URBAN FOREST SOILS

A REFERENCE WORKBOOK

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INTRODUCTION

The idea of a workshop in urban forest soils evolved over a period of several years, with the collective input of many people. The first serious discussions for a workshop took place at the annual meeting of the Soils Working Group of the Consortium for Environmental Forestry Studies, in conjunction with the Consortium's Tenth Anniversary celebration in May, 1980.

Prior to that time the Working Group struggled with the development of a problem analysis for the planning and initiation of a comprehensive research program in urban forest soils. It soon became evident that many of the scientists involved, together with other colleagues, were being called upon to address problems that could be solved with existing technology and practical information, rather than problems arising from the lack of research information. Hence, the problem was (and still is!) one of making the best information available to the practitioner.

With this fact in mind the group proceeded with plans for a workshop to be held sometime in 1981. A steering committee was formed in June 1980 to establish a format and location for the workshop. Washington, D.C. was chosen because of the wealth of practical applications of present technology to a multitude of problems presented by soil, planning, and use conditions. Thus, a field tour to examine the solutions to some problems faced by landscape architects and urban foresters would be a major feature.
The committee also felt strongly that a review of fundamental soil and tree relationships is needed, but should not take valuable workshop time. From this need, the idea of the workbook emerged. It is hoped the participants would read the workbook prior to attendance at the workshop so that the presentations of the workshop could be on topics that could best be explored as a group, or would require some "hands-on" activity. During the workshop additional material will be provided that can be inserted in the workbook. It is hoped that the workbook will become a handy reference on urban soils for the practitioner.

Basic soil properties and tree root relations are covered in the first two chapters, followed by the common soil problems of compaction, fertility, and drainage. Some long-term silvicultural implications are discussed in Chapter 6 to help place in perspective the planning to overcome soils-related problems. Finally, Chapter 7 is presented to provide some information on how to make on-site soil analyses, completing the logical exposition of urban forest soil concepts.

Obviously, the workshop and workbook cannot examine all the problems that may arise in the urban soil. But an honest attempt has been made to provide information on those problems that most frequently present themselves to the practitioner and for which solutions are possible with our present state of knowledge.

Another objective of the workshop, of more immediate importance to the committee and the Consortium, is to gain additional insight
from the practitioners on what research is needed in urban forest soils to enhance the success of urban silvicultural plans. A twofold effect would result: improved urban forests with less economic and management input.

The steering committee has been enthusiastic in their efforts to prepare the workbook. Each of the chapter authors are acknowledged therein. James Patterson deserves much praise for doing most of the planning and footwork for the field tour. He was ably assisted by John Short, Robert Cook, and Del Fanning. We hope this enthusiasm is transmitted to the workshop participants and workbook users. We all look forward to a mutually rewarding three days in April!

The Steering Committee:

Robert N. Cook
Del W. Fanning
Howard G. Halverson
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Syracuse, N.Y.
March 12, 1982
BASIC SOIL PROPERTIES

Soil Defined

Concepts of Formation

The Profile

The Physical, Chemical, and Biological Properties

Phillip J. Craul
INTRODUCTION TO BASIC SOIL PROPERTIES

AND THEIR CHARACTERISTICS

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ABSTRACT -- The soil forms at the interface between the atmosphere and the lithosphere. In its natural condition it supplies water, nutrients, and mechanical support in varying degrees from locality to locality depending upon the environmental factors determining its formation. The formation process renders physical, chemical and biological properties to the soil. These basic properties can be characterized into capabilities and limitations for plant growth or other uses. Disturbance or manipulation of the natural soil will modify the properties in such a way that they may or may not be favorable for tree growth. The landscape architect and urban/city forester must recognize the occurrence and magnitude of these modifications in order to provide a plan for overcoming the problems presented therefrom. This chapter provides information for the landscape architect and urban/city forester to become familiar with the basic soil properties as a foundation to understanding urban soil conditions presented in subsequent chapters of this workbook.

INTRODUCTION

Definition of Soil

The definition of soil usually reflects the viewpoint of the person expounding it. Ramann, an early pedologist, defined soil in 1928 as "the upper weathering layer of the solid earth's crust." Geologists and engineers, as suggested by Way (1973) defined soil as that part of the earth's crust which is "loose, unconsolidated material above bedrock which has been weathered from its original
Basic Soil Properties

condition." Later, more specific definitions evolved from those of the early 20th century, and Craul (1967 and 1974) extracted this definition from the pedological viewpoint: "soil is a dynamic, natural system synthesized in profile form at the earth's surface, from variable mixtures of weathered minerals and decaying organic matter under the influence of climatic and topographic conditions and living organisms: which supplies, when containing the proper amounts of air and water, mechanical support, and in part, sustenance for plants." Thus, the geologist, engineer, and planner may be concerned with everything above bedrock, usually termed the regolith, while the agronomist, forester, soil scientist and landscape architect are concerned with the portion containing roots.

Soil is the great link between the physical (inanimate) and biological (living) components of the earth, and landscape architects must be concerned with both phases. It little matters in what way soil is defined as long as the importance of soil as a component of the ecosystem is recognized and understood.

Concepts of Soil

There are several natural facts that must be fixed in the mind if we are to understand why soil exists as it does on the terrestrial surface of the earth, and exhibits a certain form with several physical and chemical, as well as biological characteristics. Therefore, some of these concepts overlap with some of
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those studied in geology and in botany. Stated briefly, the concepts of natural soil are:

1. Soil is formed under processes and conditions that have existed for a long time.

2. It exists at the earth's surface as the interface between the atmosphere and the lithosphere, with the hydrosphere as a component (Figure 1.1).

3. Soil is a natural, dynamic system consisting of physical, chemical and biological processes.

4. Some processes are unique to soil development such as the formation of clay.

5. Soil has various physical, chemical and biological properties that are the result of the forming processes. These properties lend to the soil certain capabilities and limitations for plant growth and use.

6. Environmental factors such as climate, vegetation, and parent material modified by topography, all integrated over time, influence the soil development process. Since these factors vary over the earth, different soils are found in different regions and localities.

7. Resistance to change is a characteristic of rocks, vegetational communities, and soils. Once a soil develops, it is more resistant to change (weathering) than mere weathered geologic material.

The Soil Components

Soil is fundamentally a porous matrix formed from the weathering of rock. The rock fragments, of varying size, comprise the skeleton of the soil and forms the mineral component of soil. In an idealized soil, about 50 percent of its volume is made up of the mineral component. Because the soil is porous, air fills the voids between the mineral particles; hence, the air component. If
Figure 1.1. Illustration of the soil as the interface between the atmosphere and the lithosphere.
the soil is moistened, water displaces a proportionate volume of
the air and becomes the water component. In our idealized soil,
the air and water components make up about 45 percent of the total
volume, the two being about equally divided. The remaining 5
percent of the volume is occupied by the soil-inhabiting organisms
and the decomposed organic tissues of the plants and animals that
have their life cycles on or within the soil forming the organic
component.

The characteristics of size, shape and chemical composition of
the mineral particles together with the relative proportions of the
four components render to the soil basic physical, chemical, and
biological properties which in sum determine its capabilities and
limitations for growth of plants and other uses. These basic
properties will be discussed later.

The interface-gradient effect described earlier causes
significant changes in the soil components as depth increases below
the surface giving rise to what is termed the soil profile.

The Natural Soil Profile

An examination of the vertical cross-section of a soil reveals
that differences in appearance occur with depth. This illustrates
the "layering" effect as the result of the atmosphere-lithosphere
interface phenomenon. In some soils the differences are sharp and
contrasting; in others they are slight. These layers are referred
Basic Soil Properties

to as horizons and the vertical cross-section is called the soil profile. Each of these horizons have different dominant properties, and so the entire profile must be considered for the efficient utilization of a soil for any purpose.

An individual soil is a three-dimensional body with recognizable boundaries (sometimes only when excavated), and with overall properties distinct from another soil individual. These boundaries occur on the landscape where there exists a change in the soil developmental process governed by such factors as climate, vegetation, parent material, topography, and time since profile development began. A boundary is usually diffuse over several meters of length, creating a continuum over the landscape. On any one given tract of land, there may be a number of different soil individuals.

We will now closely examine the soil profile and its horizon nomenclature (Figure 1.2). The major portion of our profiles are mineral horizons. The organic layers or horizons, which exist at the profile top in most forest soils, are composed exclusively of organic materials in varying degrees or stages of decomposition. These horizons are commonly absent in urban and agricultural soils. The upper mineral horizon has organic matter incorporated within it. This horizon is usually called the topsoil, whereas the mineral horizons that lie below are collectively called the subsoil. These two groups comprise the solum, and the parent
Figure 1.2. The complete soil profile including the major horizons.
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Material normally occurs below it. If bedrock exists, its upper limit acts as the lower boundary of the regolith.

It is the arrangement or sequence of these horizons and their concomitant properties, determined by the four basic components, that provide a medium for the growth and development of plant root systems. The roots are then provided with water, nutrients, oxygen, heat, and mechanical support. These factors approach optimum levels near the soil surface and become less so with increasing depth in the soil. We shall now examine the basic properties of the soil.

BASIC SOIL PROPERTIES

Physical Properties

The soil fabric consists of solid particles from fragmented rock. Soil texture refers to the size distribution of the mineral particles, and structure to the arrangement of these solid particles in the fabric. Waterholding capacity and available water refer to the content and plant-available status of the soil water, and aeration to the amount of void (pore) space occupied by air. Permeability is the rate of water movement through the soil, and infiltration is the rate at which water enters the soil. The water relations of the soil are all influenced by the volume and size distribution of voids or the porosity. Bulk density is the weight of a unit volume of soil, including the solid particle volume and
Basic Soil Properties

the pore volume. Texture, structure, organic matter content and porosity all have effect on bulk density.

Soil depth, drainage, color, penetration resistance, and bearing capacity are other physical properties usually considered in a discussion on basic soil properties.

Texture. This term is used to classify the size of the mineral particles forming the solid phase of the three-phase soil system; hence, the soil fabric. Size of the mineral particles may range from boulders as large as a house, through stones several inches in diameter to gravel 2 mm or more in diameter, and descending on through what are termed sand, silt, and clay particles. These size classes are given in Table 1.1.

<table>
<thead>
<tr>
<th>Fraction</th>
<th>Diameter limits, mm</th>
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<tr>
<td>Very coarse sand</td>
<td>2-1</td>
</tr>
<tr>
<td>Coarse sand</td>
<td>1-0.5</td>
</tr>
<tr>
<td>Medium sand</td>
<td>0.5-0.25</td>
</tr>
<tr>
<td>Fine sand</td>
<td>0.25-0.1</td>
</tr>
<tr>
<td>Very fine sand</td>
<td>0.1-0.05</td>
</tr>
<tr>
<td>Silt</td>
<td>0.05-0.002</td>
</tr>
<tr>
<td>Clay</td>
<td>&lt;0.002</td>
</tr>
</tbody>
</table>

Most soil material has several particle classes represented, and it is the relative proportion of the various size fractions that defines soil texture. Texture designations are formed by
Basic Soil Properties

using the names of the predominant size fraction present in the soil material. A "sandy" soil is one in which the predominant size fraction may range from 2 to 0.05 mm. A "silty" soil is one dominated by particles of 0.50 to 0.002 mm, and a "clayey" soil is one comprised predominantly of particles less than 0.002 mm in diameter. Very few soils are purely of one fraction or another - usually a mixture. If all major fractions (the separates of sand, silt and clay) are well represented, the term loam is used to characterize the soil texture. If two separates predominate, such as silt and clay with little sand, the term silty clay is applied. The textural triangle, Figure 1.3, illustrates the 12 classes developed for the United States.

Soil texture significantly influences soil moisture relationships, soil structure, porosity and chemical activity of the soil, and in turn, plant growth. Therefore, it is important for the practitioner to perceive the relationship that texture has with these properties. These relationships are listed in Table 1.2.
Figure 1.3. The soil textural triangle.
### Basic Soil Properties

**Table 1.2 - Textural Relationships to Other Soil Characteristics**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Textural Class</th>
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<tr>
<td>Identification moist state</td>
<td>Sand</td>
</tr>
<tr>
<td></td>
<td>Loose</td>
</tr>
<tr>
<td>Permeability</td>
<td>Excessive</td>
</tr>
<tr>
<td>Available water</td>
<td>Low</td>
</tr>
<tr>
<td>Tillability</td>
<td>Easy</td>
</tr>
<tr>
<td>Runoff potential</td>
<td>Low</td>
</tr>
<tr>
<td>Water detachability</td>
<td>High</td>
</tr>
<tr>
<td>Water transportability</td>
<td>Low</td>
</tr>
<tr>
<td>Wind erodibility</td>
<td>High</td>
</tr>
<tr>
<td>Nutrient storage capacity</td>
<td>Low</td>
</tr>
<tr>
<td>Compactability</td>
<td>Low</td>
</tr>
</tbody>
</table>

It is seen from Table 1.2 that sandy soils may have ease of root penetration and low runoff potential, but they have the disadvantages of low available water and excessive permeability. The loam soils, on the other hand, would offer nearly optimum plant growing conditions. Soil fertility also tends to be related to texture as is seen in the nutrient storage capacity for the textural classes.

Since texture influences so many soil characteristics, it is important that those involved in evaluating planting sites be able to determine texture in the field with reasonable accuracy.
Basic Soil Properties

Fortunately, this is possible and the procedure is given below.

1. A representative handful of soil is placed in the palm of the hand.

2. Add sufficient water drop by drop until the soil is well-moistened, but not wet.

3. Rub a portion of the soil between the thumb and forefinger to detect presence of a gritty feel, or sand.

4. Add more water drop by drop to determine whether additional moisture makes the sample feel (1) gritty, (2) smooth or velvety, or (3) smooth, velvety, and plastic.

5. Then take the cast and attempt to "ribbon it" between the thumb and forefinger.

By comparing your results with the classes listed below, determine the textural class of the soil.

**Sand:** Loose and single-grained. The individual grains can readily be seen or felt. Squeezed in the hand when dry it will fall apart when the pressure is released. Squeezed when moist, it will form a cast, but crumble when touched.

**Sandy loam:** A soil containing much sand but which has enough silt and clay to make it somewhat coherent. The individual sand grains can be readily seen and felt. Squeezed when dry, it will form a cast which will readily fall apart, but if squeezed when moist a cast can be formed that will bear careful handling without breaking.

**Loam:** A soil having a relatively even mixture of different grades of sand and of silt and clay. It is mellow with a somewhat gritty feel, yet fairly smooth and slightly plastic. Squeezed when dry, it will form a cast that will bear careful handling, while the cast formed by squeezing the moist soil can be handled quite freely without breaking.

**Silt loam:** A soil having a moderate amount of the fine grades of sand and only a small amount of clay, over half of the particles being of silt size. When dry, it may appear cloddy but the lumps can be readily broken, and when pulverized it feels soft and floury. When wet the soil readily runs together and puddles. Either dry or moist it will form casts that can be freely handled without breaking, but when
moistened and squeezed between the thumb and forefinger it will not "ribbon" but will give a broken appearance.

Clay loam: A fine-textured soil which usually breaks into clods or lumps that are hard when dry. When the moist soil is pinched between the thumb and finger it will form a thin "ribbon" which will break readily, barely sustaining its own weight. The moist soil is plastic and will form a cast that will bear much handling. When kneaded in the hand it does not crumble readily but tends to work into a heavy compact mass.

Clay: A fine-textured soil that usually forms very hard lumps or clods when dry and is quite plastic and usually sticky when wet. When the moist soil is pinched out between the thumb and fingers it will form a long, flexible "ribbon". Some fine clays very high in certain colloids are friable and lack plasticity in all conditions of moisture.

Most landscaping specifications include some attempt at using soil materials that exhibit favorable properties for root penetration, drainage and mechanical support. If the soil material is unfavorable for these, it may be corrected through the addition of other materials such as peat moss, bark chips, sawdust, sand or waste byproducts such as sintered fly ash, expanded slates, and composts.

The swelling and shrinkage of the soil on wetting and drying is due mostly to the clay content and the type of clay minerals present. For temperate region soils there are three broad types of clay minerals: kaolinites, illites, and the montmorillonites. The degree of water adsorption, and hence, the degree of swelling-shrinkage is progressively greater in the respective groups. Soils containing high amounts of the montmorillonite types would exhibit extreme swelling-shrinkage. Some soils swell and shrink so much that it is not feasible nor recommended to construct buildings with
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foundations on them. These soils are also very sticky and plastic when wet. Kaolinitic soils would exhibit a much reduced degree of swelling-shrinkage.

**Structure.** This is the aggregation of primary soil particles into units of approximate geometric patterns. These units are called peds. The type and degree of aggregation has profound influence on the porosity and pore-size distribution of the soil. Thus, structure modifies the effect of texture from the standpoint of particle packing. The particles are held together by various cementing agents such as microbial gum, organic matter, clay, iron, silica, or other inorganic compounds. The peds themselves contain pores and contribute to the porosity as do the pores between peds.

Soil structure is a descriptive field term and cannot be readily measured as can texture. Because of differences in texture, organic matter content and organism activity, the type and degree of development will vary from horizon to horizon within the soil profile. Mechanical mixing of soil by plows or bull dozers, or compaction of soil by moving machinery or trampling feet can destroy soil structure. The best example is when soil is excavated, stockpiled, then spread at completion of construction—little structure remains in the reworked soil. Subsequent plant root growth and incorporation of organic matter will do much in restoring structure to the soil.

**Bulk Density.** This term is defined as the weight of a unit volume of the soil, including its pore space. It is profoundly
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influenced by texture, structure, organic matter content and degree of compaction. Particle density, on the other hand, is defined as the weight of a unit volume of soil solids, and assumed to have a value of 2.65 g/cc.

The packing together of the soil particles, and their arrangement as influenced by structure, determines not only the amount of total pore space but also the size and arrangement of the pores within the soil volume. In some cases, poor plant growth may be caused by the presence of many small pores and the lack of connecting pores or channels between them. Bulk density and total pore space influences aeration, waterholding capacity, permeability and infiltration, and the ease of root penetration.

Bulk density is calculated as:

\[
BD, \text{ g/cc} = \frac{\text{weight, oven-dry soil, g}}{\text{volume of soil sample, cc}}
\]

Total pore space is calculated from the bulk density volume by:

\[
\text{Total pore space \%} = 100 - \left( \frac{BD}{2.65} \times 100 \right)
\]

The bulk density of forest soils varies from 0.2 g/cc in the organic layers to 1.8 g/cc in well-packed sandy soils. Total pore space for these bulk density values would be 92.4 percent and 32.1 percent, respectively. Compacted soil horizons whose bulk density exceeds 1.75 g/cc for sands and 1.55 g/cc for clays may inhibit root penetration. The coarse-textured soils have less pore space than fine-textured soils because of their smaller surface area, closer contact of the particles, and smaller organic matter contents. Organic matter enhances structure development which
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increases porosity. It should be evident then, that soils with low bulk densities would compact to a greater degree than soils that already have a high bulk density.

Bulk density tends to increase with depth in the soil profile, due to an increase in the silt and clay in many soils, lower level of organism activity and organic matter content, and increase in overburden pressure on the lower soil horizons. Surface soil bulk density in most natural soils ranges from about 1.0 to 1.3 g/cc. Subsoil bulk density may range from 1.2 to 1.5 g/cc for those soils exhibiting favorable tree growth.

Aeration and Drainage. Plant roots require oxygen in their metabolic activity. This oxygen is normally obtained from the soil atmosphere which contains about 20 percent oxygen, 79 percent nitrogen and 0.25 percent carbon dioxide, with the balance comprised of other gases. The source of soil oxygen is the atmospheric oxygen which must diffuse into the soil under a partial pressure gradient. This diffusion can occur only in air-filled pores. Hence, little, if any, gaseous diffusion occurs in saturated soils. Coarse-textured soils are well-drained, and moderate to small portions of the pore space are water-filled. Gaseous diffusion readily occurs in large air-filled pores. These soils will have a relatively high oxygen concentration deep in the profile, enhancing root development to great depth, if nothing else impedes them. Finer-textured soils have a smaller proportion of air-filled pore space, decreasing the diffusion rate. This decreases the
oxygen concentration and increases the carbon dioxide concentration, the latter gas being formed by root respiration, which is toxic to roots if present in large concentration. Well-developed structure in medium- and fine-textured soils would tend to offset this trend. Compacted soils would have a greatly decreased air-filled pore space and a low rate of gaseous diffusion. For most soils the oxygen concentration decreases and carbon dioxide concentration increases with depth. Aeration status is the primary factor determining the total rooting depth in most soils. Most plants growing on upland soils require about 10 percent of the soil volume be air-filled pore space. Sugar maple, white ash, and basswood require greater than 15 percent air-filled pore space. Norway spruce, on the other hand, grows well with only 5 percent of the soil as air-filled pore space.

Soil drainage, influencing the aeration status of the soil, has the three components of runoff, internal drainage, and permeability. On the basis of these three, general soil drainage classes as used by the Soil Conservation Service can be described as below (see Figure 1.4).

**Very poorly drained** - water is removed from the soil so slowly that the water table remains at or on the surface most of the time. These soils occupy level or depressed sites and are frequently ponded. Mottling occurs to the surface.

**Poorly drained** - water is removed so slowly that the soil remains wet for a large part of the year, the water table being at or near the surface during this period. Poorly-drained conditions are due to a high water table, to a slowly permeable layer within the profile, to seepage, or to a
Figure 1.4. Soil drainage classes showing zones of dominant oxidation, hydration, and reduction.
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combination of these conditions. Mottling occurs below 10 to 20 cm.

Somewhat poorly drained - water is removed from the soil slowly enough to keep it wet for sufficient periods, but not all of the time. Mottling occurs below 20 to 50 cm.

Moderately well-drained - water is removed from the soil somewhat slowly, so that the profile is wet for a small but significant part of the time. Moderately well-drained soils commonly have a slowly permeable layer within or immediately beneath the solum, or a combination of the previous conditions. Mottling occurs below 50 to 76 cm.

Well-drained - water is removed from the soil readily but not rapidly. These soils are commonly medium textured, although other textured soils may also be well-drained. They may be mottled deep in the C horizon or below depths of several feet. Well-drained soils commonly retain optimum amounts of moisture for plant growth after rains.

Somewhat excessively drained - water is removed rapidly from the soil. Many of these soils are sandy and very porous. They do not retain optimum amounts of moisture for plant growth long after rains.

Excessively drained - water is removed from the soil very rapidly. These soils are very porous, shallow, steep, or all three. Optimum amounts of moisture for plant growth are seldom present in these soils.

The mottling mentioned in the soil drainage classes exists as the result of the hydration and/or reduction of iron in that portion of the profile that is frequently or continuously wet. The mottled colors may range from yellow to bluish-gray, depending upon the degree of hydration, and are in contrast to matrix colors of the soil which may be yellowish-brown, reddish brown, gray brown, olive, etc. These matrix colors are inherited from the soil parent material or result from the soil forming process. Soil scientists use the depth to mottling as an indication of the level
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of a temporary or the permanent water table in the soil profile. Well-drained soils would not exhibit mottling.

