Fertilization and Woody Plant Nutrition in the Context of the Urban Forest

by

James R. Watkins

Professional Paper submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of

Master of Forestry

in

Forestry

Approved:

D. Wm. Smith, Chairman

R. J. Stipes

J. R. Seiler

October, 1998
Blacksburg, Virginia

Fertilization and Woody Plant Nutrition in the Context of the Urban Forest

James R. Watkins

Abstract

Fertilization of urban trees is often based on traditional forestry objectives. These objectives and resultant attributes may not be desired in urban trees. The majority of research and the ensuing recommendations regarding fertilizer amounts and formulations comes from agricultural models, pomology, and industrial forestry – very little from arboriculture.

Lack of water and inadequate soil volumes are responsible for many of the problems that beset urban trees. More research is needed in water deficit mitigation, establishing nutrient sufficiency and deficiency levels in urban trees, the role of fertilization in disease remediation and increased pathogenesis, and the effects of long term fertilization on trees in the urban landscape.

Acknowledgements

I would like to acknowledge Dr. David Wm. Smith, Dr. John Seiler and Dr. R. Jay Stipes for their scholarship, guidance and friendship.

This paper is dedicated to Reverend Sw. Satchidananda – whose loving example gives my life meaning.

Table of Contents

Acknowledgements	iii
Section	**Page**
1. Introduction	1
2. The Urban Forest	3
3. The Growth Medium - Soil	5
4. Soil Characteristics that Affect Fertilization	6
Soil Texture	6
Soil Structure	7
Cation Exchange Capacity	7
pH (Soil Reaction)	8
5. Urban Soils	11
Aeration of Urban Soils	11
Soil Amendments	13
pH of Urban Soils	14
Nutrient Cycling of Urban Soils	15
Toxic Elements in Urban Soils	15
Modified Temperature Regimes and the Urban Climate	16
6. The Essential Mineral Elements	18
Macronutrients	19
Nitrogen	19
Phosphorus	23
Potassium	24
Calcium	26
Sulfur	26
Magnesium	27

Micronutrients 28
Iron 28
Manganese 29
Copper 30
Boron 30
Molybdenum 31
Chlorine 31
Zinc 32

7. Determining Nutrient Requirements 32

Visual Observation 33
Nutrient Deficiency Symptoms 33
Soil Analysis 36
Foliar Analysis 38
DRIS 39

8. Relationships of Plant Nutrients 41

9. Nutrient Uptake – The Role of Roots 44

10. Fertilization of Woody Plants and Trees 46

Water Management 47

Timing of Fertilizer Applications 49

Nutrient Application Methods 52
Surface Application of Nutrients 53
Surface Application vs. Other Application Methods 57
Drill Hole or Auger Method 59
Liquid Injections 62
Foliar Sprays 64
Implants and Trunk Injections 65

Rates of Application 67
Calculating Dosages 68
Recommended Amounts of N Fertilizer 74

Fertilizing at Planting and Transplanting 77
Fertilizing Established Trees 82

Types of Fertilizers 85
Forms of Organic and Inorganic Fertilizers 86
Slow-Release Fertilizers 87
Nitrification Inhibitors 89
Phosphorus and Potassium Fertilizers 90
Complete Fertilizers 92

11. Fertilization and Disease 96

Pathogens 97
Insects 99
Chlorosis 100
Maple Decline 102

12. New Approaches to Fertilization Theory – The Nitrogen Addition Theory 103

13. Conclusion 104

Literature Cited 108

Appendix I 126

1. INTRODUCTION

The majority of what we know about trees, their biology and interactions with the environment, comes from forest research and the study of trees in non-urban environments. We lack similar knowledge of urban trees, and often impose cultural practices on the care and cultivation of these trees that reflect the objectives of traditional forestry - objectives and resulting attributes that may not be desired in urban trees and in urban landscapes.

Fertilization of urban trees is one cultural practice that lacks substantial research and tends to be governed by traditional forestry objectives and rule of thumb (Harris1992). While traditional forestry and pomology have used addition of nutrients to maximize growth, size, fiber and fruit yield of trees, arboriculturists are more apt to fertilize trees to ameliorate nutrient deficiencies, to maintain aesthetic appeal by improving color, or to restore the condition of trees that have been weakened by disease, insect attack or unfavorable environmental conditions (Himelick et al. 1965).

In addition to different objectives, the majority of published information concerning response of trees to fertilization comes from the fields of pomology and forestry, very little from arboriculture (Himelick et al. 1965). In orchards, the response is usually measured in units or yields of fruits, which may or may not be related to tree growth. The fertilization studies in forestry are often directed toward improving height and diameter growth of nursery seedlings or of young trees in plantations. The responses may be quite different from those of established (as well as young) trees in lawn and urban areas (Himelick et al. 1965).

The objectives of this paper are to 1) discuss the urban forest – its benefits and objectives; 2) review the function of the various nutrient elements essential for tree growth and the soil factors, both physical and chemical, which affect the uptake of these nutrients; and 3) examine the components of a fertilization program through a review of the literature. Using this information fertilization will be addressed in the context of the urban environment and answers will be sought for the following questions:

- Is fertilization necessary to achieve healthy urban trees? If so, under what conditions is fertilization advisable?
- Are current forms of fertilizers and recommended amounts appropriate for urban trees?
- Are there other cultural practices used singularly or in combination with fertilization that better serve the objectives of the urban forest?

2. THE URBAN FOREST

Vegetation in cities is an integral component of the urban infrastructure. It mitigates many problems of urban development and can operate as an environmentally friendly alternative to traditional technologies by lowering energy use, reducing air pollution, and controlling storm water runoff. Other benefits provided by urban vegetation include improved physical and mental health and well-being, aesthetic environments, increased property values (Sacamano et al 1993), wildlife habitat enhancement and noise abatement.

It is well documented that air pollution can injure trees (Karnosky 1981) but within certain concentration levels plants can effectively act as a sink for airborne pollutants and reduce air quality problems (Sacamano et al 1993). The magnitude of this impact can be significant, given that forest ecosystems may be the major sink for pollutants within terrestrial ecosystems (Little 1977).

By transpiring water, blocking winds, shading surfaces and modifying the storage and exchanges of energy among urban surfaces, trees affect local climates and consequently energy use in buildings (McPherson et al 1994). Trees can reduce building energy by lowering summertime temperatures, shading buildings during the summer, and blocking winter winds. However, trees can also increase building energy use by having their branches shade buildings during the winter, and can increase or decrease building energy use by blocking summertime breezes. The potential climate modification and building energy use impacts from trees vary with building characteristics, species attributes, climatic region, planting configuration and locations (Sacamano et al 1993).

Trees also have impacts on the hydrology of an urban environment. As areas become developed, the relative amount of impervious surface increases, i.e. parking lots, roads, and buildings begin to dominate over soil and vegetative land cover (Owe 1985). Consequently, soil infiltration is reduced, thereby intensifying the volume and rate of runoff, and increasing pollution loads (Sacamano et al 1993). These effects cause flooding and water quality problems (Ripely and Ellertsen 1971). Increasing vegetative cover in cities can potentially mitigate many of the hydrologic impacts of urban development.

In the past, wildlife management in cities meant animal control, but as Johnson (1988) points out, many urban dwellers now value wildlife in their immediate environment as evidenced by increasing positive attitudes toward urban wildlife (Sacamano et al 1993). Wildlife in cities may offer greater opportunities for environmental education and non-consumptive recreation than remote locations because of the proximity to large numbers of people (Shaw et al 1985).

In summary, understanding the environmental, social and economic benefits of trees in cities helps determine the objectives for creating and maintaining an urban forest. Some of the desirable characteristics we seek in urban trees are: rapid initial growth and then slow growth after maturation, large shade-providing crowns, aesthetic appeal, and robust health with the ability to withstand the many stresses of the urban environment (i.e., water deficiencies, soil compaction, vandalism, temperature extremes, etc).

3. THE GROWTH MEDIUM – SOIL

Soils store water and nutrients needed by trees (Kuhns 1987). In order to understand tree nutrition and to help determine a need for fertilization it is crucial to know both the physical and chemical aspects of the soil type in which trees grow. In the Eastern United States, and particularly in the southeast, most of the soils are classified in the Ultisols soil order (Brady & Weil 1996). In undisturbed areas these soils support an abundant growth of forest species.

Ultisols, however, are highly acidic and are often deficient in one or more of the following elements: phosphorus, potassium, calcium, magnesium, sulfur and various micronutrients (Pritchett and Fisher 1987). As a rule they are low in effective cation-exchange capacity (see section – Soil Characteristics that Affect Tree Nutrition and Growth), resulting in a high leaching potential. In particularly clayey soils, phosphorus is often immobilized and consequently unavailable to trees. While the physical properties of these soils are good, many Ultisols are prone to erosion. The problems associated with these soils are often exacerbated in urban areas where soils are severely disturbed (see section – Urban Soils).

4. SOIL CHARACTERISTICS THAT AFFECT TREE NUTRITION

The amount of nutrients a soil can hold and the availability of these nutrients is greatly influenced by the physical characteristics of the soil (Harris 1992) – that is its texture, structure, cation-exchange-capacity and pH.

Soil texture

Soil texture describes the size of the different mineral particles. It relates primarily to particles smaller than 2 mm (.08 in) in diameter – sand, silt and clay (Craul 1982, Kuhns 1987). Soil texture significantly influences soil moisture relationships, soil structure, the amount of nutrients adsorbed by the soil, and in turn, plant growth (Craul 1982, Harris 1992). Generally, the finer the texture of a soil, the greater its capacity to hold nutrients and water; therefore, to supply an equal amount of fertilizer or nutrient, a sandy soil will need more frequent applications of smaller amounts than will a clay soil (Harris 1992). It is important to note that a heavy clay may have more total water but water movement may be restricted by poor soil structure and limited soil porosity.

Soil Structure

Soil structure refers to the arrangement of soil particles into units called peds (Craul 1982). The form and size of these peds, or aggregates (held together by binding forces of clay and organic matter) have a profound effect on the porosity and pore-size distribution of the soil (Craul 1982, Kuhns 1987). Tree growth is strongly impacted by soil structure because of its effects on the movement of water, nutrient availability, air (aeration) and root growth (Kuhns 1987, Harris 1992).

Aeration refers to the amount of pore space occupied by air and aeration status is the primary factor determining the total rooting depth in most soils (Craul 1982). In some urban soil environments rooting depth is also affected by actual mechanical and physical impedances and barriers (i.e. sidewalks, roads, buildings, foundations and buried utilities). Plants require oxygen for root growth (and other metabolic activities), which is obtained from the atmosphere diffusing into the soil under a partial pressure gradient. This diffusion can only occur in air-filled spaces (Craul 1982). Hence, in compacted or saturated soils this gaseous diffusion is severely limited and root activity is adversely affected.

Cation Exchange Capacity

The soil acts as a reservoir for nutrients in that the surfaces of clay and organic matter particles are negatively charged and are able to adsorb positively charged nutrient cations (Craul 1982, Funk 1990). The amount of the negatively charged sites in soil is called its cation-exchange-capacity or CEC. It is called this because the cations are loosely held and can be easily absorbed by the roots by exchanging them for hydrogen ions (Craul 1982, Kuhns 1987). The hydrogen ions account for the acidity of the soil and offer no direct nutrient value to the plant. Often lime is added to the soil to neutralize acidity and replace the hydrogen on the soil particles with Ca and Mg if dolomitic limestone is used (Kuhns 1987).

The greater the clay content and/or organic matter content, the greater the CEC. The types of clay minerals produced from weathering greatly influences their nutrient storage capability; low for kaolinitic types, high for montmorillonitic types (Mader and Cook 1982, Pritchett and Fisher 1987). The amounts of nutrients stored by a soil are directly related to the cation-exchange-capacity, and in turn, the fertility of the soil (Craul 1982). Soils with low clay and organic matter such as sands or loamy sands would have low fertility.

pH

The hydrogen ion concentration (pH) of the soil solution is a measure of a of a soil's acidity or alkalinity (Harris 1992) and is highly dependent upon the parent material of the soil, regional precipitation , the organic matter content and the major nutrient elements in the soil (Craul 1982, Craul 1985). Total moisture available to trees and the length of the growing season play predominant roles in the relation between the pH value of soils and the distribution of plants. The longer the season, the higher is the tolerance of plants toward soil acidity (Wilde 1958).

Soil pH affects the solubility and availability of soil nutrients; each nutrient's maximum solubility occurs over a certain pH range, outside of which the nutrient is likely to form insoluble compounds (Wilde 1958, Funk 1990). Therefore, soil pH greatly influences nutrient absorption (Funk 1990). The pH value of soils is not a constant; it varies with the soil: water ratio and the salt concentration (Bould and Hewitt 1963). Lowering the amount of water and increasing the salt concentration (displacing hydrogen and aluminum ions from the exchange sites) both increase the pH value.

White oak (*Quercus alba* L.), tulip poplar (*Liriodendron tulipifera* L.) and sycamore (*Platanus occidentalis* L.), and other hardwoods often grow exceptionally well on fine-textured soils with a pH as low as 4.6 (Wilde 1958), although the recommended optimum ranges for tulip poplar and sycamore are between 6.0 – 7.5 (Spurway 1941). Aslander (1952) found that soil nutrient content influenced the distribution of Norway Spruce (*Picea abies* A. Dietr.), European birch (*Betula pendula* Roth*),* oak (*Quercus spp.),* basswood (*Tilia spp.*) and beech (*Fagus spp.)* far more than did the pH value of soils. Hemlock (*Tsuga* *spp*.) and balsam fir (*Abies balsamea* (L.) Mill.), known to be acid-loving species have also been reported growing successfully on calcareous (calcium or lime containing) soils of pH 7.3 to pH 8.0 (Galloway 1940).

If a soil is too acid, adding lime can increase its pH; if a soil is too alkaline, sulfur can be added to decrease its pH (Harris1997). Soil texture, organic matter, material used, and how much the pH is to be changed will all influence the amount of lime or sulfur needed.

When the pH of a mineral soil is 4.5 or below, Al, Fe and Mn are so soluble that they may become toxic to certain plants (Kuhns 1987). Harris (1997) believes these elements may become toxic at a pH of as high as 5.5. High acidity has also been shown to inhibit earthworms (Craul 1982). Very low pH (3.0 – 5.0) may cause P to be tied up in unavailable iron and aluminum phosphates (Pritchett 1979). This problem is less severe with most trees than with agricultural crops because of the ability of the mycorrhizae associated with trees to obtain P from these compounds (Mader and Cook 1982).

Soils that are excessively alkaline or have a very high pH (above 7.5) inhibit the solubility of Fe and may lead to chlorosis, particularly of oaks (Baule and Fricker 1970) and white pine (*Pinus strobus* L.), on limestone soils low in organic matter. The same problem may occur with Cu and Zn (Stone 1968). Highly alkaline soils of 9.0, as may be the case in many urban soils (especially in arid regions of the western U.S.), result in deficiencies of Mn as well as N. Toxic release of K, S, Ca and Md are also possible at such high pH (Smith 1978).

5. URBAN SOILS

Under urban conditions, natural soils generally undergo considerable alteration; their physical and chemical characteristics do not resemble their natural conditions (Patterson 1990). Urban trees are often adversely impacted by removal or disturbance of soil due to construction, which results in the loss of the primary storage site of organic matter and nutrients in the soil profile (Mader and Cook 1982) as well as loss or significant alteration of water storage and movement capability. Severe disturbance may also result in the inversion of soil materials so that topsoil is buried and nutrients become less available. Infertile subsoil may be left at the surface where the primary root zone would normally develop (Mader and Cook 1982).

Aeration of Urban Soils

Of all soil stresses in urban areas, the most common may be poor aeration due to soil compaction (Steiner 1980). Compaction destroys macroporosity; and because pore space is reduced, soil resistance, hardness and bulk density are increased (Patterson and Mader 1982). Bulk density is the weight of a unit volume of soil, including the soil particle volume and the pore volume (Craul 1982). Because there is little pore space in compacted soil with high bulk density, root penetration is inhibited, water movement through the soil is slow, and there is usually insufficient oxygen for root growth (Craul 1986).

The bulk density in natural surface mineral soil in forests ranges from about 0.5 to 1.3 g/cubic centimeter (Patterson and Mader 1982). Many urban soils have bulk density values ranging from 1.6 – 2.2 g/cubic centimeters (Patterson and Mader 1982,Craul 1986). A bulk density of 1.5 – 1.6 is often considered to be the threshold value, above which significant negative growth impacts are likely to occur.

It is important to select planting materials that will best tolerate soil compaction for heavily trafficked areas. A list by Pirone et al.(1988) rates species as follows:

1) most severely injured: sugar maple (*Acer saccharum* Marsh.) , beech (*Fagus* spp.), flowering dogwood (*Cornus florida* L.), oak (*Quercus* spp.) tulip poplar, pines (*Pinus* spp.) and spruce (*Picea* spp.).
2) less severely injured: birch (*Betula* spp.), hickory (*Carya* spp.), and hemlock (*Tsuga* spp.).
3) least injured: elm (*Ulmus* spp.), poplar (*Populus* spp.), willow (*Salix* spp.), plane tree (*Platanus* spp.), pin oak (*Quercus palustris* Muenchh.) and locust (*Gleditsia* spp., *Robinia* spp.)

Soil Amendments

Amending the soil with porous, yet durable materials ameliorates compaction (Craul 1985). Amendment materials are generally divided into organic and inorganic categories. The organics by their nature tend to be short lived in an aerobic soil system and decompose thus enhancing the cation-exchange-capacity and structure of the soil (Patterson 1990). Several kinds of materials are available as mulches to protect the soil surface in heavily used areas such as coarse wood or bark chips, composted leaves, sawdust, straw, and peat moss (Patterson and Mader 1982).

The inorganics tend to be longer lived or even resist decay in the soil system. When cost is not prohibitive, inorganic mineral materials including marble chips, vermiculite, pumice or gravel may be used. In general, solid mineral materials cushion less than organic mulches (Patterson and Mader 1982) but they all contain internal pore space within their matrices that seems to provide additional benefits such as water holding capacity (Patterson 1990).

When using amendments, it is important to consider the percentage by volume required in a soil mixture. The answer will vary depending upon the type of amendment, use of the proposed site, the intensity of use, and the degree of maintenance the site will receive (Patterson 1990). Organic matter can absorb up to 400% its own weight in water. Incorporating high amounts (10, 20, 30%) of organic matter by volume into a soil could easily result in an anaerobic soil system. Most often a 5 to a maximum of 10% by volume of organic material is recommended (Patterson 1990). For inorganic materials, and those areas designed for heavy use, Patterson (1990) concludes from his research that the ideal percentage of soil incorporation appears to be between 30% and 40% by volume for areas where use will be heavy and maintenance activities intermittent.

pH of Urban Soils

Urban soils characteristically have near neutral to alkaline pH, which are not optimal for many tree species (Craul 1986). The weathering of calcium-containing mortar, concrete and other building materials mixed or washed into the soil, as well as the application of calcium or sodium chloride as road and sidewalk de-icing compounds in northern latitudes bring about a higher soil pH (Craul 1985). Craul (1985) reported streeside soils of Syracuse, New York had a pH range of 6.6 to 9.0 with an average of about 8.0. Urban soils of Philadelphia, Pennsylvania ranged from 3.7 to 9.0 with a mean of 7.6. In Berlin, a pH of 8 was observed at streetside and less than 4 within a forest a short distance from the street. Applying granular elemental sulfur (or ammonium sulfate) is an effective means of lowering pH (Craul 1986). Applying organic mulches he contends will also effectively lower pH within a limited depth.

