phosphate[a]	$H_2PO_4^-$	—	97.0	97.0
Potassium	K	1.0	39.1	39.1
Calcium	Ca	0.5	40.1	20.0
Magnesium	Mg	0.2	24.3	12.2
Sulfur	S	0.1	32.1	8.0
Sulfate[a]	SO_4^{2-}	—	96.0	48.0
Micronutrients				
Iron	Fe	0.01	55.8	18.6
Manganese	Mn	0.005	54.9	27.5
Zinc	Zn	0.002	65.4	32.7
Copper	Cu	0.0006	63.6	31.8
Boron	B	0.002	10.8	3.6
Chlorine	Cl	0.01	35.5	35.5
Molybdenum	Mo	0.00001	96.0	32.0

a Most-common nutrient form of element.
b With ions of different valences, most-common form is used.
Source: modified from Hanan et al. (1978) and Epstein (1972).

Table 4.1.2—*Biochemical characteristics of essential mineral nutrients*

Essential elements	Form utilized by plants	Biochemical functions in plants
Group 1 Carbon (C) Hydrogen (H) Oxygen (O) Nitrogen (N) Sulfur (S)	In the form of CO_2, H_2O, O_2, NO_3^-, NH_4^+, SO_4^{2-}: the ions from the growing medium solution, the gases from the atmosphere	Major constituents of organic material. Essential elements of atomic groups involved in enzymatic processes. Assimilation by oxidation-reduction reactions.
Group 2 Phosphorus (P) Boron (B)	In the form of phosphates, boric acid, or borate from the growing medium solution	Esterification with native alcohol groups in plants. The phosphate esters are involved in energy transfer reactions.
Group 3 Potassium (K) Magnesium (Mg) Calcium (Ca) Manganese (Mn) Chloride (Cl)	In the form of ions from the growing medium solution	Nonspecific functions establishing osmotic potentials. More specific reactions by which the conformation of the enzyme protein is brought into optimum status (enzyme activation). Bridging of reaction partners. Balancing indiffusible and diffusible anions.
Group 4 Iron (Fe) Copper (Cu) Zinc (Zn) Molybdenum (Mo)	In the forms of ions or chelates from the growing medium solution	Present predominantly in a chelate form incorporated in prosthetic groups. Enable electron transport by valency change.

Source: modified from Jones (1983).

4.1.2 Mineral Nutrients and Seedling Growth

An understanding of how fertilization affects the growth of container tree seedlings is essential to the design and implementation of a nursery fertility program. Fertilizers break down into nutrient ions in an aqueous solution: e.g., ammonium sulfate [$(NH_4)_2SO_4$] yields ammonium (NH_4^+) ions and sulfate (SO_4^{2-}) ions. These nutrient ions become adsorbed on ion-exchange sites on particles in the growing medium, such as peat or vermiculite, or remain in the growing medium solution until they are taken up by the seedling root system (fig. 4.1.1). A tree seedling, like all plants, obtains these mineral elements from the soil solution as ions, although some nutrients can also be taken up as molecules or organic complexes. The molecule urea, which is a soluble form of nitrogen, can be absorbed by plant roots as well as some chelated complexes of micronutrients, such as FeEDTA (see section 4.1.4.3) (Jones 1983).

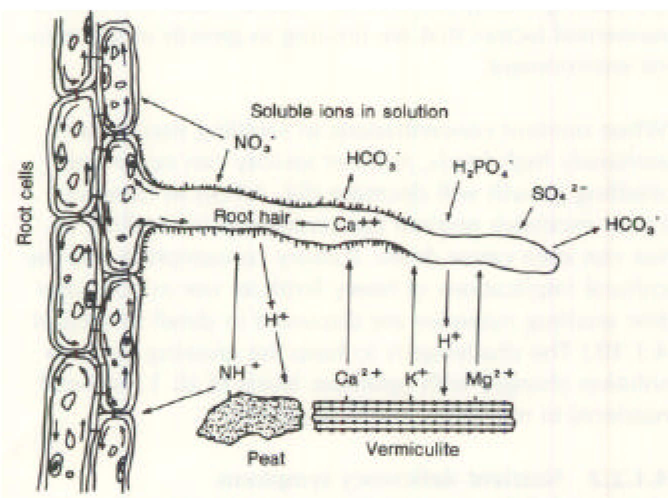


Figure 4.1.1—*Mineral nutrient ions are absorbed directly from the growing medium solution surrounding the root, which is replenished through ion exchange with growing medium particles (adapted from Donahue and others 1977).*

4.1.2.1 Nutrient uptake and utilization

The actual process of mineral nutrient uptake is complicated and well beyond the scope of this manual. Nutrient uptake by plants can be divided into active and passive absorption. Passive absorption means that ions are carried into the plant root along with the transpirational water stream. The factors controlling passive absorption are the volume of water moving into the plant (transpirational demand) and the concentration of the ions in the growing medium solution that surrounds the roots. Active absorption occurs when nutrient ions are taken up against the osmotic gradient that normally exists between the root cells and the growing medium solution. The biochemical processes involved in active uptake are not completely understood, but there is general agreement that active uptake is the dominant mechanism. There are three things that we do know about nutrient uptake by plants (Jones 1983).

1. The plant is able to *take up nutrient ions selectively,* even though the ion concentration and ratio of the surrounding solution may be quite different than that in the root cells.

2. *Ions accumulate* in the root across a considerable gradient.

3. *Active ion uptake requires energy,* which is generated by cellular metabolism.

For a complete treatment of the biochemical aspects of mineral nutrient uptake by plants, the reader is referred to Marschner (1986) or Black (1968).

In the soil or growing medium, mineral nutrient availability is affected by the passive movement of ions with the soil solution, by diffusion, and by the growth of plant roots (Barber 1962). The passive movement of nutrient ions towards the plant root with the soil water during transpirational uptake is called "mass flow" (A in figure 4.1.2), the rate of which is controlled by transpirational demand. Within the growing medium solution surrounding the roots, nutrient ions are taken up from the rhizosphere (B in fig. 4.1.2), either by passive diffusion (movement from a relatively high concentration to lower concentration) or by active absorption processes. Plants also reach mineral nutrients through root extension (C in fig. 4.1.2), where the plant root tip grows into new supplies of mineral nutrients (Jones 1983). These processes are much simplified with liquid fertilizer applications in container tree seedling nurseries because the seedling roots are periodically bathed with a fresh supply of a complete nutrient solution.

There is a characteristic relationship between the concentration of a nutrient ion in seedling tissue and its growth (fig. 4.1.3). When a nutrient is present in low concentrations in seedling tissue, it is said to be deficient and limiting to growth. At the lower end of this

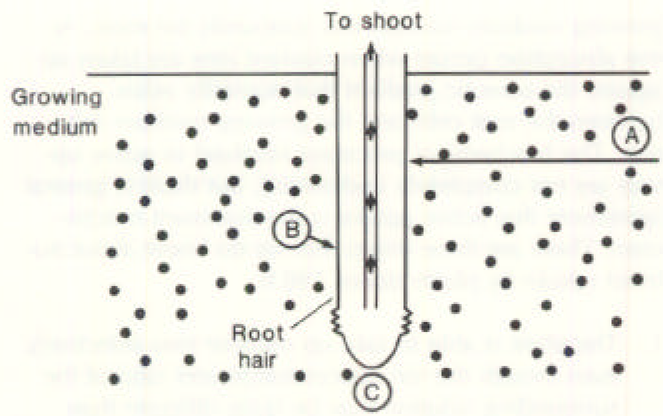


Figure 4.1.2—*Plant roots can access mineral nutrient ions in the growing medium solution in three ways:* **A**—*Mass flow during transpirational uptake.* **B**—*Diffusion or active uptake at the root surface.* **C**—*Root extension to new areas in the growing medium (modified from Jones 1983).*

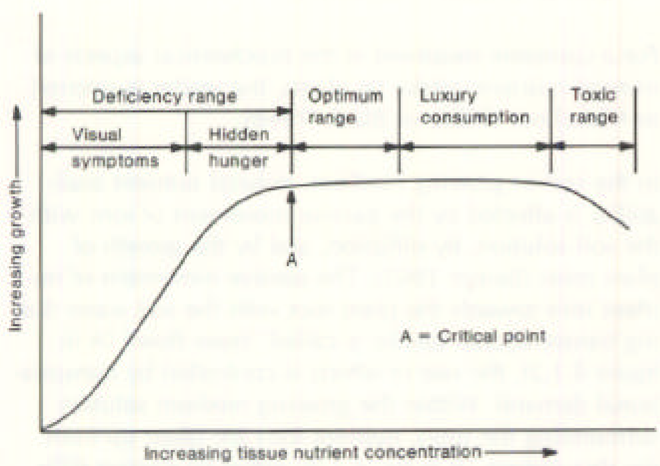


Figure 4.1.3—*The relationship between seedling growth and seedling tissue nutrient levels follows a characteristic pattern. Growth increases with increasing nutrient levels up to a critical point (A). Beyond this point, increasing nutrient levels do not result in more growth, but lead to luxury consumption or even toxicity.*

deficiency range, the plant often exhibits certain visible abnormalities and these "deficiency symptoms" are characteristic of the specific nutrient deficiency (see section 4.1.2.2). At slightly higher tissue concentrations, the nutrient is still deficient enough to limit seedling growth but not enough to produce deficiency symptoms (fig. 4.1.3). This condition is called "hidden hunger" because, although plant growth is reduced, the nutrient deficiency is difficult to diagnose from deficiency symptoms alone. Seedling nutrient analyses are often helpful in identifying this condition.

When the mineral nutrient supply is no longer limiting, the growth of the seedling reaches a plateau (fig. 4.1.3), termed the optimum nutrient range. The actual width of this optimum range varies between different nutrients but it is in this range of nutrient concentration that maximum growth occurs. (Normal mineral nutrient concentrations that are considered adequate for container tree seedlings are discussed in section 4.1.9.3) When mineral nutrients are present in the growing medium in surplus quantities, seedlings may continue to take up additional nutrients even though there is no measurable increase in growth; this condition is termed "luxury consumption" (fig. 4.1.3). Luxury consumption is relatively common in container tree seedling nurseries because of the ideal growing environment and the lack of the environmental factors that are limiting to growth in the natural environment.

When nutrient concentrations in seedling tissue reach extremely high levels, nutrient toxicity can occur and seedling growth will decrease (fig. 4.1.3); in extreme cases, excessive nutrient concentrations in seedling tissue can even cause death. (Luxury consumption and the cultural implications of heavy fertilizer use in container tree seedling nurseries are discussed in detail in section 4.1.10.) The challenge is to keep the growing medium solution charged with optimum levels of all 13 mineral nutrients to maximize seedling growth.

4.1.2.2 Nutrient deficiency symptoms Nutrient deficiencies are characterized by specific, observable symptoms. Although there is considerable variation between symptoms for different tree species, a list of typical nutrient deficiency symptoms for the 13 mineral nutrients is provided in table 4.1.3. These deficiency symptoms are somewhat useful in diagnosing mineral nutrient deficiencies, but many of the symptoms (e.g., chlorosis) can be caused by deficiencies of several nutrients and, therefore, seedling nutrient analysis is often necessary for an accurate diagnosis (see section 4.1.9.3). Also remember that by the time nutrient deficiency symptoms appear, a significant amount of growth may have already been lost (see hidden hunger, section 4.1.2.1).

Nitrogen deficiency symptoms. Nitrogen (N) deficiency symptoms include chlorosis and stunting (fig.

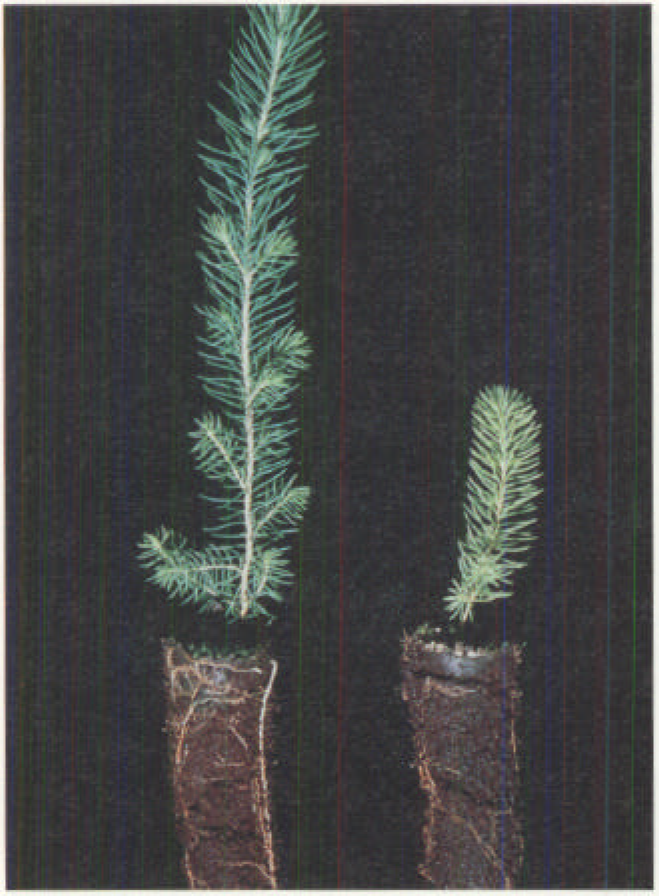
Table 4.1.3—*Mineral nutrient deficiency symptoms for tree seedlings*

	Deficiency symptoms
Macronutrients	
Nitrogen (N)	General chlorosis followed by stunting; in severe cases, foliage is short, yellow-green to yellow; this may be followed by purpling and eventual necrosis of leaf tips. Distinguishable from iron chlorosis because older foliage is affected first.
Phosphorus (P)	Entire seedling is often stunted although leaf size may or may not be reduced. Leaf symptoms are variable between species with color ranging from dull green, yellow to purple-tinged.
Potassium (K)	Variable symptoms between species: usually short, chlorotic foliage with some green at base; in severe cases, purpling and necrosis with top dieback. Browning and necrosis may also occur.
Calcium (Ca)	Stunting and minimal growth at all meristems; in severe cases, terminal buds may die or fail to elongate. Broadleaf species show tip scorching and chlorosis of newest leaves. Browning and mortality of root tips is also common.
Magnesium (Mg)	Yellow or orange tips of current foliage followed by necrosis in severe cases. Broadleaf species often show interveinal necrosis of leaves.
Sulfur (S)	Foliage chlorotic to pale yellow-green, youngest leaves most affected. Stunting of leaves and eventual necrosis in severe cases.
Micronutrients	
Iron (Fe)	Chlorosis appearing first on younger foliage. In severe cases, foliage is bright-yellow to white.
Manganese (Mn)	Chlorosis of foliage, similar to iron deficiency.
Zinc (Zn)	Extreme stunting of foliage with tufting or rosetting, followed by tip dieback in extreme cases.
Copper (Cu)	Needles twisted spirally with yellowing or bronzing of needle tips.
Boron (B)	Chlorosis and necrosis of terminal bud.
Molybdenum (Mo)	Foliar chlorosis followed by necrosis, beginning at tip.
Chlorine (Cl)	No deficiency symptoms are listed for tree seedlings.

Sources: adapted from Armson and Sadreika (1979), Erdmann et al. (1979), Hacskaylo et al. (1969), Morrison (1974), and Tinus and McDonald (1979).

4.1.4A); chlorosis usually appears first on the lower leaves or needles, because N is a mobile element within the plant and is transferred to the newer foliage (fig. 4.1.4B). (Compare this pattern to that of iron chlorosis.) N stunting is usually easy to diagnose, and subsequently correct, because deficient seedlings rapidly respond to applications of N fertilizer.

Phosphorus deficiency symptoms. Phosphorus (P) deficiency symptoms are extremely variable between species and, therefore, this problem is difficult to diagnose from symptoms alone. Because P is required relatively early in seedling development, one of the classic symptoms of P deficiency is "purple heart;" a purpling of the new primary needles (fig. 4.1.5A). Foliar P deficiency symptoms range from no color change to dark-green, pink, or purple (fig. 4.1.5B), general chlorosis, and marginal scorch (fig. 4.1.5C), mottled interveinal chlorosis (fig. 4.1.5D), and chlorosis of the lower leaves (fig. 4.1.5E). Swan (1971) found that P deficiency symptoms varied between two different species of spruce: white spruce showed the characteristic stunting and purple foliar symptoms whereas red spruce, although equally stunted, showed almost no purpling. Obviously, foliar deficiency symptoms should not be considered diagnostic for P deficiency.



4.1.4A

4.1.4B

Figure 4.1.4—*Typical nitrogen deficiency symptoms are chlorosis and stunting (**A,** white spruce). Often only the older leaves are chlorotic (**B,** paper birch) because nitrogen is a mobile element in plants. Compare this chlorosis pattern to that of iron chlorosis. (**A,** courtesy of Ronald Hallett, Canadian Forestry Service, Fredericton, NB; **B,** courtesy of USDA Forest Service Northern Hardwoods Laboratory, Rhinelander, WI.)*

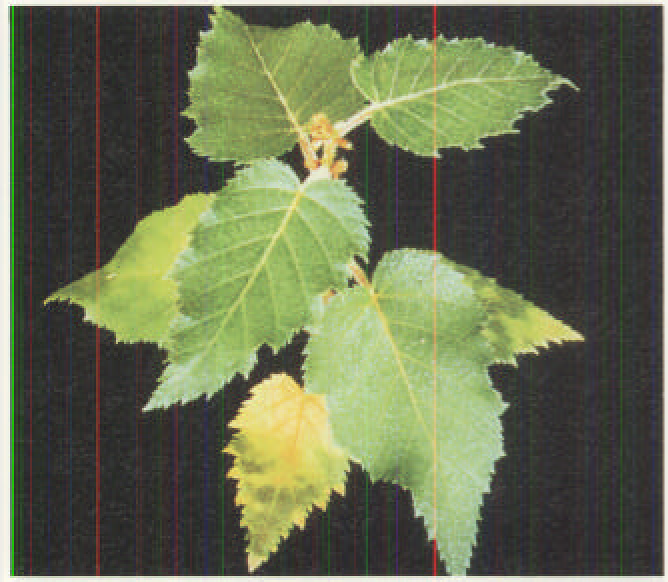
4.1.5A

4.1.5B

Figure 4.1.5—*Phosphorus deficiency symptoms are variable between different species. Young black spruce germinants (**A**) have primary needles with a purplish-tinge, a symptom called "purple heart." Foliar phosphorus deficiency symptoms of hardwood seedlings include reddish-pink in red maple (**B**), general yellowing (chlorosis) in white ash (**C**), marginal chlorosis in sugar maple (**D**), to chlorosis of the older leaves in paper birch (**E**). (**A,** courtesy of Ronald Hallett, Canadian Forestry Service, Fredericton, NB; **B–E,** courtesy of USDA Forest Service, Northern Hardwoods Laboratory, Rhinelander, WI)*


4.1.5C


4.1.5D


4.1.5E

4.1.6A

4.1.6B

Figure 4.1.6—*Magnesium is another mineral nutrient whose principal deficiency symptom is chlorosis. In this case, however, the deficiency is exhibited as yellow-tipped needles in conifers (**A**, black spruce), or interveinal chlorosis in hardwood seedlings (**B**, paper birch). (**A**, courtesy of Ronald Hallett, Canadian Forestry Service, Fredericton, NB; **B**, courtesy of USDA Northern Hardwoods Laboratory, Rhinelander, WI.)*

Magnesium deficiency symptoms. Magnesium is another mineral nutrient whose lack produces a characteristic chlorosis, but the chlorosis, in this case, is almost always strongly patterned: needle tips in conifers (fig. 4.1.6A) and interveinal in hardwood seedlings (fig. 4.1.6B).

Micronutrient deficiency symptoms. Micronutrient deficiency symptoms are extremely variable between nutrients and species. Iron (Fe) chlorosis is a relatively common disorder in horticultural nurseries, and some species are particularly sensitive (Bunt 1976). Chlorosis is the first symptom of minor iron deficiency and this condition is usually expressed first in the newer foliage (fig. 4.1.7A). In severe cases, the entire seedling becomes chlorotic and stunted and the disorder is almost impossible to correct at this stage. Copper (Cu) deficiency is commonly seen in plants grown in peat-based growing media and one of the characteristic symptoms is the twisted, chlorotic needles at the terminal of the seedling (fig. 4.1.7B). Micronutrient deficiencies are difficult to diagnose and correct because the symptoms are often a result of an imbalance between several different micronutrients. Seedling nutrient analysis can be helpful in confirming visual symptoms, although foliar levels of some micronutrients, notably iron, can be higher in symptomatic seedlings.

4.1.7A

Figure 4.1.7—*Micronutrient deficiencies are particularly difficult to diagnose through foliar deficiency symptoms. Two of the more common micronutrient deficiencies in conifer seedlings are iron chlorosis* (**A**) *in jack pine (note that the younger needles are chlorotic, compare with figure 4.1.4B) and copper deficiency* (**B**) *in white spruce. (Courtesy of Ronald Hallett, Canadian Forestry Service, Fredericton, NB.)*

4.1.7B

4.1.3 Physical and Chemical Factors Affecting Nutrient Availability

There are several factors that make the nutrient relations of container seedlings different from a natural forest wildling or a seedling in a bareroot nursery bed. These factors must be considered when designing a fertilization program because they have a significant influence on the mineral nutrient availability.

4.1.3.1 Growing media

The majority of container tree seedlings produced in North American nurseries are grown in soil-less or "artificial" growing media (artificial media are composed of materials other than soil). Many early growing media formulations such as the John Innes composts contain a substantial portion of loam soil, which provides some supply of mineral nutrients; this slight advantage is far outweighed by other drawbacks including the excessive weight of soil and the need for pasteurization to eliminate disease organisms and weed seeds.

The exact proportions may vary, but most artificial growing media are composed of an organic component, usually peat moss, and an inorganic component such as vermiculite. The high percentage of peat moss makes these growing media fall into the class of organic soils. Although vermiculite contains some mineral elements (5 to 8% K and 9 to 12% Mg), and sphagnum peat moss does contain some N, the nutrients are released so slowly that peat-vermiculite growing media can be considered infertile for all practical purposes (Bunt 1976). Scarratt (1986) analyzed a peat-vermiculite growing medium and found very low levels of all macronutrients (1.56 ppm NH_4 -N, 1.3 ppm P, 5.2 ppm K, 1.8 ppm Ca, and 1.2 ppm Mg); the growing medium also contained small amounts of most micronutrients except Cu.

The shift from soil-based to artificial growing media has produced some problems in plant nutrition (Nelson, as quoted in Appleton 1986):

1. *Ammonium sensitivity*--Artificial media typically have relatively low pH values, slowing the bacterial conversion of ammonium to nitrate. Some plants suffer ammonium toxicity because they take up and store excessive amounts of ammonium-nitrogen; plants can store up to *20,000* ppm N03-N, compared to only a few hundred parts per million of NH, -N. Ammonium toxicity often causes injury to the root system, and injured plants show typical root injury symptoms: a wilted appearance, leathery-textured or curled leaves, and chlorosis or necrosis of lower leaves. The roots may have orange-brown spots with dead tips.

2. *Phosphorus leaching-Because* artificial media lack the iron and aluminum oxides and other chemicals that fix P in natural soils, this essential nutrient can rapidly leach out of soil-less growing media and may lead to P deficiency.

3. *Micronutrient deficiency-Artificial growing* media do not contain the normal complement of micronutrients that is found in most natural soils. Some micronutrients, such as iron, copper, and boron, can become unavailable for plant uptake because they become fixed to insoluble humic acids as the organic component of the growing medium decomposes. Iron deficiency is particularly common in artificial media, and Scarratt *(*1986*)* found mild chlorosis and low foliar Fe levels in jack pine seedlings grown with most general-purpose fertilizers.

4. *Lower pH requirement-Soil-less growing* media should be kept at a lower pH to keep micronutrients available (see section 4.1.3.3).

Both peat and vermiculite have very high cation-exchange capacities, which means that the growing medium can maintain a nutrient reserve of cations, such as NH_4^+, K^+, Ca^{2+} and Mg^{2+}. Vermiculite has even been reported to have some degree of anion exchange capacity and may retain significant amounts of $P0_4^{3-}$ (Bunt *1976).* While these adsorbed nutrient ions supply a fertility buffer under normal conditions, they can be flushed from the media during heavy leaching, which permits changes in fertility programs or induction of a nutrient stress if desired.