Soil Water. We are interested in soil water for four reasons: (1) trees require large amounts of water to supply their transpiration needs, and nearly all of it must come from the soil; (2) the soil must be able to supply the water in adequate amounts when the trees require it; (3) the soil must hold sufficient amounts of water in storage to carry the needs of trees over a period of time until the supply is replenished; (4) the soil water, as a solution, is involved in the exchange and transport of nutrients and other soluble salts.

Soil water is held in the pore space of the soil. When the soil is water saturated all pores are filled with water. As the soil drains, the largest pores drain first until the water no longer drains in response to the force of gravity - the retaining force of the soil acting on the water equalling that of gravity. The pores drained to this point are termed macropores, those yet retaining water are termed micropores. The soil moisture content at this point in the drainage cycle is called field capacity. The soil dries further by root absorption and capillary adjustments to evaporation from the soil surface. Further drying causes the decreasing amount of water to be retained in progressively smaller diameter pores. The retaining force on the water becomes progressively greater until the force equals or exceeds the absorbing force of the roots. Since no more water is available, the plants
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wilt. The soil moisture content at this level is termed *wilting point*. It can be seen then, that the water held by the soil between field capacity and wilting point contents is available to plants, and is called *available water*. Figure 1.5 illustrates the effects of texture and its related structure and bulk density on soil water availability.

The graph shows that a sand holds only 1 inch of water per foot of soil, while a silt loam may hold over 2 inches of water per foot of soil. The clay will hold just slightly more than the sand. Many common plants (trees included) require at least one inch of moisture a week. The sand soil could not store sufficient water in a locality that received less than 1 inch of rainfall a week, nor could the clay soil. The silt loam soil would perhaps have sufficient moisture to last 10 days to two weeks. Soil modification, including compaction, tends to reduce available water as well as aeration.

The fine absorbing roots tend to concentrate in the surface soil horizons (Chapter 2). As a result, the upper portion of the soil profile dries more rapidly and frequently than the lower horizons. The absorption of water shifts to the lower roots and the soil they occupy after the surface dries. So, there are periods of time when water absorption is greatest in the subsoil.

**Soil Depth.** This characteristic is influenced by the soil-forming processes in the natural profile. It is measured as the depth to bedrock or an impermeable layer in the profile, or depth
Figure 1.5. Soil texture effects on available water. (Adapted from USDA Yearbook of Agriculture, 1955, and Foth, 1978.)
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to the watertable where this feature occurs close (within reach of the roots) to the soil surface. It should be obvious that deep soils provide greater root volume and all attendant attributes than shallow soils. There probably is no one optimum soil depth for plant growth, since rooting depth is more often determined by depth of favorable aeration than by depth of soil. However, there are many instances in the urban situation where soil depth may be the limiting factor due to reshaping of the landscape in the process of development. Ordinarily, 18 to 24 inches of soil would provide sufficient moisture storage and rooting volume in the humid eastern U.S. However, lack of mechanical support could cause tree wind-throw under wet soil conditions. It is felt by tree physiologists that a depth ranging from 30 to 36 inches provides sufficient rooting volume, moisture storage and mechanical support under well- to moderately well-drained conditions. Adequate research documentation on this characteristic is lacking.

Chemical Properties

Nearly all 16 chemical elements (plant nutrients) required by plants to complete their life cycle are supplied by the soil. The three major exceptions are carbon (atmospheric carbon dioxide), hydrogen, and oxygen (the latter two from the splitting of water in the light reaction of photosynthesis). The amount and availability of these nutrients are influenced by such things as: the soil parent material, amount and kind of clay, organic matter content, soil pH, and organism activity.
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Some chemical elements or compounds may be present in the soil which are toxic or noxous to plant growth. These frequently occur in urban soils due to the inherent pollution problems of the urban environment. Road salt and sulfur compounds are examples.

Chemical properties, as contrasted to the physical properties, can be easily manipulated to provide suitable conditions for favorable growth. This can be done by the addition of plant nutrients through fertilization, manuring or composting, and liming. Since soil fertility is an important consideration in urban forest soil management, a separate chapter (Chapter 4) is provided. The material presented here is to provide an introduction to the basic soil factors that influence soil fertility.

Nutrient Elements. Carbon, hydrogen, and oxygen comprise about 90 percent of plant dry matter. The remaining 13 elements are divided into the macro- and micronutrients, based upon the quantities required by plants. The former group includes nitrogen, phosphorus, potassium, calcium, magnesium, and sulfur, while the latter group includes manganese, iron, boron, zinc, copper, molybdenum and chlorine.

The total amounts of these nutrients found in the soil is largely dependent upon the parent material of the soil. If derived from weathered limestone the nutrient content could expect to be high. If the soil is derived from weathered sandstone (mostly silica) or acid shales, the nutrient content of the soil would be low. However, it should be recognized that many tree species do
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not have very high nutrient requirements and grow well on soils that may be unfavorable for other woody species or field crops.

Not all the nutrient content of a soil is available to plants. The compounds containing nutrient elements are varied and complex in their solubilities and reactions. Some portions then are unavailable while other portions are available to plants.

Cation Exchange Capacity. The soil acts as a reservoir for plant nutrients in that the surfaces of clay and organic matter particles are able to adsorb nutrient ions. Here, they are protected against removal by leaching and yet may be exchanged for hydrogen ions by roots or water, the roots then absorbing them. The greater the clay content and/or organic matter content, the greater the cation exchange. The amounts of nutrients stored by a soil is directly related to cation exchange capacity, and in turn, the fertility of the soil. Soils with low clay and organic matter contents such as sands or loamy sands would have low fertility.

Soil Reaction or pH. The hydrogen ion concentration (pH) of the soil solution is a measure of a particular chemical condition in the soil. This condition relates to the availability, hence the chemical form, of many of the plant nutrients. For example, at near neutrality, (pH=7), phosphorus forms the relatively soluble calcium monobasic phosphate. At pH=5.5 or less the phosphorus forms into iron phosphate which is insoluble and unavailable to plants. At pH above 8, the tricalcium phosphate is formed, which is highly insoluble. Other nutrient compounds affected much the
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same way include copper and zinc. Because pH is a measure of base saturation, soluble calcium, magnesium and potassium are indirectly measured by pH, being low at low pH (<6.0) and high above this value. Iron and manganese are soluble and abundant below pH 6.0, but become insoluble above 6.5.

Another major effect of soil pH is that on biological activity and composition. Most soil-inhabiting organisms are very sensitive to changes in pH. Fortunately, the soil is generally well-buffered against wide pH fluctuations unless drastically modified, as may be the case in urban situations. Soil bacteria are favored at pH 6.5 to 7.0, while fungi are favored at pH below 5.5. Actinomycetes and nitrifying bacteria are favored in slightly acid to neutral soils. High soil acidity has been shown to inhibit earthworms. Also, iron, manganese, and aluminum may become toxic in these acid soils.

Thus, the conclusion can be reached that many plants (trees) would prosper in soils slightly acid to moderately acid (5.5 - 6.5). Optimum pH ranges have been developed for most plants and are contained in several standard soil texts. Liming raises pH and use of acid-forming material such as raw organic litter lowers pH. It should be mentioned that pH of soils with high cation exchange capacity would be more difficult to alter.

**Conductance.** This is a measure of the amount of soluble salts in the soil such as chlorides, sulfates, nitrates. When present they raise the osmotic pressure of the soil water. If raised to a critical level, the water cannot be readily absorbed by the plant
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and wilting occurs. In localities where road salt is used to melt ice and snow, salt buildup along streets and highways can be a significant detriment to healthy trees. Normal conductance values for some eastern U.S. soils may range from <.60 to .80 mmhos/cm (Craul and Klein). High values would reach 2.60 mmhos/cm or more. If road salt is not used, conductance can be generally ignored, unless the site is exposed to sea spray, or occurs in an arid or semi-arid region.

Biological Properties

Contrary to widespread belief, the soil is a dynamic living system; thus, the role it plays as a link between the biosphere and the lithosphere. The terrestrial community is very complex, ranging from single-celled organisms to large burrowing animals. The community is characterized by well-defined food chains and competition for survival, consisting of primary producers, consumers, predators, and decomposers, as well as mixers and movers, all involved in the transformation of energy. The primary source of energy is the organic litter deposited and later incorporated into the soil, and the residues of dead plants and animals within the soil itself. As a byproduct of the decomposition (an oxidation process), nutrient elements are released and made available for plant root absorption, especially nitrogen, contributing to nutrient cycling on the site.

Soil Organisms. The organism community may be subdivided and classified in several ways. A convenient one is primarily on the
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basis of size. The microorganisms includes the viruses, bacteria, fungi, actinomycetes as microflora and nematodes, protozoa and rotifers as microfauna. The macro-organisms include earthworms, slugs and snails, mites, ants, beetles, spiders, moles and other mammals as the macrofauna. The roots of higher plants (trees) are considered as macroflora. Particular attention should be paid to the biochemical activity. It should be recognized that the higher plants comprise the primary producers, which utilize sunlight to produce complex organic compounds from inorganic elements. The plant material is fed upon by the microflora (bacteria, algae, etc.) and the fauna which live on dead and decaying plant tissues such as mites, earthworms, insects and small mammals such as mice, shrews and woodchucks. The microflora bring about chemical changes while that of the fauna cause physical breakdown as well as chemical action. These primary consumers are food sources for the secondary consumer such as centipedes, moles, mites, springtails and protozoa. In turn, these organisms are fed upon by the tertiary consumers such as ants, centipedes, and beetles, completing the food chain.

Organic Matter. The substrate attacked by the primary consumers is the dead litter of the soil surface or that incorporated into the upper horizons. By a complex set of reactions, mostly oxidative, the organic matter is decomposed. Large quantities of energy in the form of chemical potential energy and heat are evolved. The highly decomposed residual material is termed
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**Humus.** This substance contributes to the physical and chemical properties in a number of ways, particularly the increases in waterholding capacity and cation exchange capacity and the enhancement of soil structure development. The high humus content of the topsoil gives this material its favorable rooting qualities.

There is a direct correlation between organism activity and organic matter content. Also, fine-textured soils with their greater waterholding capacity and fertility status would have greater organic matter contents than coarser textured soils. Organic matter content tends to offset the detrimental physical effects of both sandy and clayey soils. Farmers, gardeners and nurserymen attempt to maintain organic matter content of their soils at moderate but stable levels. Forest soils generally have greater organic matter contents in the surface horizons than many agricultural or urban soils, as cultivation or other modification tends to increase the decomposition of the organic matter. Forest soils may have organic contents of 10-15 percent where agricultural soils have a range of 2-10 percent, usually somewhere around 5 percent. Many topsoil specifications are written so that organic additives are used to achieve a content near this level. Some specifications require two parts of soil to one part of peat, yielding a very high organic matter content.

**The Rhizosphere.** The roots of the higher plants, especially trees are considered soil organisms because of the effect of their presence in the soil. Exudates rich in nutrients and organic sub-
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stances from the roots create an environment immediately surrounding each root (within about 2 cm) unlike that in the remaining bulk volume of the soil. Here very high concentrations of soil organisms are found and a high level of activity exists. This soil volume under the influence of the roots is called the rhizosphere. Large quantities of energy and nutrients are exchanged between the organisms and the roots, benefiting both groups.

Most plant roots are characteristically infected by members of a group of fungi called mycorrhiza, forming a symbiotic relationship - a relationship that is mutually beneficial. The mycorrhizae act as root extensions and enhance the water and nutrient uptake of the root. The mycorrhizae in turn receive food (mostly carbohydrates) from the host plant. This relationship aids some plants to survive on unproductive soils.

Nitrogen Fixation. Some soil organisms are able to transform gaseous nitrogen from the soil atmosphere into the ammonium and the nitrate forms, making it available to plants. These organisms, mostly bacteria, may exist independent of plant roots as free fixers or are associated with roots in a symbiotic relationship. This nitrogen fixation makes a significant contribution to the nitrogen budget of a site, in addition to that nitrogen which is released through decomposition of organic matter. These nitrogen fixers are quite sensitive to extremes in moisture content, temperature, and pH - conditions frequently encountered in urban soils.
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A discussion on soil biological properties would not be complete without the mention of the fact that some soil organisms are harmful to plant roots giving rise to various diseases and injuries. These maladies arise when soil conditions do not favor the beneficial soil organisms.
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LITERATURE CITED


TREE ROOTS

Root-Top Relationships
Growth and Development
Variations and Misconceptions
Practical Consequences

Thomas O. Perry
THE ECOLOGY OF TREE ROOTS
AND
THE PRACTICAL SIGNIFICANCE THEREOF

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Abstract -- Tree root growth is opportunistic and occurs whenever the environment is favorable. A balance exists between the root system and the remainder of the plant, so that if part of the root system dies, part of the crown will also die. Both parts are connected by a well-developed conduction system. Approximately 99 percent of the roots occur within the surface meter of soil and extend outward over an area one to two or more times the height of the tree. Large woody roots form the framework and are typical in pattern for each species. The fine feeder roots occur in the leaf and litter layer, if present, and the surface mineral soil. Keen root competition occurs at the surface if a turf exists under the tree. Also, herbicides, etc. used on lawns may have detrimental effects on the trees through these fine absorbing roots. In the urban environment roots may follow cracks and crevices in pavements, pipelines, sewers and cables. At the same time the installation of these utilities may cut across established tree root systems with unfortunate consequences.

Introduction

Plant roots, including tree roots, grow in the soil, on the surface of the soil, in the water, and in the air -- wherever the essentials of life are available. Except for the first formed roots which respond to gravity, roots do not grow toward anything or in any particular direction (up, down, or sideways). Root growth is opportunistic and takes place wherever the environment is favorable, typically in soil from which roots obtain water, oxygen,
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minerals (nutrients), support, and warmth. Proper functioning of roots is as essential to the processes of photosynthesis and plant life as are the leaves and chlorophyll-bearing parts of a plant. Typical roots are the sites of synthesis of essential nitrogenous compounds that are transported up through the woody tissues of the plant, along with water and mineral nutrients.

This chapter describes the gross physiology of tree roots in relation to the aerial portions of the plant. The patterns of growth and extent of tree roots and the relationship of typical roots to typical forest soils are illustrated. Then, the behavior of roots in more atypical circumstances is described (in deep sands, in swamps, under pavement, down crevices, in shopping centers, and down sewerlines).

The practical consequences of these root-soil relationships are explored in relationship to human activities. People kill trees in hundreds of ways. Most of the ways involve soil disturbance and ignorance of where roots grow in the soil and what roots do (what function roots perform). The latter portion of this chapter is devoted to describing a few ways tree death is brought about and how the causes can be avoided.

THE RELATIONSHIP BETWEEN ROOTS AND THE REMAINDER OF THE PLANT

Growth of a plant is an integrated phenomenon that depends on a proper balance and functioning of all plant parts. If a large
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portion of the roots are killed, a corresponding portion of the leaves and branches will die. If a tree is defoliated repeatedly, some of its roots will die. The finest roots of a tree are connected to the leaves by an elaborate plumbing system of larger transport roots, trunk, branches, and twigs. Many researchers have weighed and estimated the proportions of plant parts (for examples of early work: Moller 1945, Ovington 1957, Baskerville 1965, 1966, Duvigneaud and Denayer-DeSmet 1970). Weighing and counting every root tip and every leaf is a heroic if not impossible task, and sampling is essential to making estimates. Sampling errors and variation among species produce variable results. However, the biological engineering requirements of plants are apparently similar, and the relative proportions of both mature herbs and mature trees are of the same order of magnitude: ±5% of fine or feeder roots, ±15% of larger or transport roots, ±60% of trunk or main stem, ±15% branches and twigs, and ±5% leaves (Bray 1963, White et al. 1971, Meyer and Gottsche 1971).

A tree possesses many thousands of leaves and correspondingly hundreds of kilometers of roots with hundreds of thousands of root tips. The numbers, lengths, and surface areas of roots per tree and per hectare are huge. Plant scientists try to make the numbers comprehensible by talking about square units of leaf surface per unit of land surface -- the "leaf area index". If both sides of the leaf are included, the leaf area index of a typical forest or

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typical crop is about 12 during the height of the growing season (Moller 1945, Watson 1947 and many modern texts on crop physiology). The leaf area index of pines is commonly calculated by multiplying the length of the needles by their circumference.

The number of square units of root surface per unit of land surface, the "root area index" can be calculated approximately from studies that report the number of grams of roots present in a vertical column of soil. Such data are determined by taking core samples or digging out successive layers of soil and screening and sorting the roots and determining their oven dry weights. The quantity of roots decreases rapidly with increasing depth in normal soils, so that 99% of the roots are usually included in the surface meter of soil (Coile 1937 and others). A reasonable approximation for non-woody tissues is that the oven-dry weight is 0.1 of the fresh weight and that the density of fresh roots is very close to one. If one makes these assumptions for Lelbank et al.'s (1974) data for winter wheat (Triticum aestivum) and for Braekke and Kozlowski's (1977) data for red pine (Pinus resinosa) and paper birch (Betula papyrifera), the calculations indicate a root area index between 15 and 28. E. W. Russell's data (1973) are of the same magnitude. The surface of the root system concealed in the soil can be greater than the surface of the leaves! Nearly all tree roots are associated with symbiotic fungi (mycorrhizae) that
grow out and functionally amplify the effective surface of the finer roots a hundred times or more.

The pattern of conduction between the roots and leaves of a tree varies between and within species. Injection of dyes and observation of their movement indicates that, in oaks and other ring porous species, a given root is directly connected to a particular set of branches usually on the same side of the tree as the root. (Zimmermann and Brown 1971, Kozlowski and Winget 1963). Death or damage to the roots of trees with such restricted, one-sided plumbing systems usually results in death of the corresponding branches. Other species possess different anatomies in which dyes ascend in zigzag and spiral patterns, indicating that the roots of the tree serve all of the branches and leaves (see Figure 2.1 from Rudinski and Vite 1959). Death or injury to the roots of such trees does not lead to a one-sided death in the crown of the tree. The anatomy of trees can vary within species, and the patterns of connection between the roots of most species is not known. Sometimes the pattern can be detected by examining the pattern of bark fissures which usually reflects a corresponding pattern in the woody tissues concealed beneath the bark. Knowledge of the pattern of conduction between roots and leaves is of practical importance in predicting the results of treating trees with fertilizers, insecticides, and herbicides or in predicting the results of one-sided injuries to trees during construction.
Figure 2.1. Five types of water-conducting systems in various conifers as shown by the tracheidal channels that were dyed by trunk injection. The numbers give the height in centimeters of the transverse section above injection. A. Spiral ascent, turning right: Abies, Picea, Larix, and Pinus (Rehder's section 3: Taeda). B. Spiral ascent, turning left: Pinus (Section 2: Cembra). C. Interlocked ascent: Sequoia, Libocedrus and Juniperus. D. Sectorial, winding ascent: Tsuga and Pseudotsuga. E. Sectorial, straight ascent: Thuja and Chamaecyparis. From Rudinski and Vite 1959, Courtesy of Boyce Thompson Institute for Plant Research. Oaks and many ring porous species have a pattern similar to E.
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PATTERNS OF GROWTH AND DEVELOPMENT OF TYPICAL ROOTS IN TYPICAL SOILS

Early observations of tree roots were limited to examining the taproot and larger roots close to the trunk of the tree, or examining the vertical distribution of severed roots exposed by digging trenches and pits (Busgen and Munsch 1929, Coile 1952, Garin 1942, Rohm 1979). Attempts to examine the depth and extent of the system of larger roots of an entire tree were not really possible until bulldozers, back hoes, front-end loaders, and fire pumps became available (see for example Stout 1956, Berndt and Gibbons 1958, and Kostler et al. 1968). Most tree roots are less than 1 mm in diameter and are destroyed by the rough action of back hoes and fire hoses.

Examination of the small, non-woody roots of trees and their relationship to the larger roots requires years, infinite patience, and the gentle use of tweezers, fingers, small brushes, sharp implements and an ear syringe, plus the back hoes, fire hoses and other heavy equipment. Lyford and his colleagues (Lyford and Wilson 1964, Lyford 1975, Pritchett, and Lyford 1977, Lyford 1980) were among the first to combine tweezers and patience with bulldozers and haste to develop a comprehensive picture of the normal patterns of root development for trees growing in natural situations. Lyford's papers contain over 50 references to earlier literature on tree roots. These references plus the following
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books cover the recent literature on plant roots in general and tree roots in particular: Kostler et al. 1968, Bohm 1979, Torrey and Clarkson 1975, Russell, R. S. 1977, Russell, E. W. 1973. The following description of tree roots is a synthesis of these and other publications plus personal observations and conforms closely with the descriptions of Lyford.

Tree roots vary in size from woody roots 30 cm (12 in) or more in diameter to fine, non-woody roots less than 0.2 mm (0.008 in) in diameter. The variation in size form large to small, and the variation in categories from woody to non-woody, perennial to ephemeral, and absorbing to nonabsorbing is continuous. This continuous variation makes the sorting of roots into various categories arbitrary. Classification and sorting is nonetheless essential to comprehending the pattern and integrated function of the total root system.

The first root (or radicle) to emerge from the germinating seed of some species (pines and oaks for example) sometimes persists and grows straight down into the soil to depths of 1 to 2 meters (3 to 7 ft) or more until supplies of oxygen become limiting. If this "taproot" persists, it is usually largest just beneath the tree trunk and decreases rapidly in diameter as secondary roots branch from it and grow radially and horizontally through the soil. The primary root of other species (spruces, willows, and
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poplars, for example) does not usually persist. Instead a system of fibrous roots dominates early tree growth and development.

Between four and eleven major woody roots originate from the "root collar" of most trees and grow horizontally through the soil. Their points of attachment to the tree trunk are usually at or near the groundline and are associated with a marked swelling of the tree trunk (see Figure 2.2). These major roots branch and decrease in diameter over a distance of 1 to 4 meters (3 to 15 ft) from the trunk to form an extensive network of long, rope-like roots 10 to 25 mm (.25 to 1 in) in diameter. The major roots and their primary branches are woody and perennial, usually show annual growth rings, and constitute the framework of a tree's root system. The general direction of the framework system of roots is radial and horizontal.

In typical clay-loam soils, these roots are usually located less than 20 to 30 cm (8 to 12 in) below the surface and grow outward far beyond the branch tips of the tree. The system of framework roots, often called "transport" roots, extends frequently to encompass a roughly circular area four to seven times the area delineated by an imaginary downward projection of the branch tips. It is not uncommon to find trees with root systems having an area with a diameter one, two, or more times the height of the tree (Stout 1956, Lyford and Wilson 1964).
Figure 2.2. Plan view diagram of the horizontal woody root system developed from a single lateral root of red maple about 60 years old. Solid circles show the location of other trees in the stand. Arrows indicate that the root tips were not found and therefore these roots continue somewhat farther than is shown. (From Lyford and Wilson 1964).
In drier soils, pines and some other species can form "striker roots" at intervals along the framework system. These striker roots grow vertically downward until they encounter obstacles or layers of soil with insufficient oxygen. Striker roots and tap-roots often branch to form a second, deeper layer of roots that grow horizontally just above the soil layers where oxygen supplies are insufficient to support growth (see Figures 2.4 and 2.5).