Nutrient Cycling in Urban Soils

Nutrient cycling poses another problem in urban soils. In a natural, undisturbed forest situation the nutrient cycling processes are a stable, well-balanced, self-maintaining system. In urban area the cycle is disturbed in several ways. Often the twig and leaf fall is collected and disposed of in landfills so that a continuous loss of nutrients from the soil occurs (May 1949). This can also occur from mowing of grass or other understory vegetation. Excessive runoff from compacted soil or paved surfaces may also carry away leaves and soil, depositing them in surface drainage systems (Mader and Cook 1982). Input of nutrients to urban soils may occur via wet and dry deposition from the atmosphere on trees or soil (Pritchett 1979); from dogs, cats, birds, etc.; and from mulches or fertilizer in some cases. Both nitrogen and sulfur inputs can cause soil acidification and leaching of basic elements from soil (Likens et al 1977). Low organic matter content disfavors aggregation and prevents good soil structure (Craul 1985)

Toxic Elements in Urban Soils

Urban soils receive varying inputs of toxic materials from automobile exhausts, industrial plant emissions, road-salting, and chemical spraying programs (Westing 1966). Increased amounts of lead in road-side soils are well documented. Salt has received widespread attention as a roadside pollutant (Westing 1966). A great deal of injury to trees is attributed to sodium chloride excess in the trees, particularly chloride, where salt is used for de-icing in the winter. In addition to direct injury, the uptake of basic elements may be disrupted by excess sodium in the soil (Mader and Cook 1982). If sodium represents more than 15% of the exchange-capacity, a medium or fine-textured soil will lose its granular structure and become exceedingly impervious to air and water (Harris 1992).

Modified Temperature Regimes and the Urban Climate

It is a well-documented fact that urban development modifies the local climate (Harris 1992). Temperatures (often called urban heat island), precipitation, and cloud cover increase relative to surrounding rural environments while wind, humidity, and radiation decrease (Table 1). In many cases the soil is surrounded by large capacity heat-absorbing and re-radiating surfaces, increasing the heat flux to the cooler soil (Craul 1985). Evaporation of water from the soil surface eventually dries it and imposes greater stress upon the plants.

Nighttime minimum soil temperatures tend to be high because of the high air temperatures from the heat retention of structures. Plant metabolism rates potentially remain high (Craul 1985). Unfortunately, few actual soil temperature data are available for urban soils.

Table 1. Average Changes in Climate Elements Caused by Urbanization (Adapted from Harris (1992) and Landsberg (1970)

Element	Comparison with rural environment
Wind Speed	
Annual Mean	20 to 30% less
Extreme Gusts	10 to 20% less
Temperatures	
Annual Mean	0.9 – 1.8 degrees F higher
Winter Average	1.8 – 3.6 degrees F higher
Precipitation	
Total	5 to 10% more
Days with less than 5 mm	10% more
Relative Humidity	
Winter	2% lower
Summer	8% lower
Cloudiness	
Cover	5 to 10% more
Radiation	
Total	15 to 20% less
Sunshine Duration	5 to 15% less
Contaminants	
Condensation Nuclei and Particulates	10 times more
Gaseous Admixtures	5 to 25 times more

Soil temperature is important since it controls the growth environment of roots and soil organisms, and inorganic chemical processes. A warmer temperature increases rates of reaction and biological processes. The rate of organic matter decomposition is increased, provided the necessary organisms are present, and the overall soil-weathering process may be intensified. The latter may have a beneficial effect from the release of nutrients for absorption by roots. Root growth may be extended well into the fall and early winter (Craul 1985).

6. THE ESSENTIAL NUTRIENT ELEMENTS

Arnon (1954) proposed three criteria of essentiality for a nutrient for higher plants. These criteria are: 1) the organism cannot complete its life cycle (vegetative or reproductive) without the particular element, 2) its action must be specific and cannot be replaced by another, and 3) its effect on the plant must be direct. Sixteen elements have been found essential for woody plant growth - arbitrarily divided into macronutrients and micronutrients on the basis of their normal concentrations in plant tissue (Harris 1992, Robinson 1986). Fowells (1959) notes that macronutrients are usually required in amounts of the order of 1 part per million or more while micronutrients are adequate when present at rates of much less than 1 part per million or as low as a few parts per billion.

The macronutrients are nitrogen (N), phosphorus, (P), potassium (K), magnesium (Mg), sulfur (S), and calcium (Ca). The micronutrients are iron (Fe), manganese (Mn), copper (Cu), boron (B), zinc (Zn), molybdenum (Mo), and chlorine (Cl) (Huber 1980, Kuhns 1987, Whitcomb 1987, Pirone et al.1988, Harris 1992). These elements are derived and absorbed from the soil. The elements carbon (C), hydrogen (H) and oxygen (O), which comprise about 90% of plant dry matter (Craul 1982), are also needed by plants; however, carbon is obtained from carbon dioxide (CO_2) in the air, and oxygen and hydrogen from water (Whitcomb 1987).

As stated earlier, soils in the Eastern U.S. support abundant growth of many forest tree species but these soils can lack P, K, Ca, Mg, S and various micronutrients. Excessively alkaline urban soils in this region (above 7.5pH) can immobilize Fe, Cu and Zn. Potassium, S, Ca and Mo may reach toxic levels in urban soils due to high pH. Nitrogen and Mn can also become deficient in highly alkaline soils of 9.0.

MACRONUTRIENTS

Nitrogen (N)

Nitrogen is the most commonly deficient nutrient in soils, particularly urban soils (Christians 1989, Harris et al. 1977). Nitrogen deficiencies are also often reported in coniferous forests of cold climates under conditions that favor accumulation of thick acid humus. Incipient N deficiencies are also found in many sandy soils of warmer climates including the flatwoods and sand hills of the U.S. coastal plain and the Douglas fir region of the Pacific Northwest (Pritchett and Fisher 1987). Lack of optimum nitrogen supply is probably both a cause and effect of poor tree vigor, resulting in thin crowns, yellowish-green foliage, lack of chlorophyll and progressive twig and branch die-back (Mader and Cook 1982). Adequate nitrogen is essential for the production of amino acids, proteins, and growth hormones; it promotes vigorous growth and delays maturity (Huber 1980). N is also an integral part of the chlorophyll molecule (Pritchett and Fisher 1987).

Unlike other essential nutrients nitrogen is not a product of the weathering of rock parent material. Organic matter decomposition is the prime source of nitrogen for trees (Mader and Cook 1982). Ovington and Madgwick (1959) studied a 33 year old stand of Scotch pine (*Pinus sylvestris* L.) in a natural forest ecosystem and found the distribution of elements between the living trees and the rest of the organic material on the site to be roughly as follows: One-half of the Ca, Mg, K and P was in the living trees, while only about one-sixth of the N was in them. This led them to conclude that the natural N equilibrium on the site favors its accumulation in the forest humus and organic matter rather than in the trees. Soils low in organic matter, such as in many urban soils, often support trees suffering from nitrogen deficiency (Wilde 1958).

Although nitrogen composes 78% by volume of the air (Harris et al 1977) and is one of the most abundant of the essential nutrient elements, it is largely unavailable to plants. Atmospheric nitrogen that does get incorporated into the soil occurs from the fixation of N_2 to NH_3 (anhydrous ammonia) by microorganisms. Rainfall, because of electrical activity in the atmosphere, provides a small quantity of NH_3, as well (Kramer and Boyer 1995). The NH_3 is released to the soil as organic matter after the microorganisms complete their life cycle and begin to break down

Microbes further break down these complex organic forms of N into inorganic forms (ammonia and ammonium) in a process called mineralization (Funk 1990, Kramer and Boyer 1995). Mineralization must occur before plants can utilize N (Bould and Hewitt 1963).   N becomes available to higher plants only as the C:N ratio approaches 10:1 (Pritchett and Fisher 1987).

Through another microbial process, nitrification, ammonium (NH_4^+) is transformed into nitrite – a transitional compound present in trace amounts – and finally into nitrate (NO_3^-); the amount of nitrate finally produced depends on the relative amounts of decomposable organic matter present (Bould and Hewitt 1963). Nitrification is most efficient in well-aerated soils (Funk 1990) and at a pH of about 7.5 to 9.0 (Eno and Blue 1957) – conditions that are rare in most Eastern U.S. soils. At low pH (5.0) the rate of nitrate production from ammonium or from organic matter is slow (Stanford 1959).

Assimilation of N is more complicated than other essential elements because it is assimilated both as the NH_4^+ cation and as the NO_3^- anion, and because interactions of N with other nutrients is common (Huber 1980). Potassium increases NO_3^- uptake, while P and Cl decrease uptake of NO_3^- and enhance uptake of NH_4^+ (Huber 1980).

Both NH_4^+ and NO_3^- can be removed from the soil solution by soil organisms and converted into organic N through the process of immobilization. This N is then temporarily lost to the plant until made available once again through mineralization. Some N is volatilized into the atmosphere in the form of ammonia (NH_3) gas. This is particularly a problem in coarse-textured soils with high pH (Christians 1989).

Although plants respond more slowly to NH_4^+ than to NO_3^- (Kuhns 1987) there is no evidence to show that there is any difference in the eventual use to which plants put them (Webster 1959). Kramer and Boyer (1995) state that N usually is taken up by trees as NO_3^- which is then reduced and incorporated into amino acids. The plant will probably take up in greatest quantity whichever form predominates in the soil, although the relative amounts absorbed may be modified by the age and kind of plant, soil pH, and other environmental factors (Hauck 1968). In highly leached and acid forest soils, ammonium can be the predominant N form as a result of low soil nitrifying capacity (Hauck 1968).

In summary, N becomes available to trees through: mineralization of organic matter, addition of fertilizers and fixation of N in the air by microorganisms (Harris 1992, Kuhns 1987). N in the soil becomes unavailable to trees through absorption by grasses, weeds (plants growing where they are unwanted) and other organisms during decomposition of organic matter, volatilization into the atmosphere, and denitrification by soil organisms – a problem in waterlogged soils low in oxygen. Finally, nitrates are lost from the root zone by leaching (Harris et al.1977, Kuhns 1987, Christians 1989). Climate plays a dominant role in determining the N status of soils. Within areas of uniform moisture conditions and comparable vegetation, the average N and organic matter contents of the soil decrease exponentially as the annual temperature rises (Jenny 1941).

Phosphorus (P)

Soil phosphorous can be divided into two primary classes, organics and inorganics (Bould and Hewitt 1963). Organic P occurs in the form of phospholipids, nucleic acids and inositol phosphates. Most inorganic phosphorus is derived primarily from the calcium phosphates (apatites) and iron and aluminum phosphates in soils, and it is believed to be absorbed by plants mostly as the primary orthophosphate ion (Pritchett and Fisher 1987).

Phosphorus is tightly held in soils, even those that are nearly 100% sand, and its availability to plants is low (Whitcomb 1987, Harris 1992). P is commonly deficient in agricultural soils but it is seldom deficient in soils in which trees and large shrubs grow (Huber 1980, Harris 1992). The availability of insoluble soil P, like N, is primarily dependent on mineralization (microbial activity) in the rhizosphere (Bould and Hewitt 1963). Availability of P is influenced by soil acidity, as well, as it tends to form insoluble precipitation products with Fe, Al and Mn in very acid soils. In neutral to alkaline urban soils where there is microbial activity P would tend not to be deficient. Huber (1980) reports that mycorrhizae of woody plants appear as important to P nutrition as symbiotic N fixation is for N.

The surface horizons of some coastal acid sands and organic soils of the southeast U.S. are particularly low in P because of their weak capacity for P retention. They contain very low concentrations of Fe, Al and Mn; therefore most of the P in the surface layers has been leached to lower horizons (Pritchett and Fisher 1987).

Phosphorus provides the energy for several chemical reactions within the plant in the form of high-energy organic complexes: ATP (adenosine triphosphate and ADP (adenosine diphosphate)(Whitcomb 1987). Phosphorus deficiency, even though mild, will reduce this energy transfer system and slow growth functions of the plant.

Potassium (K)

Bould and Hewitt (1963) report that potassium occurs as primary and weathered minerals, and in non-exchangeable, exchangeable and water-soluble forms. The most important K-containing minerals in soil are orthoclase, microline feldspar, muscovite and the clay mineral, illite. For plant nutrition, the exchangeable and water-soluble forms are the most readily available, the non-exchangeable acting as a reserve (Bould and Hewitt 1963, Funk 1990).

Most soils contain enough potassium for woody plants and trees but potassium can be deficient in soils that are acid, low in organic matter, or sandy (Harris et al. 1977, Leaf 1968). K is very mobile in the plant tissue, and unlike most other essential elements, it does not become a structural component of the plant (Huber 1980, Whitcomb 1987).

As a regulator of enzyme activity, potassium is involved in essentially all cellular functions, including photosynthesis, phosphorylation, protein synthesis, water maintenance, reduction of nitrates, and reproduction (Huber 1980). A balanced level of K induces thicker cell walls, accumulation of amino acids (arginine), and production of new tissues (Huber 1980). The element tends to be concentrated in the actively growing portions of trees such as buds, current year's foliage and growing root tissues, while the proportion of K is relatively low in older, mature tissues (Leaf 1968). K plays an important role in frost hardening of trees, involving sugar-starch conversion at the end of the growing season (Leaf 1968). Its level in plants depends upon the availability of Mg and Ca and a deficiency of K impairs the utilization of P (Huber 1980).

Calcium (Ca)

Calcium is rarely deficient since some calcium source, generally calcium carbonate or dolomite, is widely used to adjust the pH of acidic soils. In addition, most soils contain sufficient calcium for plant growth even when soil pH is relatively low (Whitcomb 1987). Calcium exists in soils mostly in inorganic forms, and from 50 to 1000 ppm or more may be held in an exchangeable form in the surface soil. Soils developed in regions of relatively low rainfall generally contain larger supplies of calcium than soils in humid regions (Pritchett and Fisher 1987). In urban systems, calcium is also released from the degradation of sidewalks and streets and when lime is used for road and sidewalk salt in winter.

Calcium has critical roles in cell division, cell development, cell wall formation, and carbohydrate movement. It complements the functions of K in maintaining cell organization, hydration and permeability. In these capacities it is involved in mitosis, enzyme activation and regulation, and membrane function (Huber 1980).

Sulfur (S)

Sulfur occurs in rocks, especially basic igneous rocks as sulfides, e.g., the mineral pyrite, which in turn oxidize to sulfates under aerobic conditions (Leaf 1968). S is available to trees as SO_4 ions via the roots, and as SO_2 via the leaves (Alway et al. 1937).

Although sulfur is used in approximately the same amounts as phosphorus, it is much more readily available in the soil. Sulfur-oxidizing bacteria can convert free sulfur and sulfur in organic compounds to sulfates and sulfuric acid. Sulfur can be readily absorbed as sulfate by plants or leached from the soil in the absence of plants. Sulfur deficiency is very rare in industrial countries; rainfall, irrigation water, decomposing organic matter, the burning of fossil fuels, and fertilizers provide enough sulfur for normal plant growth in most soils (Bould and Hewitt 1963, Harris 1992). S is an essential component of three amino acids necessary for synthesis of proteins, and of two plant hormones (Leaf 1968); it is also incorporated into enzymes and vitamins (Huber 1980).

Magnesium (Mg*)*

Magnesium is the only mineral constituent of chlorophyll and is also associated with rapid growth, carbohydrate metabolism and oxidative phosphorylation in young plant cells (Leaf 1968, Huber 1980, Whitcomb 1987). Mg tends to be deficient and readily leached in sandy, acid soils. P and Mg are often deficient in the same soils and they can be antagonistic (Huber 1980, Harris 1992). Mg occurs in several minerals, e.g., micas, hornblende, dolomite, serpentine and montmorillonite (Leaf 1968).

MICRONUTRIENTS

Most soils contain sufficient amounts of micronutrients to promote tree growth (Pirone et al. 1988). Deficiencies do develop, however, and are found most often in soils outside a pH range of 6.0 – 7.0 or in sandy, well drained soils where heavy rainfall encourages leaching (Pirone et al. 1988). Iron and manganese are the micronutrients most frequently found deficient even though these nutrients are present in the soil in concentrations adequate to support growth (Kuhns 1987). The situation is usually corrected by adjusting the pH, which removes the elements from fixed, insoluble compounds and renders them available for root uptake (Kuhns 1987, Pirone et al. 1988).

Iron (Fe)

Harris (1992) states that iron deficiency is the most common micronutrient deficiency. Fe deficiency is common on many species grown in areas of low rainfall and in alkaline soils (pH above 7.0) where high levels of calcium tie up the iron in insoluble forms - its deficiency is sometimes called lime-induced chlorosis (Harris 1992, Huber 1980). In many studies, chlorosis of pin oak (*Quercus palustris* Muenchh.), white oak (*Quercus alba* L.) and red maple (*Acer rubrum* L.) have been reduced or eliminated by surface and subsoil application, as well as, trunk injection of sulfur (Messenger 1984, Whitcomb 1987, Harrell et al. 1988, Messenger and Hubry 1990). It is not uncommon to find Fe deficiencies in many urban soils. High levels of P, either alone or in conjunction with calcium, may also tie up iron in insoluble complexes.

The ferrous forms of iron are the most available for plant nutrition (Huber 1980). Iron is essential for chlorophyll and the reactions of photosynthesis and plays a role in the synthesis of proteins and the function of certain enzymes (Huber 1980, Whitcomb 1987).

Manganese (Mn)

Manganese reacts similarly to iron in many respects – it is essential in the synthesis of chlorophyll and is similarly affected by calcium and phosphorus (Huber 1980). Manganese deficiency is more likely to occur in poorly drained soils that are high in organic matter (Harris 1992). The temperature of soils affects its solubility. As the temperature of soils decreases, so does manganese solubility (Whitcomb 1987). It could potentially be deficient in alkaline urban soils; the solubility of manganese decreases as soil alkalinity increases, and it is not readily available to plants above pH 6.5 (Harris 1992).

Manganese is a constituent of only one known plant component, but it activates various enzymes involved in nitrate reduction, carbohydrate metabolism, and respiration (Huber 1980). At high concentrations, Mn competes with Fe for absorption and translocation (Huber 1980, Whitcomb 1987).

Copper (Cu)

Field experiments have shown that copper sulfide acts as a source of copper for plant growth - copper sulfide probably originated from the most important copper compound in primary rocks, chalcopyrite (Bould and Hewitt 1963). There is some evidence that atmospheric sources may provide significant amounts of Cu, as well (Huber 1980).

Copper deficiency is fairly widespread and is not likely to occur on soils that are sandy, organic, alkaline or calcareous. Copper deficiency can be aggravated by alkaline irrigation water and by nitrogen or phosphorus accumulation (Harris 1992) – conditions that generally would only be encountered in the arid or semi-arid regions of the western United States. Foliar and surface application of copper fertilizers can successfully eliminate deficiencies. Copper is toxic to cambium and sapwood and trunk injections are, therefore, not recommended (Harris 1992).

Copper is a component of several enzymes and is involved in protein and carbohydrate synthesis, and N fixation (Huber 1980, Whitcomb 1987).

Boron (B)

There is a relatively narrow range of concentration between deficiency and phytotoxicity of B (Huber 1980, Harris 1992). According to Whitcomb (1987) boron deficiency in soils is not as common as boron toxicity. It is required by plants in very small amounts and functions in translocation, cellular differentiation and development, carbohydrate metabolism, and the uptake or translocation of Ca (Huber 1980).

In the United States, areas of known boron deficiency are located in the eastern third of the country and portions of the Pacific states. In one California county, boron-deficient soils are within 6 miles of soils with excess boron (Harris 1992).

Molybdenum (Mo)

Molybdenum is also required in very small quantities in plants, but nonetheless is very essential for the transformation of nitrate into amino acids (Whitcomb 1987). In contrast to most of the other micronutrients, Mo is less available at low pH; Mo deficiency commonly occurs in soils that severely lack phosphorus and sulfur (Harris 1992).