The primary benefit of an infertile growing medium therefore, is to allow the grower to supply all thirteen mineral nutrients in the proper concentrations, in the proper balance, and at the proper time. This is a considerable advantage over the standard bareroot nursery, where the nursery manager has to constantly deal with the complicated and variable nutrient relationships in a mineral soil. The ability to design and apply a well-balanced fertility program is one of the primary reasons for the rapid seedling growth rates that can be achieved in container seedling nurseries. (Growing media are discussed in greater detail in volume two of this series.)

4.1.3.2 Container volume

One of the most important considerations in container seedling fertility is the relatively small volume of most forest seedling containers. Most containers used in container tree seedling nurseries vary from 40 to 492 cm^3 *(2* to 30 cubic inches), and this small capacity means that seedlings only have a limited amount of nutrient reserves. During the rapid growth phase, both the nutrient concentrations and the balance between nutrients in the small volume of growing medium can change rapidly. To achieve optimum growth rates, growers must insure that the growing medium contains a constant and balanced supply of all the essential mineral nutrients (Jones 1983). (Other container effects are presented in volume two of this series.)

4.1.3.3 Relationship between pH and mineral nutrition

A practical definition of pH. The pH of the growing medium is one of the most commonly discussed, yet least understood, factors affecting mineral nutrition of container tree seedlings. An excellent discussion of the chemical background of pH is given in Tinus (1980), and the definition is straightforward enough: a relative measure of the hydrogen ion (H+) concentration expressed on a logarithmic scale. pH values range from 0 (very acidic) to 14 (very alkaline), with 7 being neutral. Because pH units are logarithmic, a solution with a pH 6 has 10 times more H+ ions, a solution of pH 5 has 100 times more, and a solution with a pH 4 has 1,000 times more H+ ions, than a solution with a neutral pH (7.0).

In actual practice, the pH of a solution involves more than just H+ or OH- ions; in growing media solutions, for example, pH is often a reflection of the activity of other ions, notably $C0_3^{2-}$, HCO_3, NH_4^+, NO_3^-, SO_4^{2-}, $P0_4^{3-}$, HPO_4^{2-}, and $H_2PO_4^-$. Obviously, many different ions, whether naturally occurring in the water source or added as fertilizer, have an effect on the pH reading. The important thing to remember about nutrition for container tree seedling nurseries is that the pH reading is a symptom and not a cause: a high pH reading usually indicates the presence of an accessory ion such as CO_3^{2-} or HCO_3^- rather than the OH^- as such.

Effect of pH on nutrient ion availability. The importance of pH on container seedling nutrition is the subject of considerable debate. Gingrich (1984) supports the widely held proposition that pH is the "most important aspect" of container seedling nutrition, whereas Whitcomb (1983) states that pH has "little effect" on the nutrition of container plants as long as proper fertilization practices are followed. Tinus (1980) states that, except at the extreme values where root injury may occur, pH does not directly affect seedling growth.

One reason for this difference of opinion can be attributed to the type of growing medium that is used; growing media that contain native soil are more affected by pH than are those containing exclusively artificial media such as peat-vermiculite mixes. The negative effects of extreme pH levels on aluminum and manganese ion toxicity and the availability of micronutrients in *mineral* soils is well established. The situation is different, however, in *organic* soils. Studies on nutrient availability have shown that maximum nutrient availability occurs at approximately pH 6.5 in mineral soils, but is a full pH value lower (pH 5.0 to 5.5) in organic soils (Lucas and Davis 1961). Peterson (1981) found that 5.2 to 5.5 was the optimum pH range for nutrient availability in an artificial medium.

On an operational basis, the effect of pH on nutrient availability is not as critical in a container nursery as it is in a bareroot nursery. Natural soils contain a variety of chemical ions that react with nutrient ions, especially micronutrients, and make them unavailable to plants. This is not the case with artificial growing media, however, because of their inherently low nutrient status (Whitcomb 1983). As long as a well-balanced fertilizer is regularly applied, pH effects on nutrient availability should not be a concern in container nurseries. Whitcomb (1984) reports that even a pH-sensitive plant like the azalea can be successfully raised in artificial media ranging from pH 3.0 to 8.2 as long as an adequate nutrient supply is provided.

The optimum pH for tree seedling growth. Even though tree seedlings are able to tolerate a relatively wide range of pH values, it has been well documented that conifers grow best at around pH 5.5 whereas hardwoods prefer a slightly higher pH of 6.5. Maintenance of the growing medium solution within one-half pH unit on either side of these targets is recommended. Control of pH in the irrigation water and the growing medium solution is discussed in section 4.1.7.2.

4.1.3.4 Water content of the growing medium

Because nutrient ions are dissolved in the aqueous solution surrounding particles of growing medium, the moisture content of the growing medium affects both nutrient availability and uptake. Fertilization is therefore greatly dependent on nursery irrigation practices, and a low water content in the growing medium drastically reduces the effectiveness of fertilization. Squire and others (1987) found that N and P fertilization only affected Monterey pine seedling growth at relatively high growing medium moisture levels (0.00 to -0.10 MPa). Even within this range, seedling dry weight decreased radically with increasing moisture stress (fig. 4.1.8). The implications of these findings should be obvious: the water content of the growing medium should be maintained at optimum levels for maximum effectiveness.

4.1.3.5 Salinity of the growing medium solution

The chief sources of soluble salts in container tree seedling nurseries are fertilizer residues, irrigation water, and the growing medium (Rohsler and Wright 1984). Inorganic fertilizers are chemically considered salts, and soluble salts are also introduced with the irrigation water.

The typical peat-vermiculite growing medium used in container tree seedling nurseries does not contribute appreciably to the soluble salt problem, although lesser grades of peat moss can release salts upon decomposition. The small container volume also affects the salinity of the solution surrounding the particles of the growing medium. The salinity will drop as the seedling takes up fertilizer salts, or salts are leached from the growing medium during irrigation. Salinity can also reach damagingly high levels under high evapotranspiration conditions if the growing medium is allowed to dry out (Furuta 1978).

Although soluble salts can affect plants in several ways, high levels of specific ions can adversely affect the uptake of certain nutrients, and upset the nutrient balance that is needed for optimal growth. Nutrient ion interactions include competition, antagonism, and synergism and are discussed in greater detail in section 4.1.5.2. Salinity effects on seedling growth can be found in section 4.1.9.1 and Rohsler and Wright (1984). (For aspects of salinity of irrigation water, see section 4.2.4.2.)

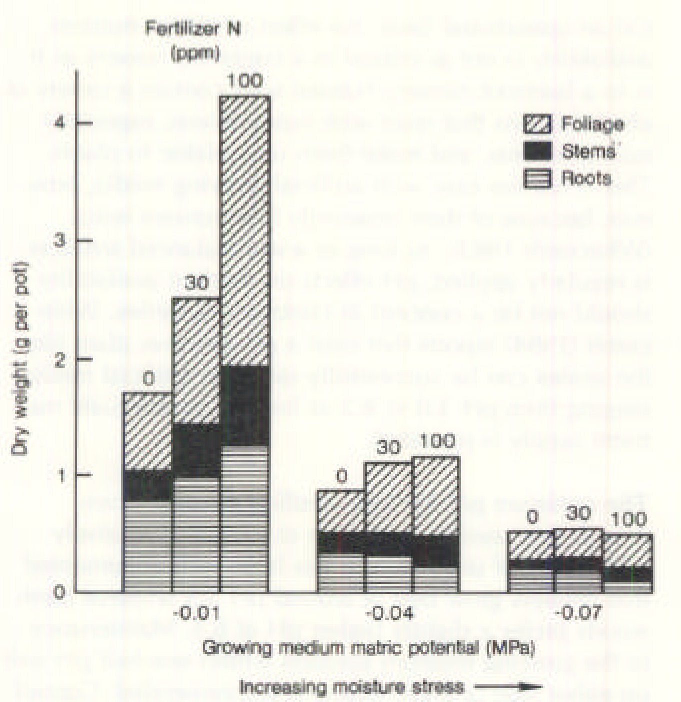


Figure 4.1.8—*The beneficial effect of nitrogen (N) fertilizer decreases with increasing moisture stress in the growing medium (from Squire and others 1987).*

4.1.4 Characteristics of Fertilizers Used in Container Tree Seedling Nurseries

Fertilizers can be categorized in several different ways, but for practical purposes there are three types of fertilizers used in container tree seedling nurseries: macronutrient fertilizers, which supply N, P, and K; secondary nutrient fertilizers, which supply Ca, Mg, and S; and micronutrient fertilizers, which supply any one or a combination of the seven essential micronutrients. Sanderson (1987) itemizes the following characteristics of macronutrient fertilizers; secondary nutrient fertilizers are discussed in section 4.1.4.2 and micronutrient fertilizers are discussed in section 4.1.4.3.

4.1.4.1 Macronutrient fertilizers

Form. Both liquid and dry forms of fertilizers are used in container tree seedling nurseries; dry fertilizers can be purchased in either granules or pellets. Liquid fertilizers are generally injected through the irrigation system, whereas dry fertilizers are incorporated into the growing medium or used as a top-dressing. (See section *4.1.6* for more information on fertilizer application techniques.)

Grade or analysis*.* Fertilizer manufacturers are required by law to state the guaranteed nutrient content of the three primary macronutrients (N-P-K) on the fertilizer container: N is specified as percent N, but P and K are specified as the oxide form of the element, P as percent P_2O_5, and K as percent K_2O. For example, a 20-20-20 fertilizer would contain 20% N, 20% P_20_5 (8.8% P), and 20% K_2O (16.6% K). (Conversion factors are listed in table 4.1.4.) High-grade fertilizers refer to the total amount of mineral nutrients in the fertilizer; for the 20-20-20 fertilizer example, the total analysis would be 45.4%. The remainder of the content is composed of accessory chemicals that are not nutrients, although some fertilizers often contain other unspecified secondary nutrients, including Ca and S. High-grade fertilizers are the only type generally used in container nurseries, especially for liquid injection, because lower grades contain an unacceptable amount of inert material, which may cause solubility problems in the nutrient solutions. The relative proportions of N-P-K determine the suitability of a fertilizer for specific species or growth stages (see section 4.1.5.3).

Nitrogen source*.* Nitrogen is by far the single most important mineral nutrient in a fertilization program because it most frequently limits the growth of container plants. N is available in many different organic and inorganic forms. Organic N forms are rarely used in container tree seedling nurseries because of their variable release rate, low nutrient analysis, and relatively high cost (Sanderson 1987), but many different inorganic sources of N are available. There are two different inorganic N ions that are taken-up by plants: ammonium, a positively charged cation (NH_4^+), and nitrate, a negatively charged anion ($N0_3^-$).

Nitrogen type has an effect on availability, possible nutrient toxicities, and the pH of the growing medium (fig. 4.1.9). Nursery managers should check the analysis on the fertilizer container to determine which N form is

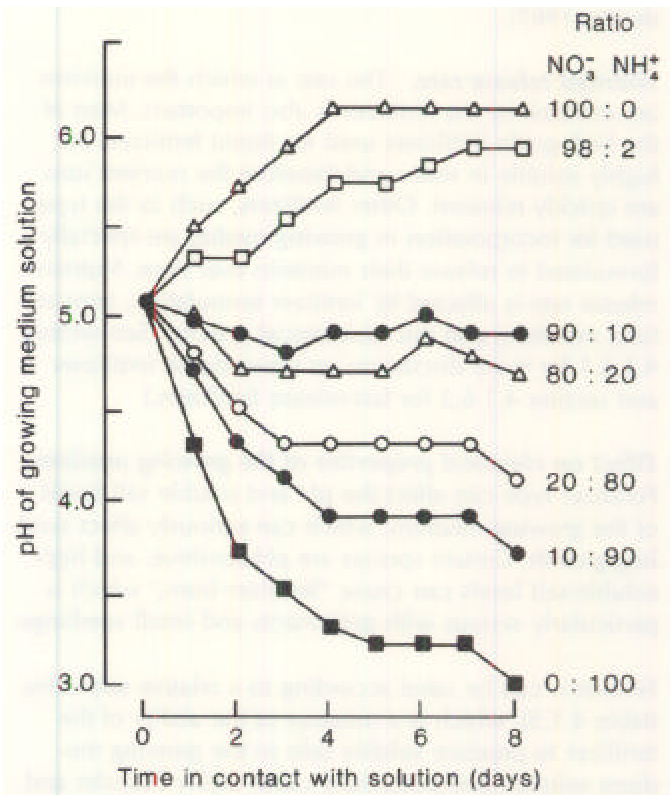


Figure 4.1.9—*The relative proportion of nitrate (NO_3^-) and ammonium (NH_4^+) ions can have a significant effect on the pH of the growing medium solution (from Trelease and Trelease 1935).*

Table 4.1.4—*Conversion factors for commercial fertilizer calculations*

To change from A	to B	Multiply A by
P_2O_5	P	0.4364
P	P_2O_5	2.291
K_2O	K	0.8301
K	K_2O	1.205

most common. Some fertilizers contain only NO_3^-, such as calcium nitrate, whereas others are composed exclusively of NH,' (ammonium phosphate). Ammo nium nitrate contains equal amounts of both nitrogen ions. Urea [$(NH_2)_2CO$] is a widely used form of N that is commonly used to formulate high-analysis fertilizers for container tree seedling nurseries. Urea is microbially broken-down to NH_4^+ and then to NO_3^- in the growing medium. These reactions are temperature-sensitive, and the artificial peat-based media used in most nurseries may not contain the proper number or type of microorganisms for these conversions. Scarratt *(*1986*)* speculated that nitrification of NH_4^+ may be inhibited under the lower light conditions and wetter growing media that often occur during winter cropping seasons. Etha-zole (Truban®), a commonly used fungicide, also inhibits the growth of these microorganisms. Under the high temperatures usually occurring in greenhouses in summer, the conversion to nitrate may occur too rapidly; the cool soil temperatures in winter may cause toxic levels of NH_4^+ to accumulate. Certain plant species are damaged by high levels of either ammonium or nitrate (Sanderson 1987*)*.

Nutrient release rate*.* The rate at which the nutrients are released by the fertilizer is also important. Most of the high-grade fertilizers used for liquid fertilizers are highly soluble in water and therefore the nutrient ions are quickly released. Other fertilizers, such as the types used for incorporation in growing media, are specially formulated to release their nutrients over time. Nutrient release rate is affected by fertilizer formulation, temperature, moisture, and microbiological activity. (See section *4.1.6.1* for more discussion on slow-release fertilizers and section *4.1.6.2* for fast-release fertilizers)

Effect on chemical properties of the growing medium*.*
Fertilizer type can affect the pH and soluble salt levels of the growing medium, which can seriously affect seedling growth. Certain species are pH-sensitive, and high soluble-salt levels can cause "fertilizer burn;" which is particularly serious with germinants and small seedlings.

Fertilizers can be rated according to a relative salt index (table 4.1.5), which is a measure of the ability of the fertilizer to produce soluble salts in the growing medium solution and potentially cause injury (Rohsler and Wright 1984). Nursery managers should select fertilizers that can provide the desired nutrient at the lowest relative salt index: e.g., to supply N, calcium nitrate (salt index = 53) would be potentially less injurious than

Table 4.1.5—*Relative salt index for several fertilizers used in container tree seedling nurseries*

Fertilizer	Relative[1] salt index
Sodium nitrate	100
Potassium chloride	116
Ammonium nitrate	105
Urea	75
Potassium nitrate	74
Ammonium sulfate	69
Calcium nitrate	53
Potassium sulfate	46
Magnesium sulfate	44
Diammonium phosphate	34
Concentrated superphosphate	10
Ordinary superphosphate	8
Gypsum	8
Limestone	5

[1] Relative to sodium nitrate, which is set at 100.
Source: modified from Rohsler and Wright (1984).

sodium nitrate (salt index = 100). Calcium nitrate also provides two different mineral nutrients (Ca and N), whereas sodium nitrate, besides N, contributes potentially harmful sodium (Na) ions to the growing medium solution.

The effect of a fertilizer on pH is specified on the fertilizer label as "potential acidity;" which is the amount of calcium carbonate needed to neutralize a ton of fertilizer. Potential acidity is useful in selecting a fertilizer for a specific crop, or for adjusting the pH of the growing medium during the growing season (fig. 4.1.9). Even slow release fertilizers can affect medium pH. Sanderson (1987) reports that Osmocote® 14-14-14 produces a more acid reaction than Pro-Grow® 25-10-10, probably a result of the nitrogen source. Ammonium-based fertilizers, such as ammonium nitrate, ammonium sulfate, and ammonium phosphate, are generally acid-forming, whereas nitrate-based fertilizers, such as calcium nitrate or potassium nitrate, will raise the pH of the growing medium. Urea, on the other hand, does not generally affect pH in soils, but in a solution will slowly hydrolyze and raise the pH.

Most inorganic fertilizers, especially the high-grade fertilizers used for liquid fertilization in container tree seedling nurseries, are chemically considered salts (e.g., calcium nitrate releases two nutrient ions: Ca^{2+} and NO_3^-.

Indiscriminate use of any salt-producing fertilizer can cause salt injury. (See section 4.1.9.1 for procedures for monitoring soluble salts in nurseries and section 4.2.4.2 for more discussion on salinity effects.)

Slow-release fertilizers produce lower salinity than standard fertilizers because, by definition, they gradually release nutrient ions into the growing medium solution. The type of N used to formulate the slow-release fertilizers can also effect the salinity of the growing medium. Sanderson (1987) reports that Pro-Grow 25-10-10, with its urea-formaldehyde base, produces less salinity than Osmocote 14-14-14, which is composed of inorganic nitrogen sources.

Plant-use efficiency. It has been estimated that plants use only one-tenth of the nutrients applied in a typical liquid fertilizer application (Furuta, quoted in Sanderson 1987). Liquid fertilizer applications require that some level of excess fertilizer must always be maintained in the growing medium solution. Slow-release fertilizers, on the other hand, provide nutrients at a rate that is more compatible with plant uptake. Whitcomb (1984) states that as soon as the nutrients are released from the slow-release fertilizer they are used by the plant. This means that salinity (electrical conductivity) measurements of the growing medium solution may appear abnormally low.

Sanderson (1987) estimates that plants lose ten times more nutrients from water-soluble fertilizer than from a slow-release fertilizer. This is not only wasteful, but such heavy leaching of soluble fertilizers also contributes to wastewater pollution. (See section 4.2.8 for discussion of wastewater disposal.)

Cost. Fertilizer cost differences can be attributed to analysis, type and source of raw materials, manufacturing costs, transportation, quantity purchased, and other factors. (For a comparison of the costs of the various chemical grades of ammonium nitrate, see section 4.1.7.4.) The individual nutrients also vary in cost, with N being the least expensive, and water-soluble sources of phosphorus the most expensive. Because superphosphate (0-46-0) is one of the cheapest forms of P, many nursery managers try to save money by incorporating this fertilizer into the growing medium (Sanderson 1987). A more practical approach is to supply P in the form of phosphoric acid (H3P04), which is primarily used to lower the pH of the irrigation water (fig. 4.1.10). Many container tree seedling nurseries are able to supply all of their P fertilizer requirement by using this technique.

Figure 4.1.10—*Phosphoric acid can be a practical and inexpensive source of phosphorus fertilizer when it is also used to acidify the irrigation water.*

Actually, the cost of the fertilizer itself can be relatively minor compared to the labor cost involved in mixing and application (Sanderson 1987). One of the real advantages of using incorporated fertilizers is the labor savings, compared to the bi-weekly or even daily costs of applying liquid fertilizers.

After considering all these factors, the choice of the best fertilizer may seem a difficult, complicated decision. On the contrary, deciding which fertilizer to use in container tree seedling nurseries should be based on one criterion alone: seedling growth response under the existing cultural and environmental conditions.

4.1.4.2 Secondary nutrient fertilizers The secondary macronutrients (Ca, Mg, and S) are generally supplied by the soil and water and are therefore not often added as fertilizers in bareroot nurseries. Adequate amounts of Ca and Mg are often supplied by irrigation water, especially in areas with "hard" water. Ca is supplied by calcitic limestone and both Ca and Mg are supplied by dolomitic limestone; both these materials are commonly used to raise the pH of acidic soils or peat moss in the case of container nurseries. S is also supplied in relatively small quantities by the breakdown of organic matter, most river water, rainwater, and from many pesticides (California Fertilizer Association 1985).

The secondary nutrients are also present in many chemicals used for fertilizers and commercial fertilizer formulations. Ammonium sulfate, $(NH_4)_2SO_4$, contains S and calcium nitrate, $Ca(NO_3)_2$, contains Ca. (For a discussion of the secondary nutrient composition of the principal chemicals used for formulating custom liquid fertilizers, see section 4.1.7.4, and for the secondary nutrient composition of a typical commercial fertilizer, see section 4.1.7.3.)

4.1.4.3 Micronutrient fertilizers

In bareroot nurseries, seedlings obtain micronutrients from the soil, and micronutrient fertilizers are not applied unless a specific problem, such as high pH or calcium levels, is identified. Micronutrient fertilizers are definitely needed in the artificial growing media that are typically used in container tree seedling nurseries (see section 4.1.3.1). The balance of different micronutrients in the growing medium is also considered critical because high levels of one micronutrient can interfere with the availability of another (fig. 4.1.11).

Micronutrients can be supplied from either inorganic or organic sources, and the properties of the various sources vary considerably. The California Fertilizer Association (1985) classifies micronutrient fertilizers as: 1) inorganic salts, 2) synthetic chelates, and 3) natural organic complexes. Naturally occurring organic complexes are byproducts of the wood pulp industry but are not recommended for container tree seedling culture because they are less stable than synthetic chelates and are more readily broken down by microorganisms.

***Inorganic salts*.** The most common inorganic micronutrient fertilizers are sulfates of the metal micronutrients (Fe, Mn, Cu, and Zn); other oxide and chloride forms of the metal micronutrients are also available but generally the sulfate forms are preferred. The major water-soluble forms of B include sodium tetraborate (borax) and Solubor®, whereas sodium molybdate and ammonium molybdate are the principal fertilizer forms of Mo (California Fertilizer Association 1985). (For a discussion of commercial micronutrient fertilizers, see section 4.1.6.1; for a list of the major fertilizer chemicals used for formulating custom liquid fertilizers, see section 4.1.7.4; for the micronutrient content of a "complete" commercial fertilizer, see section 4.1.7.3)

***Synthetic chelates*.** A chelating agent is a compound, usually organic, that can chemically combine with a metal ion, forming a ring-like structure (fig. 4.1.12). The resulting molecule is called a chelate. Chelates are frequently used to protect metal micronutrients from the chemical inactivation that so often occurs in alkaline soils. Micronutrient fertilizers can contain several different types of chelating agents, but the stability of these compounds is variable. Chelate stability varies with the metal ion and the chelating agent. The common micronutrient chelating agents used in nurseries, with their much-needed chemical names, are:

EDTA = ethylenediaminetetraacetic acid

EDDHA = ethylenediaminedihydroxyphenylacetic acid

HEDTA = hydroxyethylethylenediaminetriacetic acid

Obviously, the chemistry of synthetic chelate fertilizers is quite complicated and the reader is referred to Mortvedt and others (1972) for more information.

Chelated micronutrient fertilizers are available for single nutrients or in specially blended mixtures. (Micronutrient fertilizers are discussed further in section 4.1.6.1; for a list of the common micronutrient chelates used to formulate custom liquid fertilizers, see section 4.1.7.4.)