The zone of transition between sufficient and insufficient oxygen supply is usually associated with a change in the oxidation-reduction state and color of the iron in the soil (from reddish yellow to grey for example). Water can hold less than 1/10,000 as much oxygen as air, and limited supplies of oxygen are usually associated with wet soils. Drainage ditches in swamps reveal an impressive concentration of matted roots just above the permanent water table (see Figure 2.6).

A complex system of smaller roots grows outward and predominantly upward from the system of framework roots. These smaller roots branch four or more times to form fans or mats of thousands of fine, short, non-woody tips (see Figures 2.2, 2.3, 2.7, 2.8, 2.9). Many of these smaller roots and their multiple tips are 0.2 to 1 mm or less in diameter and less than 1 to 2 mm long. These fine, nonwoody roots constitute the major fraction of the surface of the root system of a tree. Their multiple tips are the primary
Figure 2.3. Schematic diagram showing reoccupation of soil area near the base of a mature tree by the growth of adventitious roots.  
1. Root fans growing from the younger portions of the woody roots which have extended to a distance of several meters from the tree.  
2. Root fans on adventitious roots only recently emerged from the zone of rapid taper or root collar and now occupying the area near the base of the tree.  
Figure 2.4. Drawing, not to scale, of framework system of longleaf pine tree grown in well drained soils with a second layer of roots running in the soil layers where oxygen supplies become limiting.
Figure 2.5. Photograph of framework roots of longleaf pine including striker roots. 90% of the surface root system has rotted and washed away (Kerr Lake, Corps of Engineers, North Carolina).
Figure 2.6. Mat of roots above the permanent water table exposed by digging a drainage canal. Green Swamp, North Carolina. A few species have specialized tissues containing air passages and specialized metabolisms that permit their roots to penetrate several feet below the permanent water table where there is inherently little or no oxygen. Iron oxide deposits are typically associated with such roots.
Figure 2.7. Schematic diagram showing woody and non-woody root relationships. 1. Stem. 2. Adventitious roots in the zone of rapid taper. 3. Lateral root. 4. Non-woody root fans growing from opposite sides of the rope-like woody root. 5. Tip of woody root and emerging first order non-woody roots. 6. Second and higher order non-woody roots growing from the first order non-woody root. 7. Uninfected tip of second order non-woody root with root hairs. 8. Third order non-woody root with single bead-shaped mycorrhizae. 9. Fourth order non-woody root with single and necklace-beaded mycorrhizae. The horizontal bar beneath each root section represents a distance of about 1 cm. (Lyford and Wilson 1964).
Figure 2.8. Scale diagrams of a horizontal woody third order lateral with particular emphasis on the roots that return to the surface and elaborate into many small diameter non-woody roots in the forest floor. Top view (above), side view (below). The squares are 1 m on a side. Species: red oak (*Quercus rubra* L.). From Lyford 1980.
Figure 2.9. Photograph of roots intermingling in the soil. Mixed hardwood stand. Harvard Forest, Petersham, Mass. The roots in front of the trowel have been exposed by careful brushing and pulling away of the litter. Many hours were required. The roots in the background were exposed by digging down and destroying the fine surface roots in the process. The roots have been sprayed with whitewash to make them stand out. Lyford's work. Photo by Perry.
Tree Roots

sites of absorption of water and minerals. Hence they are often called "feeder roots".

Root hairs may or may not be formed on the root tips of trees. They are often shriveled and non-functional.

Symbiotic fungi are normally associated with the fine roots of forest trees, and their hyphae grow outward into the soil to multiply greatly the effective surface of the root system (see Figure 2.10).

The surface layers of soil frequently dry out and are subject to extremes of temperature and frost heaving. The delicate, non-woody root system is killed frequently by these fluctuations in the soil environment. Nematodes, springtails, and other members of the soil microfauna are constantly nibbling away at these succulent, non-woody tree roots (Lyford 1975). Injury to and death of roots is frequent, and is caused by many agents. New roots form rapidly after injuries, so the population and concentration of roots in the soil is as, or more dynamic than, the population of leaves in the air above.

The crowns of trees in the forest are frayed away as branches rub against each other in the wind. The frayed perimeter of each tree crown is observed easily when one gazes skyward through the canopy of a mature forest. No such clear perimeters for root areas exist in the soil. Roots normally extend far beyond the branch tips and the framework root systems of various trees cross each
Figure 2.10. Photograph of root tips growing in the litter of a mixed hardwood forest. The mycorrhizae extend out from the root tips to greatly expand the functional surface area of the roots. Photo by Ted Shear, NCSU. Root diameters about 0.5 mm.
other in a complex pattern. The non-woody root systems of different trees can intermingle with each other so that the roots of four to seven different trees can occupy the same square meter of soil surface (see Figure 2.9).

Injuries, rocks, and other obstacles can induce roots to deviate 90° or more from their normal pattern of radial growth. These turnings and interminglings of roots make determination of which roots belong to which tree extremely difficult. Furthermore, natural root grafts commonly occur when many trees of the same species grow together in the same stand.

In brief, large, woody tree roots grow horizontally through the soil and are perennial. They are predominantly located in the top 30 cm (12 in) of soil and do not normally extend to depths greater than 1 to 2 meters (3 to 7 ft). They often extend outward from the trunk of the tree to occupy an irregularly shaped area four to seven times the larger than the projected crown area and having an average diameter equivalent to one, two, or more times the height of the tree. Typically, the fine, non-woody tree roots grow upward into the litter and the top few millimeters of the soil, are multiple-branched, and may or may not be ephemeral.
WHY ROOTS GROW WHERE THEY DO

Roots grow where the resources of life are available. They do not grow to or toward anything. They cannot grow where there is no oxygen or where the soil is compacted and hard to penetrate.

The number of soil pores and the availability of oxygen decreases exponentially with depth below the surface, the amount of clay (fine textured material), and resistance to penetration (hardness) which increases with soil depth.

Frost action and alternate swelling and shrinking of soils between wet and dry conditions tend to heave and break up the soil's surface layers. Organic matter from the decomposing leaf litter acts as an energy supply for nature's plowmen: the millions of insects, worms, nematodes, and other creatures that tunnel about in the surface layers. The combined effect of climate and tunneling by animals is to fluff the surface layers of an undisturbed forest soil so that more than 50% of its volume is pore space. Air, water, minerals, and roots can penetrate this fluffy surface layer with ease.

The decomposing leaf litter also binds cations and functions to trap plant nutrients and prevent their leaching into the deeper layers of soil. Soil analyses show that the surface layers contain the highest concentration of available nutrients (Woods 1957, Hoyle 1965).

Finally, evaporation and transpiration during the early growing season quickly depletes the moisture available in the upper
Tree Roots

several feet of soil. Summer rains in temperate climates of the world are usually less than 10 mm (0.4 in) and only wet the surface layer of soil (Woods 1957).

So, the greatest supplies of materials essential to plant life are located in the very surface layers of the soil. This is where most of the roots are located.

Variations

Roots are most abundant, and trees grow best in light, clay-loam soils about 80 cm (3 ft) deep (Coile 1937, 1952). Root growth and tree growth are restricted in shallow or wet soils or in soils that are excessively drained.

Roots can and do grow to great depths -- 10 meters (30 ft) and more -- when oxygen, water, and nutrients are available at these depths. Tree roots can grow down several meters in deep, coarse, well-drained sands. However, in these cases, overall plant growth is slow, and trees tend to be replaced by shrubs on topographies and soils that are drained excessively.

Pines and other trees tend to develop a two-layered root system in the deep sands of the Southeastern U.S. and other parts of the world: a surface layer of roots that absorbs water and nutrients made available by the intermittent summer rains, and a deep, second layer of roots that allows survival under conditions of drought.
Tree Roots

Some soils of the western United States are very new, deep, and unstructured, originating from the downslope movement of coarse particles of rock. Such deposits can form a layer 10 meters (30 ft) or more deep and are extremely dry -- especially on the west slope of the Sierras where summer rains are light and infrequent. Most water in the soils of this region originates from winter rains and snow-melt that travel along the surface of the unbroken bedrock. Seedling mortality in such climates is extremely high, and years with sufficient moisture to permit initial survival are infrequent. Growth takes place predominantly in the early spring, and those trees that manage to survive and grow in the area are characterized by a tap root system that plunges down and runs along the soil-rock interface. Deep cuts for superhighways sometimes reveal these roots 15 meters (40 ft) or more below the surface.

Some trees, like longleaf pine (Pinus palustris), have special adaptations to insure survival and growth on sands and other deep soils. During the initial stage of establishment, the tops of longleaf pine seedlings remain sessile and grass-like for four or more years while the root system expands and establishes a reliable supply of water. Only then does the tree come out of the "grass stage" and initiate height growth.

Spruces, willows, and other species grow characteristically on wet sites where oxygen supplies are very limited. Their root systems are shallow and multiple-branched.
Tree Roots

Tupelo, cypress, and other species of the swamps and floodplains have evolved special anatomies that permit conduction of oxygen 30 cm (12 in) or more below the surface of the water and special metabolisms that eliminate alcohols, aldehydes, and other toxic substances produced when fermentation replaces normal respiratory metabolism. Many such floodplain species can survive the low soil oxygen caused by flooding for several months (Hook et al. 1972). Other species, particularly cherries and other members of the rose family, are especially sensitive to conditions where oxygen supplies are limiting. Cherry roots contain cyanophoric glucosides, which are hydrolized to form cyanide when oxygen supplies are limiting (Rowe and Catlin 1971). Flooding of less than 24 hours killed most of the Japanese cherry trees around Hains Point in Washington, D.C. after hurricane Agnes in 1973. Sediment build-up contributed to this mortality and in some locations exceeded 20 cm (8 in).

There are important genetic differences in the capacity of tree species and varieties to germinate, survive, grow, and tolerate variations in soil chemistry, structure, oxygen supply or excessive drainage or flooding (Perry 1978). The distribution of trees in the landscape is not random.

There is no such thing as a "shallow rooted" or a "deep rooted" species of tree. Cypress, tupelos, maple, and willow trees will grow down deeply into the soil, down cracks, and down sewer
Tree Roots

lines if oxygen and water supplies are adequate. The roots of pines, hickories and other upland species will follow along the surface if the soil is too compact and hard or if oxygen supplies are limited to the surface.

Roots grow parallel to the surface of the soil so that trees on slopes have sloping root systems. Roots often grow along cracks, crevices, and through air spaces for unbelievable distances under the most impermeable pavements and impenetrable soils (Figure 2.11). Roots commonly grow down cracks between fracture columns ("peds") in heavy clay soils that they could not otherwise penetrate.

THE MAJOR SOURCE OF MISCONCEPTIONS ABOUT TREE ROOTS

The rope-like roots at or near the surface of the soil have been obvious to diggers of holes for fenceposts and ditches for thousands of years -- as obvious as Galileo's "shadow of the earth on the moon". However, trees are huge -- larger than the biggest whale. Individual leaves and roots are extremely small in relation to the whole tree. Very few human beings have had the privilege of actually seeing even a comprehensible fraction of the root system of an entire tree. Illustrations in textbooks, natural history books, and in manuals of landscape architecture and tree care are usually creations of artistic imagination and are usually terribly wrong (see Figure 2.12 for example).
Figure 2.11. Roots growing in crevices of bricks. There was no oxygen below the bricks which overlie a compact clay on the N.C. State University Campus. Tree roots commonly follow cracks and crevices or air passages under pavement.
Figure 2.12. Roots do not grow as this artist's conception indicates. Inaccurate illustrations like this one have led to harmful practices in the management of trees in both forest and urban situations. Illustration from a brochure of the Society of American Foresters.
An insurance company heard of Lyford's work on tree roots and wanted to use an idealized picture of tree roots solidly penetrating into the depths of the soil and securely anchoring the tree in an upright position as the symbol of the security their customers would achieve by purchasing their insurance. The company commissioned an artist to visit Walter Lyford, examine his findings, and prepare an appropriate logo of tree roots for them and their advertising campaigns. The projected logo and advertising scheme was never started. It is impossible to accurately portray or represent an entire tree with its roots on the page of a typical textbook. The problems of scale are overwhelming and can be appreciated by examining Figures 2.13 and 2.14 and Table 2.1. A typical typeface of a letter 0 is 2.5 mm (.1 in) high and 2 mm (.08 in) wide with the thick portion of the print being 0.4 mm (.016 in) while the thin portion is 0.3 mm (.012 in). The finest lines in a textbook drawing are 0.2 mm (.008 in) -- about the average diameter of a typical "feeder root" (a human hair is 0.008 inches in diameter).

A healthy, open-grown oak tree, 40 years old, has a trunk 70 feet (21 m) tall and 2 ft (.6 m) in diameter. The spread of the branches of an open grown tree is rarely less than two-thirds of the height of the tree and is often equal to or greater than the height. The leaf bearing surface of the tree extends to within 10 to 20 ft (3 to 6 m) of the ground, and a typical branch forks four to five times from its origin to the smallest twigs. As described
Figure 2.13. Scale drawing of Memorial Oak Tree, Schenck Forest, North Carolina State University. The original drawing was made by tracing the projected image of the tree (Figure 2.14) onto a piece of 8.5" x 11" paper. A #2 Rapidograph pen point was used to produce a line 0.4 mm thick. This is the thinnest line that can be reasonably reproduced in publications. The original drawing was 24 cm or 9.45" wide and represents a typical root spread of 212 ft. The Schenck Oak is ±106' tall and is represented on the vertical axis as 12 cm of 4.72". The original drawing represented a 274 fold reduction in the actual height of the tree. Further reduction would be required to represent the tree on a normal textbook page. Most branches and tree roots would not be visible if drawn to this scale. The width of a typical white oak leaf would be about the thickness of the lines in the drawing. Ninety percent of the tree roots would not be visible at this scale. Most of the roots of the tree would be located in the soil layer represented by the thickness of the line representing the soil surface. The dash dot line is located 5' below the surface and very few if any roots would penetrate beyond this depth in a representative soil.
Figure 2.14. This photograph of the Schenck Memorial Oak was projected and traced to produce Figure 2.13. The Schenck Memorial Oak is 106' tall and has a crown spread of 94 ft. and a DBH of 42". The tree is a white oak.
Tree Roots

previously, root spread of a typical, open-grown tree is usually greater than 30 (9 m) ft beyond the tips of the branches and can commonly extend in a circle with a diameter two or more times the height of the tree. Table 1 gives the typical sizes of the leaves, branches, trunk, and roots of a open-grown oak tree. The figures in the table assume a root spread of 130 ft (40 m) 70 ft (21 m) of crown spread + 2 x 30 ft (9 m).

Illustration of a tree in proper scale with a textbook held in its upright position would require a 317:1 reduction in the dimensions of all parts. Lines representing the fine roots of a tree would be only $6 \times 10^{-4}\text{mm}$ or $0.6\ \mu\text{m}$ ($0.2\ \text{mm}\ 1/317$). If it were practical to print a line so fine it would be barely visible with the best quality light microscope. A tree part must have dimensions of at least $0.2\ \text{mm} \times 317 = 63.4\ \text{mm}$ (2.5 in) in order to be visible on a printed page with a minimum line thickness of 0.2 mm.

THE PRACTICAL CONSEQUENCES OF IT ALL

A significant portion of the root system of all trees in all soils is concentrated in the top few millimeters of soil. Indeed, tree roots grow right in the litter layer of the forest, in among the grass roots of a city lawn, and in the crevices of the bricks, concrete, and asphalt of city pavements (Figures 2.11 and 2.15).

Fertilizer broadcast on the surface of the soil is immediately available to tree roots. It does not have to move down into the soil. Even the reportedly immobile phosphates are immediately
Table 2.1. Tree dimensions and the problem of scale. Representative dimensions for an open-grown oak tree, 40+ years old.

<table>
<thead>
<tr>
<th>Plant Part</th>
<th>Dimension in ft</th>
<th>Dimension inches</th>
<th>Dimension mm</th>
<th>mm Dimension x 1/317</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tree Ht</td>
<td>70</td>
<td>840</td>
<td>21336</td>
<td>67</td>
</tr>
<tr>
<td>Trunk DBH</td>
<td>2</td>
<td>24</td>
<td>610</td>
<td>1.9</td>
</tr>
<tr>
<td>Crown Width</td>
<td>70</td>
<td>840</td>
<td>21336</td>
<td>67</td>
</tr>
<tr>
<td>Crown Length</td>
<td>55</td>
<td>660</td>
<td>16764</td>
<td>52</td>
</tr>
<tr>
<td>Root Spread</td>
<td>130</td>
<td>1560</td>
<td>39624</td>
<td>125</td>
</tr>
<tr>
<td>Leaf</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blade Width</td>
<td>0.25</td>
<td>3</td>
<td>80</td>
<td>.25</td>
</tr>
<tr>
<td>Blade Length</td>
<td>0-5</td>
<td>6</td>
<td>160</td>
<td>.50</td>
</tr>
<tr>
<td>Main Branch</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thickness Range</td>
<td>1→+.23</td>
<td>12→2.8</td>
<td>300±→70±</td>
<td>.94→.22</td>
</tr>
<tr>
<td>Length 2/3 Crown</td>
<td>23.3±</td>
<td>280±</td>
<td>7102</td>
<td>22</td>
</tr>
<tr>
<td>2nd Order Branch</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thickness Range</td>
<td>.23→.07</td>
<td>2.8→+.8</td>
<td>70±→20±</td>
<td>.22→.063*</td>
</tr>
<tr>
<td>Length 1/3 Crown</td>
<td>23.3</td>
<td>592</td>
<td>7112</td>
<td>22</td>
</tr>
<tr>
<td>3rd Order Branch</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thickness Range</td>
<td>.07→.03</td>
<td>.8→.4</td>
<td>20→10</td>
<td>0.063*→0.032*</td>
</tr>
<tr>
<td>Length 1/4 Crown</td>
<td>17</td>
<td>210</td>
<td>5334</td>
<td>16.8</td>
</tr>
<tr>
<td>Twigs</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thickness Range</td>
<td>8x10^{-3}→16x10^{-3}</td>
<td>1→.2</td>
<td>5→3</td>
<td>0.015*→0.0094*</td>
</tr>
<tr>
<td>Length</td>
<td>.66</td>
<td>8±</td>
<td>200±</td>
<td>.63</td>
</tr>
<tr>
<td>Main Roots</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thickness Range</td>
<td>8</td>
<td>8±→2±</td>
<td>200±→50±</td>
<td>.63→.16</td>
</tr>
<tr>
<td>Length</td>
<td>10±</td>
<td>120</td>
<td>300±</td>
<td>.94</td>
</tr>
<tr>
<td>Rope-Like Roots</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thickness Range</td>
<td>0.0833</td>
<td>1±</td>
<td>30±→10±</td>
<td>0.094*→.032*</td>
</tr>
<tr>
<td>Length</td>
<td>65±</td>
<td>780±</td>
<td>19812±</td>
<td>62</td>
</tr>
<tr>
<td>Non-Woody Roots</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Thickness Range</td>
<td>6x10^{-4}→1.5x10^{-3}</td>
<td>0.008→0.19±</td>
<td>.2±→.5±</td>
<td>1.5x10^{-3}→6.3x10^{-2}</td>
</tr>
<tr>
<td>Length</td>
<td>0.04</td>
<td>0.5&lt;</td>
<td>10&lt;</td>
<td></td>
</tr>
</tbody>
</table>

*Too fine to reproduce in a line drawing.

1The dimensions that would appear in a line drawing scaled to fit the page of a typical textbook (6 in x 9 in or 155mm x 230mm). A 317:1 reduction would be required to make a properly scaled illustration. The problem is nearly as difficult for herbs.
Figure 2.15. Many roots of trees grow closely intermingled with grass roots - right in the surface millimeters of a lawn. Fertilizers and herbicides do not have to move in the soil in order to affect trees.
available to tree roots. That is why Himelick (1965) and van de Werken (1981) were unable to show any differences in the response of trees to fertilizer placed in holes or broadcast on the surface. Foresters broadcast fertilizers on millions of acres of land and achieve rapid and large returns on their investments. Except where slow release fertilizers are used for special effects, there is no justification for "tree spikes" or other formulations of fertilizer in holes bored in the ground or for injecting fertilizer into the soil.

Herbicides and other chemicals should be used only with extreme care near trees and shrubs. Again; many tree roots are in and near the surface of the soil and extend far beyond the tips of the branches of the tree tips. Trees are really "broad leaved weeds" when they grow in a lawn and application of "Dicamba" (also called "Banvel") alone or in combination with other herbicides ("Trimek" for example) or in combination with fertilizers will injure trees. This chemical or its formulations, when improperly applied, can distort and discolor leaves and even defoliate and kill trees. Several tree and lawn care expert companies are selling these chemicals mixed with fertilizer at home garden centers or are applying the chemical on a contract basis. Improper use of Dicamba will distort the leaves of oaks and sycamores and defoliate and kill more sensitive trees like yellow poplar.

"Roundup" herbicide and its formulations are supposedly inactivated when they hit the soil or dirty water, but do not have
Tree Roots

to penetrate the soil to interact with tree roots growing in a litter layer, lawn, or mulch. Dogwoods and other trees may show extreme leaf distortion and crown dieback even when herbicides do not strike the green portions of their trunks or their foliage. More research needs to be done before this promising herbicide is used by homeowners or is used by foresters as a broadcast spray to kill understory vegetation.

Remember, root grafts are common among trees of the same species. Trees of many species (oaks, poplars, sweet gum, for example) send up sprouts from their roots. Herbicides applied to kill one tree will flash back along root grafts to kill trees that were not treated.

Roots grow in cracks and crevices of pavement. Applications of valpar, bromacil, and other sterilants and herbicides to kill weeds in these situations can kill trees 20 meters (60 ft) or more away from where they are applied (Figure 2.15).

Larger residential lots are 32 meters wide by 46 meters deep (105 ft x 150 ft). The roots of a large tree will commonly occupy the entire front or back yard and trespass into the neighboring property. No part of an urban yard can be treated carelessly with herbicides.

Care must be taken in disposing of toxic chemicals, deicing salts, old crank case oil, and high strength detergents. Careless
Tree Roots

and improper disposal of chemicals and improper use of herbicides is one of the most common causes of tree deaths in urban areas.

The largest single killer of trees is soil compaction -- compaction from excessive use of city parks by people and pigeons whose small feet exert greater pressure than heavy machines (see chapter 3). Trees are also killed by compaction from construction equipment, compaction from livestock including zoo animals, and compaction in unpaved parking areas. Compaction closes the pore spaces which are essential to the absorption of water and oxygen; hardens all but the sandiest of soils so that roots cannot penetrate them -- even when oxygen supplies are adequate (Patterson 1976).