Chlorine (Cl)

Chlorine is the only essential element for which a deficiency has not been observed under field conditions (Huber 1980, Harris 1992). Excess chlorine is much more of a concern, particularly in irrigated arid regions and near seacoasts (Harris 1992). Trees adjacent to roadways treated with salt during the winter can experience serious injury, as well (Rich 1971,Craul 1982), thus the symptomology of cloride injured trees needs to be kept in mind in northern and eastern U.S. urban areas where calcium chloride is used for winter de-icing on sidewalks and streets.

Zinc (Zn)

Harris (1992) reports that zinc deficiency is common among cultivated trees and large Zinc compounds decreases in solubility as pH increases and, like many other nutrients, is more likely to be unavailable in the soil than low in total quantity (Harris 1992). Rarely would Zn deficiencies be encountered in urban areas.

The primary physiological role for Zn is its interrelationship with auxin (Huber 1980). Addition of Zn to deficient plants greatly stimulates auxin synthesis – thereby making it essential for cell elongation and growth.

7. DETERMINING NUTRIENT REQUIREMENTS

Other than nitrogen, most nutrients are supplied in adequate amounts in the majority of undisturbed soils; however, in severely disturbed urban soils there may be multiple nutrient deficiencies. To estimate how well the nutritional requirements of a tree are being met four methods of analysis are generally employed: visually observing the tree's growth and appearance, testing the soil, or testing the foliage (or other plant tissues), and various combinations of the three.

Visual Observation

A severe deficiency of any essential element is usually accompanied by symptoms which may be detected visually (see Nutrient Deficiency Symptoms discussion); however, visual nutrient deficiency symptoms can be variable, complex and often not easily distinguishable from one another, from air pollution or other tree stress symptoms (Barrows 1959, Leaf 1968). Most authorities, therefore, recommend foliar, soil or other forms of analyses to assist in or substantiate visual diagnosis.

Nutrient Deficiency Symptoms

There is voluminous literature dealing with nutrient deficiency symptoms of plants and trees. Table 2 is a compilation of the most frequently cited and definitive symptoms associated with essential nutrient deficiencies.

Table 2. Nutrient Deficiency Symptoms for Trees: Adapted from Baule and Fricker (1970), Harris (1992), Kuhns (1987) and Stone (1968)

Nitrogen (N)

Broadleaf: smaller, thinner, fewer leaves, general yellowish green color, more pronounced on older leaves; poor or stunted shoot growth; early leaf drop, thin crowns

Conifer: yellow, short needles that are close together; older plants exhibit poor needle retention; lower crowns may be yellow while upper crowns remain green

Phosphorus (P)

Broadleaf: dark green, blue green, slightly smaller leaves. Veins, petioles, or lower surface may become reddish-purple, foliage is less dense; stunting or poor growth occurs prior to reddening of leaves, older leaves show symptoms first and most severely.

Conifer: needles turn purple in young seedlings; needles of spruce (*Picea spp.*) and larch (*Larix spp.*) turn gray or bluish-green; symptoms most pronounced in later summer on older needle tips; roots are sparse with no mycorrhizae.

Potassium (K)

Broadleaf: partial chlorosis of most recently matured leaves in interveinal area beginning at tips, followed by necrosis; older leaves may become brown and roll upward; often irregular necrotic spots or lesions on leaves; may exhibit dark bronze leaf colors.

Conifer: small, yellow-green needles; most pronounced on tips of older needles in autumn, winter and spring; needle retention is poor; seedlings have short, thick, abundant buds; frost injury is frequent.

Calcium (Ca)

Broadleaf: death of terminal buds, tip dieback; leaves chlorotic and/or necrotic; leaves may be brittle and stiff; young leaves distorted and small.

Conifer: primary needles are usually normal, but secondary needles may be stunted or killed.

Magnesium (Mg)

Broadleaf: marginal chlorosis on older leaves followed by interveinal chlorosis; shoot growth not affected until deficiency is severe; symptoms disappear quickly after fertilization.

Conifer: golden or yellow-tip “halo” effects on conifer needles in late summer or autumn; sharp transition to the green portion; symptoms more severe in moist years.

Sulfur (S)

Broadleaf and Conifer: symptoms similar to those of N deficiency; yellow-green or yellowish foliage, especially in younger leaves; reduced shoot growth; older leaves usually not affected.

Iron (Fe)

Broadleaf: Interveinal chlorosis of young leaves (sharp distinction between green veins and yellow tissue between veins), especially in wet or cool years. In oaks, young leaves may be yellow on emergence; develop interveinal necrotic spots and light color; and finally curl, wither and die. Exposed leaves bleached.

Conifer: new growth will be very stunted and chlorotic; older needles and the lower crown will remain green.

Manganese (Mn)

Broadleaf: marginal leaf chlorosis, gradually extending between the major veins, with bands of green along the main veins and the midrib; necrotic spots may develop in the chlorotic areas; shoot growth may be reduced.

Conifer: symptoms essentially the same as for iron deficiency; new needles are chlorotic and pale green; tip necrosis may occur.

Zinc (Zn)

Broadleaf: marked chlorosis of younger leaves; may be uniformly yellow, sometimes mottled with necrotic spots; leaves are small (“little leaf”) and may be deformed; shoot dieback in severe cases; may be rosettes of leaves at the shoot tip.

Conifer: extreme shortening of branches, needles, and needle-spacing may occur in upper crown, plus general yellowing and loss of older needles; terminals die back.

Boron (B)

Broadleaf and Conifer: death or distortion of meristematic tissues; terminal growth dies; may be tip wilting, bending, shoots may be short, brushy, stiff; young leaves may be red, bronzed or scorched in broadleaf species.

Copper (Cu)

Broadleaf: most common symptom is stunting of over-all growth followed by leaf stunting, loss of leaf luster and leaf size; rosetting of buds on terminal branches, terminal growth may die

Conifer: young pine needles show tip burn; shoots of Douglas fir are week and often crooked; needles at the tips of shoots may discolor and drop during winter.

Molybdenum (Mo)

Broadleaf: cupping of the older leaves; marginal chlorosis followed by interveinal chlorosis; leaves are similar in color to those deficient in N; shoot internodes are stunted when deficiency is severe.

Soil Analysis

Soil analysis can also aid in evaluating nutrient status and need for fertilization. Analysis of the soil gives information about the availability of essential elements, the cation-exchange-capacity of the soil, organic matter levels, and soil pH (Smith 1978, Lilly 1993, Smiley 1994). Soil analysis information on nutrient levels is usually expressed in parts per million or pounds per acre and is less expensive than foliar analysis (Smiley 1994)

Soil analysis, although helpful, is not always a good index of the nutritional status of a tree. Soil analysis results often vary significantly across a given year for certain elements. The potential lack of consistent and accurate data make it difficult to calculate amounts of nutrients to add. In addition, the *efficiency* with which a tree utilizes the soil nutrients varies widely with different soil conditions. Cain (1959b) demonstrated this in research he conducted on apple trees in New York in which some soils (no description of the soils was given) with rather low amounts of K produced trees with high K content and vice versa. That is, even though we can calculate the amount of fertilizer to increase the soil nutrient content, we have no assurance that this will increase our tree nutrient content. Finally, it is important to note that extractants are used to determine the availability of specific nutrients. That the flushing of extractants through soil duplicates the roots ability to take up these same nutrients under the same conditions is a large assumption to make. In addition, the use of extractants is based on agricultural models modified for forestry usage.

Often the results of soil analyses are more difficult to interpret than the results of a foliar analysis. Kopinga and van den Burg (1995) support this statement by the following observations: 1) the availability of some elements depends on the physical conditions of the soil. Frequent water logging, or insufficient levels of soil oxygen, for example, have negative effects on the uptake of K and the rate of N mineralization; 2) the uptake of some nutrients, primarily N, depend on the extension of the root system; and 3) the criteria for the interpretation of the results of soil analysis have been derived from forest research – where many of the critical values for nutrient deficiencies focus on the assessment of levels at which trees react to fertilization with an increase of growth. These levels are generally higher than those required for healthy or "acceptable" growth and development. Therefore, soil analysis results of urban trees – for which acceptable growth and amenity value are normally more important than optimal production – are potentially less helpful than results of foliar analysis in providing an accurate explanation for tree health problems related to nutrient deficiencies (Kopinga and van den Burg 1995).

Foliar Analysis

The purpose of foliar analysis is to evaluate nutrient status and make possible a diagnosis of nutrient deficiency or toxicity and/or a prediction of fertilization response (Wells 1968, Kelsey 1996). Some arborists recommend sampling mature leaves that have been exposed to full sun (Smiley 1994), collected between August and mid-September (in temperate regions) when nutrient concentration levels are more or less constant (Kopinga and van den Burg 1995).

In many areas leaves are usually analyzed for the content of the macronutrients, N, P, K, Ca, Mg and sometimes Cl. In regions where micronutrient deficiencies have not been observed, the content of these nutrients may not be analyzed.

Though Lundegardh (1954) concluded that the rate of growth and size of the plant are determined by the nutrient concentrations in the foliage, other tissues than foliage might be more diagnostically suitable, at least for certain nutrients and certain tree species. White and Leaf (1965), in their work with pine, showed strong correlation among K contents of the total tree tissue, i.e. wood, live branches, bark, with tree height growth, but no statistically significant relations among foliage K levels and soil K levels and tree height growth. Perry and Hickman (1998) conducted trials to determine the effect of N fertilizer on leaf N concentrations in valley oak (*Quercus lobata* Nee) and Chinese pistache (*Pistacia chinensis* Bunge) and found no correlation between visual N deficiency symptoms and actual leaf N concentrations.

It is important to realize that none of the nutrient analysis methods suffices on its own and many authorities recommend that soil and foliar analyses are done together (Cain 1959b, Kopinga and van den Burg 1995, Lilly 1993). Foliar analysis may be a more accurate way to assess deficiencies in the uptake of an element, but this method may not indicate how the deficiency can be corrected. To know whether fertilization is of any use, more should be known about the chemical soil fertility and physical soil factors that might influence the uptake of minerals (Kopinga and van den Burg 1995).

DRIS

In the 1980s, a comprehensive diagnostic system called Diagnosis and Recommendation Integrated System (DRIS), was introduced in the United States that incorporates relative balance among nutrients as well as nutrient concentration in foliar nutrient diagnoses (Hockman et al 1989). DRIS , in short, provides indices that measure the relative deficiency or sufficiency of nutrients relative to each other based on their deviation from optimum levels that have been established for a desired group of trees.

DRIS has successfully been used on many crops (Hockman et al 1989) including corn (*Zea mays* L.), soybeans (*Glycine max* L.), wheat (*Triticum aestivum* L.) and on hybrid poplar (*Populus deltoides* Marsh.) and Monterey pine (*Pinus radiata* D. Don).

DRIS has great potential as a nutrient diagnostic system for trees in the urban forest. Desirable characteristics of urban trees such as healthy leaf color and size, certain diameter and crown size, and general appearance could be used to divide and rank trees into grades or groups. Following DRIS methodology, comparisons of nutrient ratio means and variances could then be made among the groups and important information regarding nutrient quantity and balance could be obtained. This information could then be effectively incorporated into a judiciously applied fertilization program if nutrients were found lacking.

Hockman et al (1989) used DRIS in a study of a Fraser fir (*Abies fraseri* (Pursh) Poir.) Christmas tree plantation in North Carolina. They discovered that in contrast to a critical-level approach where *higher* nutrient levels would be associated with either decreased deficiency or increased sufficiency, lower foliar Mg levels corresponded with improved Christmas tree performance. In fact, three out of the five nutrients examined (P, Ca and Mg) had lower mean concentrations in premium versus nonpremium trees.

8. RELATIONSHIPS OF PLANT NUTRIENTS

The above findings of Hockman et al (1989) suggests that tree quality is a function of nutrient balance or synchronization as well as absolute levels of individual nutrients. What appears to be the result of a deficiency of one nutrient may as well be the result of an excess of another (Fowells 1959, Davey 1968). Element relationships should be considered when contemplating any addition of nutrients to soil (Table 3). For example, the ratio of calcium to magnesium available for plant growth is important. If calcium is in excess, magnesium absorption is depressed or vice versa (Whitcomb 1987). High levels of P can induce micronutrient deficiencies, such as copper, iron and zinc. Also, the effect of large quantities of K decreasing Mg is widely recognized (Cain 1959a). Kuhns (1987) reports that when too much K causes nutrient imbalance, plant leaves are large, but relatively inefficient at photosynthesis. The resulting abnormally large concentration of N compounds compared to photosynthates (carbohydrates) in the leaves makes the leaves susceptible to fungal and bacterial diseases and drought stress.

Sometimes it is the order in which a nutrient is added that affects the uptake and availability of other nutrients. Acquaye and MacLean (1965) reported that the application sequence of nitrogen greatly influenced the availability of soil and fertilizer K. When NH_4^+ was applied alone or after K it reduced K uptake, but if applied prior to K, it enhanced K uptake.

Table 3. Important Relationships of Nutrient Elements (adapted from Whitcomb 1987).

An excess of…..	may cause a deficiency of….
nitrogen	potassium
phosphorus	iron, copper, zinc, and manganese
potassium	calcium and/or magnesium
sodium	potassium, calcium, and magnesium
calcium	magnesium, boron, iron, manganese and copper
magnesium	calcium
iron	manganese, molybdenum
manganese	iron

Among the most commonly observed antagonisms is that of the effect of N fertilizers in apparently decreasing content of K and P and sometimes increasing Mg (Cain 1959a). Cain (1959a) notes that the majority of these results, and other similar reported results for other nutrients, are based on leaf analysis and the assumption that any change in leaf concentration reflects like changes in total plant content – an assumption not always justified from the data available.

Cain (1959a) experimented with the effect of N on the distribution of P, K and Mg in New York apple (*Malus* spp.) trees and found that K and P are reduced in the leaves and that Mg is increased as a result of increased nitrogen fertilizer. He studied various plant tissues (e.g. leaves, 1 yr. bark, old bark, large roots, small roots) and found that with additional nitrogen the relative changes in the distribution of minerals and dry weight in various tissues resulted in either an *increase* or *decrease* in percentage composition with an overall *increase* in total absorption.

Cain (1959a) obtained further information on nutrient distribution from an experiment demonstrating the effect of potassium on the absorption and distribution of magnesium during the growing season. Mg distribution response did vary between plants with high K and those with low K during the growing season – K deficient trees transported Mg more rapidly to the leaves and constantly depleted their roots of the nutrient. However, at the end of the growing period (225 days) the roots of both sets of trees had approximately the same quantity of Mg but the leaves of the trees grown with low K had nearly twice as much.

These data shed a little light on the antagonism picture of N, K and Mg. They show not only that these nutrient elements are unevenly distributed throughout the plant but that changes resulting in one plant part do not necessarily reflect corresponding changes in another, or the entire plant (Cain

1959a). It also suggests that fertilizing trees without knowing the nutritional status is not only costly but may well have deleterious effects.

9. NUTRIENT UPTAKE – THE ROLE OF ROOTS

Tree nutrient absorption begins in the soil where roots absorb nutrients as charged particles or ions (Funk 1990). Regardless of the type of soil or location of the absorbing root, certain aspects of the nutrient absorption process are common to all tree species, although variations in degree can occur (Voigt 1968).

Nutrient ions are transported to and into the roots in one of three ways: 1) they may be delivered in the bulk movement of the soil solution as the result of transpiration; 2) they may diffuse along a gradient of high nutrient concentration to one of a lower concentration; and 3) the root may arbitrarily grow to the nutrient source (Voigt 1968, Mader and Cook 1982, Funk 1990, Kramer and Boyer 1995).

The significance of each process varies with the nutrient under consideration but more than likely all three processes are involved in nutrient absorption by trees (Voigt 1968). Bulk flow is dependent upon the amount of soil moisture transpired by the tree and on the concentration of nutrients in solution (Voigt 1968). Diffusion takes place because absorption during periods of low transpiration lowers the concentration at the root surface and creates a gradient along which the nutrients move from the soil solution toward the roots (Kramer and Boyer 1995).

Plant roots, also, absorb and accumulate nutrient ions selectively – often against a concentration or electrical gradient (Harris 1992, Kramer and Boyer 1995). The metabolic expenditure for some nutrient uptake can be large. Kramer and Boyer (1995) cite Pate et al. (1979) who reported that roots deprived of nitrogen for 10 days respired at only 71% of the rate for roots supplied with nitrogen. They presumed this was the case because the starved roots used less energy for ion uptake.

The outermost zone of the root surface is described as a negatively charged mucilaginous layer (Brouwer 1965, Jenny 1966). This layer is easily visible on young roots of many trees, especially pines (Voigt 1968). Passive uptake includes movement of nutrients through this layer, through parts of the cell walls, as well as through a portion of the cytoplasm (Voigt 1968). In the region between the ectoplasm and the tonoplast of the cell, the active energy-requiring process of ion uptake dominates and both cations and anions are thought to be transported across the tonoplast into the cell vacuole by a complex carrier system (Voigt 1968). It is not yet known whether each specific ion has its own carrier, but it seems that this is likely – at least for nutrients absorbed in large amounts, like nitrate, phosphate and potassium (Funk 1990). It is possible that there are dual absorption systems for many ions and that ions with similar properties must compete for the same absorption sites (Funk 1990). Absorption rates of specific ions are different for different species and often within species there can be wide genetic differences in the ability to accumulate nutrients (Harris 1992, Robinson 1986).

Once inside, the cell may use the nutrient ion for its own metabolic needs or deliver the ion out into the xylem (Funk 1990, Kramer and Boyer 1995). Driven by transpiration, cells along the way may remove nutrients from the xylem flow as needed, using the same processes that roots used to absorb them (Funk 1990).

10. FERTILIZATION OF WOODY PLANTS AND TREES

A fertilizer program should be used in urban systems when there is a documented nutrient deficiency and the nutrient requirements of the tree cannot be supplied in adequate amounts by the soil or when there is occasion to believe that our objectives would be better served by the application of fertilizer. It should take into consideration environmental factors, which can make added nutrients unavailable such as the chemistry and physical characteristics of the soil and amount and intensity of precipitation (Robinson 1986).

Water Management

Urban trees probably suffer more from water-related problems than from any other cause (Harris 1992) and urban foresters would be well advised to use irrigation first in attempting to correct a tree's health problem. It is often difficult, however, to distinguish between the effects of nutrient deficiency or drought (Gilbertson et al 1987). Nutrient deficiencies limit root growth and make plants more susceptible to drought; similarly, moisture deficits will restrict nutrient uptake in soil.

Many factors exacerbate the water problem in the urban environment (Goldstein et al 1991). Water is added to the soil primarily through rainfall, but much of this essential water is lost either as runoff over impervious paved surfaces, through drainage beyond the reach of roots or as evaporation from the soil surface. We have already established that the many reflective and absorptive surfaces in the urban environment are responsible for an increase in daytime and nighttime temperatures, for drying the air and creating a "heat island" which increases the tree's water needs. If water is scarce, tree growth will be slow. Under extreme conditions, the tree may die (Goldstein et al 1987).

An experiment at the 1984 International Garden Festival, Liverpool, England, showed that after a single watering, stomatal resistances were significantly reduced by up to 50% in a group of standard alders (*Alnus spp.*).

Such dramatic responses were measurable as early as 24 hours after watering and persisted for many days, despite the severity and length of drought that the trees had been subjected to. Even more importantly measurable growth increases were evident at the end of the season (Gilbertson et al 1987).

Along with irrigation, restricting unnecessary evapotranspiration losses from the soil using weed control and mulch techniques (Gilbertson et al 1987) can increase the supply of water in the soil. Davies (1987) confirmed in experiments with oak, sycamore, alder (*Alnus* spp)and cherry (*Prunus* spp)that fertilizing can increase the vigor of weeds and cause harm to trees due to competition for water and nutrients.