S	Ca	Mg	Mn	Fe	B	Cu	Zn	Mo	Cause of deficiency: mineral nutrient imbalances
Deficiency observed									
●	●	●		●		●			High nitrogen
		●		●		●	●		High phosphorus
				●					Low potassium
	●								Low calcium
		●		●	●				High calcium
							●		High magnesium
				●		●		●	High manganese
			●			●			High iron
			●	●				●	High copper
						●			Low zinc
			●	●		●			High zinc
	●	●	●					●	Low pH
		●	●	●	●	●	●		High pH
								●	High sulfur
	●	●	●						High sodium
				●					High bicarbonates
				●					Iron: copper: magnesium imbalance

Figure 4.1.11—*Many different chemical interactions can occur in the growing medium solution. Nutrient availability can be reduced by excessively high levels of another nutrient or another chemical condition, such as high pH. Micronutrients are especially susceptible to imbalance problems. (Modified from the Stoller Chemical Company's Product Manual and Nutrient Deficiency Guide.)*

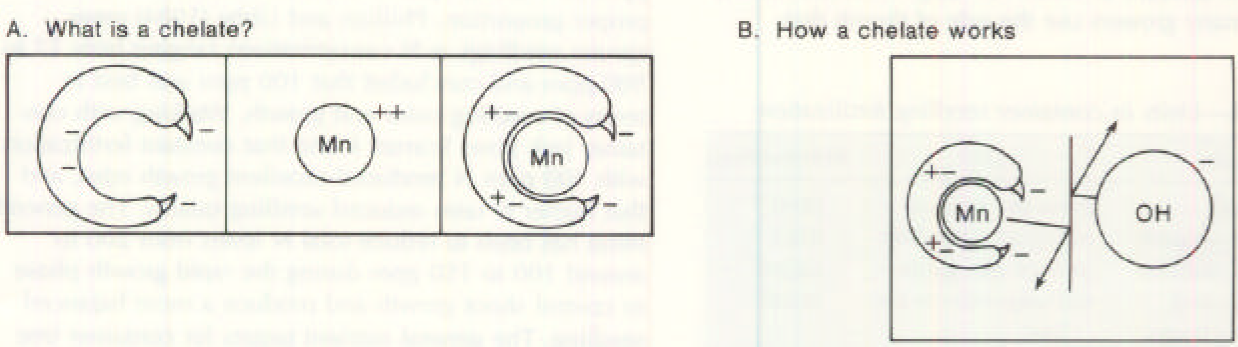


Figure 4.1.12—*Chelated micronutrient fertilizers are composed of a negatively charged organic complex and a positively charged cation, in this case (A), a manganese (Mn) cation. Chelated micronutrients resist nutrient tie-up by other chemicals in the growing medium solution, in this example (B), a hydroxide (OH) ion. Unchelated Mn would be precipitated out of solution as $Mn(OH)_2$. (Modified from the Stoller Chemical Company's Product Manual and Nutrient Deficiency Guide.)*

4.1.5 Determining Fertilizer Needs

A fertilization program for a container tree seedling nursery should be designed to maintain specific concentrations of different mineral nutrients in the growing medium, keep them in balance, and should also be designed to allow necessary nutritional changes during the growing cycle.

4.1.5.1 Nutrient concentration

The concentration of each mineral nutrient in the growing medium solution is the most important aspect of nursery fertilization. Too low a concentration and seedling growth will be reduced, whereas succulent container seedlings can be easily damaged by the high salt levels caused by high nutrient concentrations. High levels of certain nutrients, especially N, can also affect seedling quality (see section 4.1.10).

Units. Mineral nutrient concentrations can be described in several different ways (table 4.1.6). Proportional units [parts per million (ppm)] are most useful for describing and comparing nutrient regimes, whereas the weight per volume [milligrams per liter (mg/l) or ounces per gallon (oz/gal)] are necessary for the actual fertilizer calculations. Parts per million refers to the concentration of a material without regard for any specific unit of weight or volume (Bonaminio 1983). To describe chemical activity, milliequivalents (meq) or millimoles (mmol) per liter are most accurate. The conversion between parts per million and milligrams per liter is quite easy for aqueous solutions: 1 ppm = 1 mg/l because 1 liter of water weighs 1 kg (1 mg/kg = 1 ppm).

Although parts per million are the most useful units for calculating liquid fertilizer application rates, many nursery managers prefer to use the weight of actual bulk fertilizer to the amount of water. Although not scientifically accurate, many growers use the rule of thumb that 28.4 g (1 ounce) of fertilizer dissolved in 378.5 liters (100 gallons) of water equals 75 ppm. For example, if you want 225 ppm N in the applied fertilizer solution, add 85.2 g (3 ounces) of actual N or 426.5 g (15 ounces) of bulk 20-20-20 fertilizer to 378.5 liters (100 gallons) (Bonaminio 1983). (For a handy table for determining the amount of actual bulk fertilizers to add per standard volume of fertilizer solution, see section 4.1.7.3.)

Table 4.1.6—*Units in container seedling fertilization*

Class	Unit	Abbreviation
Proportional	parts per million	ppm *
Weight per volume	milligrams per liter	mg/l *
Weight per volume	ounces per gallon	oz/gal
Weight adjusted for ionic charge per volume	milliequivalents per liter	meq/l
Milligram molecular weight per volume	millimoles per liter	mmol/l

* In aqueous solutions, 1 ppm = 1 mg/l.

Nitrogen level. N is one of the most important nutrients affecting plant growth and is the most frequently applied fertilizer element. Most fertilizer programs are based around the N concentration, and the levels of all the other nutrients are generally established relative to N. The best N level for seedling growth has been the source of much discussion among nursery scientists, and the levels prescribed in the literature show considerable variation (table 4.1.7). Rather high N levels of around 200 ppm or more have been commonly used, probably because much of the early work was based on fertilizer regimes for horticultural species. Another reason for the high N levels reported in the literature is that many N recommendations are for periodic fertilizer applications and are therefore higher than for continuous fertilization (see section 4.1.8.3). The Container Nursery Survey revealed that North American nurseries use N levels ranging from 55 to 260 ppm for the period of most rapid seedling growth (rapid growth phase, table 4.1.7).

In recent years, however, more research has been done on tree seedling nutrition and the latest recommendations are for lower N concentrations during the rapid growth phase. Ingestad (1979) recommended N concentrations of 20 to 50 ppm for Scotch pine and 60 to 100 ppm for Norway spruce when all other nutrients were in proper proportion. Phillion and Libby (1984) grew spruce seedlings at N concentrations ranging from 12 to 500 ppm and concluded that 100 ppm was best in terms of seedling color and growth. Working with container jack pine, Scarratt found that constant fertilization with 100 ppm N produced excellent growth rates, and that higher N rates reduced seedling quality. The general trend has been to reduce total N levels from 200 to around 100 to 150 ppm during the rapid growth phase to control shoot growth and produce a more balanced seedling. The general nutrient targets for container tree seedlings (table 4.1.8) will need to be adjusted for individual species as more knowledge becomes available. (See section 4.1.10 for a discussion of effects of heavy fertilizer use in container tree seedling nurseries.)

Table 4.1.7—*Comparison of recommended nitrogen fertilizer application rates during three seedling growth phases*

Source	Application rate (ppm)		
	Establishment phase	Rapid growth phase	Hardening phase
Mullin and Hallett (1983)	50	100	25
Carlson (1983)			
Pines	229	229	45
Spruce	112	112	45
Interior Douglas-fir	62	100	62
Tinus and McDonald (1979)	–	223	20
Peters Bulletin PTB–114	75–100	100–150	25–50
Container Tree Nursery Survey (1984)	12–125	55–260	0–141
Ingestad (1979)			
Scotch pine	–	20–50	–
Norway spruce	–	60–100	–
Morrison (1974)	–	50–300	–
Brix and van den Driessche (1974)	–	28–300	–

4.1.5.2 Nutrient balance

The relative proportion of the various mineral nutrients to one another in the growing medium solution is the next factor to consider when designing a container tree seedling nursery fertilization program. Jones (1983) states that nutrient concentration ratios are more important than the absolute concentration of any one element. The balance between the various mineral nutrients is biologically important for two reasons:

1. Excesses of certain nutrient ions in the growing medium solution may affect the uptake and utilization of other nutrients (figure 4.1.11).

2. The ionic balance affects the pH of the growing medium solution.

One feature of active nutrient uptake (see section 4.1.2.1) is that ion uptake from the growing medium solution involves ion competition, antagonism, and synergism. Monovalent ions, such as potassium (K^+), are taken up more rapidly than divalent or trivalent ions. If the principal form of nitrogen in the growing medium solution is nitrate (N03-), then the certain cations (K^+, Ca^{2+}, and Mg^{2+}) are taken up in greater amounts than if ammonium (NH_4^+) is present. The presence of $NH4^+$ has been shown to increase the uptake of NO_3^-, whereas Cl^- ions inhibit NO_3^- uptake (Jones 1983).

Steiner (1980) states that most plants will grow well in one universal nutrient solution if certain ratios of cations and anions are followed (table 4.1.9). He has designed a "universal nutrient solution" that is based on relative cation and anion ratios, total ionic concentration, and pH (Jones 1983). One of the most widely used nutrient balance theories for tree seedling culture is based on the work of Ingestad, who sets the ratios of all other nutrients in relation to N. Ingestad (1979) proposed "nutrient ratios" for several conifer and hardwood seedlings; the ratios for Douglas-fir are listed in table 4.1.10, along with the actual nutrient concentrations for all 13 mineral nutrients at 100 and 200 ppm N.

The ratio between the nitrate (NO_3^-) and ammonium (NH_4^+) ions has been investigated, and researchers found that the total concentration of these two ions was not as important as their relative balance. Seedling growth was reduced if either NO_3^- or NH_4^+ was used exclusively for the N source. van den Driessche (1978) found that equal proportions of both N ions resulted in the greatest seedling growth at pH 5.5, although root growth may be greater with higher NO_3^- levels. The relative proportion of NH_4^+ and NO_3^- in the growing medium solution is also important as these two ions have a significant influence of the pH level of the solution (see fig. 4.1.9). Seedling root systems may be damaged by high NH_4^+ levels in artificial growing media

Table 4.1.8—*General nutrient targets for applied liquid fertilizer solutions for constant fertilization of container tree seedlings*

Mineral nutrient	Target application rate (ppm)		
	Establishment phase	Rapid growth phase	Hardening phase
Macronutrients			
N*	50	150	50
P	100	60	60
K	100	150	150
Ca	80	80	80
Mg	40	40	40
S	60	60	60
Micronutrients (same for all growth phases)			
Fe	4.00	4.00	4.00
Mn	0.80	0.80	0.80
Zn	0.32	0.32	0.32
Cu	0.15	0.15	0.15
Mo	0.02	0.02	0.02
B	0.50	0.50	0.50
Cl†	4.00	4.00	4.00

* N levels are very species dependent. Some N-sensitive species such as western larch and quaking aspen require lower levels, whereas slower-growing species such as spruces and true firs require higher N levels.

† Small levels of Cl are present in most irrigation water sources, and Cl is a contaminant in many fertilizers; so additional Cl is almost never required.

Source: modified from Tinus and McDonald (1979).

Table 4.1.9—*Ion concentration recommendations in the "Universal Nutrient Solution"*

General ion ratios	
Percentage of total anions	
Nitrate (NO_3^-)	50–70%
Phosphate ($H_2PO_4^-$)	3–20%
Sulfate (SO_4^{2-})	25–45%
Percentage of total cations	
Potassium (K^+)	30–40%
Calcium (Ca^{2+})	35–55%
Magnesium (Mg^{2+})	15–30%
Specific ion ratios	
$NO_3^-:H_2PO_4^-:SO_4^{2-}$	60:5:35
$K^+:Ca^{2+}:Mg^{2+}$	35:45:20

Source: Steiner (1980).

Table 4.1.10—*Comparison of Ingestad's nutrient ratios for Douglas-fir and complete nutrient levels at two N concentrations**

	Nutrient ratios	Fertilizer nutrient levels	
		100 ppm N	200 ppm N
Macronutrients			
N	1.00	100	200
P	0.30	30	60
K	0.50	50	100
Ca	0.04	4	8
Mg	0.05	5	10
S	0.09	9	18
Micronutrients			
Fe	0.007	0.7	1.4
Mn	0.004	0.4	0.8
Zn	0.0003	0.03	0.06
Cu	0.0003	0.03	0.06
Mo	0.00007	0.007	0.014
B	0.002	0.2	0.4
Cl	0.0003	0.03	0.06

*Some of the nutrient levels, especially Ca, Mg, S, Fe, and Cu, appear low.

Source: Ingestad (1979).

and Nelson (as quoted in Appleton 1986) recommends that nursery managers use fertilizers with less than 40 to 50% ammoniacal nitrogen.

The question of mineral nutrient balance in fertilization solutions is obviously one of the most confusing aspects of plant nutrition, for much of the published research appears contradictory. The situation is analogous to that surrounding vitamins and human health: a nutrition-conscious consumer will be completely baffled by published vitamin recommendations that range from those that state that no supplemental vitamins are necessary to those that advocate megadoses of certain vitamins. The practicing nursery manager should realize, therefore, that no "hard and fast" recommendations of the best nutrient balance can be made. The best course is to be aware that nutrient ratios are important and try to design a well-balanced fertilization program that produces acceptable seedlings based on trial-and-error in an operational nursery situation. Obviously, more research on the best mineral nutrient ratios for growing tree seedlings is needed but, in the meantime, nursery managers should try to develop fertilization programs that work under their own cultural regimes.

4.1.5.3 Adjusting for seedling growth stages

Because of the pronounced effect of fertilization on plant growth, nutrient levels are traditionally adjusted for the various growth stages during seedling development. For development of seedling growing schedules, three separate growth stages can be recognized: the *establishment phase,* which covers emergence and seedling growth through the cotyledon stage; the *rapid growth phase,* when seedlings grow in height at an exponential rate; and the *hardening phase,* which begins when the seedlings have set their terminal bud and shoot growth ceases but caliper and root growth increase.

Control of the N level is the most important factor for manipulating seedling growth, and recommended N fertilization levels vary considerably during these different growth stages (table 4.1.7). The results from the Container Nursery Survey show that nursery managers are using a wide range of N levels during each growth stage. Although the optimum N level will vary between nursery and tree species, the trend is towards levels similar to those recommended by Mullin and Hallett (1983): moderate N during the establishment phase, higher levels during the rapid growth phase, and low N levels during the hardening phase (table 4.1.7).

The proper form of N to supply during the hardening phase has been the subject of much discussion but operational experience with western conifer seedlings suggests that nitrate-based fertilizers should be preferred over ammonium-based fertilizers. NH_4^+ is thought to stimulate succulent shoot growth and delay hardening, and therefore fertilizers such as calcium nitrate are often used during the hardening period. Gingrich (1984) states that NO_3^- fertilizers should be used during the low-light periods of late fall or winter. Matthews (1987), however, reports that conifer seedlings in British Columbia container nurseries have been grown with NH_4^+ based fertilizers during the hardening period with no apparent problems.

The recommended ratios of the three principal macronutrients (N-P-K) also vary between the three growth stages; Carlson (1983) reports different ratios for different species of conifer seedling. Hahn (1978) recommended a N-P-K ratio of 1:5:1 during early seedling growth and a 3:1:1 ratio during the rapid growth phase. Recent fertilizer experiments, however, cast some doubt on the need for special fertilizers during the different growth stages. Scarratt (1986) reports that special "starter;" "grower;" and "finisher" fertilizers showed no significant improvement over standard "general purpose" fertilizers for growing jack pine seedlings in containers. Different seedling species react differently to different fertilizer regimes, however, although some specific recommendations have been published (Tinus and McDonald 1979).

4.1.6 Methods of Fertilizing Container Seedlings

According to Handreck and Black (1984), there are three basic ways to apply fertilizers in a container nursery:

1. Incorporating a slow-release fertilizer into the growing medium.

2. Injecting a liquid fertilizer solution into the irrigation water.

3. Top dressing solid fertilizers to the surface of the growing medium.

In North American container tree seedling nurseries, liquid fertilizer injection is the most common fertilization technique followed by incorporation of slow-release fertilizers (Container Nursery Survey). Top dressing is usually impossible because of the small top opening of the containers used for growing tree seedlings and so will not be considered in this manual.

4.1.6.1 Incorporating dry fertilizers into the growing medium

Incorporation of a dry fertilizer into the medium is most commonly used with plants grown in large volume containers in ornamental nurseries but is also used in some container tree seedling nurseries. The Container Nursery Survey revealed that, although no nurseries used incorporated fertilizers exclusively, 26% used them in combination with liquid fertilizer injection. Matthews (1982) reports that, when seedlings are being grown with liquid fertilizer injection, incorporating a low rate of slow release fertilizer into the growing medium improved seedling growth.

Incorporating fertilizers into the growing medium has several advantages in container nurseries:

1. No specialized fertilizer injection equipment is necessary.

2. Low labor costs involved in the frequent mixing and application of liquid fertilizers.

3. Mineral nutrient levels can also be maintained during wet months when irrigation is not required and nutrient leaching can be a problem.

Incorporation of slow-release fertilizers is necessary in nurseries that do not have well-designed irrigation systems or nutrient injectors. The labor costs of incorporating fertilizers are less than with liquid fertilizer injection, as labor is required only during the initial mixing process. Formulating, mixing, and applying liquid fertilizer solutions requires a certain amount of training and must be done at least weekly. In outdoor growing areas, many mineral nutrients (N in particular) are subject to leaching during periods of high rainfall because irrigation, and therefore liquid fertilizer injection is not necessary. In British Columbia container nurseries, slow-release fertilizers are commonly incorporated into the growing medium in containers that are grown in open, uncov ered compounds where heavy rainfall causes severe leaching losses (Matthews 1982).

There are three major drawbacks to incorporating fertilizers into the growing medium in container tree seedling nurseries:

1. It is impossible to control the concentration and balance of mineral nutrients in the growing medium solution.

2. It is difficult to obtain even distribution of the fertilizer particles throughout the growing medium with the mixing equipment commonly used in container nurseries.

3. Incorporation requires extra mixing of the growing medium, which may breakdown particle size and cause compaction problems.

One of the real advantages of container seedling culture is that growth can be precisely controlled through all phases of seedling development, especially during the critical hardening period. Complete control of all 13 mineral nutrients is one of the most effective "tools" available to the container nursery manager, but this control is sacrificed by fertilizer incorporation. Nutrient release rates of slow-release fertilizers are controlled by factors, such as temperature, moisture content, and microorganism activity, that are beyond the control of the nursery manager. Once the nutrient charge has been introduced into the medium, it is impossible to completely regulate nutrient availability. This is particularly important for N because shoot growth and dormancy are sensitive to N availability, and it may be difficult to set bud and induce dormancy if residual N from incorporated fertilizers continues to be released into the growing medium solution.

The problem of uneven distribution of incorporated fertilizers is a real concern, particularly with small capacity containers. It is always difficult to achieve even mixing when working with materials of two different sizes or textures because such materials tend to separate during storage or handling. It may be hard to obtain even distribution of a small volume of small fertilizer particles in a much larger volume of larger, lighter-weight peat-vermiculite particles. This problem is made worse when dry fertilizer is added to a moist growing medium-the dry fertilizer may adhere to the wet particles of the medium and not mix evenly. The even distribution of fertilizer particles is of special concern when dealing with the small-volume containers used in container tree seedling nurseries; the chances that each small 41- or 66-cm3 (2.5- or 4-cubic-inch) container will receive the proper amount of fertilizer when a charge of dry bulk fertilizer is mixed into a batch of moist growing medium are relatively low.

Unnecessary mixing of growing media is always discouraged because of the fragile nature of the peat and vermiculite particles; overmixing of growing media can lead to reduction of particle size, compaction, and subsequent root growth problems. Many types of mixers do not perform an adequate job of mixing without damaging the texture of the mix and for that reason, incorporation of dry fertilizers should be done only during the manufacture of the growing medium. Matthews (1982) states that mixing equipment must be able to incorporate slow-release fertilizers into the growing medium without breaking or fracturing the fertilizer prills (the effects of overmixing growing media is discussed in the chapter on growing media in volume two of this series).

Coated slow-release fertilizers, such as Osmocote® and Nutricote®, should not be mixed into the growing medium in advance of the actual sowing process, because leakage from the fertilizer pellets can raise the electrical conductivity (EC) of the growing medium solution to dangerous levels (fig. 4.1.13). Handreck and Black (1984) state that, whenever possible, media containing incorporated slow-release fertilizers should be used immediately after mixing. Other incorporated fertilizers, such as gypsum or dolomite, do not affect the salinity of the growing medium (fig. 4.1.13).

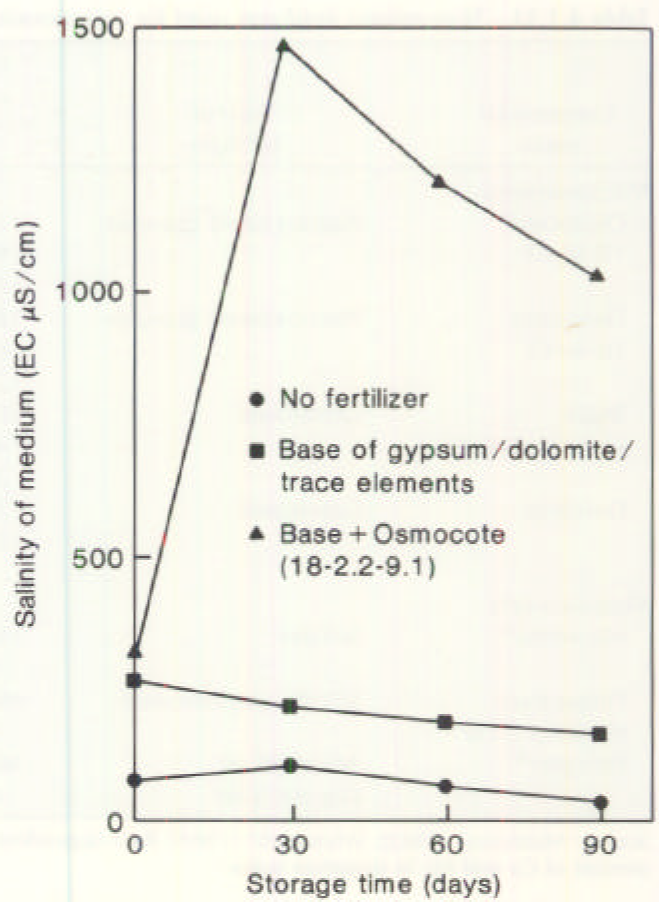


Figure 4.1.13—*The incorporation of slow-release fertilizers, such as Osmocote, into the growing medium should be done immediately before sowing because the fertilizer particles will release fertilizer salts during the storage period and cause the salinity of the growing medium to increase. Other incorporated fertilizers, such as gypsum or dolomite, do not affect growing medium salinity (Handreck and Black 1984).*

Macronutrient fertilizers used for incorporation. Several mineral nutrients can be mixed into the growing medium during the container filling process. The most common type of fertilizers used for incorporation into growing media contain nutrients that are relatively insoluble and do not leach readily, such as P, Ca, and Mg.

Several commercial brands of especially formulated "slow-release" fertilizers are also available.

Limestone or dolomite. Because of their insolubility, Ca and Mg are difficult to supply in liquid fertilizers and are therefore added as calcitic limestone (Ca only) or dolomite (Ca and Mg) during the mixing of the growing medium. [Many nursery managers erroneously use the term "lime" when referring to limestone; lime is calcium oxide (CaO), whereas limestone is calcium carbonate ($CaCO_3$).] Recommended incorporation rates range from 3 to 5 kg/m^3 (5 to 8 pounds per cubic yard) (table 4.1.11). The particle size of the limestone is also impor-

Table 4.1.11—*Slow-release fertilizers used for incorporation into growing media in container tree seedling nurseries*

Commercial name	Type of fertilizer	Nutrient analysis	Nutrient release rate	Suggested incorporation rate	
				kg/m^3	lb/yd^3
Macronutrients					
Osmocote® 17–9–13	Plastic-coated granules	17% N 9% P_2O_5 13% K_2O	70–90 days at 21 °C	3–5	5–9
Osmocote 18–6–12	Plastic-coated granules	18% N 6% P_2O_5 12% K_2O	8–9 mo at 21 °C	4–6	6–10
Triple super-phosphate	Granulated	46% P_2O_5 14% Ca 2% S	—	0.6–1.2	1–2
Dolomite	Granulated	17% Ca 12% Mg	—	3* 0–5†	5* 0-8†
Micronutrients					
Micromax®	Sulfates	Micronutrient mixture + S	over 18 mo	0.6–1.2	1–2
Fritted trace elements (FTE)	Silicate glass-encased	Micronutrient mixture	6–9 mo	0.13	0.22
Esmigran®	Adsorbed on clay particles	Micronutrient mixture	—	3–4	5–6

Source: Matthews* (1983); Whitcomb† (1984): Rate dependent on amount of Ca and Mg in irrigation water.

tant because the chemical effects on pH and nutrient release rate are faster with smaller particles. Agricultural grade dolomitic limestone generally has a particle size of 60 mesh or finer (Ruter and van de Werken 1986).