Excessive use of mulch can induce fermentation, immobilize nutrients, cut off the oxygen supply, and kill trees. Use of broad expanses of plastic as a mulch, under mulch, or under pebble and bricks or other materials is a sure way to cut off oxygen supplies and kill trees (see chapter 5).

The maximum leaf area index that a normal ecosystem can support is about 12 (when both surfaces of the leaf are counted). There is a corresponding maximum root area index, probably between 25 and 30. Gardening under trees, planting lawns, daffodils, liriope, or azaleas and rhododendrons, tears up tree roots and will produce a corresponding death of twigs and branches in the crown of the tree. A large leaf area and root area index of grass, bedding plants, or shrubs demand a corresponding reduction in the root area.
and leaf area of trees. Gardening is another common cause of tree death in urban situations. Gardeners should be aware of the biological compromises they must make to achieve a proper balance between trees and garden plants.

It should be obvious that any grading or other activity that buries or cuts off tree roots will result in the death of a corresponding portion of the branches in the tree. Yet this simple fact is ignored when utility lines, parking lots, and even irrigation lines are being installed. Smearing six inches of B-horizon clay over the root system of an established tree is usually as lethal as covering its roots with pavement or cutting it down with a chain saw. Even a one-quarter inch soil covering can cause root mortality.

A residential yard in a new development may have six different ditch-witch lines cut from the street to the house: for water, for sewer, for electricity, for telephone, for gas, and for cable television. Over 90 percent of the roots in the front yard are destroyed in construction and utility line installation, and the soil structure in the entire yard is usually completely destroyed by compaction and the spreading of excavated heavy soil on top of undisturbed soil. The proud new homeowners wonder why all of their trees have severe crown dieback and continue to decline and die for a decade or more after they move in. It is because the builders and all the utility people cut off 90 percent of the roots, mis-
Tree Roots

treated the soil, and because the new owners tore up the rest of the roots to plant a lawn and garden.

People often try to save trees under impossible circumstances. The root systems of a large tree often occupy the entire building site and it is impossible to complete development without damaging some or all of its roots. Tunneling and concentrating utility line installations and other techniques can minimize this damage. Careful watering and thinning of the tree crowns to compensate for root losses can allow the residual roots time to supply extra water and nutrients while new roots grow and become established. There are other techniques that require a general knowledge of physiology that are beyond the topics covered in this chapter. It is often wise and cheapest to accept the situation and cut down the tree and plant a new one. Tree surgery and tree removal, after construction is complete and crown dieback is obvious, can cost hundreds of dollars per year and require annual investments for ten or more years after construction.

Surprisingly, soil compaction and limited oxygen supplies are the major restraints to growing trees in city parks and highly paved areas. Inadequate supplies of water are usually secondary to these fundamental problems. Compact soil and lack of oxygen make tree species adapted to swamps and flood prone areas the very best ones to use in city parks and along city streets (pin oak, willow oak, sycamore and honey locust, for example). Different trees grow
Tree Roots

on different sites in nature, and it is not reasonable to expect species adapted to upland or sloping topography to possess roots that grow well in the compacted soils of a heavily used recreation area, a residential clothes yard, or in areas with lots of pavement.

There are hundreds of expensive ways to kill or injure trees. They range from zapping them with laser beams (in the Omni shopping mall of Atlanta) to girdling them with the grinding tugs of chained dogs left outside of college classrooms. Most tree deaths are accidental and involve misconceptions about tree roots. Why else would the city of New Orleans keep a rhinoceros caged on the root system of its symbolic Centennial Oak? Why else would the State of North Carolina use a ditch-witch in late June to install an irrigation system among the stately trees of the old Capitol building? Why else would the National Capital Parks allow rows of newly planted, expensive, 8-inch-caliper trees to remain unwatered in front of the new Aerospace Center while the need for irrigation was obvious and abundantly supplied on the mall across the street?

The expansive root systems of trees grow in every crevice of the nearby pavement and trespass into sewers and across property lines. People must know where their roots are if trees are to be a gratifying part of the urban environment.
Tree Roots

LITERATURE CITED


Tree Roots


Tree Roots


2-43
SOIL COMPACTION

Effects on Soil Properties

Effects on Roots and Trees

Causes

Prevention and Amelioration

James C. Patterson

and

Donald L. Mader
ABSTRACT -- Compaction of soil by pedestrians, vehicles, and construction activities is common on soils supporting urban trees. Soil hardness and poor aeration restrict root growth and function, causing stress which can result in poor vigor or mortality of trees. Organic matter content and texture of soils affect compactability. Good design and planning can reduce or eliminate many compaction problems. Proper soil amendments from various organic and inorganic materials can improve or maintain structure and aeration in areas subject to compaction. Appropriate management programs should be designed and implemented to avoid compaction and preserve the health of urban trees.

Soil compaction is a universal problem for urban foresters and others responsible for management of urban vegetation. High intensity traffic from pedestrians and vehicles, coupled with never-ceasing construction activities, inevitably compacts and degrades the upper soil layers in many places and contribute to poor vigor and health of urban trees. In most cases the impacts on the soil could be avoided or greatly reduced, thereby preserving aesthetic values and physical amenities (shade, etc.), as well as minimizing
Soil Compaction

costs for removal and replacement of sick or dead trees. This chapter summarizes the wide knowledge about soil compaction, its effects on trees and how that knowledge can be most effectively brought to bear on urban tree management.

WHAT ARE THE PHYSICAL AND CHEMICAL CHANGES CAUSED BY SOIL COMPACTION?

In most cases, soil compaction results from forces exerted on the surface of the soil, which sometimes is subsequently covered over. These forces compress the soil, change the soil structure, and reduce the pore space. The large or macropores, which are air-filled when the soil is at maximum waterholding capacity, tend to be crushed to smaller sizes (Legg and Schneider 1977). Macroporosity tends to be destroyed by the first footprint (Patterson 1976). Smaller capillary pores are less affected in most cases. Because pore space is reduced, the bulk density, or weight per unit of volume, is increased by compaction (Patterson 1976, Legg and Schneider 1977). The bulk density in natural surface mineral soil in forests ranges from about 0.5 to 1.3 g/cubic centimeter (cc), and in subsoil layers from 1.0 to 1.4 g/cc. Very dense pans or compact subsoils range from 1.5 to about 2.0 g/cc. Heavily compacted soils may range from about 1.3 to 2.2 g/cc., depending on texture and organic matter content.

Soil structure tends to be degraded by compaction and a structureless or massive condition results. The latter breaks into plates when disturbed. The resistance and hardness of the soil increase greatly with severe compaction.
Soil Compaction

The effects of compaction on the moisture storage properties of the soil can vary. If the main effect on pore space is to change macropores to micro- or capillary pores, which store water, the storage capacity may be increased (Rosenberg 1964). But, if the soil contains mostly micropores and these are reduced in size by compaction, the moisture storage capacity will be reduced. If both processes occur, moisture storage change may be insignificant. However, in almost all cases infiltration and transmission of water will be drastically reduced by compaction because of the elimination of flow channels through macropores. The continuity of pore space is disrupted, and there is greater resistance to flow in micropores.

Because macropore space is reduced by compaction, the space available for soil aeration is reduced in compacted soils, especially when they are at high moisture content. Continuous avenues of air space to the outside atmosphere are greatly reduced, so that inward diffusion of oxygen and outward diffusion of carbon dioxide and other gases produced in the soil are inhibited, causing the soil to become deficient in oxygen and to contain excess carbon dioxide (Russell 1973, Yelenosky 1963, 1964). Compact layers at the surface prevent gas exchange in the deeper soil layers, so that they may also be very poorly aerated and suffer from anaerobic (reducing) conditions.
Soil Compaction

EFFECTS OF SOIL COMPACTION ON ROOT GROWTH AND TREE VIGOR

High bulk density and the increased resistance encountered by root tips in compacted soil may slow or prevent root penetration and elongation. Penetration of compact layers such as pans may be improved by good oxygen supply to the roots (Russell 1973). Temperature and other factors may also influence root response to compacted soil. Depending on soil texture, bulk densities of about 1.5 to 1.7 g/cc may hinder root growth, and values above 1.7 g/cc generally preclude root development (Russell 1973). Dry soils further impede root growth because shear strength increases as moisture content is reduced (Wiersum 1957). If roots encounter impenetrable material, they may turn and grow in a different direction, but often will resume the original direction of growth (Wilson 1970). If root tips die, new tips will develop further back on the root causing the typical "brush like" formation of terminal roots.

Excessive accumulation of CO₂ in the soil stops root growth, and very high levels may kill the roots. The same effects result from oxygen deficiency, which is usually more critical than CO₂ content. Trees vary greatly in tolerance to poor aeration, so exact critical values cannot be given (Pritchett 1979); however, 10% oxygen is often reported as a critical value (Patterson 1976).

Uptake of both water and nutrients depends on root density in the soil and growth rate of root tips. The smaller numbers of
roots in compacted soil and poor growth rates both contribute to poorer ability to absorb water and nutrients. In addition, up-take of water and nutrients by roots is reduced by poor soil aeration (Russell 1973). Soil compaction may control distribution of roots in soil, since roots will tend to proliferate in non-compacted zones that are adequately aerated. Compaction of surface layers may encourage rooting somewhat deeper than normal, but prevent rooting in deep soil layers because of poor aeration. Rooting may be so severely hindered by compaction that tree growth declines.

The derimental effect of soil compaction and poor aeration on tree growth have been documented by numerous research studies (LaPage 1962, Perry 1964, Steinbrenner and Gessel 1955, Youngberg 1959). Reduced diameter growth and poor vigor resulting in dieback and decline are commonly observed in heavily compacted recreation areas.

CAUSES OF SOIL COMPACTION

Soils differ in susceptibility to compaction, which mostly occurs in the upper 15 cm. of soil (LaPage 1962). High organic matter content of soil increases the resistance to compaction (Steinbrenner and Gessel 1955). Thick humus layers or organic mulches are very resistant to compaction and protect the underlying mineral soil by providing a resilient soil surface.

Soil texture is an important factor in compaction. Coarse-textured soils with single grain structure are more resistant to
Soil Compaction

compaction (Hatchell et al. 1970); medium and fine-textured soils are easily compacted, especially at high moisture content. Clay soils at high moisture content are susceptible to severe compaction. The greater strength of dry soils will tend to restrict compaction to a shallow surface layer. Compaction often creates a soil crust with a thin layer of clogged pores just below the surface (Hegearty and Royle 1978).

Compaction of soil in urban areas is caused by both vehicles and pedestrian traffic. The bearing pressure on the soil surface is an important factor in the amount of compaction produced. Tracked vehicles tend to exert less pressure per square inch (3-9 lbs.) than most wheeled vehicles (30-100 lbs.) (Lull 1959). Oversize tires, low tire pressures, and light-weight vehicles will result in relatively low pressures on soil. Pedestrian traffic and horses can exert relatively high ground pressures because of the small area of bearing surface, and the force of impact on the soil. Logging research has shown that where moist, medium or finetextured soils are concerned, only one vehicle trip can cause serious compaction (Hatchell et. al. 1970). On dry, coarse-textured soils several trips may cause only slight compaction. Equipment vibration may cause more pronounced compaction, especially in loose soils. Severe compaction in recreation areas from pedestrians has been noted by several investigators (Kalisz and Brown 1976, LaPage 1962).
Soil Compaction

Construction activities are another cause of soil compaction. In addition to surface traffic by very heavy vehicles, soil removal, disturbance, and replacement may cause structural breakdown and placement of highly compactable subsoil at the surface. Bulldozing and grading may exert very high soil pressures and also expose compactable material. Once again, vibration from equipment breaks down soil structure, compacts and disturbs the soil, and breaks fine roots.

PREVENTION AND AMELIORATION MEASURES

Advance Planning

Careful planning and incorporation of design features to prevent or minimize the effects of compaction are important. Assessment of anticipated visitor traffic in an area is necessary, as well as knowledge of use concentration patterns, vehicle access, routes, and traffic load. Areas most susceptible to damage from compaction, such as wet sites, should be identified and avoided. Areas which will receive intensive use should be located where soil compaction will produce the least serious consequences.

Design considerations related to soil compaction are several. Numbers of people and vehicles can be controlled. Access of vehicles into an area can be restricted or eliminated. Service vehicle movement can be restricted. Vehicles can be restricted to the hard-surfaced routes provided for them. Visitation level can
Soil Compaction

be restricted by controlling parking space, visibility and/or awareness of the area, walking distance, etc. Hours of access to areas can be limited. Dispersion of visitors over larger areas or rotation of use of areas to allow recovery from compaction can be utilized (LaPage 1962). Foot traffic can be restricted to paths or to limited areas protected from compaction by mulches, surfacing, wooden walks etc., in order to minimize general damage. Additionally, where trees are to be an integral part of the design, soil modification to a depth of 92 cm (3 ft) should be accomplished prior to implementation of the landscape features. Most of these procedures involve not only planning, but careful and continuous implementation and maintenance practices.

Selection of planting materials which will best tolerate soil compaction is an important design consideration for heavy-use areas. Patterson (1976) presents information from several sources on tolerance to poor soil aeration. The list by Pirone (1972) rates species as follows: (1) most severely injured: sugar maple (Acer saccharum Marsh), beech (Fagus grandifolia Ehrh), dogwood (Cornus florida L.), oak (Quercus spp.), tuliptree (Liriodendron tulipifera L.) 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 (Platanus spp.), pin oak (Quercus palustris Muench), and locust (Robinia and Gleditsia spp.).
Soil Compaction

Mulches and Soil Amendments to Reduce Compaction

Soils supporting urban trees are often more susceptible to compaction because of low organic matter content in the upper mineral soil and lack of protective humus layers. Leaves, twigs, and other organic residues are customarily removed so that the natural replenishment of organic matter and nutrients does not take place, resulting in gradual reduction in organic matter content (Patterson 1976). Surface humus layers likewise tend to disappear, a process hastened by foot traffic in heavily used areas.

Several kinds of materials are available as mulches to protect the soil surface in walkways or heavily used areas. Coarse wood or bark chips are generally most effective because they stay in place better than other finer materials such as sawdust, straw, peat moss or other bedding materials. Some mineral materials such as marble chips, vermiculite, or gravel may be useful in limited areas, but cost is prohibitive for widespread use, and solid mineral materials cushion less than organic mulches. Several inches of wood chips or bark are desirable to absorb impacts, and retaining boards are helpful to prevent spreading and loss of mulch. In particularly sensitive areas, such as wet site nature trails, elevated wooden boardwalks can be used to control traffic and prevent compaction or other impacts on the site. Frequently, wood chips are readily and economically available in urban areas because of the common practice of chipping logs and brush by city tree maintenance crews and
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private contractors doing tree removal and pruning. Bark and wood chips can be obtained at many sawmills where debarking of logs and chipping of slabs and edgings are common practices.

Incorporation of organic materials into many urban surface soils by roto-tilling or disking, or into soil used to fill planting holes, is essential to maintaining soil physical condition and resistance to compaction, as well as soil nutrient levels. Sources of organic matter have traditionally been peat moss or additions of topsoil or humus material, but recycling of leaves and other natural materials may be feasible since they are usually collected in urban areas. Composting will further improve their effectiveness. Wood chips can also be used as a soil amendment although they decompose slowly, and beneficial effects may be gradual. Sewage sludge or composted mixtures of sludge and wood chips, or other residues, can be effective and cheaper than other materials. Patterson (1976) describes the use of these in creating artificial topsoil in the Washington, D.C., area. Where materials with a wide carbon-nitrogen ratio are used, nitrogen may be a required amendment.

Several inorganic materials can be roto-tilled into compacted surface soil to reduce bulk density and increase porosity. Patterson (1976) describes the use of sintered fly ash and expanded slate for this purpose; both were effective. Expanded vermiculite and other materials are also commercially available. These materials will provide long-term benefits to soil structure, tilth, and resistance to compaction.

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Maintenance Practices

Areas which will be continually subjected to the pressures of visitors must be "engineered" to resist this potential impact during early stages of site planning. Various soil amendments must be thoroughly incorporated into the soil, whether they are organic or inorganic materials. Likewise, whenever and wherever possible, the soil should be chemically and physically homogeneous. This system will encourage more favorable moisture and aeration relationships at depth, therefore deeper rooting of the prospective planting. By encouraging deeper rooting, plants will be less susceptible to abuse from natural or imposed sources.

In very heavily used urban sites, a well-planned (seasonally timed) and implemented maintenance program is essential. By and large, natural sources of organic matter are removed from the soil surface in the name of aesthetics; therefore, the soil's natural system of topsoil rejuvenation is interrupted. Consequently, a management system such as is used on golf courses may be in order and should be included in the maintenance budget. Timely (even monthly under heavy use) spiking and/or verti-cutting (verti-cutting is not recommended in areas where trees are growing) is recommended to penetrate the compacted soil surface and open vertical channels into the soil. Verti-cutting should be practiced so that a checkerboard pattern is achieved. Top dressing should follow using perhaps a coarse sand-compost mixture followed by a drag-
type of distribution of these amendments such that the vertical channels are filled. Performed at least annually, this practice can maintain better soil aeration and moisture regimes and encourage more vigorous root growth. Prudent use of fertilization will enhance root growth of the landscape species.

Often it may be desirable to place strict use limits on an area, as is common practice in Europe (England, Ireland, etc.). By restricting use and providing proper maintenance practices a better landscape will be realized.

CONCLUSION

Soil compaction is a serious problem on many urban soils, adversely affecting the growth, vigor, and survival of many trees and other types of vegetation. Soil resistance and poor aeration are the most serious deterrents to root growth in compacted soils. Fine-textured soils when wet are easily compacted by vehicle or foot traffic. Lack of organic matter in soil reduces resistance to compaction and permits loss of macropore space for aeration.

Careful planning and implementation of control measures are required to minimize compaction problems. Surface mulches of wood chips or bark can reduce surface compaction. Incorporation of various organic amendments (composts) or inorganic materials such as fly ash can improve the structure and aeration of surface soil. Management regimes should be designed to provide long-term soil
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maintenance for areas with different intensities of use. Only through timely, aggressive programs will compaction be controlled and tree health and longevity improved.
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LITERATURE CITED


Soil Compaction


SOIL FERTILITY

Tree Nutrient Requirements

Soil Nutrient Supplies

Preventing and Correcting Nutrient Problems

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and

Robert N. Cook
SOIL FERTILITY FOR URBAN TREES

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ABSTRACT. -- Urban trees often suffer from nutrient deficiencies. Poor foliage color and density, followed by die-back and decline, may result. Nutrient deficiencies can be diagnosed by foliage symptoms or nutrient content, and by soil analysis. Nutrient supplies and availability in soils depend on organic matter, texture, soil chemistry, soil moisture, soil physical properties, and nutrient cycling. Nutrient problems can be avoided by site protection and maintenance. Deficiencies can be corrected by soil, foliar, or tree injection treatments with fertilizers. Species should be matched to the site to avoid deficiencies.

NUTRIENT REQUIREMENTS OF URBAN TREES

The need of trees for an adequate, well-balanced supply of nutrients has become very clear in recent years (Pritchett 1979). Both foresters (Baule/Fricker 1970) and arboriculturists (Williams 1981) have found that trees are often deficient in nitrogen, phosphorus, magnesium, potassium, iron, and other elements, resulting in decreased growth and vigor, poor foliage color and density, and increased susceptibility to pathogens and adverse environmental factors (Baule/Fricker 1970). The nutritional status of urban trees is particularly important because of the many other stresses
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placed upon them and the need for maximum resistance and recovery capacity.

Symptoms and Effects of Nutrient Deficiencies

The visual symptoms of deficiencies of various nutrient elements in different tree species have been observed and recorded to a considerable extent in greenhouse studies, fertilizer trials, and natural examples. Table 4.1 briefly summarizes the symptoms as described in the literature. A list of selected publications where detailed descriptions, many with colored illustrations, can be found is appended to Table 4.1. However, visual nutrient deficiency symptoms can be variable, complex, and often not easily or accurately distinguishable from one another or from pollution damage and other symptoms of stresses (Leaf 1968). As more information accumulates, our ability to diagnose from visual symptoms will unquestionably improve, but foliar, soil, or other analyses will probably always be needed to assist in or substantiate visual diagnosis (Leaf 1968).

Each nutrient plays very specific roles in the structure and/or metabolic processes in the tree (Baule/Fricker 1970). These are briefly enumerated in Table 4.2. The symptoms which result from deficiencies or imbalances in nutrition tend to culminate in the general syndrome of die-back or decline, progressing gradually to mortality (Westing 1966, Mader, Thompson and Wells 1969). The underlying causes and course of this syndrome probably stem from
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the common factor of loss of photosynthetic capacity, either by lack of growth, death of leaves, or inability to carry on the photosynthetic process. Lack of photosynthates subsequently initiates a vicious cycle of reduced top and root growth, reduced ability to photosynthesize and absorb nutrients, and reduced resistance to disease and stress until the tree finally dies. Where other stresses are not severe, the process may take many years. If these stresses are combined with drought or injury, death may occur in a short time.

Lack of optimum nitrogen supply is common in forest and urban trees in many parts of the country (Pritchett 1979), probably both as 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.

Table 4.1 Nutrient Deficiency Symptoms for trees
(Adapted from Raul/Fricker (1970) and Stone (1968)

<table>
<thead>
<tr>
<th>Nutrient</th>
<th>Symptoms</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen</td>
<td>Small needles or leaves, general yellowish-green color, thin crowns, poor growth, reduced chlorophyll content.</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>in conifers, needles of spruce (Picea spp.) and larch (Larix spp.) turn grey or bluish-green or sometimes, as in pines (Pinus spp.) turning to purple, brownish-purple, or red. Symptoms most pronounced in late summer on needle tips, especially older needles which are retained and contrast with less affected younger ones. In broad-leaved trees, oaks (Quercus spp.) leaves become dark green or reddish, foliage is less dense, and growth is poor.</td>
</tr>
</tbody>
</table>
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Potassium: needles in conifers are small and turn yellow-green and yellow with symptoms most pronounced on tips of older needles in autumn, winter, and spring. With severe deficiency tip-browning, needle-shedding, and branch and twig death occur. Younger twigs often remain green.

Broad-leaved trees exhibit dark bronze leaf colors with bright yellow margins with necrotic spots, finally leaves shrivel and die.

Magnesium: golden or yellow-tip "halo" effects on conifer needles in late summer or autumn. There is a sharp transition to the green portion. The color extends further back the next year and tip necrosis may occur. Symptoms are more severe in moist years.

In broad-leaved trees irregular yellow spots occur between the leaf veins. Symptoms are more severe on older leaves. In severe cases entire leaves yellow and premature fall may occur. Symptoms disappear quickly after fertilization.

Sulfur: symptoms are similar to those of nitrogen deficiency according to Leaf (1968) consisting of general yellow-green or yellowish color, especially in younger foliage, and reduced growth.