Following weed control, response to added fertilizer may be small. Not only are the weeds no longer competing for soil reserves of water and nutrients, but there is a flush of released nutrients from the killed weed biomass, either or both of which may make additional fertilizer unnecessary on reasonable soils (Gilbertson et al 1987).

On industrial or derelict urban soils there may be a demonstrable need for the addition of nutrients. If this is the case, recommendations for fertilization should specify: 1) the appropriate timing of fertilization, 2) the right form and amount of fertilizer, and 3) the appropriate method or methods of application (Himelick et al 1965).

Timing of Fertilizer Application

To make the best use of fertilizers an arborist must know when trees benefit most from their application (Svihra 1987). The timing of nutrient application is determined and affected by many factors including: climate, rainfall, soil type, and plant species and their associated physiological and developmental states (Neff et al. 1955). Most of the current literature recommends application of nutrients in either the spring or fall (Mader and Cook 1982, Pirone et al. 1988, Harris 1992).

For northern climates, an April or May application may make the most efficient use of nitrogen supplied according to a review of the literature done by Hamilton et al (1981), with October and November being suggested as second best. Leaching could be a potential hazard with mid-fall applications of fertilizers in colder northern or northeast U.S. soils where heavy precipitation coincides with slow or ceased root activity. In southern or west coast climates where the temperatures are mild the year round, application should be made before the growing season starts (Hamilton et al 1981). As long as soil temperatures are above 40-45 F, roots can absorb nutrients (Hamilton et al 1981). An added advantage is that in spring and mid-fall, soil moisture conditions also favor plant nutrient uptake.

Early research on fertilization of shade trees was conducted for 2 years on American elm (*Ulmus americana* L.*)* and Norway maple (*Acer platanoides* L.) by Jacobs (1929) in Kent, Ohio. Comparing the fall and spring treatments of 5.75-8-3 fertilizer (see discussion of Complete Fertilizers) to established street trees he found that timing made little difference and trees derived a decided benefit from either treatment. Schrader and Auchter (1925) fertilized apple trees with sodium nitrate and ammonium sulfate in both fall and spring. They found that foliage was greener for spring applications than for fall applications. Growth, however, measured as trunk increment and terminal shoot elongation was not significantly different between treatments.

Over a 5-year period, Neely et al (1970) compared data on the effect of fertilizing urban Illinois pin oaks during different seasons of the year. A one-block area was treated with surface application of four nitrogen fertilizers. They found the greatest growth stimulation was obtained by applying all of the nitrogen in April. Trees receiving a portion or all of the nitrogen in June or October grew less than trees receiving all of the spring (April) nitrogen. Trees fertilized in October grew more than untreated trees.

Smith (1978) favors autumn fertilization in the October to December period over very early spring, his next choice. Because nitrogen cannot be used directly as nitrate or ammonium ions by the plant, there is a lag time between the fertilizer application and the plant's growth response to that application (Kuhns 1987). Kuhns (1987) believes, therefore, that fall applications of nitrogen provide a greater increase in spring growth than spring applications if the potential for leaching does not exist. Nutrients applied in the spring are either used in later season growth or stored for the following year.

Shigo (1989) recommends timing nitrogen application (especially in stressed trees) to coincide with one or more of five phenological periods (such as wood formation or shoot growth). However, as Harris (1992) points out our current level of knowledge regarding species, soils, fertilizers, weather and their interactions is not sufficient for us to accurately time nitrogen applications for specific phenological periods.

Numerous studies involving many species of trees show that the carbon and nutrient resources that support the initial phases of early shoot growth (first four to six weeks) are derived from nutrient reserves accumulated in late summer/autumn of the previous year and stored in the roots, trunk and branches (Kozlowski 1971, Weinbaum 1988, Harris 1992). These reserves are almost entirely responsible for early spring flush even though soil nutrients are abundant. The availability of nutrients from tissue storage, which can sometimes be as high as 70 to 90 percent of the nutrients present in current shoots, represents a nutrient buffer until soil conditions favor nutrient absorption by roots

(Tukey and Meyer 1965, Weinbaum 1988, Harris 1992). Tukey and Meyer (1965) contend that fall nutrient applications offer advantages over spring applications, most important of which is the critical timing necessary for spring applications. They maintain that soils in spring are often wet and cold and the areas around plant roots may not warm above 40 degrees until the flush of growth of the tops is well under way. In such cases, nutrients may not be absorbed until too late for that season's growth.

Most authorities are in agreement that later summer applications of fertilizers in temperate climates should be avoided because of possible stimulation of new growth that may not harden off before frost occurs (Holmes and Mosher 1975, Williams 1981, Pirone et al. 1988). Such late growth would be very susceptible to damage by cold weather. Pirone et al. (1988) state that fertilizing lawns even at some distance from trees could cause trees to produce late season growth.

Nutrient Application Methods

The primary methods of applying nutrients that are commercially practiced today include: surface broadcasting, deep-root feeding (also called punch bar system, auger holes or soil drill holes), liquid soil injection, foliar spraying and injection or placement of nutrients in holes (implants) in tree trunks (Hamilton et al. 1981, Mader and Cook 1982, Harris 1992). Other methods used, more appropriate for orchards and plantations, include soil incorporation by rototilling or discing and addition to irrigation water (Mader and Cook 1982).

Each application method serves a specific role depending on the site and plant condition. The appropriate method will depend on the types of fertilizer used, the specific objective of fertilizing, costs, the equipment available, other plants in the vicinity, nature and slope of the soil surface, and, in certain cases the species to be treated (Hamilton et al. 1981, Harris 1992, Smith 1978).

Surface Application of Nutrients

The broadcast application of fertilizer to the soil surface was one of the first methods employed and is the easiest and least expensive method of applying N, most micronutrients, and, where roots are shallow. (Chadwick 1941, Mader and Cook 1982, Harris 1992, Lilly 1993). It requires the least amount of time and does not require sophisticated equipment (Lilly 1993).

The fertilizer is broadcast over the soil surface using a spreader that is calibrated to apply the desired amount of N per 1000 sq. ft. Suggested rates of application for homeowners range from 1 to 3 lbs. of actual N/1000 sq. ft (Ferrandiz 1990, Good 1985, Lilly 1993). It is generally recommended that an area that extends from the trunk to the dripline and a third of that distance beyond the dripline be covered (Good 1985, Ferrandiz 1990, Lilly 1993).

Ferrandiz (1990) finds that use of surface applications are most appropriate in trees and shrubs in open beds, and where water penetration is not limited by compaction or excessive slopes. On compacted soils, and, when possible he recommends raking the area or using other scarifying methods to loosen the soil.

There are some objections to the surface method of applying nutrients. On lawns, some professionals believe that turfgrass will significantly compete for available N and turf in fertilized areas will be much greener than in surrounding areas (Hamilton et al. 1981, Lilly 1993).

Turf competition can influence nitrogen availability and tree growth (Messenger 1976, Khatamian et al 1984, Neely 1984). When turf limits only the nutrient availability – without affecting water availability – applied nitrogen will increase tree growth (Smith 1978, van de Werken 1981, Khatamian et al 1984). However, excess nitrogen applied to trees can slow growth and create stress (Khatamian et al 1984). Although relatively little is known about the nutritional needs of urban trees, their requirements are generally less than those of turfgrass species (Feucht and Butler 1988). Thus, fertilizer regimes designed for turf may impact tree health.

Burning of grass or injury to roots from excessive surface fertilizer application is, also, often cited as a disadvantage of this method of application

(Chadwick 1941, Mader and Cook 1982, Lilly 1993). Fertilizer burn results when excessive soluble fertilizer in the root zone increases the salt concentration, and hence, the osmotic pressure of the soil solution. This can prevent water from entering the root cell and may even cause water to move out of the cell. When this occurs the root cell dies and may trigger the death of the entire plant (Knoop 1976, Lilly 1993). Fertilizer burn is most problematic when soil moisture is limited; often at the driest part of the summer months.

There is not extensive literature written on the effects of fertilizer burn to grass and roots but early research by Wyman (1936) showed that as high as 50 lbs. of ammonium sulfate to 1000 sq. ft could be applied to the lawn without injury to the grass if the applications were made before growth started in spring and there was sufficient soil moisture. Up to 15 or 20 pounds per 1000 sq. feet were applied without injury after growth started. These tests were conducted on silty clay loam soils. Such applications to other soils might react differently. Adding excessive amounts of fertilizer acidifies soils and consequently could cause immobilization or toxicity of other essential nutrients as well as inhibit soil microbial activity – not to mention the increased potential for excessive pollution from leaching and runoff.

Ferrandiz (1990), Lilly (1993), Mader and Cook (1982), and others recommend generous watering to dissolve the soluble salts, dilute them, and wash them down into the soil to avoid fertilizer burning of grass and injury to tree roots. Applying the fertilizer in smaller quantities, dividing it into two or more applications at different times, and spreading the fertilizer uniformly may also reduce the hazard of injury from salt concentrations (Mader and Cook 1982) but is much more costly.

There is controversy over the surface application of K and P (See Section – Phosphorus and Potassium Fertilizers). Chadwick (1941) stated that P fertilizers applied to the surface and not worked into the soil seldom reach the feeding roots of deep rooted plants where they can be utilized. Soil scientists, according to Good (1985) have shown that K has limited mobility in the soil. P, he states, has even less, and is usually rendered unavailable near the point of application thus limiting movement in soil. The degree to which P is unavailable depends largely on the pH and soil chemical characteristics. Harris (1992) disagrees with these conclusions citing Perry (1982) and the work of van de Werken (1984) with phosphorus and that of White (1956) with potassium. Perry (1992) believes that the reportedly immobile phosphates are immediately available to tree roots for uptake. That is the reason, he states, that Himelick et al. (1965) and van de Werken (1981) were unable to show differences in the response of trees to fertilizer placed in holes or broadcast on the surface.

On a P-deficient soil in Tennessee, van de Werken (1981, 1984) compared two N and two complete (N-P-K) fertilizers on six shade tree species Norway maple*, Ulmus carpinifolia,* pin oak*,* Gingko *(Gingko biloba L.) ,* honeylocust (*Gleditsia triacanthos* L.)and little-leaf linden (*Tilia cordata* Mill.). Fertilizers were applied either on the surface or in 18-inch holes. At the end of the eight year period, the slow-release 14-14-14 fertilizer, applied broadcast, gave a higher growth index (the trees were 56 percent larger) for 5 out 6 cultivars tested than 14-14-14 fertilizer applied in holes.

In potassium deficient soil, White (1956) reported improved growth of approximately 100 acres of coniferous plantation Red pine (*Pinus resinosa* Ait.), Norway spruce (*Picea abies* (L.) Karst.), and Western spruce (*Picea glauca* var. *albertiana*) in upstate New York when an aerially broadcast formulation of granular potassium was applied. There was improved tree growth and the percent of exchangeable potassium in the soil increased from 48 to 104 percent in the various plots.

Surface application vs. other application methods

There is evidence that no significant benefits are derived from nutrient application techniques other than simple broadcast surface techniques (Himelick et al. 1965, van de Werken 1981).

Chadwick et al. (1950) undertook an investigation to study the methods of applying fertilizer to small shade trees in Ohio starting in 1941 and terminating in 1948. Four hundred thirty Norway maples averaging approximately 1.5 inches DBH (diameter at breast height, 4.5 feet from ground)at the start of the experiment were included in the study. The soil type was a silt loam derived from sandstone and shale, well aerated with good natural drainage. A 10-6-4 fertilizer was applied by the Aerofertil, Fertigator, crowbar, drilled-hole and broadcast surface methods. Surface application of the complete fertilizer resulted in a greater caliper increase than any of the other methods employed.

Good (1985) reports that shade tree trials in New York show that surface placement of N-P-K fertilizers produced as much growth or more than, subsurface applications to trees 4 inches DBH at rates ranging from 1 – 2 lbs. of actual N/1000 sq. ft.

Fertilization experiments were carried out in 1963, 1964 and 1965 on pin oak, white ash (*Fraxinus americana* L.) and honey locust established for 7 years in Illinois by Himelick et al. (1965) and Neely et al. (1970) on 10 different soil types – ranging from sandy to heavy clay soils. Various fertilizer formulations and four methods of application were used: surface broadcasting, placement of dry fertilizers in holes, injection of liquid fertilizers into the soil, and foliar spraying. Statistically the results from foliar treatments were not significantly better than the results from no treatment. All three methods of applying fertilizer to the soil stimulated tree growth. The three methods of soil application appeared to be equally effective, with minor variations among the tree species. Himelick et al. (1965) stated that surface application produced the greatest amount of total growth on trees of the three species considered together. Neely et al. (1970) maintain that they were equally effective. However, the latter researchers do point out that there is a great difference in the economic aspects of application by these three methods.

Solution injection is slow and expensive requiring soluble fertilizers and a hydraulic system. Dry fertilizer placement in holes is expensive and time consuming because it requires extensive manpower. Broadcasting on the surface remains the fastest and relatively most economical method of application (Neely et al. 1970).

Drill Hole or Auger Method

Placement of fertilizers in auger or drill holes is a common practice by commercial arborists. It is more costly than surface broadcasting but may be the preferred application method under certain conditions.

According to Mader and Cook (1982) one of the main benefits is encouragement of deeper rooting by improving subsoil fertility. Where lateral-rooting space is limited, or soils cause superficial rooting, these procedures may be therapeutic. Harris (1992) believes these methods are useful only in soil where tree roots are not near the surface, such as in bare or cultivated soil. It is under these circumstances that P, K and other nutrients of low solubility usually need to be incorporated into the soil, closer to the root zone where they will be more readily available.

The drill hole method of fertilization also places fertilizer below turfgrass roots, avoiding fertilizer burn (given there is ample soil moisture) and providing less competition with turf roots for nutrients (Mader and Cook 1982, Ferrandiz 1990, Lilly 1993). The soil is aerated and water penetration increased by this method, as well (Ferrandiz 1990, Harris 1992, Lilly 1993). It is especially beneficial for opening up heavily compacted soils (Smith 1978). Smith and Reisch (1975) experimenting in poorly drained silt and clay-loam soils in Ohio, found that young maple (*Acer spp.*), little-leaf linden and apple trees produced 20 percent more caliper growth when holes were drilled 1 foot deep and no fertilizer added as they did when 6 lbs. each of N, P and K per 1000 sq. ft were applied in holes or on the surface. These results are significant and one might conclude that in many soils, including compacted derelict urban soils, tree health and growth could be improved simply by modifying the soil structure, thereby improving soil aeration and water movement.

One and one half inch to 2 inch diameter holes can be cored or punched with a bar or electrically drilled by hand into the soil (Holmes and Mosher 1975, Koelling and Kielbaso 1975, Hamilton et al. 1981, Mader and Cook 1982, Pirone et al 1988, Harris 1992, Lilly 1993). Some researchers recommend drilling over punching to reduce compaction and glazing around the holes (Lilly 1993). Harris (1992) advocates the soil water be below field capacity before holes are made to prevent compaction. Recommendations for the depth of the holes range from 6 - 8 inches (Harris 1992) to 12 inches (Pirone et al. 1988, Lilly 1993); not to exceed 15 to 18 inches (Koelling and Kielbaso 1975, Hamilton et al. 1981, Williams 1981).

Although I found no empirical experimentation in the literature to support these numbers it is commonly recommended that approximately 250 - 275 holes per 1000 sq. ft be placed 2 to 3 feet apart around the tree in concentric circles or in a grid pattern in drill hole fertilization (Hamilton et al. 1981, Williams 1981, Pirone et al. 1988, Harris 1992, Lilly 1993). It is suggested that holes extend anywhere from 1 foot to one-fourth the radius beyond the dripline of the tree (Harris 1992, Holmes and Mosher 1975, Lilly 1993).

Holes should be placed at adequate distances from the trunk to avoid damaging the root collar with high concentrations of fertilizer and severing main transport roots (Mader and Cook 1982, Pirone et al. 1988). Hamilton (1981) and

Pirone et al. (1988) suggest holes not be drilled within 2 feet of the trunk of trees with a twelve inch diameter or within 3 feet of trees with an 18 inch diameter.

Mixing of fertilizers with soil amendments such as peat moss, humus, topsoil, sand, perlite or small crushed stone is often recommended to reduce the possibility of burning (Mader and Cook 1982, Lilly 1993). Use of less soluble or slowly available materials may be preferable for this reason, as well (Mader and Cook 1982).

It is my observation that the placement of holes in the drill hole method is based on tradition rather than science. The absorptive roots for most trees lie mainly in the outer two-thirds of the circular area of the tree (Pirone et al 1988) yet in none of the literature pertaining to fertilization methods is it recommended to beginning drilling holes in this region.

Liquid Injections

Liquid formulations (fertilizers suspended in water) or any soluble dry fertilizer may be injected into the soil with water using a lance and hydraulic sprayer (Lilly 1993, Pirone et al. 1988). The advantages to this method are the better distribution and rapid uptake of fertilizer and when available water is the factor limiting fertilizer absorption by roots liquid injection reduces this problem (Smith 1978, Lilly 1993). Smith (1978) recommends this method when deficiencies are readily apparent provided that the soil physical characteristics allow for adequate nutrient movement in solution.

The same hole distribution as with the drill hole method is suggested; 8 to 18 inches at 2 to 3 feet apart (Pirone 1988, Lilly 1993) although Harris (1992) does say that injections can be spaced somewhat farther apart than can holes for dry fertilizers because the fertilizer is in solution. Approximately 200 gallons of water is recommended per 1000 sq. ft and the liquid formulation should be forced into the soil under moderately high pressure of 150 to 200 pounds per sq. inch (Hamilton et al. 1981, Pirone 1988, Ferrandiz 1990, Harris 1992, Lilly 1993).

In an attempt to address the controversy over which method of fertilization is most effective in trees with limited rooting space, Smiley et al. (1998) experimented on willow oaks (*Quercus phellos* L.) in parking lots of South Carolina exhibiting general chlorosis symptoms. Foliar nutrient levels were lower than optimum and the trees were considered to be macronutrient deficient. Two application methods of complete fertilizers were compared: trunk injection and liquid injection below the soil surface. In their study, soil injection of the slow-release fertilizer increased the foliar nitrogen level and improved color more than two applications of trunk injected macronutrients.

There are several disadvantages to the soil injection method that require consideration. Fertilizers must be soluble to be used in this method. Water-soluble fertilizers containing P, K and other nutrients are usually more expensive than the less soluble compounds making this method rather costly (Harris 1992, Pirone et al.1988). The procedure is also time consuming (therefore, more costly) and fertilizer solutions are notoriously corrosive to equipment (Pirone et al. 1988, Ferrandiz 1990, Harris 1992). The effects of liquid injection may be less persistent than that of dry fertilizer and if the soil will not absorb the large amounts of water the possibility of runoff and leaching exist (Ferrandiz 1990, Swanson and Rosen 1990).

Pirone et al. (1988) comment that for optimum growth the injection methods have generally not been shown to be superior to surface broadcast of nitrogen fertilizer but, Smith and Reich (1975) demonstrated earlier, they can provide improvement of aeration and water penetration in compacted soil.

Foliar Sprays

Although foliar sprays can be used for macronutrients (N, P, K, Mg, Ca), which are subject to immobilization and leaching, they are best used as a rapid way to overcome deficiency symptoms involving micronutrients like iron, zinc, manganese, copper and boron (Williams 1981, Mader and Cook 1982, Robinson 1986, Ferrandiz 1990, Harris 1992).