These fertilizers are sometimes added to peat-based growing media during the mixing process to raise the inherently low pH. Some manufacturers of commercial growing media routinely add limestone or dolomite to their mixes, so it would be wise to inquire about this practice when purchasing commercial media. Ruter and van de Werken (1986) and Whitcomb (1984) present a good discussion of all the aspects of this traditional practice and conclude that nursery managers should consider all aspects before adding dolomitic limestone to the growing medium. Factors to consider include:

1. Levels of Ca and Mg in the irrigation water source—Waters rated as "hard" contain significant amounts of calcium and magnesium. Ruter and van de Werken (1986) report that acceptable levels range from 40 to 120 ppm Ca and 6 to 24 ppm Mg. Whitcomb (1986) states that irrigation water with only 40 ppm Ca can supply most, if not all, of the calcium needed for container plant production. Whitcomb (1984) presents a table to calculate the amount of dolomite to add to a growing medium for irrigation waters containing different amounts of Ca.

2. Ability to supply Ca and Mg in soluble forms-Calcium carbonate and dolomite are very insoluble in water (table 4.1.12) and Whitcomb (1986) estimates that, under the irrigation regimes used in container nurseries, it would take over 7 years to release all the calcium in dolomite whereas the magnesium would be released after one-third of the growing season. This disparity in nutrient release rates could lead to an imbalanced calcium/magnesium ratio and resultant nutritional problems (Whitcomb 1984). Many nurseries inject all their Ca and Mg as the soluble fertilizers calcium nitrate and magnesium sulfate (table 4.1.12). Liquid fertilizer injection allows

Table 4.1.12—*Solubility of potential fertilizer sources of calcium and magnesium*

Chemical compound	Solubility in water (g/100 ml at 25 °C)
Magnesium oxide	<0.01
Calcium carbonate	0.01
Dolomite (calcium and magnesium carbonates)	0.03
Calcium oxide	0.12
Calcium sulfate	0.24
Magnesium sulfate	91.00
Calcium nitrate	100.00

Source: Jones (1982).

the nursery manager to control both the total level and nutrient balance of these important macronutrients.

3. Individual species response to pH and Ca and Mg levels-some acid-loving species have relatively low requirements for these nutrients and can actually be harmed by high Ca levels.

Addition of dolomite to artificial growing media has resulted in growth problems with some conifer seedlings. Dangerfield (1978) found that the addition of dolomite to peat-vermiculite media induced lime chlorosis in Douglas-fir seedlings, and Hathaway and Whitcomb (1984) report that dolomite significantly reduced shoot height and weight of Japanese black pine.

Phosphorus. P is another nutrient that is sometimes incorporated into growing media. P can be supplied by either single or triple (concentrated) superphosphate (table 4.1.11). Single superphosphate (0-20-0) supplies calcium, phosphorus, and sulfur whereas triple superphosphate (0-45-0) contains no sulfur (Gingrich 1984).

Slow-release fertilizers. Other fertilizer types that are commonly mixed into growing media include slow-release or controlled-release formulations. Mastalerz (1977) and Sanderson (1987) provide an excellent discussion of the various types of slow-release fertilizers and their characteristics, and Sanderson (1987) groups them into five different categories, three of which are commonly used in container nurseries.

Coated water-soluble fertilizers. Such fertilizers consist of dry N-P-K fertilizer encapsulated in a plastic resin sphere: the capsule allows water to pass in and dissolve the nutrients, which are then released osmotically to the seedlings (fig. 4.1.14). Osmocote, Nutricote, and sulfur-coated urea are examples of this group. Sulfur-coated urea is seldom used in forest tree nurseries because of concern about the nitrogen release rate, but Osmocote and Nutricote are used in some nurseries.

Both ammonium or nitrate forms of N are used in the various formulations. Irrigation frequency and growing medium temperature are the principal environmental factors controlling the rate of nutrient release (Sanderson 1987). The nutrient formulation also affects the release of nutrients; Crowley and others (1986) found significant differences in the cumulative release of fertilizer salts from three different Osmocote 8-9 month formulations (fig. 4.1.15).

Osmocote is available in several different formulations of N-P-K, with release rates varying from 3 to 14 months. A new microprilled formulation of Osmocote and a formulation that contains all macro- and micronutrients (Sierra®) are now available (fig. 4.1.14). Matthews (1983) recommended that Osmocote be used as the principal fertilizer for container tree seedlings grown outdoors and recommends incorporating the 18-6-12 formulation into the growing medium (table 4.1.11).

Inorganic fertilizers of low solubility. MagAmP® is a commercially available fertilizer of such low solubility that it can go through steam sterilization with little nutrient release. This fertilizer is available in two different particle sizes (coarse and medium), which is the factor controlling nutrient release. Nitrogen is supplied as magnesium ammonium phosphate (hence the trade name), but Sanderson (1987) reports that the N release rate is too slow for some ornamental plants.

Organic fertilizers of low solubility. This group is represented by the urea-formaldehyde fertilizers, such as Agriform® tablets and IBDU, which slowly decompose by hydrolysis or biological activity. The nutrient release of these fertilizers is controlled by the type of growing medium, medium pH, and temperature, and the micro-organism population (Sanderson 1987). Consequently, nutrient release is poor with growing media at low temperatures and or with low microorganism populations, such as artificial growing media.

Micronutrient fertilizers used for incorporation. Several commercial micronutrient fertilizers can be incorpo-

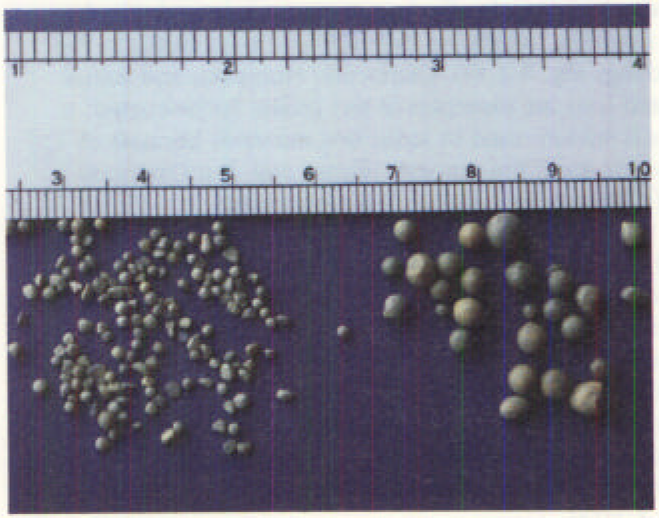


Figure 4.1.14—*Osmocote is a slow-release fertilizer that is available in several formulations, including a microprill* (**left**) *for use in small containers.*

rated into growing media (table 4.1.11). Micromax® is a balanced blend of micronutrients in a soluble sulfate form that is slowly released when it is mixed with the growing medium (Whitcomb 1984). Fritted micronutrients (FTE No. 555®) are also frequently premixed into the medium; this fertilizer consists of glass shards that contain the full range of micronutrients. The micronutrients are then slowly released into the growing medium solution during the growing season, providing a constant, balanced micronutrient supply (Bunt 1976). Esmigran® is another micronutrient fertilizer that consists of a mixture of micronutrients adsorbed on clay particles, which slowly release the nutrients into the soil solution.

Several brands of chelated micronutrient fertilizers are available. Chelates are organically bound forms of the metal micronutrients (Fe, Mn, Zn, and Cu) that prevent these ions from being chemically tied up by other nutrients such as P, Ca, Na, and HC03. Chelated micronutrient fertilizers have proven to be effective but have several drawbacks (Whitcomb 1983):

1. They are broken down by certain other micronutrients.
2. They are expensive.
3. The micronutrients in some chelates can be replaced by other elements, such as Ca, in the growing medium.

The advantages of chelated fertilizers over other soluble micronutrient fertilizers in container tree seedling nurseries have not been studied, although they should prove beneficial in nurseries with special problems such as saline irrigation water.

Broschat and Donselman (1985) investigated the extractability of Fe, Mn, Zn, and Cu from an artificial medium that had been amended with several micronutrient fertilizers and found that availability varied between the different micronutrients. Zn, Mn, and Cu were readily extractable with the sulfate, oxide or clay-adsorbed fertilizers, but Fe availability was restricted in the Esmigran® formulation. Chelated forms of the micronutrients (Sequestrene®) were effective, especially for Fe, although they leach out of the growing medium over time. Whitcomb (1983) studied the addition of different micronutrient fertilizers to artificial media and found that soluble fertilizers were more effective than fritted forms.

4.1.6.2 Injecting liquid fertilizer solutions into the irrigation system

The most popular method of applying fertilizers in container tree seedling nurseries, and the one recommended by the author, is direct injection of liquid fertilizers into the irrigation system (fig. 4.1.16). The benefits of this technique are considerable:

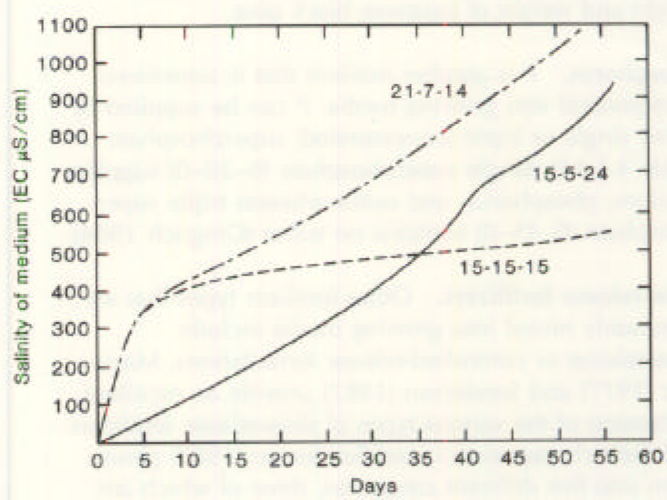


Figure 4.1.15—*Slow-release fertilizers can vary considerably in their nutrient release rates. Three different formulations of 8- to 9-month Osmocote fertilizer had different cumulative release rates of fertilizer salts (from Crowley and others 1986).*

1. Precise control of both the concentration and balance of all 13 mineral nutrients in the applied irrigation water.

2. The ability to completely change the nutrient solution at any time.

3. A very low chance of overfertilization and resultant salt injury.

Although liquid fertilizer injection is highly recommended, there are certain requirements for this procedure that may be drawbacks for small nursery operations:

1. The need for specialized injection equipment.

2. A higher labor cost associated with the frequent mixing and applying of liquid fertilizers.

3. A well-designed, automated irrigation system is essential to insure even fertilizer application.

Types of nutrient injection systems. There is a good selection of nutrient injection equipment available to the container seedling grower that vary in terms of features and cost. The choice of a fertilizer injector is often influenced by cost: the price of a new injector can range from as little as $10 to over $10,000 (table 4.1.13). The injector must also fit into the overall irrigation system so the grower must choose a model that is compatible with the existing irrigation equipment (fig. 4.1.16).

Nelson (1978) discusses the components of a basic nutrient injection system (fig. 4.1.17). The injector should not be installed on the main irrigation line but on a by pass, so that ordinary irrigation water can be applied when desired. A backflow preventer is legally required in many areas to prohibit accidentally introducing fertilizer into domestic water systems. Automated nutrient injection systems can be designed to install a soluble salt me ter in the output line to monitor the strength of the applied fertilizer solution.

The major types of liquid fertilizer injection systems in

Table 4.1.13—*Technical specifications of some common nutrient injectors*

Brand name	Mode of action	Flow rates (gpm)	Operating water pressure (PSI)	Injection ratios	Concentrate capacity	1984 Cost
Hozon	Venturi	3	Any	Fixed 1:16	Any	$10
Dosmatic (Profel)	Water pump	Up to 6	8–85	Adjustable 1:100–1:200	Any	$250
HPA*	Water or electric pump	50–400	>45	Fixed 1:100–1:1600	Any	$1,600–5,000
Gewa*	Displacement	Any	Any	Adjustable 1:20–1:300	4–26 gallon	$400–1,000
Fert-O-Ject*	Water or electric pump	2–120	20–140	Fixed 1:100–1:200	Any	$1,000–4,000
Smith*	Water pump	50–700	Any	Fixed 1:100–1:1600	Any	$1,000–13,000
Anderson*	Water displacement pump	1–160	>15	Adjustable	Any	$700–5,000

* Specifications vary between models
Source: modified from Nelson (1978).

use in container tree seedling nurseries include the following (Mastalerz 1977, Furuta 1978):

Tank and pump system. This is an economical, yet mechanically simple, way to apply liquid fertilizers. The system consists of a large mixing tank, in which the liquid fertilizer is mixed at "applied strength;" and a pump to force the solution through the irrigation system. A major advantage of the tank and pump system is that it is impossible to over fertilize and burn seedlings because the solution is always at applied strength. A major drawback is that the fertilizer solution tank must necessarily be large to hold enough application strength fertilizer to cover the entire area to be fertilized.

Venturi suction injector. This is one of the oldest and simplest types of injection systems and operates on the principle of the venturi tube. When water is forced through a narrow section of pipe, it gains velocity and creates a reduction in water pressure. When a smaller diameter side tube is attached at this narrow section, the

Figure 4.1.16—*Injection of liquid fertilizers is an efficient fertilization method, but nutrient injectors should be designed to be compatible with the irrigation system.*

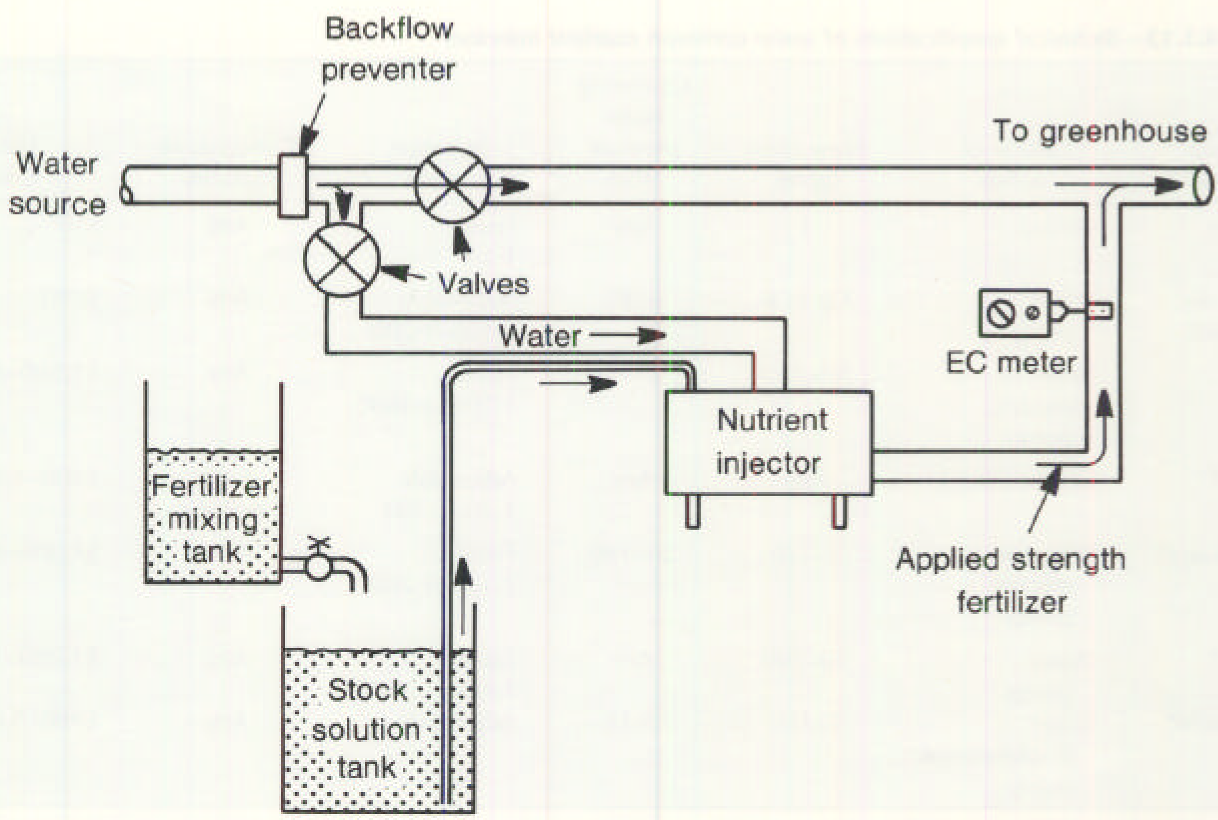


Figure 4.1.17—*Schematic diagram of a typical liquid fertilizer injection system for a container nursery (adapted from Nelson 1978).*

reduced pressure will cause a liquid in the side tube to be sucked into the irrigation pipe. These venturi injectors can therefore be used as liquid fertilizer injectors; they are accurate as long as water flow and pressure are consistent, but the injection rate may change with variable conditions. The Hozon® injector, a commercially available example of this type, injects at a ratio of approximately 1:16 (table 4.1.13).

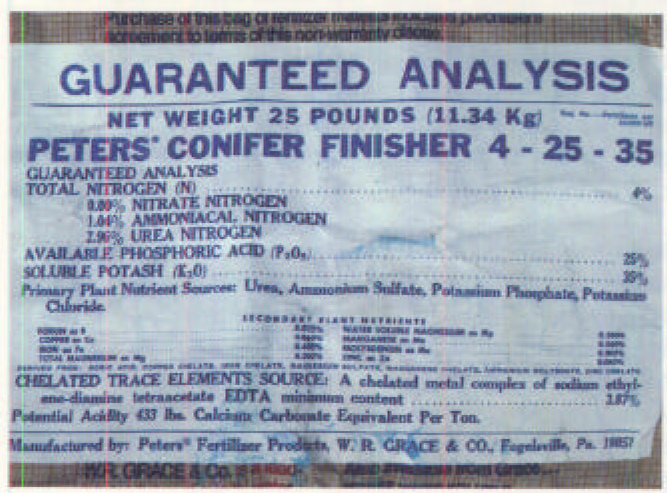
Displacement injector. This type of injector, exemplified by the Gewa®, operates on the basis of a portable tank with a collapsible plastic liner. The fertilizer solution is placed into the lined tank, which is then sealed and connected to the irrigation system. The pressure of the water entering the tank forces the fertilization solution out of the plastic liner and into the irrigation line at a specified injection ratio. The Gewa injector has a variable injection ratio that can be set from 1:20 to 1:300 (table 4.1.13).

Positive displacement pump injector. Most of these injectors use water-driven pumps to inject a fixed amount of fertilizer solution into the irrigation line and operate at a speed that is proportional to water flow. They meter accurately at any line pressure or flow rate and generally do not require a mixing tank. There are several brands of positive displacement pump-type injectors available and the Smith Measuremix® injector is a typical example; they are generally more expensive than other types and are available in a variety of injection ratios (table 4.1.13).

Commercial fertilizers for liquid fertilizer injection. There are several types of completely water-soluble fertilizer that are commercially available for use in liquid injection (fig. 4.1.18). Some formulations contain only N-P-K, whereas others also contain S and the micronutrients. These fertilizers may not contain Ca or Mg because these nutrients form insoluble precipitates in concentrated fertilizer stock solutions. The nutrient ratios are fixed, which means that although the total nutrient concentration can be changed there is no way to adjust the balance between nutrients. Commercial mixes are relatively expensive but are easy to use; another advantage is that only one stock solution is necessary and therefore a less expensive injector with only one head can be used.

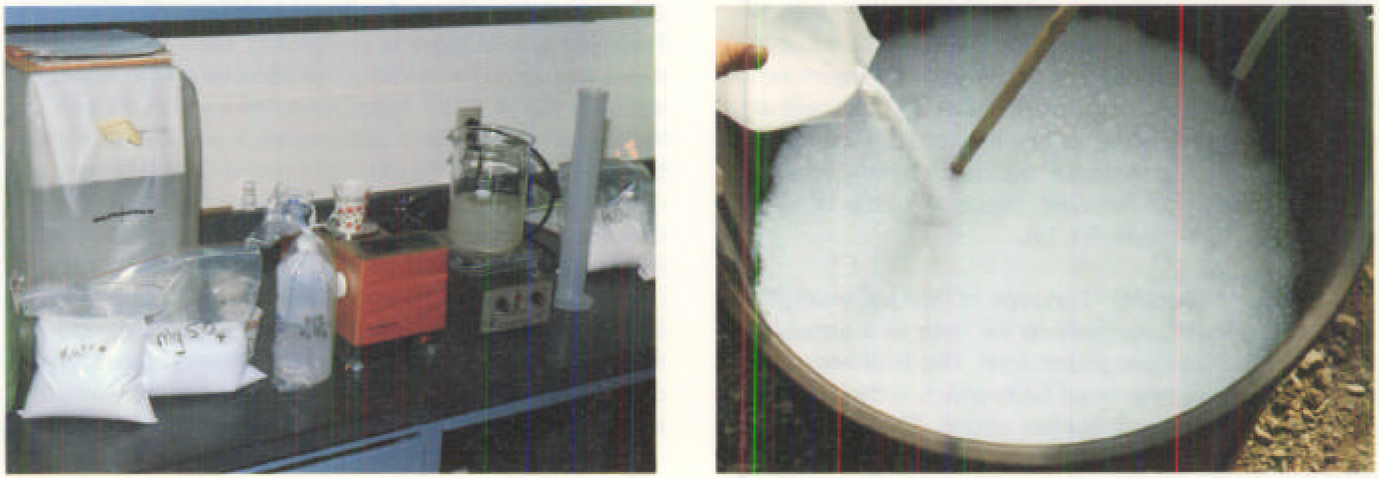
Custom fertilizers for liquid fertilizer injection. Many growers choose to formulate their own custom fertilizer mixes from technical or fertilizer grade chemicals to supply all 13 mineral nutrients (fig. 4.1.19). These separate chemicals are generally cheaper than commercial fertilizers but require more storage space because more bags of chemicals are necessary. The custom mixes have to be made up regularly so there is more labor required compared to using commercial fertilizers, and most custom mixes require a nutrient injector with two heads. The primary appeal of custom mixes is that a complete and balanced fertilizer program can be designed around the nutrients already in the irrigation water and that the concentration of each nutrient can be individually adjusted at any time during the growing season. The calcu-

4.1.18A



4.1.18B

Figure 4.1.18—*Several brands of soluble fertilizers are available for liquid injection into the irrigation system. Some are designed specifically for conifer seedlings (**A**), and others are specifically formulated for different seedling growth stages (**B**).*



4.1.19A 4.1.19B

Figure 4.1.19—*Custom fertilizer solutions can be formulated from technical grade chemicals, such as Epsom salts (**A**). These chemicals are then mixed together to form concentrated stock solutions (**B**).*

lations to formulate a custom fertilizer mix are relatively complicated compared to the commercial fertilizer mixes, but once they are completed, the actual mixing of the fertilizer stock solutions is simple.

Foliar fertilization. Liquid fertilizer injection has also been used to apply foliar fertilizers and has found limited application in ornamental seedling nurseries. Foliar sprays can be used to treat minor deficiencies of some mineral nutrients but can never be used as the only fertilizer source because mineral nutrient uptake rate is very much slower through leaf tissue than through the root system. Foliar fertilization should logically be more effective with broadleaved species because the waxy cuticle found on many conifer needles would slow nutrient uptake. Alexander and Schroeder (1987) present a good review of the practical applications of foliar fertilization in horticulture.

Foliar fertilizers are applied as dilute solutions. In formulating foliar fertilizers, urea is the preferred source of N. Handreck and Black (1984) present foliar spray recipes for N, K, and some micronutrients (Fe, Zn, Mn, Cu, and Mo). Foliar fertilizer formulations are also available iron, some commercial suppliers. Application equipment must be able to produce a fine mist, and a surfactant is often used to make sure that the fertilizer solution is spread evenly over the foliage surface. Foliar sprays are usually applied under humid conditions, often in the evening so that the solution remains in contact with the foliage for an extended period of time. Some nursery managers allow the regular applied fertilizer solution to remain on the seedling foliage to promote foliar uptake. This practice is discouraged because the more concentrated standard fertilizer solutions may burn succulent foliage. In container tree seedling nurseries, foliar fertilization has primarily been used to treat micronutrient deficiencies such as iron chlorosis but can also be used to provide a quick "green-up" before seedlings are shipped (fig. 4.1.20). As with all new cultural techniques, growers who want to test foliar fertilization should try the procedure on a small scale first.