Iron: Symptoms are chlorosis of young leaves or needles 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. Mid-rib and veins remain green while interveinal areas become yellow-green or white. Youngest leaves are most severely affected. Spraying with iron salts results in quick recovery if effects are not too severe (Stone 1968).

Manganese: symptoms in conifers are essentially the same as for iron deficiency, i.e., new needles are chlorotic and pale green, tip necrosis may occur, and needles become darker green by the second year.

Broad-leaved species show 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. No gradient of decreasing symptoms from basal to terminal leaves occurs as in Mg deficiency (Stone 1968).

Boron: generally characterized by death or distortion of meristematic tissues. Symptoms on various species include
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tip wilting, bending, or dying; distorted, small or closely spaced terminal leaves; terminal die-back at the end of the season; or bud die-back etc., (Stone 1968).

Copper: conifers generally exhibit weak, drooping, wavy or pendulous shoots; crooked stems; recurved branches; terminal bud death; terminal needle coloration; and needle-fall late in the season.

In broad-leaves new foliage may be dark or bluish-green and be distorted by cupping or stunting. Necrosis or irregularity of leaf margins and interveinal chlorosis may occur. There may be a "rosette" effect from shortened terminal growth (Stone 1968). On poplars (Populus spp.) large dark-brown spots or blackish leaves are symptoms.

Zinc: symptoms are marked chlorosis of younger leaves, particularly in the upper crown and on the sunny side of the tree. Rosette effect occurs. There may be chlorotic mottling of interveinal areas and shoot die-back in severe cases. Extreme shortening of branches, needles, and needle-spacing in upper crown may occur, plus general yellowing and loss of older needles in conifers (Stone 1968).

List of publications describing nutrient deficiency symptoms in forest and shade trees.


The Fertilizer Treatment of Forest Trees by Hubert Baule/Claude Fricker. (see literature cited).

Properties and Management of Forest Soils by William L. Pritchett (see literature cited).

Table 4.2. Roles of Mineral Nutrient Elements in Trees


Phosphorus: essential to the energy transfer and photosynthetic systems as phosphorylated sugars; component of nucleoproteins, phytin, etc.; important to flowering and seed production, protein metabolism, respiration, and enzyme synthesis.

Potassium: needed for carbohydrate formation, photosynthesis, protein synthesis; increases osmotic pressure, water absorption, and frost resistance.

Magnesium: part of the chlorophyll molecule; needed for enzyme activity, formation of carbohydrates, proteins etc., and cell-division.

Calcium: controls physiological processes in the cells, root growth, and elongation. Calcium is a component of the middle lamella of the cell wall (pectinate).

Sulfur: needed as a constituent of proteins, amino acids, and vitamins.

Iron, manganese, boron, copper, zinc and molybdenum: these trace elements function primarily as parts of enzyme systems essential for various energy transfer, assimilation and growth processes in the plant. Iron and copper are found in cytochrome oxidase, for instance. However, the exact roles of most have not been completely elucidated.

Variation in Requirements of Different Species

The requirements of different tree species for nutrients and their tolerance to deficiencies vary greatly (Leaf 1968). Many of the hard pines, pitch (Pinus rigida Mill.), scotch (Pinus sylvestris L.), red (Pinus resinosa Ait.), jack (Pinus banksiana

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Lamb), and southern pines, etc. have relatively low nutrient requirements and grow naturally on infertile soils (Wilde 1958). Several oaks, trembling aspen (Populus tremuloides Michx.), grey birch (Betula populifolia Marsh.) and black locust (Robinia pseudoacacia L.), as well as other hardwood species, also tolerate low soil fertility. Many conifers, such as white pine (Pinus strobus L.), Norway spruce (Picea abies (L.) Karst), white (Picea glauca (Moench) Voss) and blue (Picea pungens Engelm) spruces, etc., are intermediate in nutrient requirements, tolerating or preferring acid conditions and low levels of calcium. Many oaks, beech (Fagus grandifolia Ehrh.), soft maple (Acer rubrum L.), hickories (Carya spp.) and other hardwoods fall in the intermediate range. Nutrient supplies are most critical for the demanding hardwoods such as tulip poplar (Liriodendron tulipifera L.), white ash (Fraxinus americana L.), and sugar maple (Acer saccharum Marsh.) which require high levels of nitrogen, phosphorus, and basic elements such as calcium, potassium, and magnesium for good growth and vigor. Thus, for best results, inherent site fertility and fertilization programs must be matched to the species needs.

Diagnosis of Nutrient Deficiencies/Toxicities

Diagnosis of nutrient deficiencies or toxicities is based on visual symptoms, foliar analysis, or soil analysis (Leaf 1968, Armson 1973, Mader 1973). The presence of well-expressed visual
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symptoms of leaf color and necrosis, or die-back, means that severe deficiencies exist and the trees are suffering. The foliage symptoms can be compared to those given in Table 4.1. Sometimes the foliar symptoms will be clear-cut enough to allow a definite diagnosis, or at least to narrow the possibilities to only two or three. Often, however, foliar analysis can be helpful in making a more exact diagnosis or confirming a visual diagnosis. Such analyses can often be done by state agricultural experiment stations or by private laboratories. Nutrient levels associated with deficiencies have been established for many species. (Some examples are given in Table 4.3.) These values are only broad indicators since critical levels may vary greatly with season, year, climate, region, nutrient balance, and other environmental factors (Leaf 1968). Soil analysis can also aid in evaluating nutrient status and need for fertilization. Again, state agricultural experiment stations will usually perform analyses at nominal cost, but interpretation of the results will require special knowledge and expertise in tree nutrition and forest soils. Soil testing systems designed and tested for trees are generally non-existent, so our diagnostic ability from soil tests is somewhat limited.

The diagnosis of deficiency should be tested by application of proper fertilizers on a trial basis to see if the symptoms are corrected or ameliorated before undertaking widespread treatments.
Table 4.3. Foliage Nutrient Levels Associated with Deficiencies in Trees

<table>
<thead>
<tr>
<th>Nutrient</th>
<th>Species</th>
<th>Minimum Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen</td>
<td>Douglas-fir (Pseudotsuga menziesii (Mirb.) Franco)</td>
<td>less than 1% in mature current year foliage (Gessel 1968)</td>
</tr>
<tr>
<td></td>
<td>Sugar maple</td>
<td>less than 1.5% in foliage in late summer (Mader, Thompson and Wells 1969)</td>
</tr>
<tr>
<td></td>
<td>Slash pine (Pinus elliottii Engelm)</td>
<td>less than 1.0 to 1.2% in foliage (Pritchett 1979)</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>Slash pine</td>
<td>less than .085-.09% (Pritchett 1979)</td>
</tr>
<tr>
<td></td>
<td>Monterey Pine (Pinus radiate D. Don)</td>
<td>less than .09-.10% (Pritchett 1979)</td>
</tr>
<tr>
<td>Potassium</td>
<td>Norway spruce</td>
<td>less than 0.21% (Leaf 1968)</td>
</tr>
<tr>
<td></td>
<td>Red pine</td>
<td>less than 0.3% (Leaf 1968)</td>
</tr>
<tr>
<td></td>
<td>Red maple</td>
<td>less than 0.45% (Leaf 1968)</td>
</tr>
<tr>
<td>Magnesium</td>
<td>Red pine</td>
<td>less than .07-0.11% (Leaf 1968)</td>
</tr>
<tr>
<td></td>
<td>Scotch pine</td>
<td>less than .06% (Leaf 1968)</td>
</tr>
</tbody>
</table>

SOILS AND NUTRIENT SUPPLIES

Soil Organic Matter, Texture, and Mineralogy

The supply of nutrients in most soils depends on the amount of organic matter present and the amounts and types of clay mineral. Organic matter decomposition is the prime source of nitrogen for trees. Soils low in organic matter often support trees suffering from nitrogen deficiency and are best suited to non-demanding species (Wilde 1958). Since organic matter is also the source of many other nutrients, lack of organic matter may result in multiple nutrient deficiencies, especially on sandy soils low in silt and clay. Organic matter in natural forest soils in the Northeast ranges from about 2-10% in the upper mineral horizons, total
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nitrogen content from 0.05 to 0.5%. Minimum levels of 4-5% organic matter and 0.1-0.2% total nitrogen are probably desirable. As one goes farther south, levels tend to be lower and less may be required because of faster decomposition and cycling. The fine-textured mineral fraction in the soil, the silts and clays, are important in tree nutrition (Wilde 1958) because they release most of the required nutrient elements, except nitrogen, through weathering processes, thus assuring the long-term supply. The clays and organic matter have very large surface areas and serve as the primary storage system for positively charged ions in the soil, holding calcium, magnesium, potassium, ammonium, etc., on their surfaces in a form available to plant roots. These surfaces may also have nutrients precipitated on them in fixed form, such as iron and aluminum phosphates. Soil mineralogy, especially of the silts and clays, is important to nutrient supplies (Wilde 1958). Weathering of highly siliceous sands produces few or no nutrient elements; weathering by-products derived from granites or gneisses may be rich in sodium and potassium but lacking in calcium; basaltic materials and limestones produce much calcium and magnesium. The types of clay minerals produced from weathering greatly influences their nutrient storage capability; low for kaolinitic types, high for montmorillonitic types (Pritchett 1979).
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Chemical Availability of Nutrients

Chemical characteristics of the soil can cause or contribute to nutrient deficiencies and poor tree growth. Soil pH affects the solubility or availability of many elements in the soil (Wilde 1958).

Excessively high pH (above 7.0), or alkalinity, inhibits the solubility of iron compounds and may lead to chlorosis, particularly of oaks (Baule/Fricker 1970), on limestone soils low in organic matter. The same problem may occur with copper and zinc (Stone 1968).

Very low pH (3.0-5.0) may cause phosphorus 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 phosphorus from these compounds. In acid soils the exchange complex tends to be saturated mostly with hydrogen and aluminum ions. Calcium, magnesium, and potassium, which are required by trees, are held in smaller proportions and are, therefore, less available for uptake by the trees; hence, very acid soils tend to have low fertility.

Reducing and complexing processes in soils help maintain the availability of iron and manganese. Organic matter content in soils is important to both processes, and soils low in organic matter, especially where pH is high, may suffer deficiencies. In very acid soils organic matter breakdown may be retarded and nutrient cycling inhibited.
Root Distribution and Growth

Nutrients enter roots by mass flow in solution in the water absorbed in transpiration, by diffusion to root surface because of gradients toward the root, or by contact phenomena as roots grow between soil particles (Voigt 1968). Roots in general, and fine or feeder roots in particular, tend to be heavily concentrated in surface soil layers, which are also the site of the largest and most concentrated supplies of nutrients in most soils (Pritchett 1979). The mycorrhizal fungi associated with roots, and which are active in nutrient absorption, also are most abundant there. A vigorous, wide-spreading and deep-penetrating root system can draw on a large volume of soil to absorb nutrients from soil solution or by contact. Intact surface soils in good physical condition are essential for the rapid and prolific root development necessary for optimum nutrient absorption. Any adverse factors which cause loss of vigor and decline of the tree will reduce root numbers and growth rate, so that nutrient absorption will be less effective. Deep placement of lime, organic matter, and fertilizers can encourage deeper and more prolific rooting and improve nutrient uptake.

Soil Moisture Effects on Nutrient Availability

As stated above, the soil solution is a major vehicle for moving nutrients to tree roots. Lack of soil moisture not only results in moisture deficiency for trees but also interferes with nutrient absorption (Pritchett 1979). Low soil water content also
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prevents normal growth and development of the root system. Under dry conditions, decomposition and weathering processes slow down or cease in the soil so that the release of nitrogen and other nutrients for uptake is minimal. Soils with low water-holding capacity because of coarse texture and low organic matter suffer further from droughtiness because of poor nutrient supply and low availability. In deep, fine-textured, organic-rich soils, good moisture supply enhances availability. Supplementary watering of urban trees can reduce nutrient as well as moisture stress.

Excessive moisture because of poor drainage or over-watering can cause nutrient deficiencies because of limited rooting depth or lack of decomposition and cycling of nutrients. Accumulation of toxic amounts of iron, manganese, or gases may result from the severe reducing conditions caused by poor soil aeration (Pritchett 1979).

Effects of Soil Removal and Disturbance

A common problem with urban trees is removal or disturbance of soil because of construction or engineering activities. Removal or burial of the soil often occurs, resulting in loss of the prime storage site of organic matter and nutrients in the soil profile. The nitrogen supply for trees may be drastically affected. Simultaneously much of the fine-root nutrient absorption system may be killed or removed. Soil compaction may occur, which inhibits root growth and nutrient cycling processes, further interfering
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with normal nutrition. Severe disturbance may result in inversion of soil materials so that topsoil is buried and nutrients made less available. Infertile subsoil may be left at the surface where the primary root zone would normally develop.

Nutrient Cycling in Urban Soils

In a natural undisturbed situation the nutrient cycling processes are a stable, well-balanced, self-maintaining system. In urban areas 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. Inputs 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 cause soil acidification and leaching of basic elements from soil (Likens et al. 1977).

The general result is that urban soils require careful attention to determine the status and direction of nutrient supply. Careful adjustments by fertilization, liming, or correction of imbalances with other materials will be required over time. Information on natural or suitable fertility levels will be required to
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guide corrective measures. Such information is generally sparse or unavailable.

Toxic Elements in Urban Soils

This problem is closely related to the previous one. Urban soils receive varying inputs of toxic materials from automobile exhausts, industrial plant emissions, road-salting, and chemical spraying programs (Westing 1966). The increased amounts of lead in road-side soils are well documented. General soil acidification from high sulfur inputs seems likely in many urban areas. Possible toxic levels of iron and manganese could result from severe acidity. Salt has received widespread attention as a roadside pollutant (Westing 1966). Much injury to trees is attributed to sodium and chloride excesses in the trees, particularly chloride (Baker 1965), 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.

PREVENTING AND CORRECTING NUTRIENT PROBLEMS

Prevention of nutrient deficiencies can be aided by a number of measures, such as providing adequate soil space for trees to meet nutritional as well as water needs, care in retaining and replacing topsoil, allowing natural recycling of nutrients to the maximum extent possible, and preventing excessive compaction of surface soil or injury to feeder root systems. However, when
deficiencies do occur, they can usually be corrected with commercial fertilizers, which are the most commonly used materials for tree fertilization and will be effective in most cases.

Fertilizer Application

Fertilizers can be applied by surface broad-casting, soil incorporation by rototilling or discing, placement in auger holes, placement in planting holes, addition to irrigation water, or foliar spray or implantation.

Surface application is a cheap, easy, and usually effective way to fertilize existing trees, because most feeder roots are near the surface and able to obtain the nutrients readily. However, care to avoid burning of valuable turfgrass may be necessary.

Rates of application are usually based on fertilizing the area under the tree crown. For instance, a tree with a crown diameter of 60 feet would have an area of 2826 square feet under the crown. Tree roots generally extend beyond the periphery of the crown, in younger trees far beyond. In older trees root distances from the tree of greater than 80 feet have been observed (Lyford and Wilson, 1964). In most cases areas greater than the area covered by the tree crown should be fertilized. Trunk diameter is also sometimes used as a guide to the amount of fertilizer required, but is considered a less accurate measure than area of rooting (Williams 1981).
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Burning of grass or injury to tree roots from surface fertilizer application can be avoided by generous watering to dissolve the soluble salts, dilute them, and wash them down into the soil. Applying the fertilizer in smaller amounts at two or more times will also reduce hazard of injury from salt concentrations. Care to obtain uniform spreading also reduces chances of burned spots in turf.

Incorporation procedures are apt to damage feeder root systems and probably should be avoided around well-established mature trees, but should be used on areas being prepared for planting or recently planted to enhance deeper rooting. Again, fertilizer applications are best based on the ground area which the roots will occupy in the next few years, or when the tree will reach mature size in the case of long-term soil improvement materials such as lime and phosphate.

Placement of fertilizers in auger holes is a common practice by commercial arborists. It is costly. The main benefits are encouragement of deeper rooting by improving subsoil fertility, and avoidance of fertilizer burn on turf. Where lateral rooting space is limited, or soils cause very superficial rooting, these procedures may be beneficial. But, in many cases they may be unnecessary since under normal conditions fertility is naturally concentrated near the surface. Williams (1981) recommends 2-inch diameter holes, 18 inches deep, drilled on a grid pattern, 2 feet apart. Holes should not be drilled within 2 feet of the tree, where injury to large roots is apt to occur. If large amounts of soluble fertilizer are placed in the holes, the high salt...
Soil Fertility

concentrations may burn nearby roots. However, the warnings concerning this practice expressed in chapter 2 should be needed.

Mixing of fertilizers with peat, humus, topsoil, or sand is recommended to reduce possibility of burning, and use of less soluble or slowly available materials may be preferable. Williams (1981) also describes the use of fertilizer spikes, compressed air injection, and high pressure hydraulic injection of liquid fertilizers, all of which are similar to auger hole application in principle. Application of amounts of fertilizer equivalent to surface applications may be difficult by these methods because of the effort involved.

Placement of fertilizers in planting holes raises the risk of root-burning and is not recommended by some authorities (Holmes and Mosher 1975); however, it does encourage deeper rooting by placement of lime and phosphorus in unfavorable subsoils and may compensate for limited root space. Raule/Fricke (1970) recommend use of fertilizers with a low salt index for placement in planting holes. They state that fertilizers should be placed at some distance from the roots, which is facilitated by a large planting hole, and that placement in a band on only one side of the hole at the bottom is best. If soluble fertilizers mixed with the soil are to be used for filling the hole, they recommend only small quantities be used. Salt injury to roots is a greater hazard on low water-holding sandy soils, especially in dry periods during the growing season.
Soil Fertility

Maintaining good moisture content in the soil will prevent salt concentration buildup which injures the roots.

Supplying fertilizers through irrigation systems can have certain advantages. Rapid movement of the nutrients to the roots and better penetration of fertilizers into the soil can be achieved. In a few urban situations subsurface irrigation systems are in place for watering trees and other ground cover, making application costs inexpensive. By proper choice of soluble fertilizer materials, almost all combinations of nutrient needs can be met. Urea, ammonium nitrate, potassium chloride or sulfate, ammonium phosphates, magnesium sulfates, and other completely water soluble materials are available. Possible burning of grass or tree roots by excess salts is avoided with dilute liquid applications.

Foliar sprays or tree implantation can be used to supply a wide variety of nutrients, but are especially valuable for microelements (Williams 1981). Iron, manganese, zinc, boron, and copper are difficult to supply in proper amounts by soil application since they are apt to be fixed. They are required in extremely small amounts, so deficiencies can usually be quickly and safely corrected by foliar sprays or implantations containing chelated forms of these elements. The major elements in the recommended large amounts are difficult to supply by foliar application, but emergency short-term supply of nitrogen in particular can be provided.
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Application Rates for Tree Planting

Careful attention should be given to the natural fertility, acidity, and physical condition of the soil. Corrective measures should be taken prior to planting. On very acid soils lime should be incorporated prior to planting by plowing, roto-tilling or disking to as great a depth as feasible to encourage deep rooting and enhance nutrient availability. Amounts of lime needed to raise the pH to satisfactory levels vary according to soil texture. Brady (1974) suggests 2000-3000 lbs/acre (50-70 lbs/1000 square feet) for moderately acid sandy loams, 3000-5000 lbs/acre (70-110 lbs/1000 square feet) for very acid sand loams. Fine-textured silt loams would require about twice those amounts. Some highly acid clay subsoils in Southeastern United States have been found to require 12,000-24,000 lbs/acre. In general, infertile soils or subsoil materials, exposed at the surface incorporation of a multi-nutrient (N-P-K) fertilizer such as 10-6-4 is advisable at a rate of 25-50 lbs/1000 square feet. In soils where phosphorus availability may be a problem, such as acid clay subsoils, placement of phosphate fertilizer at the bottom of the planting hole is desirable. However, care must be used to avoid burning the tree roots. Since both lime and phosphate tend to move very slowly in soils, it is difficult to add them to deeper levels after trees are established without injuring root systems or using expensive soil-auger techniques, which may be ineffective.

Where specific nutrient deficiencies can be identified by observation of trees, or foliar and soil analysis, there is a wide
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range of fertilizer materials available for specific needs (Pritchett 1979). Nitrogen deficiency can be alleviated by surface soil application of urea, ammonium nitrate or a high nitrogen, multi-nutrient fertilizer. Fertilizers with some or all of the nitrogen in organic or slowly available forms, such as lawn fertilizers, may be desirable to give a more steady supply over a longer period, to avoid fertilizer burning, or to minimize grass and weed stimulation. Rates of nitrogen of 100-250 lbs/acre (about 2.5-6 lbs/1000 square feet) are recommended. These rates equal about 5-12 lbs/1000 square feet of urea, 7.5-18 lbs/1000 square feet of ammonium nitrate, or 25-60 lbs/1000 square feet of 10-6-4 fertilizer. Often slightly better responses are noted with a multi-nutrient (N-P-K) source than with nitrogen alone (Neely 1980). However, straight nitrogen sources are usually considerably cheaper to purchase and apply. Fertilizers with a 3-1-2 or 3-1-1 ratio are recommended by Smith (1978).

According to Smith (1978) about 3 lbs of nitrogen per 1000 square feet per year or 6 lbs every other year are sufficient to maintain good health and vigor of shade trees on a maintenance basis. If deficiency symptoms are observed the rates should be increased to about 6 lbs of nitrogen per 1000 square feet per year. Williams (1981) also recommends 3-6 lbs of nitrogen per 1000 square feet/year and every 3-5 years an application 3-4 lbs of phosphorus and 6 lbs of potassium per 1000 square feet. Good lawn fertiliza-
Soil Fertility

tion of 3-4 lbs of nitrogen per 1000 square feet per year should be adequate for most needs of trees. However, broadcast applications of more than 1 lb per 1000 square feet of readily available nitrogen to lawn areas will overstimulate the grass. Amounts of nitrogen in fertilizer from readily and slowly available sources needs to be considered. Total nitrogen applications of more than 4 lbs per 1000 square feet are not recommended for lawn areas.

Where fertilizer recommendations are based on the trunk diameter (Pirone 1941), 2-4 lbs of 10-6-4 or 10-8-6 fertilizer are recommended for trees larger than 6 inches. Smaller trees should receive half this rate.

Phosphorus sources include ordinary super phosphate and double or triple super phosphate, the more concentrated high analysis formulations, which will be less expensive per unit of phosphate. Approximately 100 lbs/acre of available $P_2O_5$ (about 2.5 lbs/1000 square feet) is sufficient for most trees (Wilde 1958), so ordinary super phosphate (0-20-0) at about 12 lbs/1000 square feet could be applied. However, phosphate becomes fixed and unavailable in many soils, so placement in holes or bands is often preferable to broadcast spreading. Where both nitrogen and phosphorus are deficient, mono-ammonium phosphate (MAP) and diammonium phosphate (DAP) can be used (Pritchett 1979). About one-third the amount of these would supply an equivalent amount of phosphate as ordinary
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superphosphate, while they supply nitrogen at about the same and twice the rate of 10-6-4 respectively.