Micronutrients are required in extremely small amounts and can usually be absorbed quickly through the leaves, so deficiencies can usually be quickly and safely corrected by foliar sprays (Mader and Cook 1982, Ferrandiz 1990). Foliar application is particularly effective in treating iron chlorosis (Ferrandiz 1990, Smith et al. 1992). Small-scale spray applications of a single micronutrient may quickly determine a plant's response, which can be a very useful diagnostic tool to plan a longer corrective treatment program (Harris 1992). In some commercial practices foliar spray material is also used to help get young and recently transplanted trees established in the landscape (Smith et al. 1992).

Lilly (1993) remarks that micronutrient spray applications are most effective when made just before a period of active growth; but that not all plants respond to foliar treatments. Sprayed materials may penetrate young leaves more readily than older leaves and the chelated forms of micronutrients are generally absorbed well. Temperature and spray concentration can also affect the tree's ability to take in the sprayed materials; high temperatures and low humidity reduce absorption (Ferrandiz 1990).

A way to allay the expense of foliar sprays is to include pesticides in the formulation (Harris 1992). Although this is being incorporated in many horticultural crop spray programs, it is not being done routinely on landscape plants. Large trees and shrubs are often difficult to spray and the danger of involving non-targeted plants, people and property exists (Harris 1992).

Implants and Trunk Injections

Implants (such as capsules) and injections (micro- or macro-injections) are two techniques, which introduce chemicals directly into the xylem – relying on the transpirational stream to move materials systemically through the tree (Lilly 1993). Like foliar sprays, these methods are most often used for the correction of micronutrient deficiencies. They have also been used to treat certain pest problems (Lilly 1993).

Trunk injections were used commercially to treat over 250,000 pear trees (*Pyrus* spp.) in California for pear decline in the 1970s (Reil 1979). Neely (1976) and Williams (1981) observe that injection and implantation have consistently provided the most thorough and prompt correction of iron chlorosis.

Some authorities are hesitant to recommend this method because it has the potential to provide easy access for fungi diseases and rot, and Harris (1992) believes these fertilization methods should only be used when other methods are too difficult or have failed. Numerous holes must be routinely drilled (every 3 to 4 years) into the bark which can lead to: excessive sap leakage, toxicity to the cambium and xylem where salts are inserted and toxicity to foliage when too much nutrient is applied at the incorrect time to sensitive plants (Harris 1992, Lilly 1993). Neely (1976), however, in his experimental work with chlorotic pin oaks did not observe these injuries regardless of the amount of nutrient (iron) implanted or the time of treatment.

Shigo et al. (1977) in a West Virginia study of 40 year old red maples, white oaks and shagbark hickories (*Carya ovata* Mill.) sought to determine the amount of discolored wood and extent of cambial dieback associated with injection wounds. In all the control wounds they found negligible amounts of discolored wood and cambial dieback indicating that the wound made by the injection tube is not serious. Similar holes that were injected with nutrients were more seriously affected. Cambial dieback above and below the holes ranged from .75 inch when injected with Mg to 2 to 2.3 inches when injected with other nutrients. The holes injected with Bidrin (a pesticide) fared much worse and dead cambium extended 14 inches above and below the wounds. Two years after injection the dead cambium extended only 4.3 inches. Harris (1992) citing this study speculates that although the wounds apparently heal rapidly there is always a possibility of decay, especially in stressed trees.

Rates of Application

Discussion of fertilizer application rates and later discussion of types of fertilizers will focus on the fertilizer element nitrogen. Of all the nutrients N has the greatest effect on plant growth, is almost always deficient, is required in the largest quantity by the plant, and generally is the most difficult nutrient element to manage (Epstein 1972, Kramer and Kozlowski 1979, Whitcomb 1987, Pirone et al. 1988, Harris 1992, Lilly 1993). In fact, it is often the only nutritional element that accelerates growth in young shade trees (Neely et al. 1979,van de Werken 1984). Nitrogen deficiency and management are major issues in disturbed urban soils under stressful urban micro-climatic conditions.

Recommendations and rates of application for all nutrients except N must be based on a soil test or analysis of the foliage (Kuhns 1987). The application rate of N depends on several factors including species, stage of development of the plant, location and formulation (Kuhns 1987). Environmental factors which make N and any other added nutrient, for that matter, unavailable or encourage volatilization and leaching losses should also be considered (Robinson 1986). Precipitation amounts and distribution, natural fertility, chemistry and physical structure of the soil should all be given careful attention, as well (Mader and Cook 1982, Robinson 1986). Whitcomb (1987) states that rate of N application is more influenced by the porosity of the soil and leaching of the N below the root zone than by any other factors. Heavy clay or silt soils may require limited N, whereas sandy soils require more frequent application and, in extremely sandy soils slow-release N sources are most beneficial (Whitcomb 1987). Rates of actual N are usually expressed in lbs. per acre or in lbs. per 1000 sq. ft.

Calculating Dosages

Several methods of calculating fertilizer dosages have existed over the past 60 years. In some of the earliest published work done on fertilizing shade trees, Beilman (1936) based the amount of fertilizer on the following calculation (although I found no data that this calculation was based on actual tree response) : to the height (in feet) of the tree add the branch spread (in feet), and to this add the trunk circumference (in inches). The result was the number of pounds of 10-8-6 fertilizer required for that tree. Using Beilman's method, an 80-ft high tree, with a branch spread of 60 ft and a circumference of 125 inches would require 265 lbs. of fertilizer. He did add the caveat, however, that this amount could be reduced for some types of trees; the street or lawn tree having a higher crown may need only two-thirds of this amount. Deuber (1939) also used this calculation method to test effects of different fertilization rates on young and mature shade trees – halving and quartering rates on some tests to determine effects.

Chadwick (1941) reported that applications of fertilizers made to shrubs and evergreens are usually based on the sq. ft area of the planting bed while recommendations for applications of fertilizers to shade trees are most often based on the caliper of the tree. From his experience gained experimenting on shade trees he recommended that for trees below 6 inches in diameter, application of 1/4 lbs. of available N, and for trees over 6 inches in diameter, application of 1/2 lbs. of available N per each inch in trunk diameter was sufficient. In other words, if the tree to be fertilized was 10 inches in diameter, the requirement would be 5 lbs. of available nitrogen. He also noted that a tree which has its roots restricted by curbs, sidewalks, or buildings cannot be fertilized as heavily as a tree growing under lawn conditions with an unrestricted root system.

Some authorities and arborists relate the amount of fertilizer to be applied to trunk diameter – usually 2 lbs. of complete fertilizer for every inch of trunk diameter (Agricultural Research Service 1973, Agricultural Research Service 1977, Holmes and Mosher 1975, Smith et al. 1992). However, fertilizer rates based on root zone are considered a better practice than rates based on trunk diameter and application rates based on the latter practice are becoming obsolete (Wikle 1963, Himelick et al. 1965, Williams 1981, van de Werken 1984, Whitcomb 1987, Doughty 1988). Van de Werken (1984) states that there is no functional relationship between root spread and trunk diameter and points out that by using the trunk diameter method application rates actually drop as larger trees are fertilized. For example, a tree with a 2-inch trunk would receive 4lbs. of fertilizer; a six inch tree would get 12lbs. But even if the size of the root system was related to the trunk diameter, this method would reduce the rate of fertilization. While the diameter of the root system would be tripled the area of the root zone would increase 9 times; so in fact, the area would need 9 times more fertilizer, or 36 lbs. instead of 12.

Application rates of fertilizer based on area of root zone appear most appropriate in light of research done on fibrous root networks of shade trees showing that roots extend far beyond the tree's crown or dripline (Stout 1956, Watson and Himelick 1982). Perry (1982) citing work by Stout (1956) and Lyford and Wilson (1964) reports that it is not uncommon to find trees with roots systems having an area with a diameter one, two or more times the height of the tree.

As stated earlier, the area to be fertilized is governed by the location of the absorptive roots which for most trees lie mainly in the outer two-thirds of the circular area around the tree. Trees growing in sandy well-drained soils have more extensive roots systems than those in finer texture soils and root extension also varies greatly among species (Pirone et al 1988). Roots of narrow or columnar trees extend well beyond twice the crown radius. The root area of sugar maples can be 1.75 times larger than the crown area and root area of tulip poplar 2.5 times larger, whereas for pin oak area is about the same as crown area (Pirone et al. 1988).

Van de Werken (1984) created a tree fertilization calculation that he called the Universal Tree Fertilization Computation. It is a calculation to determine how much fertilizer (usually complete) to broadcast to achieve the recommended amount of nitrogen per acre. To apply the calculation it is first necessary to determine the size of the root zone – which as discussed earlier is a function of species, planting site and soil type. Once this area is established, the radius of the root zone (from trunk of tree to periphery of extended roots) is measured in feet. Step 1: square this measurement and multiply the result by the recommended number of pounds of nitrogen per acre. Step 2: multiply the percentage of nitrogen in the fertilizer being used by 140 (a constant in the van de Werken method). Divide the number obtained in step 1 by the number obtained in step 2. The result is the number of pounds of fertilizer needed to cover the entire root zone (Appendix 1). Again, the literature provided no empirical research of tree response to substantiate this method of calculation.

There are other similar methods to calculate application rates of complete fertilizers that use the square footage of the circular or rectangular area under the tree's canopy (Doughty 1988, Smith et al. 1992, Williams 1981). Examples of these calculations can also be found in Appendix 1.

Fertilizer rates and dosages, for the most part, appear to be based less on empirical evidence and experimentation than on anecdotal impression and general "common sense". None of these calculation methods addresses itself to the urban environment where the roots of the tree are frequently overlooked and disrupted. The small volumes of compacted soil that the roots have access to are either poorly drained, or more likely, cannot hold enough water to meet demand, and the trees experience periodic to prolonged drought. In other words, lack of soil volume accounts for most urban tree survival problems (Goldstein et al 1991) and fertilization could be more injurious than beneficial under these conditions.

Urban (1989) conducted an exhaustive comparative case study of more than 1300 mature trees from landscape projects in intensely developed urban settings (no soil type data was provided). The “average” tree in the study had been in place for 17 years (range: 10-27 years), was planted initially into 149 cubic feet of soil (range: 40-600) and had grown less the ¼” in diameter at breast height (DBH) per year (range: .03-.51”). The average tree was typically in fair to poor condition although, on one project, all original trees were rated excellent; on another, all had died and had been replaced at least once. Trees planted in 200 cu. ft. or more of soil were in better condition than nearly all their counterparts in smaller volumes. Below this soil volume, tree vigor and condition generally decreased with decreasing amounts of soil.

Goldstein et al (1991) cite work done by Bassuk and Lindsey at Cornell University where information on total tree canopy size (the primary determinant of water use),crown density and pan evaporation (NOAA data) were coupled with determinations of soil water-holding capacity and precipitation data to specify minimally adequate soil volumes. As an example, Bassuk and Lindsey calculated that a tree with a 20-foot-canopy diameter and an average canopy density would use approximately 30 gallons of water a day in Ithaca, New York. Using this methodology, they calculated that a total of more than 300 cu. ft. of soil with good water-holding capacity would be needed to support this tree. Growing large, mature trees would require significantly greater volumes of soil – up to 1000 cu. ft. (Goldstein et al 1991).

Given the constraints imposed on tree roots in many urban environments it might be wise to develop a method of calculating fertilizer dosages based on the relationship between rooting volume and soil volume - as this would also incorporate information on water usage and availability – crucial to any type of fertilization. Calculating fertilizer application in this way could also better minimize risk of root injury, leaching and would invariably be more cost effective.

Recommended Amounts of N Fertilizer

Research at the University of Tennessee, Knoxville, has shown 150 lbs. actual N per acre (3.4 lbs. N/1000 sq. ft) greatly accelerates the growth of established young shade trees (van de Werken 1984). Wright and Hale (1983) experimenting on the influence of N rates on growth of red maple, pin oak and flowering dogwood at Virginia Polytechnic Institute and State University, demonstrated that a rate of 300 lbs. N per acre (6.8 lbs. N/1000 sq. ft) was wasteful after the third year because it did not significantly increase growth beyond that obtained with 150 lbs. per acre (3.4 lbs. N/1000 sq. ft)

In general, for most soils, recommendations range from 2 – 6 lbs. of N per 1000 sq. ft (about 90 to 260 lbs. per acre) per year (Kuhns 1987, Smith 1978, Williams 1981). Pirone et al. (1988) advocate applying rates of 2 – 4 lbs. of N/1000 sq. ft. Hamilton et al (1981) concur and recommend these yearly amounts be divided into two or more applications during the growing season. 3 – 6 lbs. of N/1000 sq. ft ; 3 to 4 lbs. of P and 6 lbs. of K per 1000 sq. ft are recommended by Williams (1981) for woody plant growth. For established landscape trees, Doughty (1988) considers 1 – 2 lbs. of actual N/1000 sq. ft adequate.

For infertile soils or subsoil materials exposed at the surface Mader and Cook (1982) advise incorporation of a multi-nutrient (N-P-K) fertilizer such as 10-6-4 at a rate of 25 – 50 lbs/1000 sq. ft (2.5 – 5 lbs. N/1000 sq. ft). Neely and Himelick (1966) state that the need and frequency of application of P and K should be determined by chemical tests. If needed, these nutrients may be added at intervals of 3 – 5 years at the following rates: P at 2.5 - 3.6 lbs/1000 sq. ft and K at 5 - 6 lbs/1000 sq. ft (Mader and Cook, 1982, Neely and Himelick 1966). K remains readily available and cycles from tree to soil for many years, so unless leached away or removed in leaves one application will last for several years (Leaf 1968).

When turf is present, Hamilton et al. (1981) and Doughty (1988) advise applying a concentration of no more than 2 lbs. total N per 1000 sq. ft. The total yearly amount of fertilizer should be calculated to include the amount that is applied for the turf grass. If the lawn is already being fertilized, it is unlikely that the tree will need much more fertilizer (Pirone et al. 1988) or any at all. Koelling and Kielbaso (1978) recommend fertilizing trees surrounded by turf using the drill hole method to avoid harming the grass. They recommend 6 lbs. N/1000 ft applied in 3 applications at 2 week intervals for trees (with grass growing beneath) less than 25 ft high; and 6lbs N/1000 sq. ft in one application for trees greater than 25 feet high. They discourage fertilization of ornamental flowering trees and other small fruit trees unless a definite needs exists. They maintain that heavy applications of N may tend to reduce flowering.

Again, further research needs to be undertaken specifically on urban trees which often grow in limited spaces under unique and adverse conditions. Fertilizer amount recommendations, for the most part, are made based on trees growing in adequate spaces in relatively undisturbed soils. In addition, many of the recommendations are not derived from experimental data. And lastly, recommendations are often made assuming that increased growth is a desirable attribute – when in fact it may not be the objective we are seeking for our large, mature urban shade trees.

Fertilizing at Planting and Transplanting

Tree care authorities differ greatly in their recommendations on fertilizing newly planted trees. According to Whitcomb (1987), much of what has been written about the detrimental effects of adding fertilizers in the planting holes probably was based on experiments in the 1920s and '30s when the principal form of N fertilizer available was sodium nitrate. Sodium nitrate, which is almost never used today, has one of the highest salt indexes of any fertilizer material. The higher the salt index, the greater the likelihood that the plant will experience water stress or fertilizer burn. Despite other sources of N, placement of fertilizers in planting holes is still not recommended by some professionals (Holmes and Mosher 1975). Baule and Fricker (1970) recommend fertilizers with a low salt index for placement in planting holes. They advise placing the fertilizers at some distance from the roots, which is facilitated by a large planting hole. Shoup et al. (1981) evaluated the effects of fertilizing at time of planting of barerooted deciduous species – pin oak, redbud (*Cercis canadensis* L.), Bradford pear (*Pyrus* calleryana 'Bradford'), green ash (*Fraxinus pennsylvanica* Marsh.) and Kwanzan cherry (*Prunus serrulata* 'Kwanzan'). Fertilizing with 4 lbs. of N/1000 sq. ft of a 10-20-10 complete fertilizer they did not detect any detrimental effect which they believe significant is in light of the widespread recommendation that no fertilizer be added at planting time. They concluded that in good soils, as those used in their study, adding fertilizer at planting time has little beneficial or detrimental impact. In a study of 288 newly planted trees in a sandy loam soil Whitcomb (1987) found that fertilizing at planting time had no effect on tree growth the first growing season and was only detectable as darker foliage the second season. He, too, concluded that the lack of response to fertilization was due in this instance to the naturally high fertility of the field soil.

Newly planted trees in sandy soil where rainfall is high and leaching is a problem may benefit from additions of N before establishment. Slow-release formulations added to the planting hole and then covered with several inches of soil will provide a continuous supply of nutrients for up to 18 months (Pirone et al. 1988).

Hamilton et al. (1981) recommend fertilizing at planting to supply P in certain Indiana soils, however, in a shade tree experiment conducted by van de Werken and Warmbrod (1969) in Tennessee, P was shown to have little effect on newly planted trees even after four years. In fact, in that same experiment, fertilization with N had little effect on the rate of growth of the trees until the third year. Wyman (1936) reported similar results in a 4-year test on nursery sized pin oaks. His fertilizer treatments began the first growing season following planting. He reported limited tree growth until the third growing season.

A newly planted tree in a typically poor urban soil is at considerable risk. While the soil can be improved to some extent by fertilization, part of the problem remains due to the restricted root system. There are other management practices that can be employed to improve the situation for the tree.

Gilbertson et al (1987) recommend planting early in the dormant season. In an experiment carried out over winter 1983 – 1984 in England they showed that trees (species not stated) planted in late November had up to twice as much root by full leafing out compared with those planted in late March. The actual amount of root growth was dependent on soil temperatures.

Reduction of canopy through pruning may be another way to assist a newly planted tree. It has been suggested that shoot pruning, by restricting carbohydrates and growth regulator flow down the stem, can actually restrict the ability of the tree to produce roots (Fayle 1968). But in preliminary results of experiments done with plane tree, birch, sycamore and ash Gilbertson et al (1987) found that shoot pruning not only increases overall shoot extension, but there was a depression in water deficits. There was also a parallel increase in individual leaf areas, and an improvement in aesthetic value in regrowth after the first season.

Fertilization of transplanted trees is also disputed. Much of the controversy focuses on the concept of top (or shoot): root ratio. Experiments carried out by Brouwer (1962) and others (Ingestad 1960, 1979) demonstrated that increasing nutrient supply tended to increase the top growth relative to root growth, increasing the top:root ratio. It means that the shoot:root system has a much larger top to support in terms of water and nutrients (which may increase stress on the tree during periods of low precipitation) and a root system that may be disproportionately small to provide adequate anchorage for tree. (Warren 1993b).

Only a small percentage of the original root system is moved with a transplanted tree (Watson 1986). Watson and Himelick (1982) state that up to 98 percent of a root system can be lost in certain types of transplanting. procedures. Therefore, rapid root regeneration and adequate soil moisture are the most important factors for the successful establishment of transplanted trees. Warren (1993a) grew flowering dogwood seedlings with 3 levels of N after removal of 0, 25, 50 or 75 percent of the root system (by weight). He discovered that leaf area and top dry weight increased with increasing N but that root dry weight and relative growth rate decreased with increasing N. As results from this study imply that heightened N levels decrease root growth following root pruning, Warren (1993a) recommends minimal N application during the first season after transplanting.

Similarly, Yeager and Wright (1981) found that higher N rates applied to *Ilex crenata* 'Helleri' holly grown in the greenhouse increased shoot growth but decreased root growth resulting in a greater shoot:root ratio. Holly grown at 50 ppm N lowered the shoot:root ratio due to stimulation of root growth while 300 ppm N caused the shoot:root ratio to increase due to increased shoot growth.

Brouwer (1962) proposed that in the absence of other growth limiting factors, shoot growth continues at a rate that depends on the minerals and moisture supplied *over and above* the roots requirement. Root growth, he surmised continues at a rate dependent on the carbohydrate supplied by the shoot. Considering this theory, Yeager and Wright (1981) concluded that at 50 ppm N the nutrients being supplied to the holly were preferentially utilized by the roots with less available for shoot growth; therefore, much of the photosynthate was available for root growth. When the plants were fertilized with 300 ppm N, more N was available for shoot growth, which became the sink for photosynthate, limiting the supply of photosynthate to the root and consequently reducing root growth.