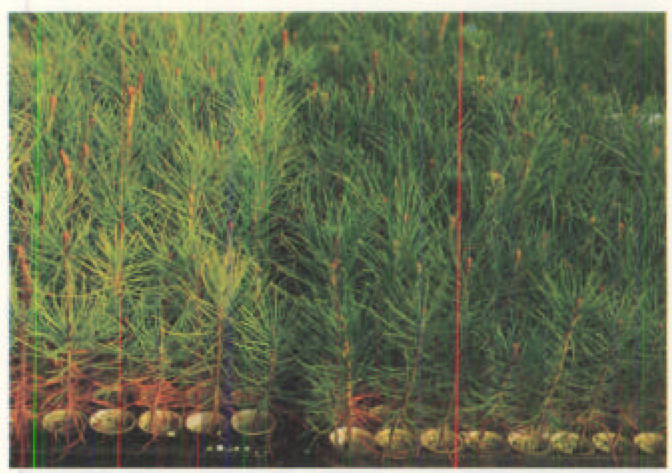


Figure 4.1.20—*Although foliar fertilization cannot be used to supply all the mineral nutrients for container tree seedling production, foliar sprays can be used to correct micronutrient deficiencies or "green-up" seedlings prior to shipping (seedlings on right were treated; those on the left are the control).*

4.1.7 Formulating Liquid Fertilizer Solutions

4.1.7.1 Determining the nutrient status of the irrigation water

Regardless of the type of fertilizer used, the first step in developing a liquid fertilizer injection program is to determine which nutrients are present in the irrigation water and in what concentration (Vetanovetz and Knauss 1988). Unfortunately, this important step is often neglected by many growers because they mistakenly assume that irrigation water is uniform in quality. Natural waters usually contain appreciable concentrations of several plant nutrients, especially Ca and Mg, and some "hard" waters may contain enough of these nutrients to partly or even completely supply plant requirements (Jones 1983, Whitcomb 1986). The Container Nursery Survey found that only a small percentage of container nursery managers ever analyzed their irrigation water for the complete range of mineral nutrients.

Table 4.1.14—*Comparison of nutrients in irrigation water and liquid fertilizer solution with target levels (Mt. Sopris Nursery 1980)*

	Units	Irrigation water	Applied fertilization solution	Target levels
Macronutrients				
Total N	ppm	3	181	222
NO_3–N	ppm	3	170	156
NH_4^{3}–N	ppm	0	11	66
P	ppm	0.07	54	60
K	ppm	2	140	155
Ca	ppm	82	80	60
Mg	ppm	14	48	40
SO_4–S	ppm	43	135	63
Micronutrients				
Fe	ppm	ND	2.6	4.0
Mn	ppm	ND	1.1	0.5
Zn	ppm	ND	0.07	0.05
Cu	ppm	ND	0.07	0.02
Cl	ppm	3.00	4.00	4.00
Mo	ppm	ND	ND	0.01
B	ppm	0.06	0.14	0.5
Water quality				
pH	—	6.9	6.0	5.5
EC	µS/cm	470	1680	1200–1800

ND = Values too low to be detected by instrument.

Mineral nutrient analyses of irrigation water can be performed by most analytical testing laboratories, but growers should be sure to specify that they want a nutrient analysis, instead of a standard water quality test. Actually, since many of the ions are the same in both tests, it would be wise to have water quality checked at the same time. A complete water analysis for both nutrients and quality should cost around $50 to $100. (Water quality testing is discussed in more detail in section 4.2.4.2.)

A nutrient analysis of the irrigation water at Mt. Sopris Nursery, Carbondale, CO, is listed in table 4.1.14. The concentrations of all the nutrient elements in the irrigation water are reported in parts per million. When requesting a water test, all nutrients should be reported in parts per million although the lab report may give the values in milligrams per liter (mg/l), an equivalent unit of measure (see table 4.1.6). In table 4.1.14, both the NO_3^- and NH_4^+ forms of N were analyzed but, for most purposes, a test for total N is sufficient. Note that some macronutrients, such as P, and many micronutrients may exist at very low concentrations in natural waters, some of which may be too low to be detected by the analytical instruments. The pH and electrical conductivity (EC) of the water are routinely reported along with the mineral nutrients. Electrical conductivity is the relative concentration of dissolved salts in the irrigation water, and is reported in units of micro-Siemens per centimeter (µS/cm). Each nursery should have its own pH and EC meters and should perform its own tests regularly to monitor changes in water quality; monitoring fertilization is discussed in more detail in section 4.1.9.

4.1.7.2 Controlling irrigation water pH

Once the base nutrient level of the water is known, the buffering capacity of the water should be determined by acid titration. Titration is a process in which small increments of an acid are added to a sample of irrigation water to determine the amount of acid that will be required to lower the pH of the water to the desired level (pH 5.5). Titrations can be done by any water testing lab or by nursery personnel using a pH meter and a burette or pipette. Any acid can be used for titrating as long as the normality is known so that conversions for relative acidity can be made.

To keep the calculations simple, one procedure is to use a 1 % phosphoric acid (H_3PO_4) solution, because either 75 or 85% phosphoric are often used in custom fertilizer mixes to lower pH and add nutrient F A 1 H3P04 solution can be made from stock 85% H_3PO_4 by adding 11.75 ml of 85% acid to enough distilled water to make up 1 liter of solution. For safety reasons, always add acid to water: partially fill the flask with water, add the acid to it, and then add the rest of the water. Once the amount of 1 % H_3PO_4 needed to lower the pH of the water sample is known, the conversion to either 75 or 85% stock acid solution is made by dividing by either 75 or 85.

Titration curves for the irrigation water at Mt. Sopris Nursery and the Colorado State Forest Service Nursery in Ft. Collins, CO, are given in figure 4.1.21. Note the difference between the two curves: the steeper the slope of the line, the lower the buffering capacity of the water. The water at the Colorado State Nursery has a very low buffering capacity and requires only 3 ml of H_3PO_4 to lower the pH of 1 liter of irrigation water to the desired level, whereas the Mt. Sopris Nursery water requires almost 16 ml of 1 % H_3PO_4. Because the amount of acid will probably need to be adjusted for seasonal changes, regular pH monitoring is necessary. The pH will also change after the fertilizer chemicals have been added to the fertilizer solution, so other minor adjustments may be necessary.

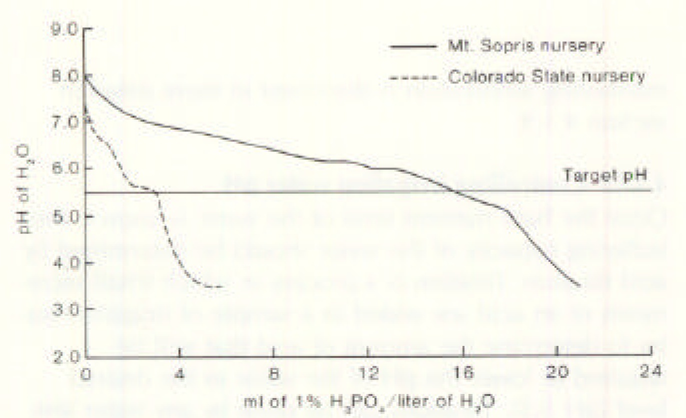


Figure 4.1.21—*Acid titration curves for irrigation water from two different container tree seedling nurseries in Colorado. These curves were developed by adding successive 1-ml increments of 1% phosphoric acid to 1 liter of irrigation water.*

Table 4.1.15—*Actual nutrient concentration in a typical applied commercial fertilizer solution at a 1:200 injection ratio to provide a target of 100 ppm N*

	Nutrient level (ppm)
Macronutrients	
N	100
P	15
K	79
Ca	0
Mg	1.5
S	2.0
Micronutrients	
Fe	2.0
Mn	0.3
Zn	0.3
Cu	0.3
Mo	0.025
B	0.125
Cl	Not given

Several acids have been used for acid injection in container tree nurseries including nitric, sulfuric, phosphoric, and even acetic acid. Phosphoric acid should be used whenever possible because 1) it is the safest acid to handle, 2) it does not react violently with water or produce toxic fumes, and 3) it is a source of fertilizer P Jaramillo and Owston (1977) concluded that phosphoric acid is safest to use even though it is more expensive and recommended "food" or "reagent" grade because other grades may contain phytotoxic heavy metals. Considering how little acid is used in acidification, however, the possibility of a serious phytotoxicity problem is remote. (For a list of chemical grades, see section 4.1.7.4.) If the irrigation water is very alkaline, sulfuric acid may have to be used because the amount of phosphoric acid that would be required to lower the pH will add an excessive amount of P to the solution.

4.1.7.3 Liquid fertilizer calculations for commercial fertilizers

Based on the results of the Container Nursery Survey, 88% of the container nurseries in North America use commercial brand fertilizers, either alone or in combination with custom mixes for injection into the irrigation system. Some fertilizer brands contain both macronutrients and micronutrients whereas others contain only the major fertilizer elements. Check the label to deter mine the exact nutrient composition; nutrients supplied by a typical fertilizer (Peters Conifer Grower) at a 100 ppm N rate are listed in table 4.1.15.

Macronutrients. An example of the nutrient content and mixing instructions for a typical fertilizer is provided in table 4.1.16. Note that the nutrient analysis is given in total nitrogen (N), available phosphoric acid (P_2O_5), and soluble potash (K_20). The two latter terms can be converted to %P and %K using the conversion factors in table 4.1.4. The weight of fertilizer to add to 1 liter of water to make 1 liter of liquid fertilizer concentrate are given at the bottom of table 4.1.16. To calculate the concentrations of all the nutrients, use the following procedure:

1. Set the target N level for the applied fertilizer solu tion (100 ppm, for example).

2. Determine how much bulk fertilizer must be used to produce the target concentration (100 ppm) - the fertilizer in our example is 20-7-19, or 20% N:

   100 ppm = 100 mg/l = 0.20
   = 500 mg/l bulk fertilizer

3. Adjust for the nutrient injection ratio (1:200, for example):

   500 mg/l bulk fertilizer x 200
   = 100,000 mg/l bulk fertilizer

4. Convert from milligrams per liter to grams per liter:

   100,00 mg/l = 1,000 mg/g = 100 g/l bulk fertilizer

   If using English units, convert grams per liter to ounces per gallon:

   100 g/l x 0.1334 = 13.34 ounces of bulk fertilizer per gallon water

   (Note that this value agrees with the value in the mixing instructions in table 4.1.16.)

5. Now that we have established the amount of 20-7-19 bulk fertilizer (step #2) needed to supply our N target (step #1), we need to calculate how much P will be contained in the applied fertilizer solution (the fertilizer contains 7% P_2O_5):

   500 mg/l x 0.07 = 35 ppm P_2O_5

6. Using the conversion factor from table 4.1.4, convert from the oxide form (P_2O_5) to the elemental form:

   35 PPM P_2O_5x 0.4364 = 15 ppm P

7. Using a similar process as in steps #5 and 6, compute the amount of K that the 20-7-19 fertilizer supplies to the applied fertilizer solution (the fertilizer contains 19% K_2O):

   500 mg/l x 0.19 = 95 ppm K_2O

   95 ppm K_2O x 0.8301 = 79 ppm K

Record the concentrations of the other nutrients that are listed on the fertilizer label for that N concentration. For example, the actual nutrient concentrations for a typical fertilizer at 100 ppm N are listed in table 4.1.15.

A set of tables has been developed to quickly and easily determine the amount of bulk fertilizer to add for a range of desired N concentrations and for different nutrient injector ratios (table 4.1.17). Remember that these tables only provide N levels and that levels of P, K, and other nutrients are determined by the chemical make-up of the bulk fertilizer.

Table 4.1.16—*Nutrient content and mixing instructions from a typical commercial fertilizer (20–7–19) label*

Nutrient	Guaranteed analysis (%)
Total nitrogen (N)	20
Nitrate	11.6
Ammonium	7.0
Urea	1.4
Available phosphoric acid (P_2O_5)	7
Soluble potash (K_2O)	19

	Amount of fertilizer to make concentrate			
	100 ppm N		150 ppm N	
Injector ratio	g/l	oz/gal	g/l	oz/gal
1:100	50.1	6.68	75.1	10.01
1:200	100.2	13.35	150.2	20.03

Table 4.1.17—*Tables for determining the amount of commercial fertilizer to add per gallon of water for different nitrogen (N) concentrations and nutrient injector ratios*

Injector ratio	Amount of fertilizer to add to 3.78 liters (1 gallon) water					
	100 ppm N		150 ppm N		200 ppm N	
	g	oz	g	oz	g	oz
30% Nitrogen fertilizers (e.g., 30–10–10)						
1:300	382.7	13.5	574.1	20.2	765.5	27.0
1:200	255.2	9.0	382.7	13.5	510.3	18.0
1:100	127.6	4.5	191.4	6.8	255.2	9.0
1:50	63.8	2.2	95.7	3.4	127.6	4.5
1:15	19.1	0.7	28.7	1.0	38.3	1.4
25% Nitrogen fertilizers (e.g., 25–10–10)						
1:300	476.8	16.5	701.7	24.8	935.6	33.0
1:200	311.8	11.0	467.8	16.5	623.7	22.0
1:100	155.9	5.5	233.9	8.2	311.8	11.0
1:50	78.0	2.8	116.9	4.1	155.9	5.5
1:15	23.4	0.8	35.1	1.2	46.8	1.6
20% Nitrogen fertilizers (e.g., 20–20–20)						
1:300	574.1	20.2	861.1	30.4	1148.2	40.5
1:200	382.7	13.5	574.1	20.2	765.4	27.0
1:100	191.4	6.8	287.0	10.1	382.7	13.5
1:50	95.7	3.4	143.7	5.1	191.4	6.8
1:15	28.6	1.0	43.0	1.5	57.4	2.0
15% Nitrogen fertilizers (e.g., 15–15–15)						
1:300	765.4	27.0	1148.2	40.5	1530.9	54.0
1:200	510.3	18.0	765.4	27.0	1020.6	36.0
1:100	255.2	9.0	382.7	13.5	510.3	18.0
1:50	127.6	4.5	191.4	6.8	255.2	9.0
1:15	38.3	1.4	57.4	2.0	76.5	2.7

Source: modified from Ball (1985).

Micronutrients. Some commercial fertilizers do not contain a complement of micronutrients. Supplemental fertilization with micronutrient fertilizers is usually necessary, therefore, because artificial growing media contain few, if any, micronutrients (see section 4.1.3.1). Iron deficiency is one of the most common micronutrient deficiencies in container tree seedling nurseries and is expressed as chlorosis and stunting (see fig. 4.1.7A). Scarratt (1986) reports mild chlorosis and low foliar Fe levels for container jack pine grown under commercial "general-purpose" fertilizers. Biweekly applications of ferrous sulfate are prescribed to supplement standard commercial fertilizers and prevent iron chlorosis in British Columbia nurseries (Matthews 1982). Chelated iron fertilizers are sometimes preferred over iron sulfate because, although more expensive, chelates are more available for plant uptake under a wider range of growing media conditions. Copper deficiency may also be a problem with peat-based growing media and deficiency symptoms have been identified in some conifer seedlings (see figure 4.1.7B). Scarratt (1986) reports that, in a chemical analysis of a standard peat-vermiculite growing medium, copper was the only micronutrient that was totally absent.

Several soluble micronutrient fertilizers are available in either single element or micronutrient mixtures; mixes are recommended over individual micronutrient fertilizers unless a specific deficiency has been identified. Overfertilization with a single-element fertilizer can result in direct toxicity or a nutrient imbalance that can inhibit the uptake of other micronutrients. Micromax® is a sulfate-based mixture that is generally incorporated into the medium but can be used as a liquid topdressing if the foliage is rinsed immediately after application (Whitcomb 1984). Soluble trace element mix (S.T.E.M.®) is a mixture of sulfur and six micronutrients that is derived from sulfates and other inorganic chemicals. Many nutrition specialists feel that chelated forms of micronutrients remain more available in the medium, and a mix of soluble chelated micronutrients (Compound 111®) is available for liquid fertilizer injection. Several commercial formulations of individual chelated micronutrients are also available, such as Sequestrene 330 Fe® (EDTA chelate) and Sequestrene 138 Fe® (EDDHA chelate).

Application rates are provided on the fertilizer label, usually specified as amount of micronutrient fertilizer to use per amount of macronutrient fertilizer (micronutrient fertilizers are also discussed in section 4.1.4.3).

4.1.7.4 Liquid fertilizer calculations for custom fertilizer mixes

Selection of chemicals. Custom fertilizer mixes utilize bulk chemicals to supply all the mineral nutrients necessary for tree seedling growth. There are several grades of commercial chemicals that are classified according to use (table 4.1.18); the technical or purified grades are most practical for custom fertilizer mixes in terms of purity and cost. Fertilizer grade chemicals are not recommended for soluble fertilizer mixes because they contain a relatively high percentage of impurities. The Container Nursery Survey found that 12% of the container nurseries used custom mixes exclusively and another 6% used them in combination with commercial fertilizers.

The specific chemicals for custom fertilizer mixes are chosen based upon four criteria:

1. *Availability and ability* to supply the desired nutrient-Commonly available soluble chemicals suitable for use as fertilizer are listed in table 4.1.19; note that some nutrients, such as N, are available in several soluble compounds whereas others, such as Ca, have only one soluble form.

2. *Solubility in water and compatibility with other nutrient chemicals*-The solubilities and compatibilities of some of the major fertilizer chemicals are compared in fig. 4.1.22.

3. *Cost per supplied nutrient*-Several chemicals contain more than one nutrient and are therefore more cost efficient and contain fewer unwanted ions. Multiple nutrient chemicals make fertilizer calculations slightly more complicated, however, because of the need to keep the other nutrients in balance.

4. *Absence of potentially toxic ions*-Some commonly used fertilizer chemicals contain undesirable secondary ions in addition to the nutrient ion. A good example of this is KCI, which contains 47% CI; because of the high concentration of K+ desired in fertilizer solutions, the accompanying CI- ions could become toxic.

Mixing the stock fertilizer solutions. The fertilizer chemicals are dissolved in water to form concentrated nutrient stock solutions. It is a good idea to use hot water for the stock solutions, because most chemicals dis-

Table 4.1.18—*Commercial grades of chemicals used for custom fertilizers*

Symbol	Chemical grade	Definition and use	Relative cost of ammonium nitrate
AR/ACS	Reagent	General laboratory use	$14.45/lb
U.S.P.	Pharmacy	Pharmacy grade	—
TAC/FCC	Food	Satisfactory for approved food uses	—
Purified	Purified	Higher grade than technical	$12.97/lb
Technical	Technical	A grade suitable for general industrial use; very few impurities; **best for custom fertilizer mixes**	$ 0.21/lb
Fertilizer	Fertilizer	Lower grade than technical; will contain impurities	$ 0.16/lb

Table 4.1.19—*Characteristics of macronutrients and implications for formulation of liquid fertilizers*

Nutrient	Ionic uptake forms	Mobility in plant	Effects on seedling growth	Availability as soluble fertilizer
Nitrogen	NO_3^-	High	Fertilizer element used in largest quantities. High N levels promote rapid cell division and elongation, but may prolong succulence.	Excellent (7 forms): Ammonium nitrate, Ammonium phosphates, Ammonium sulfate, Calcium nitrate, Potassium nitrate, Sodium nitrate*, Urea
	NH_4^+	High		
Phosphorus	$H_2PO_4^-$	High	Although P is found in lesser quantities in plant tissue, relatively large amounts are needed early in the growing season for root growth and establishment.	Fair (2 forms): Ammonium phosphates, Phosphoric acid
	HPO_4^{2-}	High		
Potassium	K^+	High	Used in large amounts throughout the growing season. Thought to promote stem lignification and cold hardiness.	Good (4 forms): Potassium carbonate, Potassium chloride*, Potassium nitrate, Potassium sulfate
Calcium	Ca^{2+}	Low	Important early in growing season for root growth. Ca is a major component of cell walls and therefore promotes sturdier tissue during hardening.	Poor (1 form): Calcium nitrate
Magnesium	Mg^{2+}	Medium	Structural component of chlorophyll and required in moderate amounts.	Poor (1 form): Magnesium sulfate
Sulfur	SO_4^{2-}	Medium	Essential for proteins, so needed in moderate amounts throughout the growing season.	Good (4 forms): Ammonium sulfate, Magnesium sulfate, Potassium sulfate, Sulfuric acid

* Not recommended because of the very high salt index.

solve more quickly and completely in hot water. Mastalerz (1977) recommends preparing the stock solution in one container with hot water and then siphoning or pouring the solution into a second container so that undissolved particles are screened out. Stock solutions are also highly corrosive and so the stock solution tanks should be plastic rather than metal, with covers to keep debris out of the solution.

For safety's sake, always add the acid component to the solution first. Certain nutrients, especially Ca and Mg, cause problems in concentrated stock solutions because they form precipitates with other nutrients such as sulfates or phosphates: $Ca + SO_4 = CaSO_4$ (gypsum) (fig. 4.1.23). Three separate stock solutions are often used to supply all nutrients while maintaining the optimum solubility of chemicals in each solution. Note that Ca is

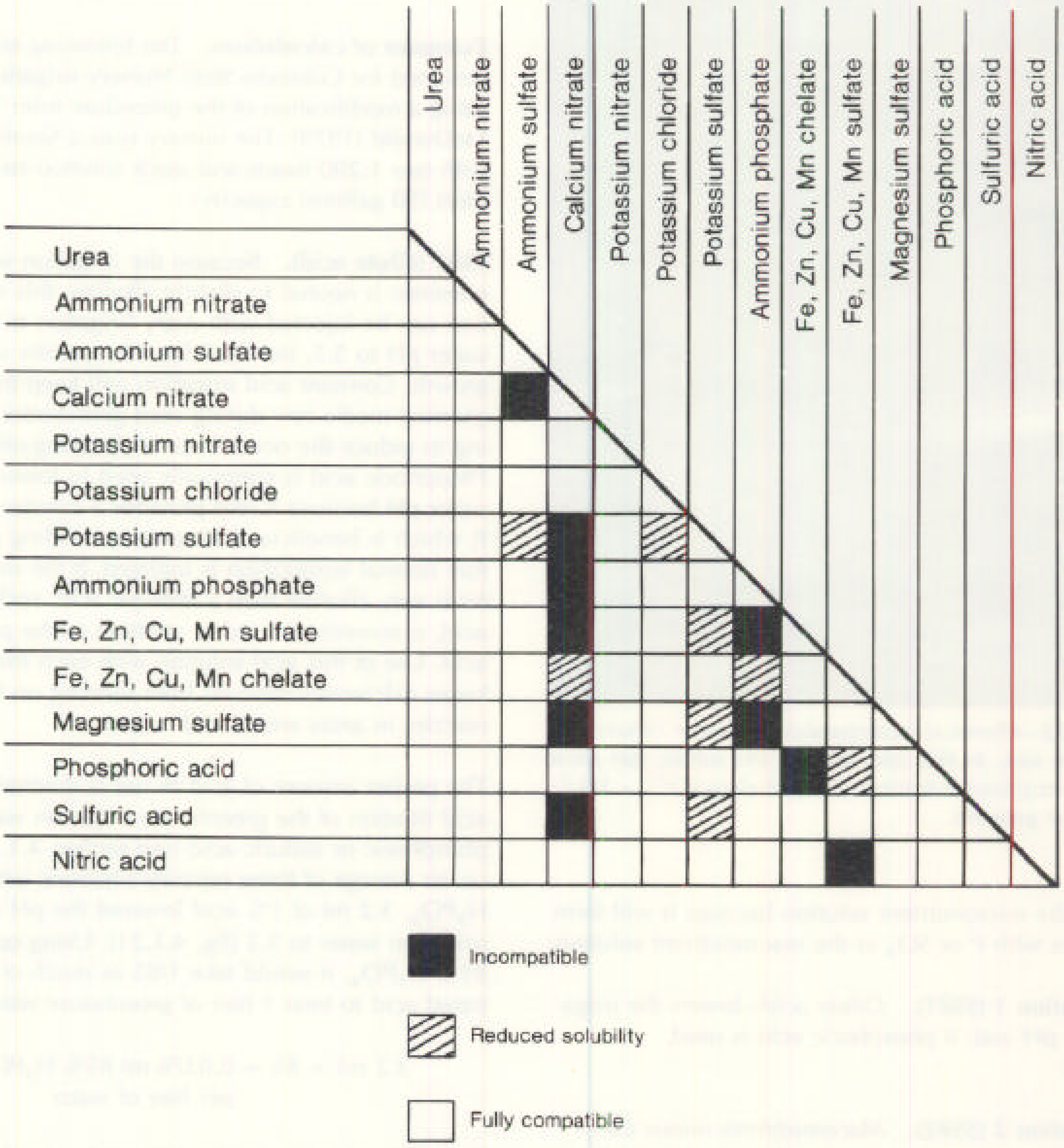


Figure 4.1.22—*Certain chemicals that are used for formulating custom liquid fertilizers are incompatible in the concentrated fertilizer stock solutions. This compatability chart illustrates some of the chemical combinations that should be avoided in the same stock solution (modified from Soil and Plant Laboratory Inc., Bellevue, WA).*

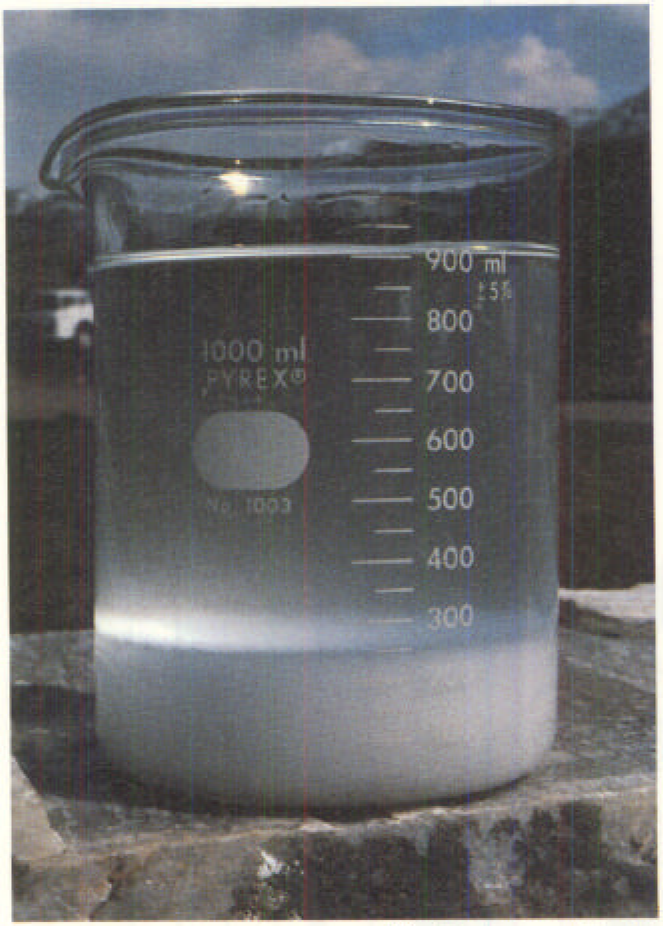


Figure 4.1.23—*Chemical incompatability between certain mineral nutrient ions, in this case calcium and sulfate, can cause insoluble precipitates in fertilizer stock solutions ($Ca^{2+} + SO_4^{2-} = CaSO_4$, or gypsum).*

added to the micronutrient solution because it will form precipitates with P or SO_4 in the macronutrient solution:

Stock solution 1 (SS#1*).* *Dilute acid*—lowers the irrigation water pH and, if phosphoric acid is used, supplies P.