Potassium deficiencies are corrected by the addition of about 200 lbs/acre (5 lbs/1000 square feet) of KCL or K₂SO₄. Potassium 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).

Less common deficiencies may be seen in some cases. Magnesium deficiency is usually corrected by addition of dolomitic limestone. Iron and manganese deficiencies can be corrected by foliar sprays with chelated sources, tree injection, or implantation. Addition of organic matter or acidifying material such as sulfur or aluminum sulfate to the soil can also be employed. Other micro-element deficiencies are usually treated by foliar sprays, injection, or implantation since correction by application of chemicals to the soil is uncertain.

Timing of Application

Most authorities recommend that trees be fertilized either in the spring or the fall. Baule/Fricker state that nitrogen should be applied at the period of maximum requirement, which is usually mid-spring or early summer, while potash and phosphate can be applied in either spring or fall. Holmes and Mosher (1975) recommend early spring or late fall fertilization, every 2-3 years. Williams (1981) recommends early spring application at bud break
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for best response. He notes poorer response from late spring applications. Both Williams (1981) and Holmes and Mosher (1975) caution that late summer applications should be avoided because of possible stimulation of new growth that may not harden off before frost occurs. Smith (1978) favors autumn fertilization in the October to December period over very early spring, his next choice. He favors frequent applications during the year and from year to year.

Organic Amendments

A variety of organic amendments can be used to improve or maintain the fertility and physical condition of urban soils. Peat moss is commercially available almost universally, and is used for soil mixes for planting holes or for surface mulches or incorporated for soil improvement. In addition to improving soil porosity and water retention, it provides some slowly available nitrogen, improves ion exchange capacity in the soil, and enhances availability of iron and some other trace elements. Planting hole mixes generally include equal volumes of peat moss, sand, and topsoil (Cool 1978). Wood and bark chips can be utilized as mulches or incorporated in the surface soil to help maintain soil organic matter; however, nutrient content of these materials is very low. Composting of leaves, twigs, and other plant material from urban areas to use as mulch or amendments is a potential means of recycling nutrients which would otherwise end up in a landfill.
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Treated sewage sludge is frequently available and can be used as an organic amendment and low analysis fertilizer for soil improvement (Pritchett 1979). Disposal of this material is often a problem for city treatment plants. Care must be taken to be sure that the sludge does not have toxic effects or contain toxic substances.

Matching Species to Site Conditions

Since trees are naturally adapted to certain site conditions (Wilde 1958), they should be planted where soils and other factors will permit reasonable survival and growth with a minimum of corrective soil treatment, and freedom from site-induced disease problems. On inherently infertile and droughty sandy soils, species such as jack pine, pitch pine, loblolly pine (Pinus taeda L.) and non-demanding oaks should be favored since they naturally occupy such sites. Sugar maples prefer high-fertility, relatively fine-textured but well-drained soils. Where poor aeration from water tables or fine textured subsoil or pans occur, trees tolerant to those conditions should be chosen, such as sycamores (Platanus occidentalis L.), willows (Salix spp.) soft maples or other wet site species. On soils with high pH, many conifers grow poorly or are disease prone. Certain oaks may suffer from chlorosis. Very acid soils are unfavorable to many demanding hardwoods such as tulip poplar, white ash, white oak (Quercus alba L.) and sugar maple. While the individual requirements of different species need much more research, current information is sufficient to avoid many...
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serious mistakes. When site requirements are combined with other limitations such as pollution resistance, size, form, and longevity, the choice of species may become very limited, and some compromises from optimum choices necessary. However, the risks and consequences should be recognized.

CONCLUSION

The importance of nutrient requirements and soil fertility is becoming more clearly recognized and integrated into overall urban tree management systems. Recognition and diagnosis of nutrient deficiencies, followed by corrective fertilization, can greatly improve health, vigor, appearance, and survival of urban trees. Proper consideration of soil fertility in tree planting and management programs can avoid many potential nutrient problems. Continued research is needed. Programs to provide better information to urban foresters and arboriculturists can be of great benefit to urban trees and urban residents.
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LITERATURE CITED


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DRAINAGE AND INFILTRATION

Soil Pores and Water Movement

Infiltration

Urban Environment Effects

Practical Applications

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ABSTRACT--Soil infiltration and drainage is governed by the character of the soil pore system and the moisture content. Urban soils generally have less porosity and macropore space, which significantly reduces water movement rates as compared to similar forest or agricultural soils. Layering of soil material during construction creates hydraulic discontinuities in the profile that reduce water movement. Lateral runoff is enhanced and the soil can be at one time too wet, and at another time, too dry for optimum tree growth. Application of several techniques for solution of urban drainage problems is discussed, together with some lessons learned in the District of Columbia.

SOIL PORE NETWORK SYSTEM

Water moves in soils through a network of soil pores. During rainfall water enters the soil through larger, surface-connected pores under a positive hydraulic head. Water diffuses vertically and horizontally into a network of smaller pores by capillarity or soil moisture tension (SMT). The flow into the soil mass quickly becomes governed by the rate of flow into the smaller pores. Water flowing into the smaller pores is not primarily governed by a positive gravitational head rather by the SMT of the small pores.
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Water will move toward the pores having the greatest SMT. Once the flow into the larger surface-connected pores stops, then the water in the soil mass will redistribute toward the areas of greatest SMT, i.e., the smaller pores. Note Figure 5.1. The insert illustrates the indirect relationship between tube diameter and height of capillary rise (tension).

The rate at which water moves through a soil is governed by the number, size, shape, continuity and arrangement of the pore network system. Urban soils characteristically have less total pore space (less porosity, fewer and smaller macropores, less macroporosity) more irregular pore shapes, poorer continuity of pores and often considerable disorder in the pore network arrangement. Therefore, water movement rates in urban soils tend to be significantly less than those of similar soils in an agricultural or forest setting.

WATER MOVEMENT

In a saturated condition water flows more rapidly through a coarse textured (sandy) soil, because a positive head occurs, transmitting water quickly through the larger pores. Once the source of the water is interrupted the soil will soon move from saturated to unsaturated. In an unsaturated state, the water movement rate in the sand slows appreciably. Note the curve for a sand in Figure 5.2. Since the sand has few smaller pores, which tend to govern unsaturated water movement, the flow rate is reduced. The sand curve is steep because of the pore size distribution, i.e., many larger pores and few smaller pores. Remember that, in an
Figure 5.1
SOIL MOISTURE TENSION RELATIONSHIP TO TUBULAR PORE SPACE
Figura 5.2

RELACIONES DE CONDUCTIVIDAD HIDRÁULICA
Soil Drainage

unsaturated condition, the water will move through the smaller pores or along the side of larger pores (not filling the larger pores) thus significantly reducing the water movement rate. If we assume flow in soil pores to be somewhat like flow of water in a pipe, one quickly realizes that a small increase or decrease in pore diameter dramatically alters the flow rate.

In contrast to the sandy soil, a sandy loam soil will have a significantly lower saturated water movement rate (note Figure 5.2) because of fewer large pores, due to the greater amount of silt, clay and a difference in soil structure. However, the flow rate in an unsaturated condition will be greater due to the larger number of small pores. Figure 5.2 illustrates the basic differences in saturated and unsaturated water movement rates for four different soil textures. Obviously, there are numerous differences between sands and between clays, but this general pattern will still hold true.

An idealized soil would have a sufficient number of larger pores to transmit water rapidly under saturated conditions and would also have sufficient smaller pores to maintain a good water movement rate under an unsaturated state. However, a silt loam soil would have a greater amount of available water than a sandy loam soil; therefore, a silt loam soil would be optimum for tree growth.
Soil Drainage

**Water Movement in Layered Soils**

Obviously, soils are not homogeneous, especially urban soils. Commonly a soil will have a coarse-textured sandy layer over a finer textured (loamy or clayey) soil layer. In this case, once the upper coarse layer is saturated, the flow rate would be governed by the saturated flow rate of the finer textured layer. This change in flow can occur rapidly. Note the curve transition within 2 to 3 minutes (in Figure 5.3).

However, the opposite situation, the finer textured soil over the coarse textured soil, has a more dramatic effect. In this case the loamy soil would hold almost all of the water due to the smaller pores and greater SMT and, thus, would allow less water to enter the sand. Not until the loamy soil became nearly saturated would water begin to enter the sandy layer. Many people would believe this phenomenon could not occur, but it does. For example, this effect applies to the case of gravel and/or sand in the bottom of a planter. The addition of the sand or gravel will do nothing to improve drainage except when a great amount of lateral drainage below the soil is required. Since a saturated or nearly saturated zone will often be maintained just above the sand or gravel, the main result of adding the sand or gravel will be to reduce the effective or aerobic rooting volume for the plant. A similar situation can occur with three layers: a planting bed of loamy material over sandy material, over a loamy subsoil kept saturated by ground water. In this situation, the sandy soil would block the upward transmission of the moisture until the sandy layer became

5-6
Figure 5.3

SUDBURY WATERSHED
AVERAGE INFILTRATION CURVES
WET ANTECEDENT CONDITIONS

Infiltration Rate, cm/hr.

Time, minutes
Soil Drainage

nearly filled with water and would also block the downward transmission of moisture until the loamy planting bed became saturated. Therefore the sandy subgrade will often cause the planting bed to be too dry or too wet at various times.

INfiltration AND WATER MOVEMENT IN URBAN SOILs

Infiltration rates are dependent upon texture of the soil material, but more important is the structural condition of the soil material. Soil in an undisturbed forest condition will have a high infiltration rate, compared to the same soil in an agricultural field. The infiltration rate is reduced still further under the highly disturbed urban condition where structure may be nearly obliterated. Infiltration rates for Cecil soils are given in Tables 5.1 and 5.2 and illustrated in Figure 5.3. A significant decline in infiltration rates is attributed to urban disturbances. A similar study in an Hawaiian urban area demonstrates a similar effect with the Wahiawa soil (Table 5.3).

A method exists for estimating infiltration rates. The SCS provides a classification of all soil series into one of four hydrologic soil groups (Table 5.4). However, this system does not indicate the wide range of values that were found in the North Carolina or Hawaiian studies. They hydrologic soil groups probably provide rates at the lower end of the scale, or are indicative of soils in poor condition. The Cecil and Wahiawa soils both fall into the B hydrologic soil group.
Soil Drainage

EFFECTS OF THE URBAN PHYSICAL ENVIRONMENT ON DRAINAGE AND INFILTRATION

Soils in urban areas tend to exhibit extremes, either too wet or too dry. The wet extremes are often due to inadequate soil drainage. Buildings, paving and compaction tend to limit the lateral drainage of soils. Unusual man-made layerings of soil material (termed lithologic discontinuities) can limit water movement. The dry extremes are often due to increased surface runoff due to soil compaction and paving. Urban drainage systems discharge much of the rainfall into streams, rather than allowing for more natural soil water movement to slowly recharge the streams. Both wet and dry extremes can be found within one city and often on one given site. The lack of vegetation will reduce the amount of evapotranspiration and thus will leave more water in the soil mass.

SOME PRACTICAL APPLICATIONS

Use of several practical examples best illustrates the application of some of the principles outlined above. These have been chosen from actual problems encountered in various projects, and should prove useful to the practitioner.

Irrigation/Drainage Time Relationships

The frequency of irrigation or the time for adequate drainage will depend upon the rate of water movement.
Example -
Clayey subsoil (1:1 clay)
Sandy loam topsoil - 4 inches deep
Topography - flat

Solve for -
Maximum irrigation amount - inches
Maximum irrigation rate - inches/hour
Minimum irrigation frequency - days

a. From Table 5.5 find -
Sandy loam topsoil has 18.6% large pores

\[ 4 \text{ inches} \times 0.186 = 0.74 \text{ inches} \] (i.e., 0.74 ac.in. of macroporosity in one acre of sandy loam topsoil at 4 inches deep)

Therefore, maximum irrigation amount is 0.74 inches. This is based upon the premise that only a portion of the porosity should be filled with water. Therefore, fill the large pores, allow for redistribution into the smaller pores and then the large pore will be available again for air diffusion.

b. From all available sources find -
Subsoil infiltration rates:

SCS hydrologic soil group 0.15-0.35 in/hr
On-site infiltration test 0.25 in/hr
Soil Drainage

Therefore, select 0.25 in/hr as maximum irrigation rate. Thus, we have chosen a sufficiently low irrigation rate to make sure no surface runoff occurs in areas where topsoil might not be as deep or may be compacted.

c. From Table 5.6 –

<table>
<thead>
<tr>
<th>Drainage time</th>
<th>4 days</th>
</tr>
</thead>
<tbody>
<tr>
<td>Re-aeration time</td>
<td>3 days</td>
</tr>
</tbody>
</table>

Therefore, use 7 days as minimum average irrigation frequency; however, actual frequency must be adjusted with rainfall and with actual observations of soil moisture conditions.

Design of Under Drains

An underdrainage system is used on a site to control the depth of the water table. Such a system is important to urban forestry when there is an inadequate aerobic rooting depth. Surface and subsurface drainage systems are covered in detail in Chapter 14 of the Soil Conservation Service, Engineering Field Manual.

The procedures for design of agricultural drainage in the field manual are generally applicable to urban sites. However, often due to unusual soil conditions (unusual soil layerings, compacted fill soil materials, limited soil porosity, etc.) in the urban area, special care must be taken. Obviously detailed on-site soil investigations and laboratory permeability tests are warranted prior to design of an expensive subsurface drainage system.
Soil Drainage

Special attention must be given to determining reasonable soil permeability values for urban soils. The compaction of loamy or clayey soils can often reduce the soil permeability by one or two orders of magnitude; therefore, such a difference will have a major effect on the design of the under drainage system. For example:

Example #1

Clayey subsoil - not compacted
Water table depth - 1 foot
Desired water table depth - 3 feet
Subsurface barrier depth - 5 feet
Soil permeability - 1.5 in/hr
Depth of proposed drains - 4 feet
Desired water removal rate (drainage coefficient) - 0.5 in/day

Using the formula:

\[ S = \sqrt{\frac{4P}{Qd} \left( b^2 - a^2 \right)} \]

Where:

- \( S \) = Spacing of drains (feet)
- \( P \) = Coefficient of permeability (in/hr)
- \( b \) = Distance from the draw down curve to barrier stratum at midpoint between the drains (feet)
- \( a \) = Distance from the drains to the barrier (feet)
- \( Qd \) = Drainage coefficient (in/hr)

Therefore:

\[ S = \sqrt{\frac{4 \times 1.5 \times (2^2 - 1^2)}{0.021}} \]

\[ S = 29.3 \text{ ft. (use 30 feet)} \]
Soil Drainage

Example #2

However, if the clayey soil is compacted then assume:

Soil permeability - 0.15 in/hr (one order of magnitude reduction)
All other variables - hold constant.

Therefore:

\[ S = \frac{4 \times (0.15) \times (2^2 - 1^2)}{0.021} \]

\[ S = 9.3 \text{ ft. (use 10 feet)} \]

Example #3

Assume severe compaction of clayey soil material:

Soil permeability - 0.015 in/hr (two orders of magnitude reduction)
All other variables - hold constant.

Therefore:

\[ S = \frac{4 \times (0.015) \times (2^2 - 1^2)}{0.021} \]

\[ S = 2.9 \text{ ft. (use 3 feet)} \]

Therefore, severe compaction can make a site exceedingly difficult and expensive to drain, saying nothing about the other problems of plant growth in compacted soils.

The site and soils investigator should take special note of lithologic discontinuities which could seriously impair water movement. It is also important to consider that lateral drainage through heavy loam, clay loam, heavy silt loam and clayey soils may be on the order of 1/10 of the vertical water movement rates for
Soil Drainage

the same soil. If laboratory permeability tests are to be performed, make sure that the soil core samples are taken in the lateral rather than vertical position. Take samples from all important soil horizons and make sure to locate samples to search for spatial variability, i.e., seek out the most limiting horizons and locations. Also consider whether soil compaction from construction work on the site will occur after the drainage design is completed. If such compaction takes place your design may be quite inadequate.

Design of Mound Planting Beds

An alternative method to managing a site with a high water table is by use of mounded planting areas. This approach can also be useful when for other reasons the existing soil material is unsuitable for plant growth, e.g., due to expansive massive clay.

The approach is to mound suitable soil material above the existing grade and then plant in the mounds. However, provisions must be made for good positive surface drainage on the existing soil away from the mounds. If water accumulates around and under the mounds, it will move up into the mounds and thus nullify the mounding benefits. One method to counteract this accumulation is to crown the subsurface contour parallel to that of the finished surface contour.

The mounded soil material should consist of a sandy loam or silt loam soil material. The following quality criteria are provided.
Proposed Topsoil Textural Standards for Mounds

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Excellent</th>
<th>Good</th>
<th>Fair</th>
<th>Poor</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Clay</td>
<td>&lt;20</td>
<td>20-25</td>
<td>25-30</td>
<td>&gt;30</td>
</tr>
<tr>
<td>% Expandable Clay(^a)</td>
<td>&lt; 1</td>
<td>1-5</td>
<td>5-10</td>
<td>&gt;10</td>
</tr>
<tr>
<td>% Silt</td>
<td>40-50</td>
<td>50-60</td>
<td>60-70</td>
<td>&gt;70</td>
</tr>
<tr>
<td></td>
<td>30-40</td>
<td>30-40</td>
<td>20-30</td>
<td>&lt;20</td>
</tr>
</tbody>
</table>

\(^a\)percent expandable clay \(\frac{CEC_{82}/100g}{230 \text{ meg/100g}}\) x 100

The normal center depth of a mound should be about 3 feet. The wider the mounds the greater the depth, since a smaller water table may occur within the base of the mound. This is especially true if the existing soil material below the mound has a very slow permeability. The size of the mound should be based upon the selected plant species and their required rooting volumes.

Subsurface Sculpturing

In situations where mounding above the proposed grade is inappropriate, a technique has been used which we term "subsurface sculpting". This system is similar to the "crowning" of an athletic field to encourage lateral water movement off of a field during heavy rainfall events. However, at an urban site the existing soil - this soil is assumed to be heavily compacted and of rather poor quality - is contoured or crowned to allow for lateral drainage off of the site. A prepared soil mix for the site is readied off-site and broadcasted over the "crowned" area to a
Soil Drainage

uniform depth, usually a minimum of 18 inches. The finished soil surface (the prepared topsoil material) is then contoured such that it is parallel to the subsurface (existing compacted soil). Therefore a uniform soil material is provided with some provision for lateral subsurface drainage. Be sure to install subsurface drains and have positive outlets for these drainage systems.

Other Techniques Learned in Washington, D.C.

**Surface Swales.** Surface swales can provide an adequate means of removal of excess surface water during heavy rainfall events. This system is particularly useful where runoff from paved surfaces is directed toward plantings or in locations where beds are placed on side-slopes. A well placed and properly engineered swale will intercept excess lateral runoff and carry it safely downslope away from the plantings.

For example, in Constitution Gardens in Washington, D.C. sod swales have been highly successful in removing excess water from areas where large walkways shed runoff. These swales are about 3 to 4 ft. across and about 6 inches maximum depth such that mowing equipment can provide necessary maintenance. The results are highly effective and affordable.

**Planting Pedestals.** Another planting technique implemented at Constitution Gardens has been the use of "pedestals". This technique involves leaving a pedestal of existing compacted soil immediately beneath the root ball of the tree and excavating a
Soil Drainage

"doughnut" like hole for the planting. The hole in the doughnut is governed by the depth of the tree ball such that the tree ball rests securely upon the pedestal and remains about 4-6 inches above the surrounding surface.

The perimeter of the pedestal is then excavated an additional 12 to 18 inches and either prepared soil or a slight modification of existing soil is replaced into the hole. The purpose of using the pedestal is to maintain the crown of the ball at the desired elevation. Often, when a tree ball is placed within a planting hole of "prepared soil", this prepared soil is generally the most porous and will tend to saturate. The tree ball will then tend to subside into the mud.

Homogeneous Soil. Total preparation of the soil is strongly recommended. By this we mean preparing of total soil profile - depths will be variable - of similar material or a homogeneous mixture. This practice must be accomplished prior to planting! A homogeneous soil system includes uniformity of the soil chemistry as well as the soil physics. Drainage and therefore aeration will be more favorable within this type of soil system, and is preferred for large area plantings.

Avoid Soil Disturbance. Often prior to implementing an urban planting, the existing soils have undergone considerable disturbance. In Washington, some nearly natural soil profiles exist - these should be preserved. The 0-horizon or organic horizon should preserved as it will encourage deeper rooting, better infiltration
Soil Drainage

and internal drainage, as well as, a reduction of impact upon plant roots due to use. Plan the entire construction program to avoid unnecessary soil disturbance. Fence areas to limit construction activities well beyond the tree drip lines. This is particularly important around larger trees which are to be preserved.

**Mulching.** Mulching is a sound concept provided it is geared to the soils existing at the site as well as the plantings. A mulch placed over a clayey soil is at best a poor situation. The soil will saturate and rapidly become anaerobic. However, if the proper soil and internal drainage is provided, a mulch will enhance the soil moisture regime. A word about plastic mulching - it should be avoided. Plastic sheeting used over the soil surface and beneath a mulch is detrimental to the planting. Roots tend to come up to the interface with the plastic, the soils tend to become anaerobic due to a sealing at the soil surface, and the planting is quickly susceptible to desiccation, wind throw (due to shallow rooting), anaerobic soils or a multitude of other problems (see chapter 2).

**Restricting Use.** Restricting use of an area is perhaps the next to last of the drastic maintenance techniques available to the urban plantsman. This system is widely practiced in Europe (England, Ireland, etc.) to control or limit access or parks and urban greenspace. The principal goal is to limit and restrict intense use so that the soils do not become compacted and the plants are given an added chance of survival. In Washington this
Soil Drainage

system has not been widely practiced but at present certain areas are routinely closed to visitation to provide maintenance. Severe compaction and resultant improper soil aeration/drainage are a cause of plant decline. Often the last resort to maintenance of the urban planting is drastic, that of paving and/or channeling visitation through the area such that a portion of the planting might remain. The threshold of plant survival is such that it cannot tolerate continued abuse; therefore, this drastic alternative may be the last resort.
TABLE 5.1
Infiltration Rates by Land Types
for Sudbury Watershed, Charlotte, NC—
Residential Subdivision (4 d.u./ac.)