Time needed to restore the plant's balance after root pruning or transplanting varies greatly based upon percent root loss, age of plant, water supply and species (Warren 1993a). Peach (*Prunus persica* (L.) Batsch) seedlings have similar top: root ratios 25 days after root pruning according to studies by Richards and Rowe (1977). Monterey pine (*Pinus radiata* D. Don) seedlings recovered in 80 days (Rook 1971).

Fertilizing Established Trees

Depending on the objectives, fertilization may benefit established trees in a variety of ways. Proebsting (1935) fertilized plots of almond trees (*Prunus dulcis* (Mill.) D.A.Webb) with ammonium sulfate and increased almond yields 175 percent. Steinbrenner et al. (1960) reported a fertilizer-induced increase in Douglas fir (*Pseudotsuga menziesii* (Mirb.) Franco) flowering from 37 to 75 percent of the trees in a stand and seed production increase from 1.2 to 10.8 lbs. per acre. Smith (1975) found that fertilization caused a marked increase in root development in Valencia orange trees and increased yields.

In a study of fertilized slash pine in Florida, Mehdizadeh (1966) found that dominant and codominant trees responded positively to fertilization, with the codominants showing the greater response. Mortality increased greatly in the intermediates and suppressed trees as a consequence of this further suppression. The net result of the fertilization was a silvicultural thinning with the better trees stimulated and the inferior trees eliminated from competition for nutrients, moisture and light (Davey 1968). Fertilizing stimulated diameter and height growth of stands of eastern cottonwood (*Populus deltoides* Bart. ex Marsh.), sweet gum (*Liquidambar styraciflua* L.) , water (*Quercus nigra* L.) and willow oak, tulip poplar and sycamore in studies conducted on seedlings and 20 year old trees by Broadfoot (1966) and Broadfoot and Ike (1968).

Deuber (1939) in a series of tests made of several rates of fertilizing young shade trees and a few older trees with a 10-8-6 formulation found that a rate of 3lbs N per tree was effective in producing an increase in vigor, growth and foliage color. This improvement continued at least three years. Doubling the rate of application did not double the increase in growth and was slightly injurious to the tree. At even higher rates (10 to 20 lbs. N per tree) the fertilizer was so injurious that earlier effects of increased growth and vigor were entirely obscured (Deuber 1939).

Van de Werken (1981) grew shade trees at various levels of N and demonstrated significant increases in growth, as did Neely et al. (1970) in their fertilization studies done with various deciduous and coniferous landscape trees. Pirone (1951) reported experiments in New York City with foliar applications of nutrients to more than 300 street trees of five species. General appearance of treated trees was superior to that of untreated trees and analyses of leaves from a number of plane trees and pin oaks showed more of both N and P.

Not all trees under all soil conditions respond to fertilization, however. Perry and Hickman (1998) studied 30 5-year-old valley oak trees in a non-turfed park area in California. The soil type was a clay loam classified as moderate in natural fertility and typical of soils developed in parks in the Central Valley of California. One application, each, of three levels of ammonium nitrate was added and data were collected for the next 28 months. N fertilizer did not affect either foliar nitrogen concentrations or tree diameter growth. From these data, it appears that the native fertility of the soil provided adequate nutrition.

Age of the tree appears to be a factor in its response to fertilization. Smith and Treaster (1987) studied the effects of fertilization on linden, apple trees and sugar maples and found that 15 years after planting there were no differences in growth increases (trunk caliper, height or branch diameter) between the control and treated trees.

Davey (1968) refers to the work of Remezov et al. (1955) in which a detailed study of patterns of nutrient accumulation by various tree species on a wide range of sites was conducted. Remezov et al. (1955) concluded that each species has its own characteristic nutrient accumulation pattern that is strongly related to age of trees and quite stable over a range of soils. They reported for pines that the maximum nutrient demands on the site occurred between ages 25 and 45 years; most nutrients returned to the soil between ages 30 to 60 years;

greatest nutrient retention by trees between ages 15 and 30 years; and in overmature stands, nutrient return to soil exceeds uptake. Thus, age of tree and timing of fertilization seem to be important.

Types and Forms of Fertilizers

There are over 2000 grades of fertilizers which contain N in a variety of formulations – these include liquid, granular, sulfur coated, and encapsulated (Hauck 1968, Kuhns 1987). Nitrogen fertilizers come in different chemical forms but are absorbed by plant roots almost entirely as ammonium and/or nitrate (Hauck 1968, Harris 1992); the most common of the inorganic forms. As mentioned earlier, NH_4^+ and NO_3^- have important chemical differences that affect their availability (Christians 1989). Generally, the nitrate anions are mobile in the soil, while the ammonium cations initially react with clay and other colloidal surfaces, remaining relatively immobile until nitrified by soil organisms (Stanford 1959).

The long-term effect of ammonium fertilizers is to reduce soil pH (Kuhns 1987). In the conversion of NH_4^+ to NO_3^-, an acid residue forms, lowering soil pH. This may lead to formation of an “acid roof” where the pH in the upper inch or two of soil may be as much as an entire pH unit less than the soil beneath (Kuhns 1987). Applying limestone may counter balance this effect and decrease chances of root and turf injury.

Forms of Organic and Inorganic Fertilizers

Fertilizers are available in both an organic or inorganic form (Lilly 1993). Some of the soluble inorganic nitrogen fertilizers include (Whitcomb 1987): ammonium nitrate (33% N), calcium nitrate (15% N), potassium nitrate (14% N, 44% potassium), monoammonium phosphate (12% nitrogen, 48% phosphorus), sodium nitrate (16% N), and ammonium sulfate (20% nitrogen). Most liquid nitrogen fertilization is done with ammonium nitrate and potassium nitrate. Calcium nitrate is sometimes used as a foliar spray but seldom for soil applications, due to the much higher cost (Whitcomb 1987).

Organic fertilizers are carbon-based and can be natural (e.g. manures, sewage sludge, bone meal) or synthetic (e.g. isobutylidene diurea (IBDU) or ureaformaldehyde). Organic fertilizers also release inorganic ions, but more slowly as the molecules are hydrolyzed or decomposed in the soil, thus reducing losses through leaching (Harris 1992, Lilly 1993). The solubility of inorganic fertilizers, however, is less affected by temperature so that the rate of availability is more uniform (Lilly 1993). When nutrients are the primary interest, inorganic forms are usually favored (Harris 1992). The principal advantage of natural organic fertilizers is that they improve soil tilth (structure) if incorporated into surface soils (Harris 1992).

Urea is technically an organic, but it is not recognized as such in the industry because of how rapidly it solubilizes and releases its nutrient ions in water (Lilly 1993). Urea has the highest nitrogen concentration (46%) and is generally the least expensive of the granular fertilizers (Whitcomb 1987). However, urea provides only ammonium nitrogen initially and under cool conditions, the conversion to nitrate is very slow. This may be an advantage or disadvantage depending on the immediate plant needs and the species involved (Whitcomb 1987). Kuhns (1987), in fact, recommends urea fertilizers be applied in cool weather. He states that significant quantities of N can be lost from urea by volatilization and these losses are accelerated by warm, moist conditions.

Slow-release Fertilizers

A justifiable belief is that control of the rate of solution, ammoniafication and nitrification of a nitrogen source will result in increased efficiency of nitrogen use (Hauck 1968). Most of the factors contributing to loss of efficiency are directly related to rapid dissolution and hydrolysis of the applied compound, i.e., N loss through leaching, denitrification of nitrate, and ammonia volatilization (Hauck 1968).

One approach to increase efficient use of nitrogen has been to develop fertilizers that release N slowly into the soil solution, over an extended period of time (Hauck 1968, Lilly 1993). These compounds are referred to as controlled release, slowly soluble or slow-release fertilizers.

The production of slow-release N fertilizers involves either compounds that have reduced dissolution rates or compounds that are encapsulated with some material which delays or slows the rate of release (Engelstad 1968, Hauck 1968). Examples of the first type are the metal ammonium phosphates, oximide, and the ureaforms, such as isobutylidene diurea and ureaformaldehyde (Engelstad 1968, Hauck 1968, Kuhns 1987). The second type of slow-release N fertilizer is attained by such coatings as waxes, parafins, acrylic resins, latex, gums, oils and perforated plastic (Engelstad 1968, Hauck 1968). Hauck (1968) reports that an effective coating has been developed by TVA (Tennessee Valley Authority) that uses a low-cost material, sulfur, sealed with a thin film of petroleum wax and a microbicide.

Applying fertilizers in the slow-release form has several advantages in urban environments. Fertilizer does not need to be applied as frequently if applied in a slow-release form and higher amounts of fertilizer can be used without raising salt levels enough to injure plant roots (Kuhns 1987). In urban soils where water deficits are the norm, applying slow-release fertilizers may reduce the risk of salt injury to roots. The primary disadvantage of slow-release fertilizers is the higher cost (Lilly 1993). They range from two to six times higher per unit of N than ammonia N before application; therefore their use must be considered on the basis of demonstrated increased efficiency (Hauck 1968). It is also important to emphasize that slow-release sources of all elements should be evaluated carefully to determine not only the rate to be used but how much of the nutrient is released over what period of time (Whitcomb 1987).

Slow-release fertilizers are especially useful on salt sensitive plants and Whitcomb (1987) maintains that, given all other factors are equal, a slow-release source of nutrients will provide for plants more efficiently than dry chemical fertilizers.

May and Posey (1956) reported equivalent growth of pine seedlings either from either a single application of 248 lbs. of ureaform N/acre or 376 lbs. of N/acre from ammonium nitrate distributed over 8 applications. Bengtson and Voigt (1962) found N in ureaform to leach to a lesser extent than ammonium nitrate and recommended its use in irrigated nurseries. Whitcomb (1987) states that slow-release fertilizers have provided little benefit in the clay loam and sandy clay loam soils in Oklahoma. However, in sandy soils of Florida, the addition of Osmocote (ureaformaldehyde) or other slow-release fertilizer has been effective.

Nitrification inhibitors

Another strategy to reduce the loss of N from applied fertilizer is to slow the conversion of NH_4^+ to NO_3^- (nitrification) by inhibiting the activity of the bacteria responsible for the process (Christians 1989). This concept is presently being used in grain crop production and on citrus trees (Christians 1989, Serna 1994, 1996).

Serna (1994, 1996) experimenting with citrus trees (*Citrus* spp.) found that nitrification inhibitors such as dicyandiamide (DCD) helped to reduce leaching losses by retaining applied N in the ammonium form. Adding DCD to trees receiving an ammonium sulfate-nitrate fertilizer (ASN) resulted in higher N concentrations in the spring flush leaves, higher number of fruits per tree, and better fruit color index than trees treated with ASN alone. These results suggest that the use of a nitrification inhibitor permitted a more efficient utilization of fertilizer N by citrus trees. Nitrification inhibitors could be of possible value in sandy urban soils and urban soils where leaching is a problem.

Phosphorus and Potassium Fertilizers

Phosphorus and potassium are rarely in short supply for trees, are deficient in fairly specific soils and overuse of fertilizers containing these elements may lead to toxicity symptoms on plants and to water pollution (Harris 1992, Pirone et al. 1988).

High concentrations of phosphorus (and nitrogen) increase plant life in lakes and streams which may result in low oxygen levels that may be fatal to fish (Harris 1992). The loss of phosphorus is almost completely due to surface soil erosion, though it can be leached from coarse-textured or sandy soils. The predominant soil type of the southeastern U.S., Ultisols, is particularly prone to erosion and fertilization with P should be undertaken only when there is a documented need and then only with caution.

Gowans (1970) advises against using phosphate to fertilize trees on sites that are susceptible to water runoff, erosion or leaching. If P is necessary for growth or health of the tree the amount used and the method of application should be carefully controlled to minimize transport of phosphate from the site.

When P is not needed application will increase soil salinity and could tie up micronutrients – especially zinc and copper (Harris 1977). P and K are largely immobile in soil; therefore incorporating them into the soil as opposed to applying them on the soil surface is recommended (Pirone et al. 1988).

Phosphorus fertilizer materials currently available range from raw rock phosphate to higher condensed forms of polyphosphates (Davey 1968). Rock phosphate has been used successfully with (*Pinus elliottii* Engelm.) slash pine (Pritchett and Llewellyn 1966) and radiata pine (Gentle et al 1963). With slash pine it was found that rock phosphate was an effective P source on flatwood sands but not on other soils tested.

Common N and K fertilizers are all water-soluble, but P products cover the range from zero to high levels of citrate or water solubility. The most common P fertilizers used are the slow-release, water-soluble superphosphates (Davey 1968, Whitcomb 1987). The water-insoluble P fertilizers include basic slag, dicalcium and tricalcium phosphate. There are also mixtures of water-soluble and water-insoluble P fertilizers (Engelstad 1968)

There are several forms of potassium fertilizer. Potassium chloride (KCl) is very soluble and has the highest salt level of any fertilizer material (Whitcomb 1987). It should not be used where salinity is a problem and in arid regions where chloride may be toxic (Pirone et al. 1988). Potassium sulfate (K_2SO_4) is preferred for most uses (Pirone et al. 1988). Potassium nitrate (KNO_3) is frequently used in liquid fertilizer systems in combination with ammonium nitrate (Whitcomb 1987) but may cause N excess problems if used to supply large quantities of potassium.

Complete Fertilizers

A complete fertilizer is one that contains significant amounts of the three primary nutrients; N, P and K (Darr 1996). A fertilizer analysis, the relative percentages of these three nutrients, is listed on the label and referred to as the N-P-K number (Darr 1996, Koelling and Kielbaso 1978).

Before addressing the use of complete fertilizers it is important to point out, again, that the effectiveness of any fertilizer and nutrient source will be directly dependent upon the moisture conditions of the site (Davey 1968). Lack of soil moisture not only results in moisture deficiency for trees but also interferes with nutrient absorption (Pritchett 1979). Bengtson and Voigt (1962) reported that readily soluble fertilizer sources were most efficient under moderate moisture levels while under conditions of high precipitation, slowly soluble forms were more effective. Allen and Maki (1955) demonstrated that survival of longleaf pine seedlings after a drought was greatly increased by a complete fertilizer, but not by N alone. Pharis and Kramer (1964) reported that either too much or too little N resulted in intensified drought damage and decreased post drought recovery in loblolly pine seedlings. These studies show that the value of any fertilizer is distinctly affected by the amount of precipitation and soil moisture, first and foremost.

Harris (1992) points out that even though scores of field experiments have demonstrated that most soils contain sufficient amounts of P and K for trees and woody plants, complete N-P-K fertilizers are still widely endorsed for trees (U.S. Department of Agriculture 1972, May 1973, National Arborist Association 1987, Swanson and Rosen 1989). These recommendations for shade tree fertilization are derived from experience with field crops (van de Werken 1981) - where N, P and K are commonly deficient (Harris 1977). Root crops have shown increased growth with high supplements of K and grain crops often benefit from the addition of P (van de Werken 1981). Primarily, one could conclude because the crop is harvested each year and the nutrient removed from the soil.   This is not the case with urban trees and therefore the logic behind using a complete fertilizer in urban environments, without demonstrated need for the element, should be seriously questioned.

Satisfactory cover crops can be grown only when P is added in some California soils; in these same soils, however, fruit trees demonstrate no response to the application of P (Proebsting 1958). In work on apple trees under field conditions, Boynton and Oberly (1966) found no significant evidence that P applications affect the trees' growth or fruiting response.

Van de Werken and Warmbrod (1969) conducted an experiment on pin oak in west Tennessee in 1960 using two fertilizer treatments – N with P and lime and N alone. The growth of the pin oak was essentially the same for both treatments.

Broadfoot (1966) measured the response of a natural established sweetgum-oak stand in Louisiana to surface application of fertilizer. From the various treatments he found that for diameter growth there was no difference between N-P-K and 150 lbs. N/acre, but each was better than 75 lbs. N/acre. For height growth N-P-K was better than 75 lbs. N/acre and 150 lbs. N/acre, but not 300 lbs. N/acre.

Increases in circumference of pin oak, white ash and honeylocust were measured in Illinois after various fertilizer treatments (Himelick et al. 1965). The application of P and K to the soil did not bring about a significant growth response; nor did a combination of P, K and N produce a response that was significantly greater than that produced by nitrogen alone.

Neely et al. (1970) studied shade trees in five test sites in Illinois. The soils at the five test sites represented sandy soils, fertile topsoils and infertile topsoils. They found that only N caused significant growth response. P and K, although they were available in relatively low quantities in some of the soils, failed to stimulate growth when added as fertilizers.

Granular N, K and P fertilizers were applied in holes near honeylocust and pin oak (Watson 1994). Each was applied separately and also together as a complete fertilizer. When root development was assessed Watson (1994) found that N, alone and in combination with the other two elements, significantly increased density of the honeylocust roots near the application holes. Pin oak root densities increased in the presence of N alone and P had no effect on the roots of either species.

Growth response of Japanese hollies to high or low N and/or high or low K showed that potash suppresses growth promoting effects of N while high N without K resulted in the greatest gain for both fresh and dry weight of new shoots (Baird and Alexander 1963). Yeager and Wright (1981) demonstrated that P added at low and high (85 – 500 ppm) rates had no effect on shoot or root growth in *Ilex crenata* grown in the greenhouse.

The indiscriminate use of complete fertilizers may lead to a nutrient imbalance that will be difficult to overcome. Kelsey (1996) reports that in the upper Midwest it is common to see chlorotic trees and shrubs in the landscape following widespread fertilization – most of the time the problem is an excess of a macronutrient usually P or K, causing a deficiency of Mn or Zn by increasing the salt concentration.

The effect of high K to N ratios on plant growth (Baird and Alexander 1963) and evidence that there is little or no growth increase of shade trees in response to nutrient addition other than N (Himelick et al. 1965, van de Werken and Warmbrod 1969, Neely et al. 1970) leads to the conclusion that for increase of growth rate of shade trees, a high level of N combined with relatively low levels of P and K is most effective (van de Werken 1981).

11. Fertilization and Disease

The nutrition of a tree determines in large part its resistance or susceptibility to disease, how tissues function to quicken or slow pathogenesis and the virulence and ability of pathogens to survive (Huber 1980). Mineral elements are, in fact, directly involved in all mechanisms of defense as integral components of cells, substrates, enzymes and electron carriers or as activators, inhibitors and regulators of metabolism (Bavaresco and Eibach 1987).

Tolerant or moderately resistant plants demonstrate the greatest response to mineral elements, while disease reactions of highly resistant or highly susceptible plants are not as readily altered by nutrition (Huber 1980). The availability of mineral elements to trees and their effect on disease depends on their form and solubility, on the presence of competing or toxic entities, and on environmental factors such as pH, moisture, temperature and aeration (Huber 1980).

Pathogens

There is a dramatic shortage of research and literature on fertilization and its effects on tree disease – especially of urban trees. Recently, however, Burks et al (1998) studied the effect of N (form $(NH_4)_2NO_3$) fertilization on Cytospora canker in aspen (*Populus tremuloides* Michx.) in a greenhouse hydroponic system.

Aspen trees are commonly used in western U.S. landscapes, but they are susceptible to infection by several canker-inducing pathogens, including *Cytospora chrysosperma* (Burks et al 1987). Cytospora canker is also common on many willows and other poplars. Although this disease is stable in native or naturalized areas, canker incidence appears to be increasing in maintained urban landscapes.

Conditions that stress host trees influence incidence and expansion of cankers caused by *C. chrysosperma*. These stresses include drought, transplant stress, pruning wounds, insect damage, excess soil salts and severe defoliation (Bloomberg 1962).