Stock solution *2 (*SS*#2*). *Macronutrients minus Ca*---supplies all macronutrients except Ca, which must be added to *SS#3* for solubility reasons.

Stock solution 3 (SS#3). *Micronutrients plus Ca*—supplies all micronutrients and Ca.

In this example, a complete fertilizer solution would consist of stock solution #2 and stock solution #3, each injected through its own injector head. Several nutrient injectors are available with two heads and they can be ordered with different injection ratios. The macronutrient solutions are usually injected at a 1:200 ratio whereas the micronutrient solutions can be more concentrated and injected at ratios as high as 1:500.

***Examples of calculations*.** The following example was designed for Colorado State Nursery irrigation water, using a modification of the procedure from Tinus and McDonald (1979). The nursery uses a Smith® injector with two 1:200 heads and stock solution tanks of 200 liters (50 gallons) capacity:

SS#1 (dilute acid). Because the irrigation water at many nurseries is neutral to slightly alkaline, this stock solution can be injected with every irrigation to lower the water pH to 5.5, the ideal level for conifer seedling growth. Constant acid irrigation will keep the pH of the growing media low during seed germination, thus helping to reduce the occurrence of damping-off diseases. Phosphoric acid is commonly used to lower irrigation water pH because it also provides a constant supply of P, which is beneficial during early seedling growth before normal fertilization is initiated. If the irrigation water is very alkaline then a stronger acid, such as sulfuric acid, is sometimes used in addition to the phosphoric acid. Use of this acid solution with each irrigation also keeps calcareous deposits from forming on the irrigation nozzles in areas with "hard" water.

The proper amount of acid to use is determined by an acid titration of the greenhouse irrigation water using phosphoric or sulfuric acid (see section 4.1.7.2). Based on an average of three separate titrations with 1 H_3PO_4, 3.2 ml of 1 % acid lowered the pH of 1 liter of irrigation water to 5.5 (fig. 4.1.21). Using commercial 85% H_3PO_4, it would take 1/85 as much of the concentrated acid to treat 1 liter of greenhouse water:

$$3.2 \text{ ml} \div 85 = 0.0376 \text{ ml } 85\% \ H_3PO_4 \text{ per liter of water}$$

If 0.0376 ml is needed for 1 liter of water, how much (X) is needed for 200 liter of stock solution?

$$\frac{0.0376 \text{ ml}}{1 \text{ liter}} = \frac{X \text{ ml}}{200 \text{ liters}}$$

$$X = 7.52 \text{ ml of } 85\% \ H_3PO_4$$

The solution will be injected at a ratio of 1:200, so the stock solution must be 200 times as strong:

$$7.52\ ml \times 200 = 1{,}504\ ml = 1.5\ liters\ of\ 85\%\ H_3PO_4$$

The recipe for SS#1, therefore, will be to add 1.5 liters of 85% H_3PO_4 to enough irrigation water to make 200 liters of stock solution.

The accuracy of these computations should be checked by collecting some of the applied irrigation water and testing its pH (a direct test of the pH of the stock solution is not indicative of the pH of the applied irrigation water). Because the quality of irrigation water will change during the year, the amount of acid added to the stock solution may have to be adjusted occasionally.

SS#2 (macronutrients minus Ca). The computations for this fertilizer solution are provided in table 4.1.20A. (A blank form is provided in table 4.1.20B.) The upper portion shows the target nutrient concentrations in parts per million, the amount of each nutrient in the irrigation water and the amount needed to add as injected fertilizer. The chemicals used to supply nutrients and their contribution in parts per million are shown in the left column. The final column on the right shows the total amount of the chemical that would be present in the applied fertilizer solution as it comes out of the irrigation nozzle.

The total parts per million of each nutrient must be converted to the weight of the chemical that needs to be added to each liter of water. This conversion is simple because 1 liter of water weighs 1 kg by definition. Therefore, on a weight per volume basis, 1 mg/l equals 1 ppm.

Based on the acid titration, 0.0376 ml of 85% H_3PO_4 will be added to 1 liter of irrigation water. To compute the amount of P added, refer to table 4.1.21, which shows that 1 liter of 85% H_3PO_4 weighs 1,436 g (if H_2SO_4 was used, use the chemical data in table 4.1.22). If 1 liter of H_3PO_4 weighs 1,436 g, how much will 0.0376 ml weigh?

$$\frac{1{,}000\ ml}{1{,}436\ g} = \frac{0.0376\ ml}{X\ g}$$

$$X = 0.054\ g = 54\ mg$$

The next step is to convert the 85% H_3PO_4 to parts per million P and table 4.1.23 shows that phosphoric acid contains 32% P. Therefore:

$$54\ mg/l = 54\ ppm \times 0.32 = 17\ ppm\ P$$

Our target concentration is 60 ppm P, so we need to add more P. Monopotassium phosphate (KH_2PO_4) can be used to supply both P and K and table 4.1.23 shows that the chemical contains 23% P and 28% K. We need 43 ppm to meet the target:

$$\frac{43\ ppm\ P}{0.23} = 187\ mg/l\ KH_2PO_4$$

$$187\ mg/l \times 0.28 = 52\ ppm\ K$$

Potassium nitrate (KNO_3) contains 13% NO_3 and 37% K (table 4.1.23) so it can be used to supply the 48 ppm K to reach the 100 ppm target:

$$\frac{48\ ppm\ K}{0.37} = 130\ mg/l\ KNO_3$$

$$130\ mg/l \times 0.13 = 17\ ppm\ NO_3$$

Ammonium nitrate (NH_4NO_3) supplies 17% NO_3 and 17% NH_4 (table 4.1.23), so we can use this chemical to fill the NH_4 and part of the NO_3 requirement:

$$\frac{60\ ppm\ NH_4}{0.17} = 353\ mg/l\ NH_4NO_3$$

$$353\ mg/l \times 0.17 = 60\ ppm\ NO_3$$

We still need 63 ppm NO_3 to make our target concentration (table 4.1.20A). Calcium nitrate ($CaNO_3$), which contains 15% NO_3 and 17% Ca (table 4.1.23), is a logical choice:

$$\frac{63\ ppm\ NO_3}{0.15} = 420\ mg/l\ CaNO_3$$

$$420\ mg/l \times 0.17 = 71\ ppm\ Ca$$

Table 4.1.20A — Sample computation for a custom fertilizer mix

	Nutrient concentration (ppm)								
	Total N	NO_3^--N	NH_4-N	P	K	Ca	Mg	S	
Target	200	140	60	60	100	80	40	60	
-Water test	0	0	0	0	0	11	2	6	
=To add	200	140	60	60	100	69	38	54	
Fertilizer chemicals									Applied solution
85% H_3PO_4				17					0.0376 ml/l
KH_2PO_4				43	52				187 mg/l
KNO_3	17	17			48				130 mg/l
NH_4NO_3	120	60	60						353 mg/l
$Ca NO_3$	63	63				71			420 mg/l
$Mg SO_4$							38	49	380 mg/l
Totals	200	140	60	60	100	71	38	49	

Fertilizer chemicals		Applied solution	Injector concentrate (1:200)	Stock solution (200 l)
Common name	Formula			
85% Phosphoric Acid	H_3PO_4	0.0376 ml/l	7.52 ml/l	1.5 l
Monopotassium phosphate	KH_2PO_4	187 mg/l	37.4 g/l	7.5 kg
Potassium nitrate	KNO_3	130 mg/l	26.0 g/l	5.2 kg
Ammonium nitrate	NH_4NO_3	353 mg/l	70.6 g/l	14.1 kg
Calcium nitrate	$CaNO_3$	420 mg/l	84.0 g/l	16.8 kg
Magnesium sulfate	$MgSO_4$	380 mg/l	76.0 g/l	15.2 kg

Table 4.1.20B — *Blank form for custom fertilizer mix calculation*

	Nutrient concentration (ppm)								
Target									
-Water test									
=To add									
Fertilizer chemicals									Applied solution
Totals									

Fertilizer chemicals		Applied solution	Injector concentrate	Stock solution
Common name	Formula		( )	( )

Table 4.1.21—*Phosphoric acid: relation between degrees Baume (Be), percent acid, and grams of acid per liter (g/l)*

Be	Specific gravity	Percent acid	Acid conc. (g/l)
0.6	1.0038	1	10.04
1.3	1.0092	2	20.18
2.8	1.0200	4	40.80
4.3	1.0309	6	61.85
5.8	1.0420	8	83.36
7.3	1.0532	10	105.3
8.8	1.0647	12	127.8
10.3	1.0764	14	150.7
11.8	1.0884	16	174.1
13.3	1.1008	18	198.1
14.8	1.1134	20	222.7
16.3	1.1263	22	247.8
17.8	1.1395	24	273.5
19.2	1.1529	26	299.8
20.7	1.1665	28	326.6
22.2	1.1805	30	354.2
25.8	1.2160	35	425.6
29.4	1.2540	40	501.6
32.9	1.2930	45	581.9
36.4	1.3350	50	667.5
39.9	1.3790	55	758.5
43.3	1.4260	60	855.6
46.7	1.4750	65	958.8
50.0	1.5260	70	1,068
53.2	1.5790	75	1,184
56.2	1.6330	80	1,306
59.2	1.6890	85	1,436
62.0	1.7460	90	1,571
63.1	1.7700	92	1,628
64.2	1.7940	94	1,686
65.3	1.8190	96	1,746
66.4	1.8440	98	1,807
67.5	1.8700	100	1,870

Source: Hodgman et al. (1953).

Table 4.1.22—*Sulfuric acid: relation between degrees Baume (Be), percent acid, and acid concentration (g/l)*

Be	Specific gravity	Percent acid	Acid conc. (g/l)
44.7	1.4453	55	749.9
45.4	1.4557	56	815.2
46.1	1.4662	57	835.7
46.8	1.4768	58	856.5
47.5	1.4875	59	877.6
48.2	1.4983	60	899.0
48.9	1.5091	61	920.6
49.6	1.5200	62	942.4
50.3	1.5310	63	964.5
51.0	1.5421	64	986.9
51.7	1.5533	65	1,010
52.3	1.5646	66	1,033
53.0	1.5760	67	1,056
53.7	1.5874	68	1,079
54.3	1.5989	69	1,103
55.0	1.6105	70	1,127
55.6	1.6221	71	1,152
56.3	1.6338	72	1,176
56.9	1.6456	73	1,201
57.5	1.6574	74	1,226
58.1	1.6692	75	1,252
58.7	1.6810	76	1,278
59.3	1.6927	77	1,303
59.9	1.7043	78	1,329
60.5	1.7158	79	1,355
61.1	1.7272	80	1,382
61.6	1.7383	81	1,408
62.1	1.7491	82	1,434
62.6	1.7594	83	1,460
63.0	1.7693	84	1,486
63.5	1.7786	85	1,512
63.9	1.7872	86	1,537
64.2	1.7951	87	1,562
64.5	1.8022	88	1,586
64.8	1.8087	89	1,610
65.1	1.8144	90	1,633
65.3	1.8195	91	1,656
65.5	1.8240	92	1,678
65.7	1.8279	93	1,700
65.8	1.8312	94	1,721
65.9	1.8337	95	1,742
66.0	1.8355	96	1,762
66.0	1.8364	97	1,781
66.0	1.8361	98	1,799
65.9	1.8342	99	1,816
65.8	1.8305	100	1,831

Source: Hodgman et al. (1953).

Table 4.1.23—*Soluble fertilizer chemicals that provide macronutrients for custom fertilizer solutions*

Compound	Chemical formula	Solubility in water (g/100 ml)	% Nutrient supplied						
			NH_4–N	NO_3–N	P	K	Ca	Mg	S
Ammonium nitrate	NH_4NO_3	118	17	17	—	—	—	—	—
Ammonium sulfate	$(NH_4)_2SO_4$	71	21	—	—	—	—	—	24
Calcium nitrate	$Ca(NO_3)_2$	102	—	15	—	—	17	—	—
Diammonium phosphate	$(NH_4)_2HPO_4$	43	21	—	24	—	—	—	—
Dipotassium phosphate	K_2HPO_4	167	—	—	18	45	—	—	—
Magnesium sulfate	$MgSO_4$	71	—	—	—	—	—	10	13
Monoammonium phosphate	$NH_4H_2PO_4$	23	11	—	21	—	1	—	3
Monopotassium phosphate	KH_2PO_4	33	—	—	23	28	—	—	—
Nitric acid	HNO_3	NA	—	22	—	—	—	—	—
Phosphoric acid	H_3PO_4	548	—	—	32	—	—	—	—
Potassium carbonate	K_2CO_3	112	—	—	—	56	—	—	—
Potassium chloride	KCl	35	—	—	—	52	—	—	—
Potassium nitrate	KNO_3	13	—	13	—	37	—	—	—
Potassium sulfate	K_2SO_4	7	—	—	—	44	—	—	18
Sodium nitrate	$NaNO_3$	73	—	16	—	—	—	—	—
Sulfuric acid	H_2SO_4	NA	—	—	—	—	—	—	33
Urea	$CO(NH_2)_2$	78	45	—	—	—	—	—	—

NA = not available.

This completes the 200 ppm N requirement, and the 71 ppm Ca is close enough to the 69 ppm target (table 4.1.20A). The only two nutrients that still need to be added are Mg and S which can be supplied by one chemical, magnesium sulfate ($MgSO_4$), ordinary Epsom salts. $MgSO_4$ contains 13% S and 10% Mg (table 4.1.23). We need 38 ppm Mg:

$$\frac{38 \text{ ppm Mg}}{0.10} = 380 \text{ mg/l } MgSO_4$$

$$380 \text{ mg/l} \times 0.13 = 49 \text{ ppm S}$$

The addition of $MgSO_4$ completes the nutrient formula because the concentrations of all nutrients in the "totals" row reasonably meet the target concentrations (table 4.1.20A).

The recipe for all the ingredients is given in the "applied solution" column in table 4.1.20A; this is the actual concentration of fertilizer that is applied to the seedlings. These values are carried down to the "Applied solution" column at the bottom of the table, where the conversions are made for the nutrient injector and the stock solution. The adjustment for the nutrient injector (1:200) consists of multiplying the applied solution values by 200 and then converting milligrams to grams. The calculations for $MgSO_4$ will serve as an example:

$$380 \text{ mg/l} \times 200 = 76{,}000 \text{ mg/l} = 76 \text{ g/l}$$

The next step again involves multiplying by 200 to compute how much chemical is needed for the 200-liter stock solution tanks and converting to kilograms:

$$76 \text{ g/l} \times 200 = 15{,}200 \text{ g} = 15.2 \text{ kg}$$

Remember that the $CaNO_3$ will not be added to this stock solution (because of solubility problems) but to the micronutrient solution (SS#3).

SS#3 (micronutrients plus Ca). The calculations for this solution are basically the same as for SS#2, using the information in table 4.1.24 to determine the amount of nutrient that each chemical provides. Chelated forms of the metallic micronutrients (Fe, Mn, Cu, and Zn) are more expensive than the sulfate forms but are thought to be more available under a range of soil conditions. When peat-vermiculite growing media are used, however, micronutrient availability should not be a problem.

Table 4.1.24—*Soluble fertilizer chemicals that provide micronutrients for custom fertilizer solutions*

Nutrient	Compound	Chemical notation*	% Micronutrient
Iron (Fe)	Ferrous sulfate	$FeSO_4$–$7H_2O$	19
	Ferric sulfate	$(Fe)_2\ (SO_4)_3$–$4H_2O$	23
	Iron chelates	NaFeEDTA	5–14
		NaFeHEDTA	6
		NaFeEDDHA	10
Manganese (Mn)	Manganese chloride	$MnCl_2$	17
	Manganese sulfate	$MnSO_4$–$3H_2O$	27
	Manganese chelate	MnEDTA	12
Zinc (Zn)	Zinc sulfate	$ZnSO_4$–H_2O	35
	Zinc chelates	$Na_2ZnEDTA$	14
		NaZnHEDTA	9
Copper (Cu)	Copper sulfate	$CuSO_4$–H_2O	35
	Basic copper sulfates	$CuSO_4$–$3Cu(OH)_2$	13–53
	Copper chelates	$Na_2CuEDTA$	13
		NaCuHEDTA	9
Boron (B)	Borax	$Na_2B_4O_7$	11
	Boric acid	H_3BO_3	17
	Solubor	B_2O_3	20
Molybdenum (Mo)	Sodium molybdate	Na_2MoO_4	39
	Ammonium molybdate	$(NH_4)_6Mo_7O_2$–$4H_2O$	54
	Molybdic acid	H_2MoO_4	59
Chloride (Cl)	Potassium chloride	KCl	48

* EDTA – ethylenediaminetetraacetic acid,
HEDTA – hydroxyethylethylenediaminetriacetic acid,
EDDA – ethylenediamine dihydroxyphenylacetic acid.
Source: modified from Hanan and others (1982).

The final recipes for all three stock solutions are given in table 4.1.25, which shows the amount of each chemical that should be added to make 200 liters of solution.

Table 4.1.25—*Stock solution (SS) recipes for custom fertilizer mixes*

Ingredients	Amount to make 200 liters of solution	
SS#1: Dilute phosphoric acid		
85% Phosphoric acid	1.5 l	(1.6 qt)
SS#2: Macronutrients (without Ca)		
85% Phosphoric acid	1.5 l	(1.6 qt)
Monopotassium phosphate	7.5 kg	(16.5 lb)
Potassium nitrate	5.2 kg	(11.5 lb)
Ammonium nitrate	14.1 kg	(31.1 lb)
Magnesium sulfate	15.2 kg	(33.5 lb)
SS#3: Micronutrients (plus Ca)		
Sequestrene 330® (iron chelate)	1.6 kg	(3.5 lb)
Potassium chloride	84.0 g	(2.96 oz)
Boric acid	24.0 g	(0.85 oz)
Manganese sulfate	80.0 g	(2.82 oz)
Zinc sulfate	2.0 g	(0.07 oz)
Copper sulfate	3.2 g	(0.11 oz)
Ammonium molybdate	0.8 g	(0.03 oz)
Calcium nitrate	16.8 kg	(37.0 lb)

4.1.8 Applying and Scheduling Liquid Fertilizer Solutions

4.1.8.1 Application techniques

Once the stock fertilizer solutions have been prepared, the next step is to inject them into the irrigation system. It is always a good idea to stir the stock solution tanks each time before injection to insure that all the chemicals are well-mixed and in solution. If there is an excessive amount of sediment at the bottom of the container (more than a couple of inches), then the fertilizer solution should be reformulated because some of the fertilizer chemicals are reacting with the natural Ca" and Mg 2, ions in the irrigation water to form precipitates (fig. 4.1.23).

Liquid fertilizer applications should be scheduled as early as possible in the day to allow the foliage time to dry before nightfall, so that the possibility of foliage diseases such as botrytis blight is reduced. The key consideration in applying liquid fertilizers is to apply enough solution each time to completely saturate the growing medium profile and flush out excess fertilizer salts. Mastalerz (1977) recommends that an extra 10% of the solution be applied each time to insure that container capacity has been reached and that the solution drains from the container. He cites a figure of 20 liters of solution per m^2 (0.5 gallons per square foot) of greenhouse bench space to properly fertilize a growing medium of approximately 15 cm (6 inches) depth. Carlson (1983) suggests 1 liter (0.26 gallon) of solution per 100 cavities of 40 cm^3 (2.5 cubic inches) capacity. Many growers have their own system for regulating the amount of fertilizer solution that is applied such as controlling the time that the sprinklers remain on, specifying the number of times that the irrigation boom passes over the benches, or limiting the quantity of solution that is applied during each fertilizer application.

The final step in liquid fertilizer injection is a "clear water rinse" to wash the fertilizer solution off the foliage to prevent possible "fertilizer burn." This is particularly important with certain fertilizers such as potassium chloride (KCl) that have a high-salt rating (see table 4.1.5). The duration of this rinse will vary with the size of the seedlings but usually takes only 15 to 20 seconds (Carlson 1983).

4.1.8.2 Timing of the first fertilizer application

Traditionally, nursery managers delay the first application of fertilizer until the germinant has become established usually when the seed coat is shed from the cotyledons of conifer seedlings (4 to 8 weeks after sowing). The reason given for this fertilization delay is that damping-off fungi are stimulated by the fertilizer (Tinus and McDonald 1979) or that the concentrated fertilizer solution may "burn" the succulent germinants. If good growing media and proper sanitation procedures are used, however, damping-off should not be a serious problem in container tree seedling nurseries, and fertilizer burn should not be a problem if the fertilizers are promptly rinsed from the seedling.

Some nursery scientists feel that early fertilization is not necessary because the seed endosperm contains enough nutrition for initial growth and establishment. Carlson (1983) states that newly germinated seedlings take up few mineral elements until 10 to 14 days after germination. Barnett and Brissette (1986), however, report that a delay in initial fertilization can have a considerable effect on seedling development: a 3-week delay can decrease loblolly pine dry weight by nearly 20% (fig. 4.1.24).