<table>
<thead>
<tr>
<th>Land Type</th>
<th>Description</th>
<th>Percent of Watershed</th>
<th>Subsoil Bulk Density g/cm³</th>
<th>Subsoil Porosity %</th>
<th>Mean Final Infiltration Rate* in/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest</td>
<td>Undisturbed Cecil soils with medium aged pine-mixed hardwood. Forest with Al horizon and leaf litter intact</td>
<td>2.6</td>
<td>1.39</td>
<td>8.3</td>
<td>12.42</td>
</tr>
<tr>
<td>Urban 1</td>
<td>Slightly disturbed Cecil soils with lawn and large trees; roads and buildings at or near original grade</td>
<td>23.8</td>
<td>1.42</td>
<td>5.3</td>
<td>4.40</td>
</tr>
<tr>
<td>Urban 2</td>
<td>Slightly disturbed Cecil soils, previously cultivated field, lawns and few young trees</td>
<td>9.1</td>
<td>-</td>
<td>-</td>
<td>1.88</td>
</tr>
<tr>
<td>Urban 3</td>
<td>Slightly disturbed Cecil soils, previously cultivated field with plow pan, lawns and few trees</td>
<td>8.7</td>
<td>1.59</td>
<td>7.3</td>
<td>0.27</td>
</tr>
<tr>
<td>Fill</td>
<td>Highly disturbed fill soils, lawns and few young trees</td>
<td>7.1</td>
<td>1.62</td>
<td>3.7</td>
<td>0.49</td>
</tr>
<tr>
<td>Cut</td>
<td>Highly disturbed cut Cecil soils (cuts or more than 20 cm or 8 inches below original grade), lawns and few young trees</td>
<td>15.1</td>
<td>1.42</td>
<td>6.0</td>
<td>0.26</td>
</tr>
<tr>
<td>Cut and Compacted</td>
<td>Highly disturbed cut and compacted Cecil soils, sparse grass, no trees</td>
<td>4.7</td>
<td>1.50</td>
<td>1.3</td>
<td>0.17</td>
</tr>
<tr>
<td></td>
<td>Wet drainage ways, bottomland hardwoods</td>
<td>1.7</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Impervious surfaces</td>
<td>27.1</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

*Measured rates for sites with less than 5% slope.
Soil Drainage

## TABLE 5.2

**Infiltration Rates by Land Types**

*for Raleigh, NC Sites*

<table>
<thead>
<tr>
<th>Land Type</th>
<th>Description</th>
<th>Subsoil Bulk Density g/cm³</th>
<th>Subsoil Macro-Porosity %</th>
<th>Mean Final Constant Infiltration Rate in/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residential Subdivision (4 d.r./ac.)</td>
<td>Forest Undisturbed Cecil Soils with mature hardwood forest with Al horizon and leaf litter intact</td>
<td>1.21</td>
<td>4.5</td>
<td>6.37</td>
</tr>
<tr>
<td></td>
<td>Cut and Compacted Highly disturbed cut and compacted, Cecil soil, lawn</td>
<td>1.31</td>
<td>4.5</td>
<td>0.14</td>
</tr>
<tr>
<td></td>
<td>Fill Highly disturbed fill soils with lawn</td>
<td>1.28</td>
<td>5.0</td>
<td>0.05</td>
</tr>
<tr>
<td>Townhouse Development (10 d.u./ac.)</td>
<td>Forest Undisturbed gravelly Cecil soils with medium aged pine-hardwood forest with Al horizon and leaf litter intact</td>
<td>1.48</td>
<td>6.5</td>
<td>&gt;4.00</td>
</tr>
<tr>
<td></td>
<td>Compacted Highly disturbed Cecil soils in open space with grass and medium aged pine stand</td>
<td>1.19</td>
<td>3.3</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>Fill Highly disturbed fill soils with lawn</td>
<td>1.48</td>
<td>5.5</td>
<td>1.08</td>
</tr>
<tr>
<td>Schenck Pasture Watershed</td>
<td>Cecil Soils</td>
<td>-</td>
<td>1.53</td>
<td>11.2</td>
</tr>
<tr>
<td>Schenck Forest Watershed</td>
<td>Cecil Soils</td>
<td>-</td>
<td>1.59</td>
<td>6.4</td>
</tr>
</tbody>
</table>

1. Measured rates for sites with less than 5% slope.

Soil Drainage

### TABLE 5.3
Infiltration Rates by Land Types in an Hawaiian Urban Area

<table>
<thead>
<tr>
<th>Land Type</th>
<th>Bulk Density</th>
<th>Final Infiltration Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Pre-urban land</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Abandoned pineapple field</td>
<td>1.12 g/cm³</td>
<td>7.03 in/hr</td>
</tr>
<tr>
<td><strong>Urbanizing land</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>grubbed land</td>
<td>1.16 g/cm³</td>
<td>2.98 in/hr</td>
</tr>
<tr>
<td>Cut &amp; shaped lots</td>
<td>1.21 g/cm³</td>
<td>0.51 in/hr</td>
</tr>
<tr>
<td><strong>Non-recreational lawns</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Residences</td>
<td>1.08 g/cm³</td>
<td>0.49 in/hr</td>
</tr>
<tr>
<td>Sidewalk area</td>
<td>1.15 g/cm³</td>
<td>0.26 in/hr</td>
</tr>
<tr>
<td>School yard</td>
<td>1.21 g/cm³</td>
<td>2.63 in/hr</td>
</tr>
<tr>
<td><strong>Recreational lawns</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Golf course</td>
<td>1.17 g/cm³</td>
<td>2.43 in/hr</td>
</tr>
<tr>
<td>Swimming pool area</td>
<td>1.35 g/cm³</td>
<td>0.19 in/hr</td>
</tr>
<tr>
<td>Recreational area</td>
<td>1.24 g/cm³</td>
<td>0.17 in/hr</td>
</tr>
<tr>
<td>Baseball field</td>
<td>1.26 g/cm³</td>
<td>0.77 in/hr</td>
</tr>
<tr>
<td>Baseball diamond</td>
<td>1.24 g/cm³</td>
<td>0.38 in/hr</td>
</tr>
</tbody>
</table>

TABLE 5.4
Hydrologic soil groups used by the Soil Conservation Service

<table>
<thead>
<tr>
<th>Hydrologic soil group</th>
<th>Sols included</th>
<th>Final constant infiltration rate, (fc), in/hr.</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>(Low runoff Potential) Soils having high infiltration rates even when thoroughly wetted, consisting chiefly of sands or gravel that are deep and well to excessively drained. These soils have a high rate of water transmission.</td>
<td>0.30 - 0.45</td>
</tr>
<tr>
<td>B</td>
<td>Soils having moderate infiltration rates when thoroughly wetted, chiefly moderately deep to deep, moderately well to well drained, with moderately fine to moderately coarse textures. These soils have a moderate rate of water transmission.</td>
<td>0.15 - 0.30</td>
</tr>
<tr>
<td>C</td>
<td>Soils having slow infiltration rates when thoroughly wetted, chiefly with a layer that impedes the downward movement of water or of moderately fine to fine texture and a slow infiltration rate. These soils have a slow rate of water transmission. (high runoff potential)</td>
<td>0.05 - 0.15</td>
</tr>
<tr>
<td>D</td>
<td>Soils having very slow infiltration rates when thoroughly wetted, chiefly clay soils with a high swelling potential; soils with a high permanent water table; soils with a clay pan or clay layer at or near the surface; and shallow soils over nearly impervious materials. These soils have a very slow rate of water transmission.</td>
<td>0 to 0.05</td>
</tr>
</tbody>
</table>

1. After table by U.S.D.A.
2. Soils are classed in the next lowest category when a high percentage of stones is present.
### TABLE 5.5
Hydrologic capacities of texture classes

<table>
<thead>
<tr>
<th>Texture class</th>
<th>Storage Capacity $S$ (percent)</th>
<th>Large pores $G$ (percent)</th>
<th>Plant-Available Porosity AWC (percent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coarse sand</td>
<td>24.4</td>
<td>17.7</td>
<td>6.7</td>
</tr>
<tr>
<td>Coarse sandy loam</td>
<td>24.5</td>
<td>15.8</td>
<td>8.7</td>
</tr>
<tr>
<td>Sand</td>
<td>32.3</td>
<td>29.0</td>
<td>13.3</td>
</tr>
<tr>
<td>Loamy sand</td>
<td>37.0</td>
<td>26.9</td>
<td>10.1</td>
</tr>
<tr>
<td>Loamy fine sand</td>
<td>32.6</td>
<td>27.2</td>
<td>5.4</td>
</tr>
<tr>
<td>Sandy loam</td>
<td>30.9</td>
<td>18.6</td>
<td>12.3</td>
</tr>
<tr>
<td>Fine sandy loam</td>
<td>36.6</td>
<td>23.5</td>
<td>13.1</td>
</tr>
<tr>
<td>Very fine sandy loam</td>
<td>32.7</td>
<td>21.0</td>
<td>11.7</td>
</tr>
<tr>
<td>Loam</td>
<td>30.0</td>
<td>14.4</td>
<td>15.6</td>
</tr>
<tr>
<td>Silt loam</td>
<td>31.3</td>
<td>11.4</td>
<td>19.9</td>
</tr>
<tr>
<td>Sandy clay loam</td>
<td>25.3</td>
<td>13.4</td>
<td>11.9</td>
</tr>
<tr>
<td>Clay loam</td>
<td>25.7</td>
<td>13.0</td>
<td>12.7</td>
</tr>
<tr>
<td>Silty clay loam</td>
<td>23.3d</td>
<td>8.4</td>
<td>14.9</td>
</tr>
<tr>
<td>Sandy clay</td>
<td>19.4</td>
<td>11.6</td>
<td>7.8</td>
</tr>
<tr>
<td>Silty clay</td>
<td>21.4</td>
<td>9.1</td>
<td>12.3</td>
</tr>
<tr>
<td>Clay</td>
<td>18.8</td>
<td>7.3</td>
<td>11.5</td>
</tr>
</tbody>
</table>

1 After table by U.S.D.A.
Soil drainage

### TABLE 5.6
Approximate Drainage and Reaeration Rates by Soil Textures

<table>
<thead>
<tr>
<th>Subsoil Soil Texture</th>
<th>Drainage Time (days)</th>
<th>Reaeration Time (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay (2:1 layer lattice)²/</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Clay (1:1 layer lattice)</td>
<td>3 ⁵</td>
<td>3</td>
</tr>
<tr>
<td>Clay loam</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Silt loam</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Loam</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Sandy loam</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Loamy sand</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Sand</td>
<td>0.5</td>
<td>2</td>
</tr>
</tbody>
</table>

---

¹ Estimates assuming drainage and reaeration over 2 feet depth for soil with topsoil and uncompacted natural porosities; also assuming no water table or other restrictive barrier problems.

² See text.
LONG-TERM URBAN SILVICULTURE

Information Needs

Benefits and Constraints

Management Decisions

Howard G. Halverson
and
Robert N. Cook
Long-term Silviculture

LONG-TERM SILVICULTURE IMPLICATIONS
IN URBAN FORESTRY

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and

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ABSTRACT. -- Long-term silvicultural management of urban trees can provide valuable benefits. In this paper, benefits ranging from aesthetics to economic values are discussed, as well as the constraints, or stresses, that are placed on the trees. One technique of management planning is also presented.

Long-term is an abstract concept interpreted differently for various purposes. For our purposes, dealing with tree sites, long-term relates to the full life cycle or longer of urban trees, usually 30 to 80 years, as contrasted with the short-term (1-5 years) management concerns dealing with the tree resources in their present state, wherever that may be in the cycle. Thus, the long-term implications provide perspective and direction for the short-term management of the urban forest. A major distinction between long-term and short-term is that fewer planning factors need to be fixed in the long-term concept.

In urban forestry, silviculture means the conscious and deliberate manipulation of site conditions and tree cover to attain
some specific objectives or benefits. This definition differentiates the scheduling and completing of activities at the site, funding and personnel decisions as management, and are not included in the term silviculture.

Soil manipulation is a part of the larger task of silviculture. Occasionally, treatments are applied to soil to solve a specific problem, such as surface mulch to prevent erosion and subsequent water quality problems. But the usual objective is to create a better soil condition for trees or other plants.

Trees cover a large portion of the urban landscape. Two cities in Kansas, for example, were more than a third covered by trees (Marotz and Coiner 1973). Although it has not been measured, cities in the northeast probably have an even higher ratio of tree cover since the general region is characterized as the most forested in the Nation.

When we consider the number of trees in our cities and the relatively high density of trees, we find that our cities are not as different from forests as we might expect. This is especially true when we consider the municipal watersheds, parks, and various other greenbelts in modern urban areas. However, the urban forest presents some environmental conditions and features more extreme than that found in the rural forest, the most distinctive being their typically limited space -- above and below ground -- combined with heavy use and high value expectations. Highly stressful sites in the rural forest can often be simply zoned for low use/low
Long-term Silviculture

priority management, whereas, they often demand more intensive counteractive management in the urban forest. This management can be acceptable as Brush (1979) found that people actually prefer managed sites over unmanaged or natural sites. Urban residents appear not to recognize a managed site as such and consider a managed area to be a natural ecosystem.

In this paper, we will look at the benefits and constraints on urban forests and show how one possible silvicultural scheme can be developed for urban forests.

INFORMATION NEEDS

Before a soil and vegetation management plan can be developed, certain basic information must be gathered and evaluated. Although there are a variety of ways to categorize the information needs, we will use the three divisions of benefits, constraints, and inventories. Divisions among and within the categories are not distinct since many factors interact, but these divisions are convenient for discussion.

Benefits

Visual qualities. These are subjective and difficult to quantify. They qualities include: Framing, highlighting, softening lines, color, shadow, and screening. However, we can draw some general conclusions from existing work. One author found that forest landowners do perceive differences in the attractiveness of stands -- enclosed spaces are more attractive.
Long-term Silviculture

than unbounded openings or dense, overstocked stands. There was
general agreement among owners and natural resource managers when
rating the attractiveness of stands (Brush 1979). Although there
is no agreement on value, at least people from diverse backgrounds
tend to rank visual qualities of landscapes in about the same
order. Since this general agreement about visual qualities exists,
it is a benefit which can be reached by silviculture. Additional
discussions of visual qualities appear in Zube et al. (1975),
especially for forest tracts.

Noise Control. Vegetation, especially trees, has been known
to reduce noise levels since the work reported by Eyring (1946). But
the mechanism of noise absorption has not been well understood.
However, it now appears that the forest floor and soil are the
absorbers, trees act as scatterers, either by sound waves
interacting with the trees or through microclimatic means (Reethof
et al. 1977). Because the interaction between trees and sound was
not understood, fairly deep bands of forest vegetation, 100 feet,
were thought needed to significantly reduce noise levels (Reethof
and Heisler 1976). Narrow bands of trees or isolated trees have
been reported effective (Cook and Van Haverbeke 1971), but
generally results have been contradictory as others have reported
no noise abatement by narrow bands of trees, to about 5 dR with a
band 90 feet wide (Borthwick, et al. 1977). Although design speci-
fication for noise absorbing tree barriers have not been developed,
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trees can be used to screen noise sources and make the source less objectionable (Reethof and Heisler 1977).

Wind Control. Winds, especially in urban areas where airflow may channel past buildings, can create uncomfortable conditions. Wind effects include pressure, additional energy expenditure to move, turbulence, wind-driven particles, and wind chill (Arens and Ballanti 1977). These wind effects have generally not been considered in urban design. Yet a fair amount of information exists about windbreaks, based largely on great plains windbreak research. Much of the work was summarized by Miller and his coworkers (1981). They found that minimum windspeed occurred an average of 4 tree heights downwind with some reduction down to 18 tree heights. On the average, wind velocities were reduced 60 percent at the point of minimum wind velocity. In the windbreak work, even a single row of conifers was found to be effective. Consequently, an effective windbreak does not require a lot of space and can be a management objective in urban areas.

Reducing Building Energy Requirements. Winds not only create uncomfortable conditions for pedestrians, but they can raise heating requirements for homes in winter. An exposed structure in a windfield develops high pressure on the windward side and lower than normal pressure on the lee side. The pressure difference, along with the tendency of warm air to rise, tends to pull outside air into the home. Cold air infiltration may cause one-third of the heat loss in a home (DeWalle and Heisler 1980). A single row
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of white pines reduced winter heating needs, and costs, by about 11 percent and additional trees might have produced increasean in savings. DeWalle and Heisler (1980) also found that a coniferous windbreak should be located one to three tree heights upwind of the home and extend 50 feet beyond the area needing protection. These authors suggest single-row windbreaks be planted on 6-foot centers, but multiple rows need 8x10 or 8x12 foot spacing with rows further apart than trees within a row and in a staggered arrangement. They also offer some suggestions, such as a row of fast-growing trees upwind of the slower- growing conifers. The first trees should be removed as the conifers become established.

The intricate scale of many urban landscapes produces very complex benefits/costs patterns -- one person's windbreak is another's shade. This can be a critical problem to the planning and management of the urban forest.

Trees have a second effect; they cast shade. DeWalle and Heisler (1980) found that a northern region house shaded in the winter lost all advantage gained by reducing windspeed and air infiltration. This is in part explained by reductions in solar heating of the house, deciduous trees without leaves still cut out more than half the solar energy a house could receive (Heisler et al. 1981). Consequently, the design is a balance, exposing the home to solar heating but protecting from wind in the winter and doing the opposite in summer. Computer programs are available to predict shadow patterns and can be used as a design tool (Halverson
and Smith 1974, Halverson et al. 1980). In different climatic regions decisions about locating trees may be altered; for example, in southern sections cooling and shade may be of most interest with little attention given to heating needs.

**Human Thermal Comfort.** Human thermal comfort is related to air temperature, humidity, radiation, and emotional and physical condition. Our interest is in the climatic variables since the personal variables are not under our control. Although trees are reputed to be "nature's air conditioners", recent studies have shown that air temperature and humidity are not altered by the generally scattered vegetation in urban areas (Plumley 1977). Radiation sources in outdoor urban spaces are direct, diffuse, or reflected shortwave solar beam, longwave from the sky, and longwave from other terrestrial surfaces. Shortwave exchange is the largest energy term. Wind interacts with radiation by providing cooling effects.

Design guides for human thermal comfort usually specify maximum solar radiation and low-wind speeds (0-3 mph) for cool periods and minimum solar radiation with moderate wind speeds (5 mph) when temperatures are high. Additional benefits can be gained by not shading ground or blocking sky views on cool days but designing the opposite on warm days. Trees, used as shade sources and wind-breaks, can be located to provide wind and solar radiation control by using the same techniques employed to reduce building energy needs.
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Water Supply and Water Quality. Water supply and quality issues can be viewed as two separate problems. The first consideration concerns the water supplied from municipal watersheds that becomes part of the public water supply. The second problem involves run-off and disposal of water from urban areas.

Water quality from forested municipal watersheds is of great concern to the ultimate user. Because of these concerns, many watershed areas have use restrictions, sometimes to the point of prohibiting any use. However, recent information suggests that with careful supervision of road location, slash disposal, skidding, and buffer strips, logging operations can be done without degrading water quality (Lynch and Corbett 1981). A general review of other current management practices is available through a symposium proceeding (U.S. Department of Agriculture 1975).

Runoff water quality has an impact on urban soil management. Urban runoff is reputed to be badly polluted and in need of treatment. As a result, combined sewer systems and large treatment plants are required to handle peak flows. During intense precipitation, runoff combined with raw sewage can bypass treatment plants and be discharged into receiving waters. However, apparently not all runoff is badly polluted. Runoff from parking lots, for example, is not badly degraded (Pham et al. 1978, Black 1980). Consequently, such water may be useful for urban vegetation irrigation and the urban forest may provide recycling sites.
Runoff Routing. Urban forest sites have also been proposed as a runoff routing technique for urban drainage. Such sites offer the advantage of relatively low cost and providing urban greenspace (Propson 1980). This idea is not fully developed, but may assume increasing importance as a method of handling runoff, reducing treatment volumes, and preventing bypasses of untreated sewage.

Air Pollution Control. Air pollution can be considered an atypical increase of trace contaminants in the atmosphere. We usually consider air pollution to be the result of human activity or unusual natural events. Although presently considered pollutants because of their elevated concentrations, many of the materials occur naturally. Examples of natural pollutants also generated by human activity are SO$_x$, NO$_x$, dusts, and hydrocarbons. Because trees have always been exposed to these materials, they may function as sinks through fallout on surfaces and uptake into tissues (Smith and Dochinger 1976). Although current research efforts have not determined removal rates for air pollutants, removal is generally conceded to be significant provided toxic concentrations are not present.

Recreation. Urban greenspaces are obviously popular recreation sites. The groups of people drawn to an area depend on the amenities of the area and the neighborhood surrounding the park (Robertson and Rowntree 1977). For example, parks in business districts draw office workers during the week, but residential parks probably have higher weekend and evening use. Owing to the
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heavy use, vegetation and trees should be managed for urban thermal comfort. But, it is difficult to maintain soil quality under heavily used, shaded areas.

Wildlife. Urban wildlife species, primarily for viewing, are an important product of the urban forest. People seem to prefer areas supporting wildlife (Payne and Degraaf 1975). Urbanization favors some species and is detrimental to others. The main aims of urban wildlife management appears to be (1) management of species favored by urbanization, and (2) developing habitat conditions to encourage additional desired species. (Curtis 1980).

Economic Value. Trees in urban settings have both benefits and costs, and the goal of long-term silvicultural considerations should be to optimize the net value of the trees over their lifetime.

Values can be assigned to trees in terms of increased property values. Payne (1980) valued trees on a home lot at 12 percent of the house and lot value; his example was $7,200 on a $60,000 home. Similar logic applied to parks and greenspaces may result in valuations of several thousand dollars per acre. Other savings, as for energy, may add up to several hundred dollars per year to the value of a small stand of trees.

There is some value to the wood products derived from the urban forest, but these may be less than the functional values. Much urban wood is considered waste material owing to defect, poor species for utilization, imbedded metal objects and short lengths...
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(Geiger 1980). However, economic changes and expanded wood needs are improving the product markets for urban wood. Fuelwood is one market for this product. Specialty wood products may have some potential value, such as the occasional walnut tree. Wood chips for mulching, composting, and other uses are a salvage value (Walker 1980) and are used in many areas. Utilization of the tremendous production of leaves from the urban forest as composting material has received little attention. Therefore, leaf litter removal remains as a real cost rather than a benefit.

Obvious costs of urban trees must also be considered. Increased costs to maintenance of buildings, sidewalks, sewers, lawns, utility service, and those due to increased hazard to property and life must be assessed. Whether or not these costs can be moderated or offset by the benefits depends on the planning and long-term silviculture of the urban forest.

Constraints

Urban forestry is high-value forestry, but also high-risk forestry. Urban trees inhabit hostile environments where urbanization may create or intensify stresses on trees. As management plans are developed, we must also evaluate the constraints on tree growth. Earlier discussions during this session have covered such soil related problems as compaction, drainage, fertility, space requirements, and the impact of people and traffic type. We have also covered analyzing these other constraints on tree establishment and growth. Since constraints are more widely recognized than
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benefits, we will comment briefly on a few that interact with soil conditions. Considering these stresses may prevent attributing planting failures incorrectly to soil conditions. Evaluation of each constraint must include techniques for moderating the stress which may be available.

Space. The primary constraint to the urban tree, or stand of trees, is space -- above and below ground. Above ground the canopy is constrained by overhead wires, shading buildings, or competition for space with other tree crowns. Below ground the root systems are constrained by pipes, walls, sidewalks, curbing, limited soil volume and competition with other tree roots (Chapter 2). Thus, mature tree size, stand density (number of trees per acre) are factors that can be considered to plan for the constraint of space. All other constraints follow from that of space.