In their research, Burks et al (1998) grew the aspens in sand and fertilized them with 1 of 5 N treatments (ranging from 0 to 13.3 lbs./gallon) for 2 growing seasons. Nitrogen deficiency contributed to significantly larger cankers. Among trees receiving moderate levels of nitrogen (4.4 lbs./gallon) cankers failed to expand which suggests that tree resistance mechanisms may involve host response to nutrient deficiencies, rather than fungal stimulation via nutrition. Cankers expanded at high levels of N indicating that excess N may stress aspen. But, because this rate (13.3 lbs./gallon) is not normal, Burks et al (1998) point out that excess N is not likely a predisposing stress of aspen.

The addition of nitrogen encouraged pathogenesis in an experiment conducted by Entry et al (1991) in which second growth stands (38-year-old) Douglas firs were thinned and fertilized with 360 kg of N (as urea) per hectare. Ten years later after treatment, trees were inoculated with two isolates of *Armillaria ostoyae.* Results demonstrated that this treatment predisposed the

Douglas firs to infection by *A. ostoyae* by lowering concentrations of defensive compounds in root bark and increasing the energy available to the fungus to degrade them. They hypothesized that trees growing extremely fast may allocate more carbon to sugar and cellulose and less carbon to tree defense compounds, such as lignin, phenolics and tannins. Citing research conducted by Kirk (1981) they state that fungi can degrade phenolic compounds only when an additional carbon source is present; the rate of degradation is directly proportional to the amount of additional growth substrate. Entry et al (1991) found that carbon utilization by *A. ostoyae* in culture was more efficient at low sugar concentrations, but fungal biomass was greater at higher sugar concentrations.

Insects

Tree damaging insects can also be affected by fertilization. McClure (1991) fertilized eastern hemlock (*Tsuga canadensis* (L.) Carr.) with nitrogen in a forest plantation in Connecticut and found that it stimulated population growth of the hemlock wooly adelgid (*Adelges tsugae*). Fertilized hemlocks had five times more adelgids, had inferior color, and produced 25% less new growth than unfertilized trees after a single adelgid generation. These trends did not differ between hemlocks which had been fertilized 6 months prior to infestation by *A. tsugae* and those which were fertilized at the same time that trees were infested.

He concluded that N fertilization of hemlock neither increased host resistance to the adelgid nor repressed adelgid population growth following establishment. These results may be generally applicable to piercing and sucking insects that feed on trees and shrubs (McClure 1991).

Chlorosis

One of the most common problems of urban trees and shrubs in many parts of the United States is chlorosis (Harrell et al 1988). Chlorosis is characterized by yellow leaves; leaves may become progressively smaller as a result of shortage of chlorophyll and food production in the leaf. As the condition worsens necrotic areas may be observed between the veins and shoot growth may be stunted (Neely 1976, Himelick and Himelick 1980). Commonly, this condition is attributed to a deficiency of either iron or manganese caused by high soil pH but may be caused by reduced availability of one or more of the soil nutrient elements such as N, K, Mg, B, Zn, Cu and Md (Himelick and Himelick 1980). Even excessive amounts of some elements may cause chlorosis. Other factors such as low temperatures, reduced sunlight, high soil moisture, and excessive applications of calcium and possibly phosphorous in fertilizers and irrigation water can also cause the development of chlorosis (Himelick and Himelick 1980).

Historically, certain tree species have exhibited habitual chlorosis, particularly when planted along streets and around homes where the original topsoil has been removed or mixed with the subsoil (Smith 1988). Oaks and maples are by far the most susceptible, with oaks heading the list, particularly pin oak (Neely 1976). Jacobs (1946) list of susceptible trees include: pin oak, red oak (*Quercus rubra* L.) black oak (*Quercus velutina* Lam.), white oak, black cherry *(Prunus serotina* Ehrh.*)*, red maple, silver maple (*Acer saccharinum* L.), sugar maple, sweet gum, flowering dogwood, American elm (*Ulmus americana* L.), American holly (*Ilex opaca* Ait.) and white pine.

Many studies have evaluated treatments for correcting chlorosis and have found iron injections and implants to be very effective (Harrell et al 1988). Himelick and Himelick (1980) in tests conducted on trees (6 – 40 inches in dbh) in 1974 on the Urbana campus of the University of Illinois found that both ferric ammonium citrate and ferric citrate effectively corrected moderate to advanced stages of chlorosis in large pin oak and sweet gum.

Some investigators have researched methods of acidifying the soil to correct chlorosis induced by unavailable iron and manganese in soils above pH 6.2 (Smith 1988). According to Messenger (1984) nutrient imbalances and normal leaf color can be restored and maintained for several years by topsoil and subsoil treatment with sulfuric acid. The author used sulfuric acid diluted in 5 gallons of water/1000 sq. ft. in 2 inch diameter holes, 2 feet apart, in two circles beneath the crown. The pH of topsoil beneath treated pin oaks was approximately neutral 3 years after application of the sulfuric acid. Subsoils receiving similar treatments were still quite acidic after 4 years (no pH readings cited).

Maple Decline

Another disease of urban trees, which is more a description of symptoms than a specific malady, is maple decline, also known as maple dieback and maple blight (Funk and Peterson 1980). These symptoms include chlorotic and scorched leaves that are often smaller than normal, premature fall coloration and leaf drop, and branch dieback initially involving the upper crown (Funk and Peterson 1980). Among the documented causes are road salts (Rich 1971), nitrogen deficiency (Jacobs 1929), high pH-manganese deficiency complex (Kielbaso and Ottman 1976) and drought. Root rots and cankers further contribute to the decline (Funk and Peterson 1980).

Research on sugar maples in Michigan between 1975-1976 by Funk and Peterson (1980) showed that leaf color can be significantly improved by high nitrogen fertilization (6 lbs. N (as ureaformaldehyde)/1000 sq. ft of root area). The authors reported that nutrient level was lower in chlorotic leaves than in healthy leaves for all of the elements listed except sodium and aluminum. The extremely high sodium level found in chlorotic leaves, they concluded, may implicate salt (sodium chloride) in maple decline along streets and highways.

Prolonged nutrient deficiency stresses urban trees and may eventually lead to disease and increased susceptibility to insect attack. Addition of nutrients can bolster resistance against disease expression and can increase tree vigor. Excessive or unneeded application of nutrients, however, may increase pathogenesis and/or increase insect feeding on succulent tissue.

12. New Approaches to Fertilization Theory – The Nitrogen Addition Technique

Ericsson (1981) citing Gauch (1972) and Hewitt (1966), states that the study of plant nutrition has historically focused on the nutrient concentration in solution as the general driving variable for nutrition of plants; thus creating the impression that the rate of ion uptake depends on the external ion concentration (Clarkson and Hanson 1980).

Ingestad and Lund (1979) and Ingestad (1979), using a nitrogen addition technique adjusted to the rate of plant growth and consumption demonstrated that high as well as low growth rates of birch seedlings may be obtained at the same very low N concentration in the solution. They showed that when optimum nitrogen supplies were reduced to little or none, typical nitrogen deficiency symptoms resulted. However, if nitrogen was then supplied at a rate proportional to the increase in plant growth, even though nutrient levels were below optimum, growth stabilized at a slower rate, leaf color returned, and the root shoot ratio stabilized higher than when the seedlings were growing under more optimum conditions. In addition, the photosynthetic rate and the amount of chlorophyll were not reduced in proportion to the reduction in the nitrogen supply or the overall growth of the plant. They concluded that the rate of addition, and not the concentration in the root medium was the decisive factor regulating nutrition and growth rate.

The nutrient concentration concept that has been the criterion for fertilizer application today has its consequences. In addition to negative effects on the environment through leaching, the high salt concentrations resulting from one or only a few nutrient applications during the growth season may result in root injury (Ericsson 1981). The nitrogen addition technique may offer the possibility to achieve high fertilizer efficiency at the same time as the nitrogen requirements throughout the whole period of growth are satisfied (Ericsson 1981).

12. Conclusion

Severely disturbed urban soils present conditions that may not meet the nutritional needs of individual trees and fertilization may be valuable in these soils. However, we need to question some of the current concepts, practices and recommendations that originated from crop and traditional forestry where yield and diameter growth/production are frequently the main objectives – objectives not always relevant to urban forestry.

It is universally reported that nitrogen is almost always deficient or growth limiting. That may not be true for all objectives. If we are interested in maintaining a mature shade tree in perpetuity and, therefore, interested in slowing its yearly growth, nitrogen may not be deficient. The addition of a nitrogen fertilizer may then be counterproductive to our objectives. However, if our intent is to promote growth in young trees, or correct a health problem caused by a demonstrated nutrient deficiency, then fertilization may be our most prudent action.

If we want to use fertilization as a cultural practice in urban forestry we need to make the practice more precise and applicable to the conditions of the urban environment. Empirical data, where it does exist, bases fertilization amounts on trees growing in adequate space, usually, under normal soil conditions. Urban trees are often, fundamentally, a compromise to their growth requirement and lack sufficient soil in which to grow. In this situation, calculating fertilization dosages by a rooting or soil volume method may be more effective.

Creating larger, more suitable soil environments and decreasing water deficits through watering, weed control and pruning, may be used in lieu of or in conjunction with fertilization. Finding alternatives to fertilization that achieve the same objectives prevents the indiscriminate and overuse of fertilizers responsible for nutrient imbalances and damage to the environment.

Use of fertilizer should always be based on diagnosed deficiencies. These deficiencies should be established and based on the objectives that are appropriate for urban tree uses and values.

More research is needed in many areas of urban forestry; such as determining the consequences of applying nutrients to trees over a period of many years and then discontinuing them. Developing a DRIS methodology to determine nutrient requirements for urban trees could also be of considerable value. Work remains to be done on the use of fertilization in disease remediation in urban trees. And, the concentration theory, on which most of our current fertilization practices are based, needs to be re-evaluated. Alternative techniques, like the nitrogen addition technique - which has shown that adequate plant growth can be obtained with sub-optimal nutrient levels – need to be investigated and developed.

Perhaps most importantly, as Tattar (1983) proposed, we should use the “natural forest” ecosystem as an ideal model for handling urban tree problems. Urban trees should be grown observing the natural processes of forest trees. Use of mulches, protection of tree bark, more appropriate use of fertilizers, moderation of environmental extremes and choosing more stress tolerant trees should all be considered for our urban forests and landscapes.

Literature Cited

Acquaye, D. K., and A.J. MacLean. 1965. Influence of form and mode of nitrogen fertilizer application on the availability of soil and fertilizer potassium. Canadian Journal of Soil Science 46:23-28.

Agriculture Research Service. 1973. Selecting and growing shade trees. U.S. Department of Agriculture. Home and Garden Bulletin 205.

_____. 1977. Transplanting ornamental trees and shrubs. U.S. Department of Agriculture. Home and Garden Bulletin 192.

Allen, R. M., and T.E. Maki. 1955. Response of longleaf pine seedlings to soils and fertilizers. Soil Science 79:359-362.

Alway, F. J., A.W. Marsh, and W.J. Methley. 1937. Sufficiency of atmospheric sulfur for maximum crop yields. Soil Science Society of America Proceedings 2:229-238.

Arnon, D. I., and Stout, P. R. 1939. The essentiality of certain elements in minute quantity for plants with special reference to copper. Plant Physiology 14:371-376.

Aslander, A. 1952. Standard fertilization and liming as factors in maintaining soil productivity. Soil Science 74:181-195.

Baird, D.D. , and J.S. Alexander. 1963. (Abstract) The influence of different levels of nitrogen and potassium on Ilex crenata in three soil series. Pp. 32 *in* SNA Seventh Annual Report of Ornamental Research.

Barrows, H.L. 1959. Evaluating the micronutrient requirements of trees. Pp. 18-31 *in* Mineral nutrition of trees: a symposium. Duke University School of Forestry Bulletin 15.

Baule, H., and C. Fricker. 1970. The fertilizer treatment of forest trees. translated by C.F Whittles. Munich, Germany: BLV Verlagsgesellschaft mbH.

Bavaresco, L. and R. Eibach. 1987. Investigations on the influence of N fertilizer on resistance to powdery mildew (*Oidium tuckeri),* downy mildew (*Plasmopara viticola*) and on phytoalexin synthesis in different grapevine varieties. Vitis 26:192-200.

Beilmann, A. P. 1936. Feeding the shade trees. Missouri Botanical Garden Bulletin 24:95-113.

Bengtson, G. W., and G.K.Voigt. 1962. A greenhouse study of relations between nutrient movement and conversion in a sandy soil and the nutrition of slash pine seedlings. Soil Society of American Proceedings 26:609-612.

Bloomberg, W. J. 1962. Cytospora canker of poplars: Factors influencing the development of the disease. Canadian Journal of Botany 40:1271-1280.

Bould, C., and E.J. Hewitt. 1963. Mineral nutrition of plants in soils and culture media. Pp. 15-134 *in* Plant Physiology. editor F.C. Steward. New York, New York: Academic Press.

Boynton, D., and G.H. Oberly. 1966. Apple nutrition. Pp. 1-50 *in* Nutrition of fruit crops: tropical, subtropical, temperate. Editor N.F. Childers. New Brunswick, New Jersey: Horticultural Pub., Rutgers University.

Brady, N. C. and R.R. Weil 1996. The nature and properties of soils. 11th ed. Upper Saddle River, New Jersey: Prentice Hall.

Broadfoot, W. M. 1966. Five years of nitrogen fertilization in a sweetgum-oak stand. U.S. Forest Service Research Note SO-34.

Broadfoot, W.M., and A.F. Ike. 1968. Research progress in fertilizing southern hardwoods. Pp. 180-184 *in* Forest fertilization: theory and practice. Muscle Shoals, Alabama: TVA National Fertilizer Development Center.

Brouwer, R. 1965. Ion absorption and transport in plants. Annual Review of Plant Physiology 16:241-266.

_____. 1962. Nutritive influences of the distribution of dry matter in the plant. Netherlands Journal of Agricultural Science 10:399-408.

Burks, S., W.R. Jacobi, and G.A. Mcintyre. 1998. Cytospora canker development on aspen in response to nitrogen fertilization. Journal of Arboriculture 24(1):28-33.

Cain, J.C. 1959a. Plant tissue analysis. Part II. Observations on antagonistic effects in leaf analysis. Pp. 63-69 *in* Mineral nutrition of trees: a symposium.

———. 1959b. Plant tissue analysis. Part I. Some factors in sampling and analyses for the diagnosis of nutritional status of trees. Pp. 55-61 *in* Mineral nutrition of trees: a symposium. Duke University School of Forestry Bulletin 15.

Chadwick, L. C. 1941. Fertilization of ornamental trees, shrubs, and evergreens. Ohio Agricultural Experimental Station Bulletin 620.

_____, P.E. Tilford, and C.F. Irish. 1950. A study of some methods of fertilizing shade trees. American Society for Horticultural Science Proceedings for 1949 55:519-526.

Christians, N. 1989. Reducing nitrogen loss, increasing efficiency in soil. ALA/Maintenance June:30-31.

Clarkson, D. T., and J.B. Hanson. 1980. The mineral nutrition of higher plants. Annual Review of Plant Physiology 31:239-238.

Craul, P.J. 1986. Assess urban soil for better tree survival. American Nurseryman 164(7):67-787.

_____, P.J. 1985. A description of urban soils and their desired characteristics. Journal of Arboriculture 11(11):330-339.

_____. 1982. Introduction to basic soil properties and their characteristics. Pp. 1-33 *in* Urban forest soils, editor P.J. Craul. Syracuse: SUNY College of Environmental Science and Forestry.

Darr, B. 1996. Tree fertilization: a world of options. Arbor Age 16(2):14-17.

Davies, R.J. 1987. Weed competition and broadleaved tree establishment. Pp. 91-99 *in* Advances in practical arboriculture. Forestry Commission Bulletin 65, editor D. Patch. London: HMSO.

Davey, C.B. 1968. Biological considerations in fertilizer evaluation. Pp. 264-73 *in* Forest fertilization: theory and practice. Muscle Shoals, Alabama: TVA National Fertilizer Development Center.

Deuber, C. G. 1939. Tests of the capacity of shade trees to utilize fertilizers. Bartlett Tree Research Laboratories Bulletin 3:3-19 .

Doughty, S. C. 1988. The basics of tree fertilization. American Nurseryman 167(7):67-77.

Engelstad, O.P. 1968. Recent trends in fertilizer development. Pp. 248-53 *in* Forest fertilization: theory and practice. Muscle Shoals, Alabama: TVA National Fertilizer Development Center.

Eno, C. F., and W.G. Blue. 1957. The comparative rate of nitrification of anhydrous ammonia, urea, and ammonium sulfate in sandy soils. Soil Science Society of America Proceedings 21:392-396.

Entry, J. A., K. Cromack, Jr., R.G. Kelsey, and N.E. Martin. 1991. Response of Douglas-fir to infection by *Armillaria osotyae* after thinning or thinning plus fertilization. Phytopathology 81:682-689.

Epstein, E. 1972. Mineral nutrition of plants: principles and perspectives. New York, New York: John Wiley & Sons.

Ericsson, T. 1981. Effects of varied nitrogen stress on growth and nutrition in three salix clones. Physiologia Plantarum 51:423-429.

Fayle, D. F. C. 1968. Radial growth in tree roots. University of Toronto, Canada, Faculty of Forestry, Technical Report 9.

Ferrandiz, L. S. 1988. The ABC's (and NPK's) of tree fertilization. Grounds Maintenance 23(4):26,28,30,134.

Feucht, J.R. , and J.D. Butler. 1988. Soils and plant fertility. Pp. 13-30 *in* Landscape management. New York, New York: Van Nostrand Reinhold Co.

Fowells, H.A. 1959. The determination of macro-element requirements of forest trees. Pp. 9-17 *in* Mineral nutrition of trees: a symposium. Duke University School of Forestry Bulletin 15.

Funk, R. 1990. How trees take up nutrients. Grounds Maintenance June:16,19,22.

Funk, R. and W. Peterson. 1980. Nutrient treatments for sugar maple decline. Journal of Arboriculture 6(5):16-21.

Gilbertson, P., A.D. Kendle, and A.D. Bradshaw. 1987. Root growth and the problems of trees in urban and industrial areas. Pp. 59-66 *in* Advances in practical arboriculture. Forestry Commission Bulletin 65, editor D. Patch. London: HMSO.

Galloway, H. M. 1940. Origin and properites of alkaline raw humus. Soil Science 49:295-301.

Gauch, H. G. 1972. Inorganic plant nutrition. Stroudsburg, Pennsylvania: Dowed, Hutchinson & Ross.

Gentle, W., F. R. Humphreys, and M.J. Lambert. 1963. An examination of *Pinus radiata* phosphate fertilizer trial fifteen years after treatment. Forest Science 11:315-324.

Goldstein, J, N.Bassuk, P. Lindsey, and J.Urban. 1991. From the ground down. Landscape Architecture Jan.112-115.

Good, G. L. 1985. Surface application of fertilizers for shade trees. St. Lawrence County Cooperative 69(10):6.

Gowans, K. D. 1970. Water pollution considerations in landscape management. Proceedings of the California Park and Recreation Administrators Institute 11(20):1-5.

Hamilton, D. F., M.E.C. Graca, and S.D. Verkade. 1981. Critical effects of fertility on root and shoot growth of selected landscape plants. Journal of Arboriculture 7(11):41-52.

Harrell, M. O., P.A. Pierce, and D.A. Mooter. 1988. Pin oak and silver maple chlorosis treatment with ferric ammonium citrate solution. Journal of Arboriculture 14(6):63-65.

Harris, R. W. 1992. Arboriculture: Integrated management of landscape trees, shrubs, and vines. 2nd ed. Englewood Cliffs, New Jersey: Prentice Hall.