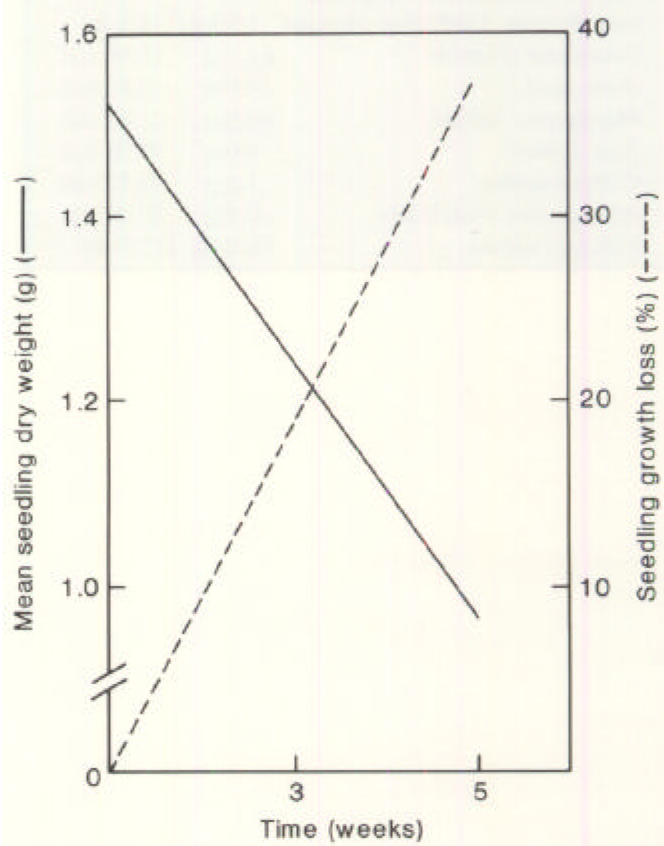


Figure 4.1.24—A delay in the initial application of liquid fertilizer caused a substantial growth loss for loblolly pine seedlings (modified from Barnett and Brissette 1986).

Many nursery managers incorporate a small amount of dry or slow-release "starter" fertilizer into the growing medium to support the germinant until liquid fertilizers can be applied. Brix and van den Driessche (1974) have reported that container seedling growth during the first few weeks could be helped with the incorporation of slow-release fertilizer into the growing medium. Edwards and Huber (1982) state that some nursery managers in the prairie provinces of Canada begin liquid fertilizer applications with high P formulations at 1 week after sowing to stimulate root development. Etter (1971) found that, although high N or P levels did not increase root growth of white spruce during the first 6 weeks of growth, a fertilization program using 50 to 60 ppm N produced significant increases in foliar and total seedling dry weight.

Observations made by Barnett and Brissette (1986) indicate that the timing of the initial fertilizer application should be reevaluated and that the starter fertilizer practice may have merit (fig. 4.1.24). Application of dilute liquid fertilizer during the germination and emergence period may stimulate growth without harmful side effects. Early fertilization, like any change in cultural practice, should be first implemented on a small scale to see if it is practical on an operational basis.

4.1.8.3 Scheduling liquid fertilizer applications during the growing season

There are two basic ways to apply liquid fertilizers: constant and periodic fertilization. The application of a dilute fertilizer solution each time the crop is irrigated is known as constant fertilization (Mastalerz 1977); the concentration of this applied fertilizer solution is exactly the nutrient concentration desired in the growing medium solution. Periodic fertilization consists of applying a more concentrated fertilizer solution according to some fixed schedule, such as once a week or every other irrigation. The applied fertilizer solution during periodic fertilization may therefore be several times more concentrated than the constant fertilization solution, which is the same as the nutrient levels desired in the growing medium solution. An example of a periodic fertilization schedule is given in table 4.1.26. The Container Nursery Survey found that 64% of the nurseries used periodic fertilization, 25% preferred constant fertilization, and the remaining 11 % scheduled fertilization based on their monitoring of crop development or growing medium nutrient levels.

Table 4.1.26—*Periodic liquid fertilizer application schedule for the USDA Forest Service Nursery at Coeur d'Alene, ID*

Seedling growth phase	Timing (weeks)	Type of fertilizer	Fertilization frequency
Germination	0–2	H_3PO_4	Every other irrigation (1–2 × per week)
Juvenile	3–4	7-40-17	Every other irrigation
Exponential	5–10	20-7-19	Every other irrigation
Bud set	10–14	4-25-35	Every other irrigation
Dormant	Prior to shipping	20-7-19	Once

Source: Myers (1987).

A conceptual view of the effect of constant and periodic fertilization on the nutrient level in the growing medium solution or the seedling foliage is charted in figure 4.1.25. Because a more concentrated fertilizer solution is applied during periodic fertilization, the nutrient level in the growing medium solution will fluctuate more than it would during constant fertilization. If this fluctuation reaches extreme levels, seedling growth could be reduced because of nutrient deficiencies or toxicities. Constant fertilization keeps the nutrient concentrations in the growing medium closer to the target concentrations that should accelerate seedling growth. Gingrich (1984) states that periodic fertilization is becoming less popular in container nurseries because of the large fluctuations in nutrient levels and EC in the growing medium solution.

Periodic application of liquid fertilizers is widely practiced in container tree seedling nurseries and obviously produces acceptable seedlings. This cultural practice should be carefully monitored, however, to avoid salt build-up in the growing medium solution (see section 4.1.9), and foliage rinses should always follow fertilization. Scarratt (1986) found that both constant and periodic fertilization produced good seedling growth but the moisture level of the growing medium was carefully monitored and leached to avoid salt build-up.

Mullin and Hallett (1983) discussed the two fertilizer application techniques and listed the following advantages to the constant fertilization (replacement) technique:

1. Regular flushing of the growing medium prevents the build-up of fertilizer salts.

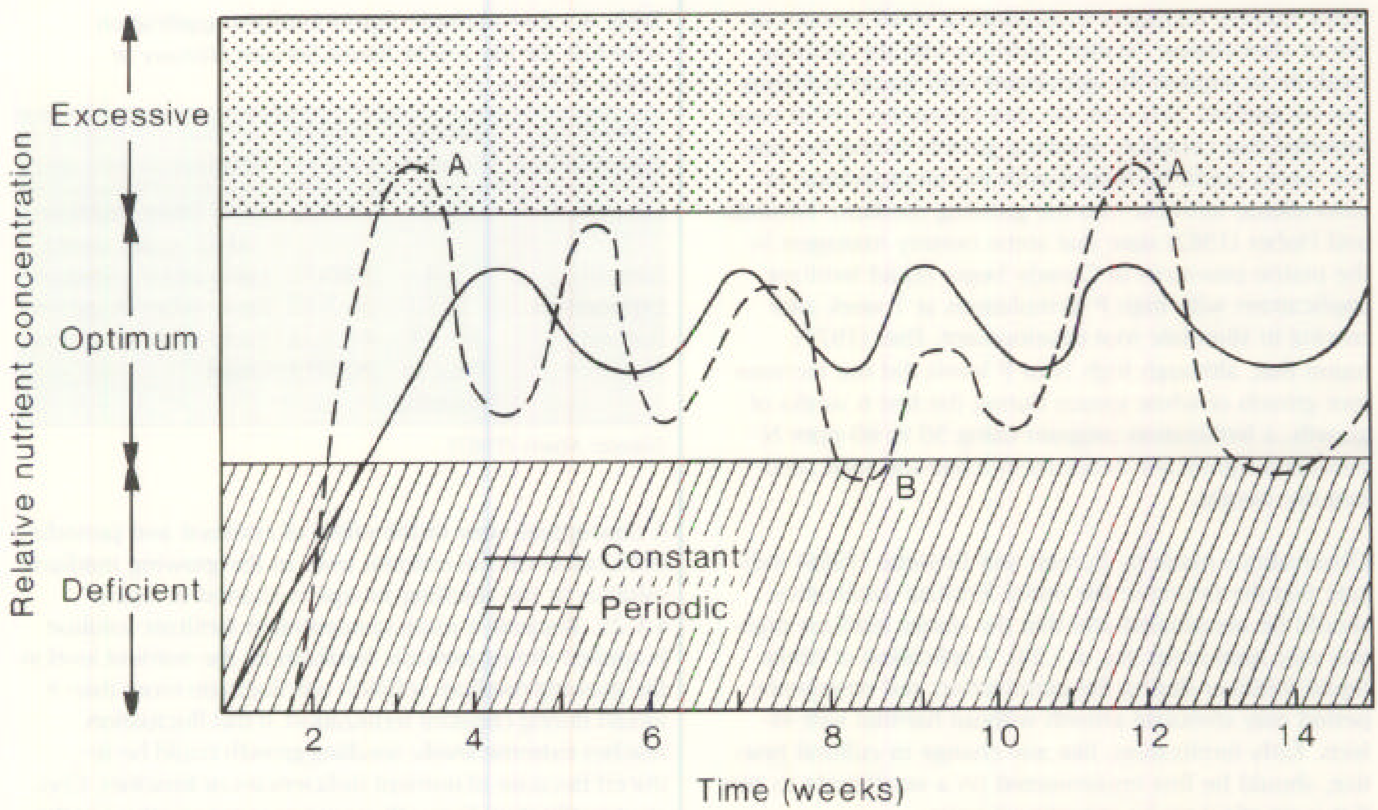


Figure 4.1.25—*Periodic applications of liquid fertilizer result in more severe fluctuations in mineral nutrient status of the growing medium, compared to a constant fertilization program. Because periodic applications contain relatively higher concentrations of fertilizer, the chance for "fertilizer burn" is greater* (**A**). *On the other hand, nutrient deficiencies* (**B**) *can develop between fertilizations.*

2. Nutrients are evenly distributed throughout the me dium profile.

3. Nutrient levels in the growing medium soluion can be changed quickly to correct imbalances.

4. Crops cannot be overfertilized because the applied solution is exactly the proper concentration for ideal growth.

5. Growing medium nutrient levels are returned to target specifications with each liquid fertilizer application.

Disadvantages of constant fertilization are slightly higher costs, in terms of fertilizer chemicals and labor, and the problem of disposing of the fertilizer solution runoff. Because the numerous advantages outweigh the few disadvantages, the constant fertilization procedure for liquid fertilizer application is usually preferable.

Exponential fertilization is a third way of applying liquid fertilizers that has recently been tested in container tree seedling nurseries. Exponential fertilization consists of starting with a low fertilization rate when the seedlings are small, and increasing the amount of fertilizer at an exponential rate that is commensurate with seedling growth. Timmer and Armstrong (1987b) showed that a N rate that was gradually increased from 5 to 125 ppm N over the fertilization period produced better seedling growth, particularly root growth, compared to conventional fertilization techniques. Exponential fertilization would also have other operational benefits, such as less chance of salinity buildup in the growing medium and better fertilizer-use efficiency, than traditional constant fertilization methods. On the negative side, exponential fertilization schedules are more complicated to compute, and the applications would be more time-consuming than conventional liquid fertilizer applications (Timmer and Armstrong 1987b).

4.1.9 Monitoring Container Seedling Nutrition

Because proper mineral nutrition is so important to seedling growth in container tree seedling nurseries, growers should regularly monitor mineral nutrient levels at various phases during the fertilization operation, and nutrient levels in the seedlings themselves. Growers can monitor several different factors during the fertilization procedure (table 4.1.27).

4.1.9.1 What to measure when monitoring fertilization

Mineral nutrient levels can best be monitored by measuring the electrical conductivity (EC) and pH of the various fertilizer solutions, and through chemical analyses of the solutions for specific nutrient levels (table 4.1.27).

Electrical conductivity. EC is a measure of the salinity (total salt level) of a solution and therefore gives an indication of the fertilizer salts that are present. An EC meter measures the electrical charge carried by the ions that are dissolved in a solution-the more concentrated the ions, the higher the reading (figure 4.1.26A). EC meters read salinity in units of conductance called mhos (pronounced "mows") or Siemens, which are the SI units. Most testing instruments measure millimhos (1/1,000 mho) or micromhos (1/1,000,000 mho) and must be adjusted for solution temperature. Following the SI convention, the EC units in the manual will be microSiemens per centimeter (µS/cm), which are equivalent to micromhos per centimeter.

Mineral nutrient levels . Chemical analysis of the nutrient solutions can be performed by testing laboratories or with portable testing kits. Laboratory tests are the most accurate but are time-consuming and costly. Several companies have developed testing kits for horticultural use, but their use requires experience for meaningful interpretation. The authors recommend that growers use testing services whenever possible because the cost of the analysis is relatively small when compared to the value of the seedling crop.

pH. The relative acidity of the untreated irrigation water and applied irrigation solutions can be monitored with a pH meter (fig. 4.1.26B). Monitoring the pH of fertilizer solutions can tell you whether the fertilizer stock solutions are properly formulated and whether the fertilizer injector is functioning, but is of little value in determining mineral nutrient levels. The pH of the growing medium solution changes with the uptake of certain ions such as K^+, NH_4^+, and NO_3^-, the production of carbon dioxide by root respiration, and the release of root exudates.

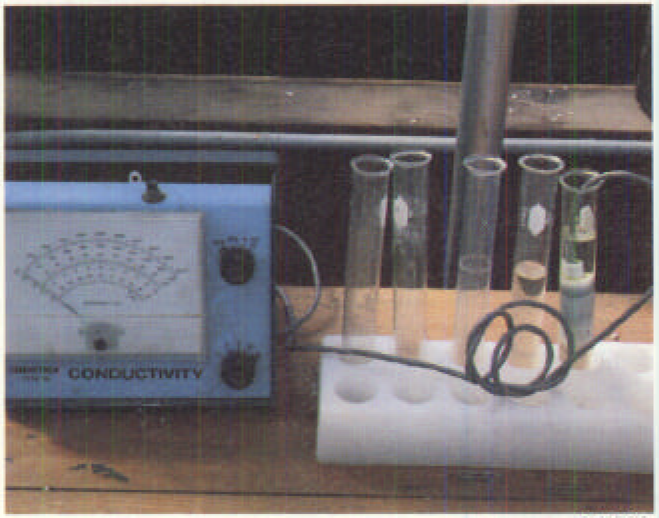
4.1.9.2 Stages to monitor during fertilization

Mineral nutrient levels can be monitored at five different steps during the fertilization process, starting with the native nutrient salts in the irrigation water and ending with the leachate solution that drains from the bottom of the container (fig. 4.1.27). The techniques for monitoring fertilization in nurseries differs, depending on whether solid fertilizer incorporation or liquid fertilizer injection is employed. Nurseries that inject liquid fertilizers can monitor the fertilization process at all five steps, whereas those incorporating solid fertilizers are restricted to only three of the five (table 4.1.27).

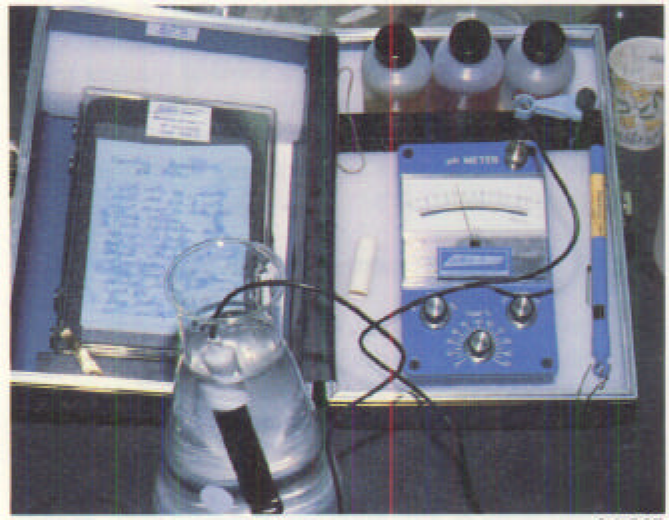
Irrigation water. The irrigation water should be checked for EC, mineral nutrient concentrations, and pH; this should be done during the initial fertilizer solution calculations (see section 4.1.7.1). Mineral nutrient

Table 4.1.27—*Five steps in the liquid fertilizer application process when fertilization can be monitored in container tree seedling nurseries*

Step	Fertilization method		Nutrition indices		
	Liquid fertilizer injection	Solid fertilizer incorporation	EC	pH	Specific nutrients
1. Irrigation water	Yes	Yes	X	X	X
2. Fertilizer stock solution (applied strength dilution)	Yes	No	X		
3. Applied liquid fertilizer solution	Yes	No	X	X	X
4. Growing medium solution	Yes	Yes	X	X	X
5. Leachate	Yes	Yes	X	X	



4.1.26A



4.1.26B

Figure 4.1.26—*Every container nursery should have certain irrigation and fertilization monitoring equipment. Electrical conductivity meters* (**A**) *can be used to measure soluble salts, and a pH meter* (**B**) *can be used to monitor the pH of irrigation water and applied fertilizer solutions.*

levels in the irrigation water will normally not change appreciably over time, but EC and pH should be tested weekly. (Irrigation water quality standards are discussed in more detail in section 4.2.4.2.)

Fertilizer stock solution. The efficiency of the nutrient injector can be checked by making an "applied strength" dilution of the fertilizer stock solution and measuring the EC level (table 4.1.27). For a 1:200 injector, add one part of stock solution to 200 parts of irrigation water; the EC reading of the diluted fertilizer solution should be approximately the same (within 10%) as the EC of the applied fertilizer solution. If the actual injection ratio is consistently different than the stated ratio, then the stock solution formulas can be recalculated for the actual ratio. If the measured injection ratio varies excessively, then the injector is not functioning properly and may need to be serviced. Erratic changes in water pressure can sometimes cause nutrient injectors to malfunction; water pressure regulators can be installed in the incoming water line to moderate pressure changes.

Applied fertilizer solution. The applied fertilizer solution is the most important of the fertilization checks because this solution actually contacts the seedling foliage and enters the root zone (fig. 4.1.27). The applied solution is collected directly from the irrigation nozzle (fig. 4.1.28) and should be checked for EC, nutrient concentrations, and pH (table 4.1.27). The EC reading of the applied fertilizer solution should be approximately the sum of the base salinity of the irrigation water plus the salts added by the fertilizer stock solution. The pH of the applied solution should be near the target pH of 5.5, or adjustments should be in the amount of acid added to the fertilizer stock solution.

The nutrient concentration of the applied fertilizer solution should be determined by submitting a sample to an analytical lab, and these values should be compared to the target values. As an example, test results from Mt. Sopris Nursery (see table 4.1.14) show that, although most of the applied solution levels are reasonably close to the target levels, the N-P-K levels are consistently low. A check of the injector efficiency revealed that the actual injection ratio was closer to 1:220 instead of 1:200, which explains the discrepancy. The SO_4 level is high in the applied solution because extra SO_4 was added with the ammonium sulfate used to supply ammonium.

Growing medium solution. This is the fertilizer solution that surrounds the seedling root system in the container (fig. 4.1.27), and so it is one of the most critical solutions to monitor. The EC and pH of the solution in the growing medium are essential measurements (table 4.1.27), because the medium solution is in immediate

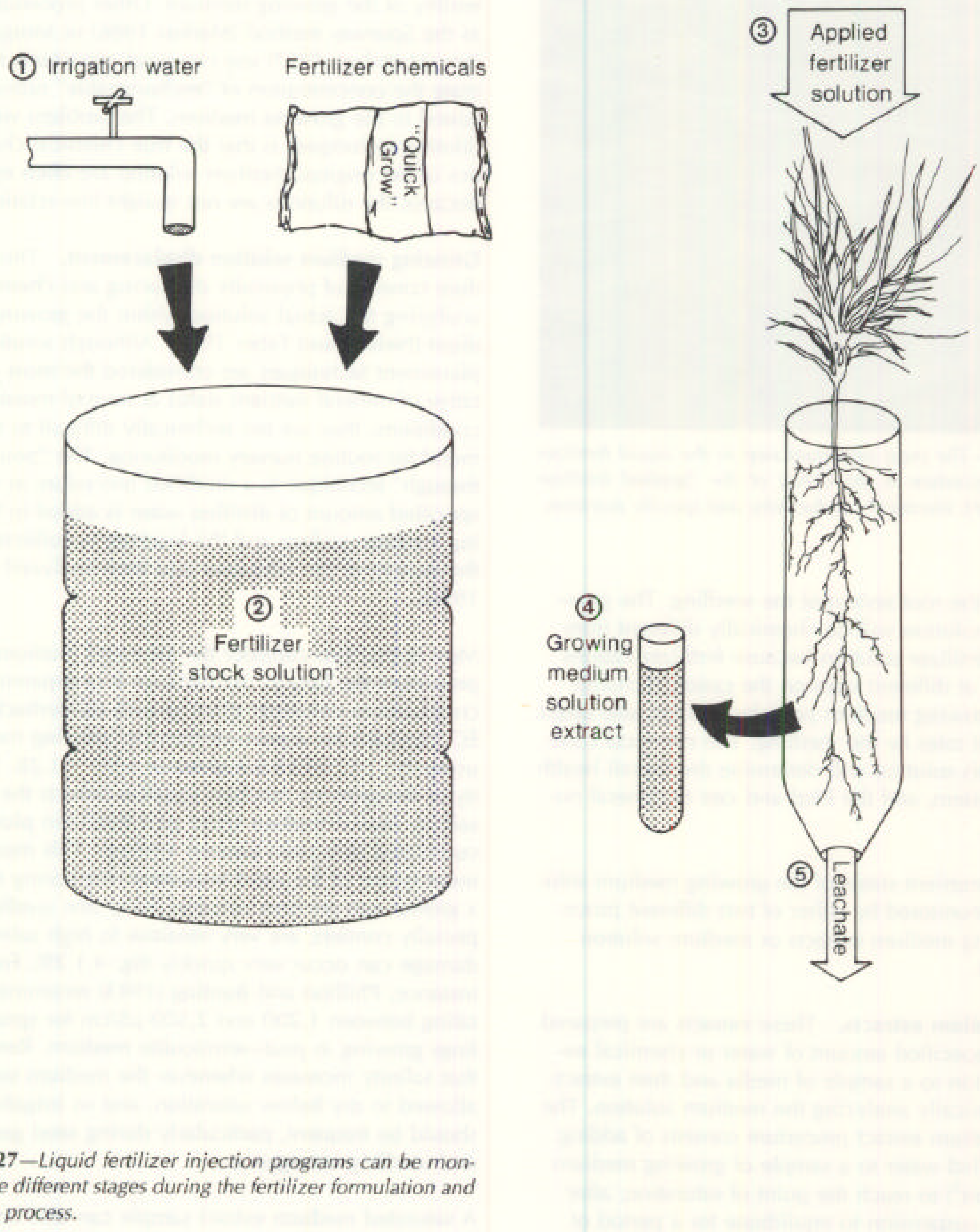


Figure 4.1.27—*Liquid fertilizer injection programs can be monitored at five different stages during the fertilizer formulation and application process.*

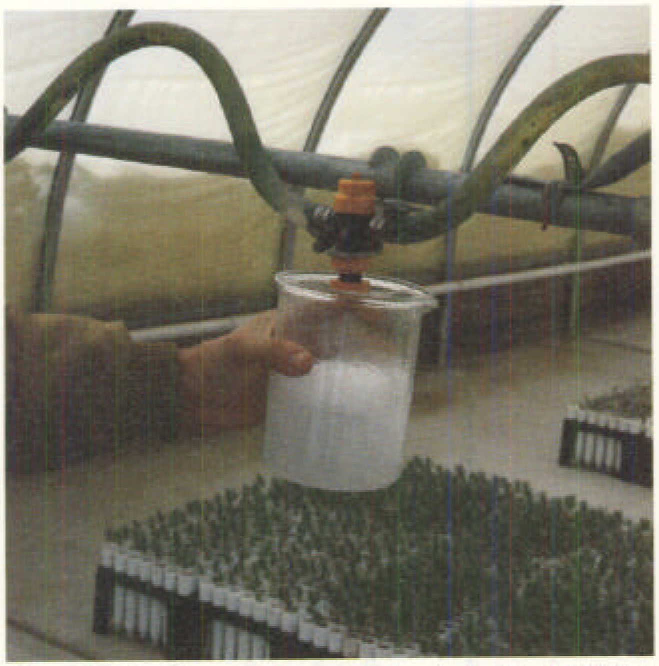


Figure 4.1.28—*The most important step in the liquid fertilizer monitoring procedure is the check of the "applied fertilizer solution" for pH, electrical conductivity, and specific nutrients.*

contact with the root system of the seedling. The growing medium solution will be chemically different from the applied fertilizer solution because fertilizer cations are adsorbed at different rates on the cation exchange sites of the growing medium particles and are also taken up at different rates by the seedling. The chemical composition of this solution will determine the overall health of the root system, and the kind and rate of mineral nutrient uptake.

The mineral nutrient status of the growing medium solution can be monitored by either of two different procedures: growing medium extracts or medium solution displacement.

Growing medium extracts. These extracts are prepared by adding a specified amount of water or chemical extracting solution to a sample of media and then extracting and chemically analyzing the medium solution. The saturated medium extract procedure consists of adding enough distilled water to a sample of growing medium (about 500 cm^3) to reach the point of saturation; after allowing the suspension to equilibrate for a period of time (about 1.5 hours), the solution is extracted with a vacuum filter and chemically analyzed (Warncke 1986).