Water. Poor drainage is often a problem, but many situations exist where inadequate water supply becomes a limiting factor. Trees in the northeast, in a forest situation, use approximately 24 inches of water a year. Most is lost to evapotranspiration. Urban trees require about 1.5 times as much water, or in the neighborhood of 36 inches a year (Halverson and Potts 1981). This water requirement is greater than growing season precipitation in most areas. The water requirement, plus water lost through drainage away from tree sites over impervious surfaces, means many trees are under water stress. This suggests that if drainage is not a problem urban sites may be more xeric than anticipated.
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**Pests.** Urban forests are afflicted with the same insect and disease pests as any other forest. Urban trees may be more prone to pest problems, because all stress factors interact to determine vigor and survival. A non-vigorous tree is more likely to develop a pest problem. Himelick (1977) reviewed stresses and lists exclusion of plant pathogens, eradication of infected trees, protection through spraying, and breeding for disease resistance as possible means of preventing pest stress. To his list we might add avoidance of disease-prone trees. For example, elms would not be recommended in the Northeast.

**Microclimate.** Site microclimate is an important constraint because different tree species have different tolerances for insolation level, temperature, moisture conditions, and competition. These are recognized and should be considered in species selection.

**Pollution and Salt Damage.** Different tree species not only have different tolerances to microclimatic conditions, they have different tolerances to pollutants and road salt accumulations. Bulletins are available that rate tolerance to pollutants and salt (for example, see Trees for Polluted Air, U.S. Department of Agriculture -- Forest Service, Misc. Pub. 1230, issued October 1973.)
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Windthrow. Windthrow is a natural event that can occur over broad areas, especially when the soil is weakened by excessive rain and high winds are generated or when tree root systems are damaged. Sometimes partial cutting will subject the remaining trees to windthrow. In urban areas, root systems can be damaged by construction activities, trenching for utilities, or related efforts. Root systems must be protected or windthrow and related damage will occur.

Fire. Fire is not a consideration in the Northeastern urban region except for some adjacent forested tracts. However, in more arid regions where vegetation types are very flammable, such as the Pacific Southwest, fire should be considered in urban situations. In arid regions nonflammable vegetation is preferred.

Safety. Vegetation or trees should not be established where they will become a safety hazard, such as restricting visibility at street intersections.

Soil Temperature. Soil temperature in urban areas do not seem to be a limiting factor, at least for trees planted into the underlying soil (Halverson and Heisler 1981). In above-ground planters additional protection may be necessary.

Inventories

After defining the possible benefits of trees and stresses they must survive, it is useful to consider what is known about similar sites in an urban area. In effect, we are talking about an
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inventory of vegetation and the conditions that promote or discourage tree growth.

Forest Inventory. In urban forests, inventories should have four components: biotic, climatic, edaphic, and man-made (Theobald 1980). Inventory systems vary, some locating each tree and some being very general. But in any case, a condition inventory is especially useful if the success or failure of past treatments is recorded.

Theobald (1980) defined a series of basic steps necessary in the planning process. He listed formulation of goals and objectives (our benefits), an inventory of existing conditions and resources (our forest inventory), and formulation of the plan, as well as implementation and review.

MANAGEMENT DECISIONS

Formulation of a plan begins with a series of decisions. Because any site offers a potential for several benefits and has several constraints, some difficult decisions must be made. Desired benefits and important constraints must be ranked, and ranking will vary depending on the site, its location, and community preference. If possible, an interdisciplinary approach should be employed. Evaluations of benefits and stresses will be more accurate if specialized ranking recommendations are available to the manager.
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Important Benefits

There is an array of some 11 potential benefits of trees ranging from aesthetic considerations at one extreme to economic values at the other. Only rare sites can provide only one benefit. Streetside planter trees, for example, can be aesthetic, but can also provide shade for human thermal comfort. As sites get larger, wind control, noise control, visual screening, air pollution control, and perhaps others join aesthetics as potential benefits. To make the best use of the site, as many benefits as possible should be accommodated in the design, while some may have to be deleted.

Important Constraints

Constraints must be evaluated as well as benefits. Several biologic constraints may be important at a site and the most critical stresses recognized. Although not a biologic constraint, community preference must also be accommodated.

Grouping Sites

If several sites are involved in the design, those sites offering similarly ranked benefits and having similar constraints should be grouped together. Grouping sites together has the advantage of reducing the number of management plans that must be developed and allows better scheduling of cultural operations. The important concept is not to view each site or planter as unique -- think of all similar planters as a group.
Cultural Options

After decisions have been reached and the basic management scheme defined, then we can develop cultural techniques for the different sites. For convenience, cultural options can be divided into vegetation selections, establishment, cultural treatments and rotation phases.

Vegetation Selection. A major value of the resource inventory is to identify the adaptation of various species to the particular site and cultural conditions of a community. Plant growth responses in the particular community provide a better basis for identifying both the most critical site constraints and best adapted species than does imported or extrapolated information from other communities or from the general literature.

We have two alternatives available to us, with intergrades between, in regards to the long-term implications of cultural options and their vegetation selections: (1) develop or modify sites to fit the desired vegetation, or (2) select vegetation adapted to the site conditions presented to us. A further subdivision in the decision-making process is in fulfilling the purpose of the planting or the urban forest stand. For example, coniferous species are more appropriate for windbreaks, noise barriers and visual screens, because they retain their foliage throughout the year. But conifers require more water than deciduous species and are more susceptible to the toxic effects of air pollutants. Conifers planted very close to houses would not be appropriate in northern latitudes because of their winter shading effects. Even
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deciduous trees may intercept half the incident solar radiation during the winter (Heisler, et. al. 1981).

Establishment. Tree establishment can be accomplished by saving part of the residual stand and providing for natural regeneration, or by tree planting. If development is occurring in a forested area, retaining part of the existing stand is an attractive option. Experience in Maryland illustrates how it can be done while retaining timber values (Heinricks 1979). Many urban trees are established through artificial regeneration because there are no remnant trees. Artificial techniques are well-known, planting stock ranges from small bare-root seedlings through bare-root or balled saplings to sizable trees moved with special tree spades. The determining factors in choosing the technique are probably economic and community preference. The bigger the tree, the more the cost, is a general rule. Community preference may override costs in some cases and force the use of more expensive techniques. Natural regeneration is most attractive due to low cost but will require a seed source, so it can be used in some larger tracts adjacent to cities. Desirable sprouting species may offer some promise at city sites. Overplanting or overregeneration is a common practice used to compensate for tree mortality and give an instant effect.

If amendments are to be worked into the soil, fertilizer, wood chips, or other material, they should be added before planting. Working the soil or underplanting is damaging to tree roots and can
cause mortality. Confining the roots of an existing tree also damages root systems.

**Cultural Treatments.** It should be recognized that urban silviculture and its attendant cultural treatments covers a range of conditions beginning with those that are indistinguishable from rural silviculture where traditional concepts of regeneration, thinning, rotation, etc. are applicable, and continuing to the highly modified concepts required where urban constraints, use, impacts and value demands are high. In the latter, the concept of tree stand, which is the basis of traditional silviculture, must be modified. The more intensive urban forest situations have a very high proportion of "edge effects," which traditional silviculture generally attempts to avoid in concept. However, the concepts of cleaning and weeding, thinning, pruning, salvage, and rotation apply to the urban forest as well as rural forests.

Cleaning is done to remove undesirable competing individuals while weeding removes all competing vegetation. These techniques are applied early in the life of the vegetation, before the sapling stage is reached. Overplanted stock should be removed before competition develops.

Thinnings are like cleaning except they occur later in the life cycle and are made to stimulate the remaining trees. This usually means distributing the trees over available space. Although there is variation with species, as open-grown trees approach 10 inches diameter, there should be no more than the
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equivalent of about 100 trees per acre (436 square feet/tree). Since trees are often planted about 6 feet apart (36 square feet/tree), the weeding, cleaning, and thinning operations should remove 90 percent or more of the planted stock (computed from data given by Krajicek et al. 1961). Failing to thin the trees results in the stagnated stand with low vigor due to intense competition. Trees exhibiting low vigor are subject to pest problems or other stresses that vigorous trees would be able to withstand. This degree of cleaning and thinning seems severe, but is necessary.

Pruning is done to remove lower branches and improve the quality of a standing tree. In urban situations, pruning allows visibility, clearance for people and vehicles, and may prevent vandalism of lower branches. Some trees in forests prune naturally, but most city trees need to be pruned manually. Either green or dry branches can be removed while they are small (less than 2 inches diameter).

Supplements, such as fertilizer or mulch, can be added to the soil but should only be applied to the surface. Working the soil will damage tree roots.

Protection, accomplished through spraying for example, should be integrated into the silvicultural plans as the need arises.

Salvage operations are designed to remove trees killed or damaged in some unexpected manner. Healthy trees may be removed to prevent the spread of insects or disease (sanitation cut). Salvage is the type of cut usually employed in urban forestry; too often
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trees are not removed until they are dead and pose a hazard. The purpose of rotation is to schedule tree removal before the tree dies.

Rotation

Rotation is the period of years required to establish, grow, and regenerate trees in order to maximize production of benefits while maintaining the forest on a permanent basis. Rotation ages are calculated within a range of plus or minus 10 or 20 percent; it is not a precise calculation because the benefit variables may change during the growth period.

Rotation ages can be determined for urban trees. The first step is to assign a benefit value of trees to a site before trees are established; this value is usually zero. Assume then that trees are established and begin to grow. Some benefits become apparent but increase slowly during the first years. If proper silvicultural practices are followed, the growth rate and benefit value then increase at an increasing rate. At some future time, growth and benefits continue to increase, but at a decreasing rate. Ultimately, growth stop and benefits reach a plateau. In the final stage, growth turns negative and benefits decline. The cessation of growth and eventual decline of benefits may be due to biologic factors (the tree is too old and begins to deteriorate), economic factors (benefit values change), or external factors (the tree has outgrown available space or become a hazard).
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In any case, the described pattern is the sigmoid curve commonly used to describe the performance of a biological population (Figure 6.1).

Most intensively cultured or landscape trees are planted as small saplings at a fairly high cost, and if they survive planting, immediately have an expectation value about equal to the planting costs. Because the major value of most such trees is visual, they gain substantial value as soon as they are visually prominent, which is fairly early in their growth curve. This would approximate the value inflection point A. Then, they continue to gain value at a decreasing rate -- hopefully for quite a long period -- as long as their growth exceeds deterioration and other liabilities. Finally, increasing liabilities with both size and age exceed the benefits of additional size (primarily diameter), and value declines (Point B). When serious deterioration occurs (Point C), value plunges rapidly to a negative benefit at D because removal costs typically exceed salvage values.

In contrast, Point B is rotation age in conventional silviculture. If the benefits are expressed on an annual basis, then the greatest average benefit per year is described by the slope of a line from the origin to Point B. If the stand is removed, the cycle starts over and maximum benefits are generated over the long-run.
Figure 6.1. The benefit-time curve illustrating the concept of urban silviculture rotation. (After N. A. Richards, 1981, personal communication.)
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Thus, the goals of silviculture in urban forests are:

1. to assure tree selection, location, and planting that can permit positive benefits,
2. to get trees to Point A quickly and in good condition,
3. to extend the period from A to B as long as feasible through good maintenance and protection,
4. to extend the period from B to C as economically as possible, but less important than (3),
5. to remove and replace trees as soon as is feasible after Point C is reached.

Applying the concept of rotation in an example may help clarify how rotation becomes part of a silvicultural plan. To start, it is necessary to make some assumptions:

1) in a class of sites, planters for example, inventories and experience suggest that the time between establishment and the point where the trees must be replaced is 20 years,
2) there are 1000 sites in the group.

Then a silvicultural plan should be set up which calls for removal and regeneration on 50 sites each year. By the end of the first cycle, you will have a regulated series with predictable number of sites to renovate each year. A one-year cycle isn't necessary, it could be 100 every second year or some other combination. Unexpected mortality, disease, or other factors may intervene in the planning cycle, so there should be a mechanism to trade sites among cycles.

In effect, greatest benefit per unit of time is achieved when the period between establishment and point A on the graph is used. But removing trees just as they approach their prime would be unpopular. That management cycle would be ideal, and perhaps become more popular as people see and recognize that although vegetation is removed, it is replaced.

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Within each 20-year cycle, subcycles of silvicultural and protective treatments are incorporated. We might anticipate something like cleaning and weeding at 1 and 5 years, thinning at 10 and 15, and spraying annually. These treatments would be scheduled based on experience and local conditions.

Implementation and Review

After a plan is developed, it must be implemented to have value. Periodic review and updating is also necessary.

SUMMARY

Urban forestry is a diverse and complex field. Trees, under careful silviculture practice, offer a variety of benefits but must survive and grow under adverse conditions.

In this report, we have listed 11 benefits of urban forests in an effort to draw attention to the advantages and very high values of trees. We feel that some benefits are currently not considered in the urban planning and management process. Considering the broader range of benefits should give urban forestry programs more appeal when compared to other programs.

Urban trees are often stressed by conditions created by the city. These stresses are well recognized. Each stress condition must be accommodated by selecting the proper species moderated by some treatment.
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In many areas, silvicultural plans for the urban forest simply do not exist. Decisions are made on a site-by-site basis, usually when a problem develops. A good silvicultural plan won't prevent all problems, but it will prevent many from developing into a situation needing immediate attention.

In some areas silvicultural plans are in use. But existing plans are often incomplete, as they include provisions only for establishment and culture of the trees. It is essential to recognize that trees, like any other biologic population, have a useful life and the removal and regeneration plans must be included.

Because there are an almost infinite number of combinations of benefits and constraints, we did not develop a model for a silviculture plan. Instead, we outlined a series of steps and decision points that can be used to develop a plan. We think that properly developed, implemented, and reviewed plans will improve our urban forests.
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ON-SITE SOIL ANALYSIS

Use of Soil Surveys

Types and Organization of Soil Investigations

Soil Sampling Methods

Barrett L. Kays
ABSTRACT -- Soil surveys in urban areas generally will provide little more than a map of the pre-urban soils. For this reason urban sites that have been altered need more detailed on-site investigations. There is a two-level approach to on-site investigations, each one requiring a different array of sampling and testing procedures.

USE OF SOIL SURVEYS

The National Cooperative Soil Survey Program when complete will have produced soil survey reports for all counties in the United States. Although the surveys are designed around agricultural parameters, they can be useful in urban areas if their applicability is understood. Formerly, urban areas were mapped simply as urban land. Now, it is common for the soil surveys to use "urban soil complexes" (soil name) which denotes the pre-urban soil and recognizes the fact that the soils have been significantly altered. Few soil surveys (an example is the Soil Survey for the District of Columbia) actually have mapped disturbed soils, usually termed Orthents. In general, soil surveys in urban areas will provide little more than a map of the pre-urban soils. For this reason, urban sites that have been altered need to receive more detailed on-site investigation. In addition, these county soil
On-Site Soil Analysis

surveys are not site specific and the information relates to only the upper 3 feet or so of the soil profile.

TYPES OF ON-SITE SOIL INVESTIGATIONS

Figure 7.1 illustrates the standard county soil survey map of a hypothetical site prior to urbanization. Figure 7.2 illustrates how the county soil survey normally would indicate the site after major urban man-made soil alterations have occurred; only limited new information is given. Figure 7.3 illustrates a portion of the extensive amount of information that can be gained with a detailed soil investigation.

Detailed on-site soil investigation requires that numerous hand or power-driven borings be conducted. Hand auger borings can be used for depths of less than 20 feet. Their use will depend upon the soil materials present and difficulty of digging. Hand auger borings require hard manual labor and will be most difficult if not impossible on sites with compacted heavy soil materials. However, hand auger borings are less expensive than power-driven borings.

There are three basic types of power-driven borings: flight augering, hydraulic coring and drive sampling. Flight augering is a rotating drill method which cuts and worms out more or less continuous ribbons of the soil material. This method is especially useful for visual investigations. The boring proceeds quickly
Figure 7.1
HYPOTHETICAL URBAN SITE
PRE-URBAN SOIL SURVEY MAP

Au - ALLUVIUM
BeD2 - SHALLOW CLAYEY SOIL, ROCK
DEPTH AT 20-30", STEEP SLOPES
CeB2 - DEEP CLAYEY SOIL, MODERATE SLOPES
Figure 7-2
HYPOTHETICAL URBAN SITE

URBAN SOIL SURVEY

Or - ORTHENT (MAN-MADE SOIL)
Au - ALLUVIUM
BeD2 - SHALLOW CLAYEY SOIL, ROCK DEPTH AT 20-30', STEEP SLOPES
CeB2 - DEEP CLAYEY SOIL, MODERATE SLOPES

PROFILE
Figure 7.3
HYPOTHETICAL URBAN SITE

ON-SITE DETAILED SOIL INVESTIGATION

1 - ALLUVIUM
2 - SHALLOW SOIL OVER ROCK
3 - ROCK OUTCROPPING
4 - SHALLOW PLASTIC CLAY
5 - DEEP CLAY
6 - WEATHERED ROCK
7 - ROCK
8 - REFUSE-CONCRETE BLOCKS
   ROTTEN DEBRIS
9 - PLASTIC CLAYEY FILL
10 - SANDY FILL
11 - SILTY LOAM FILL
12 - SANDY LOAM FILL
13 - ORGANIC LAYERS

PROFILE
On-Site Soil Analysis

allowing for more holes to be drilled per unit time than other methods. The disadvantage is that undisturbed soil samples cannot be taken with this method. However, the method is useful for site mapping and to determine the best locations to take undisturbed samples.

Hydraulic coring involves hydraulically forcing a sampling tube into the ground. The tube can be withdrawn in sections, allowing for removal of partial or complete sections of the soil. The "undisturbed" sample can be extruded or can remain in the tube for laboratory tests, such as permeability. The degree of compaction of the soil can be determined by the resistance to penetration.

The drive sampling method using a split-tube sampler is a common procedure by soil engineering firms. A standard 140-pound hammer is used to drive the sampler into the ground. The number of blows per foot is recorded as a measure of penetration resistance. The soil core can be extruded from the sampler. The pounding of the hammer tends to disturb the sample more than the hydraulic coring method.

Selecting the appropriate number, type, depth and location of the samples takes experience and good judgement. It is best to consult a soil scientist or a firm specializing in soil investigations for landscape applications. Most soil engineering firms are not experienced in soil investigations for landscape purposes and will need special directions and assistance.
ORGANIZING ON-SITE SOIL INVESTIGATIONS

There is no simple method to determine what needs to be accomplished in a detailed soil investigation. The nature and scope of the investigation will depend upon the site characteristics, the proposed use, the available financial funds and the knowledge of the landscape architect and/or engineer. In many situations it is useful to conduct preliminary investigations (Level 1) on the site with a hand auger to help better define the necessary extent and type of detail investigations.

Soil investigations for landscape planning are in essence the search for potential problems and then determining appropriate solutions. The problems can be classified as chemical, physical or morphological. Table 7.1 provides an outline of many common soil characteristics and indicates when potential landscape problems may exist. The list is useful for checking potential problems during the preliminary investigations (Level 1) and then selecting appropriate tests to be conducted during detailed investigations (Level 2). This two-level approach is strongly recommended. If no significant problems are encountered at the preliminary level, then only simple, routine fertility tests might be required at the second level, thus saving time and expense. Therefore, the preliminary investigations are quite important. Your solution to soil management on the site will depend upon how well you recognize and work with the site problems and assets. If you are not
## TABLE 7.1 - ON-SITE SOIL INVESTIGATIONS METHODOLOGY

<table>
<thead>
<tr>
<th>Soil Characteristics</th>
<th>Level 1 - Preliminary Investigations: Identification of Potential Problems</th>
<th>Level 2 - Detailed Investigations: Recommended Testing if Moderate or Severe Problems Occur at Level 1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Moderate†</td>
<td>Severe†</td>
</tr>
<tr>
<td>Morphological</td>
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</tr>
<tr>
<td>Depth to rock</td>
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<td>&lt;2 feet</td>
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<tr>
<td>Depth to seasonally high water table</td>
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<tr>
<td>Depth to apparent water table</td>
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<td>&lt;4 feet</td>
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<tr>
<td>Depth to restrictive horizons</td>
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<td>&lt;0.25 in/hr</td>
<td>&lt;0.05 in/hr</td>
</tr>
<tr>
<td>Bulk density - clay</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- dense</td>
<td>(1.4 g/cm³)</td>
<td>(1.5 g/cm³)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- loam</td>
<td>dense</td>
<td>dense</td>
</tr>
<tr>
<td></td>
<td>(1.6 g/cm³)</td>
<td>(&gt;1.8 g/cm³)</td>
</tr>
<tr>
<td>Chemical</td>
<td></td>
<td></td>
</tr>
<tr>
<td>pH</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Fertility</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>Lime requirement</td>
<td>pH &lt;6</td>
<td>pH &lt;5</td>
</tr>
<tr>
<td>Salinity</td>
<td>pH &gt;8</td>
<td>pH &gt;9</td>
</tr>
</tbody>
</table>

*Can be checked with field soil testing kit, however it is recommended to also send samples to laboratory for testing.
†Approximate determination of moderate and severe; good judgment is required.
On-Site Soil Analysis

experienced in soils, hire a consulting soil scientist, soil engineer or use an agricultural extension soil specialist for the preliminary investigation. If you have soil problems, the consultant can assist you in planning detailed investigations.

SOIL SAMPLING METHODS

Many soil properties will have significant spatial (vertical and lateral) variations. Different soil properties will require different sampling approaches. Borings can be conducted spatially on a grid basis, but more commonly, boring locations are controlled by placing more borings in the areas of most interest; for example, locating more borings along a major soil boundary to better locate it spatially, or locating more borings in an area of potential landscape problems.

Often soil samples for chemical or physical determinations are made on an area-wide basis. Samples are collected over the area and combined to produce one bulk sample. This is a common technique for fertility tests and for an average particle size analysis. The samples are gathered from each important soil horizon. Another technique for many physical determinations is to cluster samples. This is done for properties that have a large microheterogeneity and small macroheterogeneity. Infiltration tests, for example, are commonly run in triplicate at each location, while six to twelve undisturbed soil cores are required from each horizon at each location to adequately determine water movement properties.
On-Site Soil Analysis

in the laboratory. Therefore, more samples are collected at each location and a fewer number of cluster locations are used because of the type of heterogeneity. Determining the appropriate location, number and type of samples will require special assistance. However, with a little studying and good back-up assistance, the landscape architect can handle the vast majority of the sampling for many common problems in his area. Samples can be sent to a laboratory for analysis and results returned to aid in making soil management decisions and designs. A list of useful reference documents is provided.
REFERENCES


Soil Survey Staff. 1972. SOIL SURVEY LABORATORY METHODS AND PROCEDURES FOR COLLECTING SOIL SAMPLES. USDA, SCS, Report 1, USGPO, Washington, D.C.