_____, J.L. Paul, and A.T. Lester. 1977. Fertilizing woody plants. University of California Agricultural Science Leaflet No. 2958.

Hauck, R.D. 1968. Nitrogen source requirements in different soil-plant systems. Pp. 47-57 *in* Forest fertilization: theory and practice. Muscle Shoals, Alabama: TVA National Fertilizer Development Center.

Hewitt, E. J. 1966. Sand and water culture methods use in the study of plant nutrition. Bucks, England: Farnham Royal, Commonwealth Agricultural Bureau.

Himelick, E. B. and K.J. Himelick. 1980. Systemic treatment for chlorotic trees. Journal of Arboriculture 6(7):22-26.

Himelick, E. B., D. Neely, and W.R. Crowley, Jr. 1965. Experimental field studies on shade tree fertilization. Illinois Natural History Survey Biological Notes 53.

Hockman, J. N., J.A. Burger, and D.Wm. Smith. 1989. A DRIS application to fraser fir christmas trees. Communications in Soil Science Plant Analysis 20(3&4):305-318.

Holmes, F. W., and H.E. Mosher. 1975. Fertilizing trees and shrubs. University of Massachusetts, Cooperative Extension Service Publication 382.

Huber, D.M. 1980. The role of mineral nutrition in defense. Pp. 381-406 *in* Plant disease, an advanced treatise. Vol. 5: How plants defend themselves. editors J.G. Horsfall and E.B. Cowling. New York, New York: Academic Press.

Ingestad, T. 1979. Nitrogen stress in birch seedlings II. N, K, P, Ca and Mg nutrition. Physiologia Plantarum 45:148-157.

_____. 1960. Studies of the nutrition of forest tree seedlings.III. Mineral nutrition of pines. Physiologia Plantarum 13:513-533.

_____, and A.B. Lund. 1979. Nitrogen stress in birch seedlings I. Growth technique and growth. Physiologia Plantarum 45:137-148.

Jacobs, H. L. 1946. Iron deficiency chlorosis of shade trees in the eastern United States. The Arboriculturist 33:23-32.

_____. 1929. Fertilization of shade trees. Part I: Fall vs spring fertilization. Davey Tree Expert Company (Kent, Ohio) research department bulletin 4.

Jenny, H. 1941. Factors of soil formation. New York, New York: McGraw-Hill.

_____. 1966. Pathways of ions from soil into root according to diffusion models. Plant and Soil 25:265-289.

Johnson, C. W. 1988. Planning for avian wildlife in urbanizing areas in American desert/mountain valley environments. Landscape and Urban Planning 16(3):245-252.

Karnosky, D. F. 1981. Chamber and field evaluations of air pollution tolerances of urban trees. Journal of Arboriculture 7(4):99-105.

Kelsey, P. 1996. Diagnosing nutrient deficiencies in hardwood trees. Grounds Maintenance 31(6):28,32,33.

Khatamian, H., J.C. Pair, and R. Carrow. 1984. Effects of turf competition and fertilizer application on trunk diameter and nutrient composition of honeylocust. Journal of Arboriculture 10(5):52-55.

Kielbaso, J. J and K. Ottman. 1976. Manganese deficiency - contributory to maple decline. Journal of Arboriculture 2:27-32.

Kirk, T.K. 1981. Toward elucidating the mechanism of action of the ligninolytic system in basidomycetes. Pp. 131-48 *in* Trends in biology of fermentations for fuels and chemicals. editor A. Hollaender. New York, New York: Plenum Press.

Knoop, W. 1976. Why a fertilizer burns. Weeds, Trees, and Turf Nov:14-15.

Koelling, M. R., and J.J. Kielbaso. 1975. Fertilizing shade and ornamental trees. Cooperative Extension Service - Michigan State University Extension Bulletin E-786.

Kopinga, J., and J. van den Burg. 1995. Using soil and foliar analysis to diagnose the nutritional status of urban trees. Journal of Arboriculture 21(1):17-24.

Kozlowski, T. T., editor. 1971. Growth and development of trees. Vol I. San Diego, California: Academic Press.

_____, and J.S. Boyer 1995. Water relations of plants and soils. San Diego, California: Academic Press.

_____, and T.T. Kozlowski 1979. Physiology of woody plants. New York, New York: Academic Press.

Kuhns, L. J. 1987. Fertilizing woody ornamentals. Penn State Department of Agriculture Cooperative Extension Circular 353.

Landsberg, H.E. 1970. Climates and urban planning. Pp. 364-74 *in* Urban Climates. World Meteorological Organization Technical Note 108.

Leaf, A.L. 1968. K, Mg and S deficiencies in forest trees. Pp. 88-122 *in* Forest fertilization: theory and practice, Muscle Shoals, Alabama: TVA National Fertilizer Development Center.

Likens, G. E, F.H. Bormann, R.S. Pierce, J.S. Eaton, and N.M. Johnson 1977. Biogeochemistry of a forested ecosystem. New York, New York: Springer Verlag.

Lilly, S.J., and et al. 1993. Tree nutrition and fertilization. Arborists' certification study guide. Savoy, Illinois: International Society of Arboriculture.

Little, P. 1977. Deposition of 2.75, 5.0 and 8.5 um particles to plant and soil surfaces. Environmental Pollution 12:293-305.

Lundegardh, H. 1954. Physiological aspects of tissue analysis as a guide to soil fertility. Pp. 15-27 *in* Plant analysis and fertilizer problems. Paris, France: I.R.H.O.

Lyford, W. H., and B.G. Wilson 1964. Development of the root system of *Acer rubrum* L. Harvard Forest Paper No. 10. Petersham, Massachusetts: Harvard University.

Mader, D.L., and R.C. Cook. 1982. Soil fertility for urban trees. Pp. 1-28 *in* Urban forest soils, editor P.J. Craul. Syrause, New York: SUNY College of Environmental Science and Forestry.

May, C. 1949. Keeping shade trees healthy. Pp. 91-96 *in* Trees, yearbook of agriculture 1949. Washington, D.C.: United States Department of Agriculture.

May, J. T., and H.G. Posey. 1956. Urea-formaldehyde fertilizer as a source of nitrogen for 1-0 loblolly pine nursery stock. Agricultural Experiment Station Progress Report Series No. 65.

McClure, M. S. 1991. Nitrogen fertilization of hemlock increases susceptibility to hemlock woolly adelgid. Journal of Arboriculture 17(8):227-229.

McPherson, E. G., D.J. Nowak, and R.A. Rowntree, editors. 1994. Chicago's urban forest ecosystem: results of the Chicago urban forest climate project. General Technical Report NE-186. Radnor, Pennsylvania: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station.

Mehdizadeh, P. T. 1966. Response of planted slash pine (*Pinus elliottii* Engelm.) to summer application of fertilizers. Ph.D. Thesis, N.C. State University Raleigh, Raleigh, North Carolina.

Messenger, A.S. 1984. Treatment of chlorotic oaks and red maples by soil acidification. Journal of Arboriculture 10(4):122-128.

_____, and B.A. Hubry. 1990. Response of interveinally chlorotic red maple trees treated with medicaps or by soil acidification. Journal of Environmental Horticulture 8(1):5-9.

National Arborist Association (N.A.A.) 1987. National arborist association standards. Amherst, New Hampshire: National Arborist Association.

Neely, D. 1976. Iron deficiency chlorosis of shade trees. Journal of Arboriculture 2(7):6-8.

Neeley, D., E.B. Himelick, and W.A. Crowley. 1970. Fertilization of established trees: a report of field studies. Illinois Natural History Survey Bulletin 30.

Neff, M. S., M. Drosdoff, and H. L. Barrows. 1955. Effect of time of applying fertilizers on growth of newly planted lampton tung trees on lakeland fine sand. Proceedings of the SNA Research Conference Annual Report - Southern Nurserymen's Association 68:204-210.

Ovington, J. D., and H.A.I. Madgwick. 1959. Distribution of organic matter and plant nutrients in a plantation of Scots pine. Forest Science 5:344-355.

Owe, M. 1985. Long term streamflow observations in relation to basin development. Journal of Hydrology 78:243-260.

Pate. J.S., D.B. Layzell, and C.A. Atkins. 1979. Economy of carbon and nitrogen in a nodulated and nonnodulated (NO3 grown) legume. Plant Physiology 64:1083-1088.

Patterson, J. C. 1990. Urban soils as a medium for supporting urban plantings and their roots systems. Proceedings of the Society of American Foresters National Convention:225-228.

_____, and D.L. Mader. 1982. Soil compaction. Pp. 1-15 *in* Urban forest soils, editor P.J. Craul. Syracuse: SUNY College of Environmental Science and Forestry.

Perry, E., and Hickman, G. W. 1998. Correlating foliar nitrogen levels with growth in two landscape tree species. Journal of Arboriculture 24(3):149-153.

Perry, T. O. 1982. The ecology of tree roots and the practical significance thereof. Journal of Arboriculture 8(8):197-208.

Pharis, R. P., and P.J. Kramer. 1964. The effects of nitrogen and drought on loblolly pine seedlings I. Growth and composition. Forest Science 10:143-150.

Pirone, P. P. 1951. Foliage application of nutrients. National Shade Tree Conference Proceedings 27:23-35.

Pirone, P. P., J.R. Hartman, M.A. Sall, and T.P. Pirone. 1988. Tree Maintenance. New York, New York: Oxford University Press.

Pritchett, W. L. 1979. Properties and management of forest soils. New York, New York: John Wiley and Sons.

_____, and R.F. Fisher 1987. Properties and management of forested soils. 2nd ed. New York, New York: John Wiley & Sons.

_____, and W.R. Llewellyn. 1966. Response of slash pine (*Pinus elliotii*) to phosphorus in sandy soils. Soil Science Society of America Proceedings 30:509-512.

Proebsting, E. L. 1958. Fertilizers and cover crops for california orchards. California Agricultural Extension Service Circular 466.

_____. 1935. Field and laboratory studies on the behavior of NH4 fertilizer with special reference to the almond. Proceedings of the American Society of Horticultural Science for 1934.

Reil, W. O. 1979. Pressure-injecting chemicals into trees. California Agriculture 33(6):16-19.

Remezov, N. P., L.N. Bykova, and K.M. Smirnova. 1955. Nitrogen and mineral cycles in forests. Akad. Nauk SSSR. Trudy Institut Lesa 24:167-194.

Rich, A. E. 1971. Salt injury to roadside trees. Proceedings of the International Shade Tree Conference 47:77-79.

Richards, D., and R.N. Rowe. 1977. Effects of root restriction, root pruning and 6-benzylaminopurine on the growth of peach seedlings. Annals of Botany 41:729-740.

Ripley, T. H., and B.W. Ellertsen. 1971. The role of trees in water relations. Symposium on the Role of Trees in the South's Urban Environment, University of Georgia, Proceedings:34-38.

Robinson, J. B. 1986. Tree mineral nutrition. Acta Horticulturae 175:163-172.

Rook, D. A. 1971. Effect of undercutting and wrenching on growth of Pinus radiata D.Dan seedlings. Journal of Applied Ecology 8:477-490.

Sacamano, P. L., L.F. Burkhart, D.M. Cole, and R.C.Funk 1993. Consolidating and communicating urban forest benefits. Irvine, California: Davey Resource Group.

Schrader, A. L., and E.C. Auchter. 1925. First year's effect of different nitrogen fertilizers on bearing apple trees low in vigor. Proceedings of the American Society of Horticultural Science 22:150-161.

Serna, M. D., F. Legaz, and E. Primo-Millo. 1994. Efficacy of Dicyandiamide as a soil nitrification inhibitor in citrus production. Soil Science Society of America Journal 58(6):1817-1824.

_____, _____, and E. Primo-Millo. 1996. Improvement of the N fertilizer efficiency with dicyandiamide (dcd) in citrus trees. Fertilizer Research. 43(1/3):137-142.

Shaw, W. W., W.R. Mangum, and J.R. Lyons. 1985. Residential enjoyment of wildlife resources by Americans. Leisure Sciences 7(3):361-375.

Shigo, A. L. 1989. Tree pruning: A worldwide photo guide. Durham, New Hampshire: Shigo and Trees, Associates.

_____, W.E. Money, and D.I. Dodds. 1977. Some internal effects of Mauget tree injections. Journal of Arboriculture 3(11):213-220.

Shoup, S., R.Reavis, and C.E. Whitcomb. 1981. Effects of pruning and fertilizers on establishment of bareroot deciduous trees. Journal of Arboriculture 7(6):34-36.

Smiley, E. T. 1994. Soil and tissue testing: analyze before you fertilize. Arbor Age 14(4):20,22,23.

_____, B.R. Fraedrich, and D.C. Booth. 1991. Comparison of trunk injected and soil applied macronutrients. Journal of Arboriculture 17(12):322-324.

Smith, E. M. 1988. An overview of systemic nutrient treaments in trees. Journal of Arboriculture 14(10):70-72.

_____. 1978. Species, soil, location affect tree fertilization. Weeds, Trees, and Turf October:16,17,20.

_____, and K.W. Reisch. 1975. Fertilizing trees in the landscape: Progress report. Abstract. Journal of Arboriculture 1(4):77.

_____, and S.A. Treaster. 1987. Fertilizing trees in the landscape: a 15-year evaluation. Pp. 8-10 *in* Ohio Agricultural Research and Development Center Research Circular 291.

Smith, P. F. 1975. Effect of nitrogen source and placement on the root development of Valencia orange trees. Proceedings of the Florida State Horticultural Society 78:55-59.

Smith, R. C, DeCock, D, and Hill, R. 1992. Fertilizing trees. North Dakota State University Extension Service Publication H-1035.

Spurway, C. H. 1941. Soil reaction (pH) preference of plants. Michigan Agricultural Experiment Station, Special Bulletin 306.

Stanford, G. 1959. Nutrient sources for tree nutrition studies. Pp. 122-35 *in* Mineral nutrition of trees: a symposium. Duke University school of forestry bulletin 15.

Steinbrenner, E. C., J.W. Duffield, and R.K Campbell. 1960. Increased cone production of young Douglas-fir following nitrogen and phosphorus fertilization. Journal of Forestry 58:105-110.

Steiner, K. C. 1980. Developing tree varieties for urban soil stresses. Metropolitan Tree Improvement Alliance (METRIA) Proceedings 3:57-69.

Stone, E.L. 1968. Microelement nutrition of forest trees: a review. Pp. 132-79 *in* Forest fertilization: theory and practice. Muscle Shoals, Alabama: TVA National Fertilizer Development Center.

Stout, B. A. 1956. Studies of the root system of deciduous trees. Black Rock Forest Bulletin No. 15. Cambridge, Massachusetts: Harvard University Print Office.

Svihra, P. 1987. When to fertilize deciduous woody ornamentals. Arbor Age 7(6):26.

Swanson, B. T., and C. Rosen. 1990. Tree fertilization. University of Minnesota - Minnesota Extension Service AG-FO-2421-B.

Tattar, T. A. 1983. Stress management for trees. Journal of Arboriculture 9(1):25-27.

Tukey, H. B., and M.M. Meyer Jr. 1965. Nutrient applications to dormant plants. American Nurseryman June(1):7-8.

Urban, J. 1989. New techniques in urban tree plantings. Journal of Arboriculture 15(11):281-284.

U.S. Department of Agriculture. 1972. Shade trees for the Home Bulletin no. 425.

van de Werken, H. 1984. Why use obsolete fertilizer practices? American Nurseryman 159(7):65-71.

_____, 1981. Fertilization and other factors enhancing the growth rate of young shade trees. Journal of Arboriculture 7(2):29-33.

_____, H., and J.G. Warmbrod. 1969. Response of shade trees to fertilization. Tennessee Farm and Home Science Progress Report No. 72.

Voight, G.K. 1968. Variation in nutrient uptake by trees. Pp. 15-19 *in* Forest fertilization: theory and practice. Muscle Shoals, Alabama: TVA National Fertilizer Development Center.

Warren, S. L. 1993a. Growth and nutrient concentration in flowering dogwood after nitrogen fertilization and dormant root pruning. Journal of Arboriculture 19(2):57-63.

_____. 1993b. Nitrogen fertilizer and beyond. Arbor Age 15(4):10-12.

Watson, G. W. 1994. Root growth response to fertilizers. Journal of Arboriculture 20(1):4-8.

_____, 1986. Cultural practices can influence root development for better transplanting success. Journal of Environmental Horticulture 4(8):32-34.

_____, and E.B. Himelick. 1982. Root distribution of nursery trees and its relationship to transplanting success. Journal of Arboriculture 8(9):225-229.

Webster, G. A. 1959. Nitrogen metabolism in plants. Evanston, Illinois: Row, Peterson and Company.

Weinbaum, S.A. 1988. Foliar nutrition of fruit trees. Pp. 81-99 *in* Plant growth and leaf-applied chemicals. editor P.N. Neumann. Boca Raton, Florida: CRC Press.

Wells, C. 1968. Techniques and standards for foliar diagnosis of N deficiency in Loblolly pine. Pp. 72-76 *in* Forest fertilization: theory and practice. Muscle Shoals, Alabama: TVA National Fertilizer Development Center.

Westing, A. H. 1966. Sugar maple decline: an evaluation. Journal of Economic Botany 20:196-212.

Whitcomb, C. E. 1987. Landscape production, establishment and maintenance. Stillwater, Oklahoma: Lacebark Publication.

White, D. P. 1956. Aerial application of potash fertilizer to coniferous plantations. Journal of Forestry 54:762-768.

White, E. H., and A.L. Leaf. 1965. Soil and tissue K levels related to tree growth: II. Tissue K as determined by total tree analysis techniques. Soil Science 99:109-114.

Wikle, J. 1963. Some comments and questions on soil improvement and fertilization for shade trees. Arborist's News 28(8-9):61-69.

Wilde, S. A. 1958. Forest soils. New York, New York: Ronald Press.

Williams, D. 1981. Fertilizers for woody ornamentals. Grounds Maintenance 16(2):26,32,106.

Wright, R. D., and E.B. Hale. 1983. Growth of three shade tree genera as influenced by irrigation and nitrogen rates. Journal of Environmental Horticulture 1(1):5-6.

Wyman, D. 1936. Growth experiments with pin oaks which are growing under lawn conditions. Cornell Agricultural Experimental Station Bulletin 646.

Yeager, T. H., and R.D. Wright. 1981. Influence of nitrogen and phosphorus on shoot:root ratio of *Ilex crenata* Thunb. 'Helleri'. HortScience 16(4):564-565.

Appendix 1

1. Determining the amount of complete fertilizer needed for a given area using the Universal Tree Fertilization Computation developed by H. van de Werken.

radius of root zone = 7 feet

desired application amount of N per acre using 18-6-12 fertilizer = 175 lbs.

calculation: $7^2 \times 175 = 8575$

140 (constant) x 18 (% N in fertilizer) = 2520

8575/2520 = 3.4 or 3 lbs. 6 ounces of fertilizer needed to cover root zone

2. Determining the amount of a complete fertilizer (10-6-4) needed for a given rectangular area.

length in feet of two sides of a rectangular area = 40 x 50 or 2000 sq. ft

desired application amount of N per 1000 sq. ft = 6 lbs.

Since the recommendation is for 6 lbs. of N per 1000 sq. ft we need 12lbs of actual N.

Knowing that a hundred pound bag, for example, of 10-6-4 fertilizer contains 10lbs of actual N, we can use the proportion 10/100 = 12/x to get 120lbs of fertilizer needed for our area.

Vita

Jim Watkins was born in Illinois and grew up in rural Minnesota. He received his Bachelor of Arts degree in Spanish from the University of Kansas and spent many years abroad translating movies for the film industry. Motivated by his life-long interest in nature and forestry, he matriculated into Virginia Tech and completed his Master of Forestry degree in 1998.