To overcome the need to vacuum-extract the medium solution, other testing procedures make growing medium suspensions by adding a larger amount of liquid to the medium sample. Nelson (1978) reports standards for 1:2 and 1:5 dilutions (medium/water) for monitoring the fertility of the growing medium. Other procedures such as the Spurway method (Markus 1986) or Morgan system (Mastalerz 1977) use chemical extractants to estimate the concentration of "exchangeable" nutrients contained in the growing medium. The problem with these dilution techniques is that the true chemical characteristics of the original medium solution are often modified because the dilutions are not straight-line relationships.

Growing medium solution displacement. This procedure consists of physically displacing and chemically analyzing the actual solution within the growing medium (Nelson and Faber 1986). Although solution displacement techniques are considered the most representative of mineral nutrient status at normal moisture conditions, they are too technically difficult to recommend for routine nursery monitoring. The "pour-through" technique is a modified procedure in which a specified amount of distilled water is added to the growing medium surface and the leachate is collected from the bottom of the container and then analyzed (Wright 1986).

Most authorities consider the saturated medium extract procedure the best to use because it is apparently well correlated to container plant growth (Bilderback 1986). EC standards for a peat-vermiculite growing medium using this procedure are given in table 4.1.28. The salinity of the growing medium solution reflects the applied salinity load (irrigation water plus fertilizer) plus the accumulated salts from unused fertilizer. This measurement is one of the most important monitoring tests that a grower can perform because many tree seedlings, especially conifers, are very sensitive to high salinity and damage can occur very quickly (fig. 4.1.29). For instance, Phillion and Bunting (1983) recommend an EC rating between 1,200 and 2,500 /µS/cm for spruce seedlings growing in peat-vermiculite medium. Remember that salinity increases whenever the medium solution is allowed to dry below saturation, and so irrigation should be frequent, particularly during seed germination and seedling emergence.

A saturated medium extract sample can also be analyzed for individual nutrients. This nutrient analysis, which can be done with portable analysis kits or by

Table 4.1.28—*Salinity and mineral nutrient levels for black spruce seedlings in peat–vermiculite growing media using the saturated media extract technique*

EC Range (μS/cm)	Salinity rating
0–1,200	Low
1,200–2,500	Normal
2,500–3,000	High
3,000–4,000	Excessive
4,000+	Lethal
Mineral nutrient	**Optimum range (ppm)**
NH_4–N	15–65
P	35–95
K	25–115
Ca	30–60
Mg	15–35

Source: Timmer and Parton (1982).

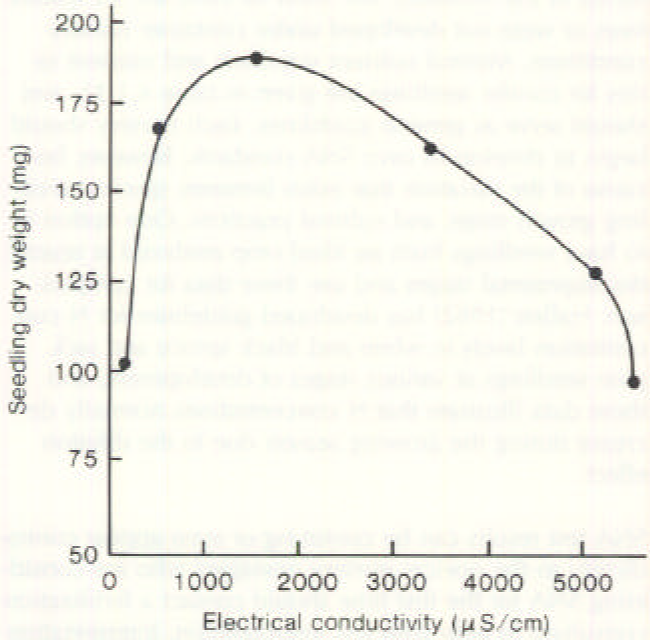


Figure 4.1.29—*Growth of container red pine seedlings increases with increasing fertilizer levels, as measured by electrical conductivity, up to approximately 1800 μS/cm. Beyond this salinity level, growth gradually decreases until mortality occurs (modified from Timmer and Parton 1982).*

sending the sample to a commercial laboratory, determines the actual levels of nutrient ions in the growing medium solution. Many different recommendations on the ideal mineral nutrient status in artificial growing media have been published for ornamental crops, and the recommendations vary between different analytical labs (table 4.1.29).

Table 4.1.29—*Guidelines developed by four horticultural testing laboratories for optimal mineral nutrient status for horticultural plant species in artificial growing media using the saturated media extract technique*

	Nutrient concentration (ppm)			
Nutrient	Mich. State	Ohio State	W. R. Grace	Univ. GA
NO_3–N	100–199	100–175	35–180	80–139
P	6–10	8–14	5–50	3–13
K	150–249	175–225	35–300	110–179
Ca	> 200	250–325	20–400	140–219
Mg	> 70	80–125	15–200	60–99

Source: modified from Kirven (1986).

Unfortunately, research on the best nutrient levels for forest tree seedlings is limited, although Timmer and Parton provide some tentative guidelines for the major nutrients (table 4.1.28). Hallett (1982) has developed recommended nutrient levels for macronutrients based on growing medium extracts, and concluded that chemical analysis of the growing medium solution is an effective tool for greenhouse managers.

Leachate. The final test for fertility involves taking EC and pH readings on the "leachate" solution that drains from the bottom of the containers (fig. 4.1.27). This leachate can be obtained by taping a test tube or other container to the drain hole of the container during liquid fertilization. It may be necessary to collect leachate from several different containers before there is enough solution to operate the EC meter. A procedure for calculating the salt level in the leachate solution was developed by Tinus and McDonald (1979) (table 4.1.30). The EC reading of the applied fertilizer solution is subtracted from the EC reading of the leachate and this value (X) is rated according to the scale in table 4.1.30. If the EC of the leachate exceeds the EC of the applied fertilizer so-

Table 4.1.30—*Monitoring container seedling leachate using the equation X = leachate − applied fertilizer solution*

EC reading (µS/cm)	Diagnosis
If X = 100 to 200	Normal seedling growth
If X = 1,000	Problems are likely
If X = 3,000	Mortality is probable

Source: modified from Tinus and McDonald (1979).

lution by 1,000 µS/cm, then excess salinity is building up in the growing medium and proper leaching is not occurring. In this situation, the containers should be irrigated immediately with water rinses until the EC reading returns to normal. If the leachate EC reading remains consistently high, then the amount of solution applied during irrigation or liquid fertilization should be increased to insure proper leaching.

4.1.9.3 Seedling nutrient analysis

One of the best ways to monitor the fertilization program in a container tree seedling nursery is to chemically analyze the foliage of seedlings and determine its nutrient status. The mineral nutrient concentration of the seedling foliage is a true measure of the effectiveness of a fertilization program because seedling nutrient analysis (SNA) reflects the actual uptake of mineral nutrients, compared to tests of the growing medium solution, which only measure the "available" nutrients in the root zone. Analytical laboratories are able to accurately and precisely measure the levels of all 13 mineral nutrients in a small sample of plant tissue. These testing laboratories are either government-owned, located at agricultural universities or research facilities, or privately owned. Most laboratories work primarily with agricultural or horticultural crops, however, so it is important to work with one that has experience with tree seedlings. These laboratories are familiar with the best analytical procedures for tree seedlings and can provide useful interpretation of SNA results.

Sample collection and handling. The accuracy of SNA depends on the care with which the samples are collected and handled prior to the actual testing. For tree seedlings, the best tissue for SNA is the entire shoot of young seedlings or just the foliage of larger trees. The sample should be clean and collected randomly from the seedling population of interest (one bench in a greenhouse or one particular seedlot). Because container seedlings are often small, tissue samples for nutrient analysis are usually submitted as a composite of individual seedlings (Landis 1985). About 60 g of fresh or 10 g of dried tissue is usually required for the actual test, so the composite sample should consist of a minimum of 20 to 50 seedlings (Aldhous 1975, Solan 1980). Seedling nutrient analyses usually cost from $10 to 50 per sample, depending on which tests are performed. The seedling sample is usually stored and shipped in a cooler, although some laboratories suggest drying the sample. It is wise to contact the testing laboratory prior to collecting the samples so that the proper sampling and handling procedures can be established.

Interpretation of seedling nutrient analysis test results and standards. It is relatively easy and inexpensive to have SNA performed, but interpretation of these test results can be difficult. Interpretation consists of comparing the test results with standard nutrient levels to determine if the seedling nutrient levels are adequate, deficient, or excessive. Many nutrient standards are published in the literature, but many of these are for mature trees or were not developed under container nursery conditions. Mineral nutrient standards and nutrient ratios for conifer seedlings are given in table 4.1.31, and should serve as general guidelines. Each nursery should begin to develop its own SNA standards, however, because of the variation that exists between species, seedling growth stage, and cultural practices. One option is to have seedlings from an ideal crop analyzed at several developmental stages and use these data for comparison. Hallett (1982) has developed guidelines for N concentration levels in white and black spruce and jack pine seedlings at various stages of development, and these data illustrate that N concentrations normally decrease during the growing season due to the dilution effect.

SNA test results can be confusing or even appear contradictory to the novice; nursery managers who are considering SNA for the first time should contact a fertilization consultant to help with test interpretation. Interpretation of SNA is actually more of an art than a science because of the complex interrelationships between mineral nutrients and the changes in relative nutrient concentrations that occur during seedling growth. A more complete discussion of seedling nutrient analysis and the relationship between nutrient levels and seedling quality is provided by Landis (1985).

Table 4.1.31—*Standards for foliar nutrient levels and nutrient ratios for container tree seedlings (dry weight)**

	Adequate range† (green shoots)	Nutrient‡ ratios
Macronutrients (%)		
N	1.40–2.20	1.00
P	0.20–0.40	0.20
K	0.40–1.50	0.55
Ca	0.20–0.40	0.06
Mg	0.10–0.30	0.05
S	0.20–0.30	0.09
Micronutrients (ppm)		
Fe	60–200	0.007
Mn	100–250	0.004
Zn	30–150	0.0003
Cu	4–20	0.0003
Mo	0.25–5.0	0.00007
B	20–100	0.002
Cl	—	0.0003

* Values will vary with different species.
†Modified data from W.R. Grace Co. and Swan (1971) and Hallet (1985); macro-nutrient levels often exceed these ranges due to luxury consumption.
‡ Modified from Ingestad (1979). To compute individual nutrient levels, multiply the N level by the decimal fraction (e.g., to determine the P level when the N level is 2.0%, multiply 2.0% by 0.20 which gives 0.40%).

4.1.10 Effects of Heavy Fertilizer Use in Container Nurseries

Container nursery managers routinely promote rapid seedling growth with high fertilization rates because greenhouse space is expensive and some growers must produce more than one crop per year. Seedling shoot growth can be "forced" with heavy fertilizer applications, especially high N levels, but nursery managers should consider the potential side-effects of overfertilization: luxury consumption of mineral nutrients by seedlings and wastewater pollution. The first of these is discussed in the following sections, and wastewater pollution is discussed in section 4.2.8.2.

4.1.10.1 Luxury consumption of nitrogen and seedling quality

High fertilization rates often lead to luxury consumption of mineral nutrients in the ideal growing environment of container tree seedling nurseries. Nutrient uptake by container seedlings is high because conditions in the growing medium, such as temperature, moisture level and pH, are conducive to rapid ion uptake. (See section 4.1.2.1 and fig. 4.1.3 for a discussion on nutrient uptake.)

Luxury consumption of any of the 13 mineral nutrient elements is possible, but seedlings accumulate high levels of certain nutrients (N, K) more than others. Some nursery scientists do not consider luxury consumption to be harmful but merely a waste of fertilizer. However, there is mounting evidence that high foliage nutrient levels, especially N, can be damaging. Timmer and Armstrong (1987a) actually refer to the negative growth effects of high N fertilization as "nitrogen toxicity."

N uptake is most likely to reach luxury consumption levels during the rapid growth phase, when high N levels are commonly used. Seedlings take up N readily and appear to store it in the foliage, because foliar N concentrations continue to increase without additional growth (Gilliam and others 1980). Ingestad (1979) grew two species of conifer seedlings at N levels from 20 to 1200 ppm and found that both species could accumulate high concentrations of N (2.7 to 3.4%) before seedling growth declined and mortality occurred (fig. 4.1.30). Seedling nutrient analysis at the end of a large-scale fertilizer trial, using a variety of liquid fertilizer and slow-release fertilization treatments, revealed that N levels ranged from 1.9 to 5.5%, with an average of 3.6% N (Matthews 1986). As Swan (1971) considers foliar levels greater than 2.5 to 2.8% N to be luxury consumption, these data indicate that many operational nurseries are applying too much N in their fertilization programs.

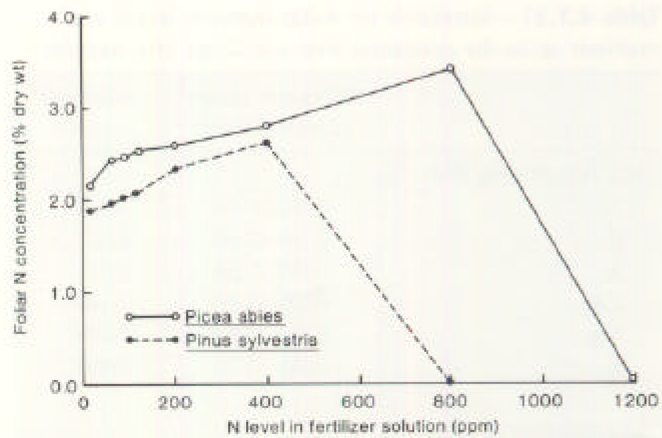


Figure 4.1.30—*Two different species of conifer seedlings exhibit different nitrogen (N) uptake patterns. Note that foliar N levels increase to a point, beyond which mortality eventually occurs (modified from Ingestad 1979).*

Certain hazards have been associated with luxury N consumption in both container and bareroot forest tree seedlings:

1. High N fertilization rates may adversely affect seedling morphology because N produces excess shoot growth at the expense of root growth. Cornea (1982) studied the effects of N concentration on the growth of container ponderosa pine seedlings and found that the seedling root to shoot ratio decreased with increasing N fertilizer levels. Timmer and Armstrong (1987b) found that high N fertilization rates may reduce the weight and fibrosity of the root system. Torbert and others (1986) found that loblolly pine seedlings grown at lower fertilization rates had root systems that were longer, more fibrous, and had a higher degree of branching.

2. Prolonged tissue succulence and production of lammas shoots late in the growing season may increase the possibility of cold injury. Gilliam and others (1980) found that high (150 to 300 ppm) N levels caused second growth flushes ("lammas growth") and delayed leaf defoliation in red maple seedlings for 3 weeks, compared to lower (50 ppm) N levels. Aronsson (1980) studied frost hardiness of Scotch pine and found a clear correlation between foliar N concentration and cold injury: seedlings with a foliar N level from 1.3 to 1.8% suffered less frost damage than those with N levels greater than 2.0%. Larsen (1978, as reported in Aronsson 1980) found

that Douglas-fir had the highest cold hardiness with foliar N concentrations from 1.3 to 1.4% (table 4.1.32). Hallett (1985) reported that balsam fir seedlings with a foliar N concentration greater than 2.2% were more subject to frost injury.

3. High levels of fertilizer salts in the growing medium have been shown to affect the formation of some mycorrhizae of container tree seedlings. Torbert and others (1986) found that, although higher fertilizer rates produced larger loblolly pine seedlings, my corrhizal colonization was 3 times higher at the lower fertilization rates. Cornea (1982) found that N fertilization level and mycorrhizal infection of ponderosa pine container seedlings was inversely correlated: mycorrhizal infection decreased linearly with increasing N concentration. Crowley and others (1986) studied the effect of slow-release fertilizers on mycorrhizal formation in shortleaf pine seedlings and found that the rate of fertilizer application, fertilizer release rate and N-P-K ratio all had an effect. Various mycorrhizal fungi respond differently to fertility, and some fungi such as *Thelephora* spp. actually appear to thrive in the high-fertility environment of container tree seedling nurseries. The effects of fertilization and other cultural practices on container seedling mycorrhizae are detailed in volume five of this manual.

4. High N fertilization has been shown to adversely affect seedling survival and growth after outplanting. Etter (1969) studied the effects of three N levels on drought survival of lodgepole pine seedlings and found that seedlings grown at higher N levels (500 ppm) had poorer outplanting survival than seedlings grown under standard N fertilization. Outplanting survival of Douglas-fir and white spruce seedlings was found to have a curvilinear relationship with foliar N concentration, with the greatest survival rate around 2.1 % N (fig. 4.1.31). Cornett (1982) concluded that the poor root to shoot ratio caused by high N fertilization would be a disadvantage for ponderosa pine seedlings outplanted on droughty sites.

5. High foliar nutrient levels may result in increased animal browsing damage after outplanting. Many reforestation specialists have noticed that container seedlings are preferred by deer and elk compared to bareroot seedlings.

See the chapter on dormancy and hardiness in volume six of this series for more information on factors affecting seedling quality.

Table 4.1.32—*Relationship between foliar nitrogen (N) levels and seedling quality*

Quality attribute	Source	Species	Recommended foliar N concentration
Cold hardiness	Larsen (1978)	Douglas-fir	1.3–1.4%
Cold hardiness	Aronsson (1980)	Scotch pine	1.3–1.8%
Cold hardiness	Hallett (1985)	Balsam fir	< 2.2%
Outplanting survival	van den Driessche (1988)	Douglas-fir white spruce	1.6–2.4%
Survival and growth	Duryea and McClain (1984)	Conifers	1.7–2.3%
General	Youngberg (1984)	Conifers	< 2.0%

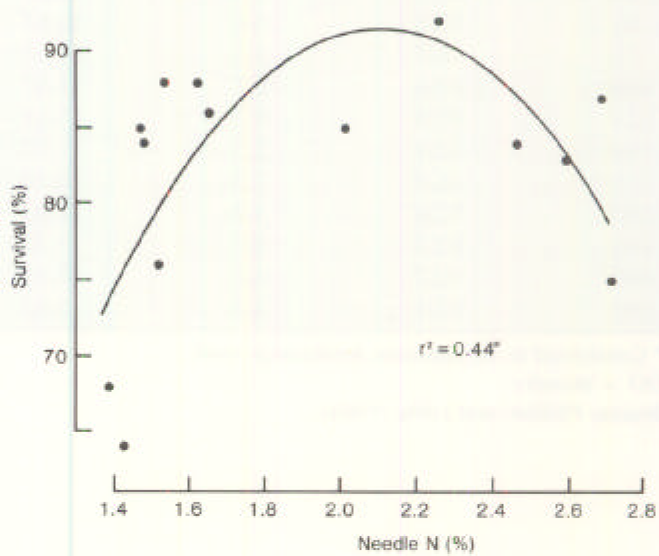


Figure 4.1.31—*Foliar nitrogen (N) concentration of Douglas-fir and white spruce seedlings was found to be related to outplanting survival after 3 years in the field (from van den Driessche 1988).*

4.1.10.2 The ideal nitrogen fertilization level

The ideal N level for the production of high-quality container seedlings has been the subject of much discussion among nursery managers. The best N fertilization level will vary with many factors, but actual nursery production experience with several species of western conifer seedlings supports a moderate N level of around 100 to 150 ppm during the rapid growth phase to encourage development of sturdy, hardy tissue. Extremely high N levels (> 250 ppm) generally promote succulent shoot growth and an unbalanced shoot to root ratio, and should therefore be avoided. Scarratt (1986) found that N levels over 100 ppm commonly lead to excessive shoot elongation and poor shoot to root ratios of container jack pine. Phillion and Libby (1984) studied the effect of N fertilization on black spruce growth using liquid fertilizers; they grew seedlings at N levels from 0 to 500 ppm and monitored seedling height, diameter, and dry weight (table 4.1.33). Based on these growth trends and foliage color, they concluded that 100 ppm N produced the best seedling. Scarratt (1986) found that, under constant fertilization, 100 ppm N was adequate for jack pine seedlings on a 10- to 12-week production cycle. For slow-release fertilizers, Crowley and others (1986) recommend that fertilizers with extended release rates (8 to 9 months) should be used at a rate of 4.5 kg/m3 (7.5 pounds per cubic yard) to produce the ideal combination of good seedling growth and mycorrhizal development.

The best N fertilization level will vary with many cultural factors and between individual species, but maintaining a moderate N level of around 100 to 150 ppm during the rapid growth phase encourages sturdy, hardy tissue development. The best way to monitor N fertility is through regular SNA during the growing season in conjunction with seedling growth monitoring both at the nursery and after outplanting. Target foliar N levels should be maintained around 2.0% for best survival and growth after outplanting (fig. 4.1.31).

Table 4.1.33—*Growth of container black spruce seedlings at different N fertilization levels*

N level (ppm)	Height (cm)	Caliper (mm)	OD wt. (g)	Foliage color
12	46.0	5.4	9.13	Pale green, yellow tips
25	46.5	5.3	8.81	Pale green, yellow tips
50	47.5	5.6	10.67	Healthy green
75	48.7	5.6	11.05	Healthy green
100*	**49.6**	**5.7**	**11.57**	**Healthy green**
125	48.3	5.5	11.11	Healthy green, some short needles
150	47.4	5.5	11.50	Healthy green, some short needles and brown tips
175	46.5	5.3	10.10	Healthy green, some short needles and brown tips
200	47.6	5.4	11.43	Healthy green, some short needles and brown tips
300	42.3	5.3	9.32	Yellow and brown needles
400	40.7	4.8	8.35	Yellow and brown needles
500	35.1	4.2	5.64	Yellow and brown needles, some seedling mortality

* Considered to be optimum fertilization level.
OD = ovendry.
Source: Phillion and Libby (1984).

4.1.11 Conclusions and Recommendations

Fertilization is one of the most important cultural practices in a container tree seedling nursery, and growers should carefully plan and regularly evaluate their fertilization programs to insure that they are producing seedlings of the highest quality. A fertilization program for a container tree seedling nursery should be designed to maintain specific concentrations of the 13 different mineral nutrients in the growing medium and keep them in balance but should also be designed to allow necessary nutritional changes during the growing cycle.

The choice of a fertilizer depends on a multitude of factors: fertilizer form, grade, nitrogen source, nutrient release rate, interaction with the growing medium, plant-use efficiency, and cost. If possible, container nursery managers should conduct their own nursery fertilization trials because fertilization rates, like all cultural practices, are related to many nursery-specific factors. Irrigation type and frequency and characteristics of the growing medium both affect mineral nutrient uptake by container tree seedlings. Because of these complex interrelationships, fertilization practices may have to be periodically adjusted in response to seedling growth and outplanting performance.

Although incorporation of dry fertilizers into the growing medium can be justified in some instances, direct injection of liquid fertilizers into the irrigation system is recommended whenever possible. The benefits of this technique include precise control of both the concentration and balance of all 13 mineral nutrients, the ability to completely change the nutrient solution at any time, and a very low chance of overfertilization and resultant salt injury.

The constant fertilization (replacement) technique is recommended because it minimizes the chances of overfertilization, promotes regular flushing of the growing medium to prevent the buildup of fertilizer salts, returns growing medium nutrient levels to target specifications with fertilization, and allows nutrient levels in the growing medium solution to be adjusted quickly.

Mineral nutrient levels can be monitored at different stages of the fertilization process, starting with the native nutrient salts in the irrigation water and ending with the leachate solution that drains from the bottom of the container. Growers should obtain their own pH and electrical conductivity meters to monitor the fertilization process. Seedling nutrient analyses should be performed regularly by analytical laboratories to track mineral nutrient utilization. Each nursery should begin to develop its own seedling nutrient analysis standards because of the variation that exists between species, seedling growth stage, and cultural practices.

The high fertilization rates used in some container tree seedling nurseries to promote rapid shoot growth may actually be detrimental. The potential side effects of overfertilization include luxury consumption of some mineral nutrients (especially N), inhibited mycorrhizal development, and wastewater pollution. Hazards associated with luxury N consumption include excess shoot growth at the expense of root growth, prolonged tissue succulence and production of lammas shoots late in the growing season, and poor seedling survival and growth after outplanting. The best way to monitor N fertility is through regular chemical analysis of the seedling tissue during the growing season and after outplanting. Target foliar N levels should be maintained at, or slightly below, 2.0% for best survival and growth after outplanting

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