Tree Roots: Facts and Fallacies

Thomas O. Perry

A proper understanding of the structure and function of roots can help people become better gardeners.

Plant roots can grow anywhere—in the soil, on the surface of the soil, in the water, and even in the air. Except for the first formed roots that respond positively to gravity, most roots do not grow toward anything or in any particular direction. Root growth is essentially *opportunistic* in its timing and its orientation. It takes place whenever and wherever the environment provides the water, oxygen, minerals, support, and warmth necessary for growth.

Human activities, such as construction, excavation, and gardening, often result in serious damage to trees. In some cases, trees can be inadvertently injured by people who are trying to protect them. Indeed, people can kill trees in hundreds of ways, usually because of misconceptions about root-soil relationships, or because of a disregard of the basic functions that roots perform.

In order to maintain the health of cultivated trees and shrubs, it is necessary to understand the morphology and physiology of tree roots in relation to the aerial portions of the plant. For those who are responsible for maintaining the health of woody plants, this article examines some widely held misconceptions about roots. It describes the typical patterns of root growth as well as their locations and dimensions underground. It also describes the relationship of healthy roots to typical forest soils as well as the behavior of roots adapted to atypical circumstances—growing through deep sands, under pavements, down crevices, inside shopping malls, and in sewer lines.

The Relationship Between Roots and Other Parts of the Plant

The growth of a plant is an integrated phenomenon that depends on a proper balance and functioning of all parts. If a large portion of the root system is destroyed, a corresponding portion of the leaves and branches will die. Contrariwise, if a tree is repeatedly defoliated, some of its roots will die back. Proper functioning of roots is as essential to the processes of photosynthesis as are the leaves and other chlorophyll-bearing parts of the plant. Typical roots are the sites of production of essential nitrogenous compounds that are transported up through the woody tissues of the plant, along with water and mineral nutrients.

The fine feeder roots of a tree are connected to the leaves by an elaborate plumbing system consisting of larger transport roots, trunk, branches, and twigs. Many researchers have weighed and estimated the proportions of various plant parts. Weighing and counting every root tip and every leaf is a heroic if not impossible task, and careful sampling is essential to making accurate estimates. Sampling errors and variation among species produce variable results, but 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 mag-

nitude: 5 percent fine or feeder roots, 15 percent larger or transport roots, 60 percent trunk or main stem, 15 percent branches and twigs, and 5 percent leaves (Bray, 1963; White et al., 1971; Meyer and Gottsche, 1971).

A tree possesses thousands of leaves and 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 typical crop is about 12 during the height of the growing season (Moller, 1945; Watson, 1947; and many modern texts on crop physiology).

The number of square units of root surface per unit of land surface, the "root area index," can be calculated from studies that report the number of grams of roots present in a vertical column of soil. Such data are determined, first, by taking core samples or digging out successive layers of soil and screening and sorting the roots and, second, by determining their average lengths and diameters as well as their oven-dry weights. The quantity of roots decreases rapidly with increasing depth in normal soils, so that 99 percent of the roots are usually included in the top meter (3 ft) of soil (Coile, 1937). A reasonable approximation for non-woody tissues is that the oven-dry weight is one-tenth of the fresh weight and that the density of fresh roots is very close to one. If one makes these assumptions for Lelbank's data (1974) for winter wheat (*Triticum aestivum*) and for Braekke and Kozlowski's data (1977) 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, clearly indicating that *the surface of the root system concealed in the soil can be greater than the surface of the leaves!* Amazingly, this conclusion does not take into account the fact that nearly all tree roots are associated with symbiotic fungi (mycorrhizae), which functionally amplify the effective absorptive 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 indicate that, in oaks and other ring-porous species with large diameter xylem vessels, a given root is directly connected to a particular set of branches, usually on the same side of the tree as the root (Zimmerman 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 the death of the corresponding branches. Other tree species possess different anatomies in which dyes ascend in zigzag or spiral patterns, indicating that the roots of the tree serve all of the branches and leaves (Figure 1). 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 are unknown. 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.

Patterns of Growth and Development in Typical Soils

Early observations of tree roots were limited to examining the taproot and the larger roots close to the trunk of the tree or to examining the vertical distribution of severed roots exposed by digging trenches and pits (Busgen and Munsch, 1929; Coile, 1952; Garin, 1942; Bohm, 1979). Attempts to examine the depth and extent of the larger roots of an entire tree were not really possible until bulldozers, backhoes, front-end loaders, and fire pumps

became available (Stout, 1956; Berndt and Gibbons, 1958; and Kostler et al., 1968). Unfortunately, most tree roots are less than one millimeter in diameter and are destroyed by the rough action of such heavy equipment.

Examination of the small non-woody roots of trees and their relationship to the larger roots requires years of study, infinite patience, and the gentle use of heavy equipment. Walter Lyford and his colleagues at the Harvard

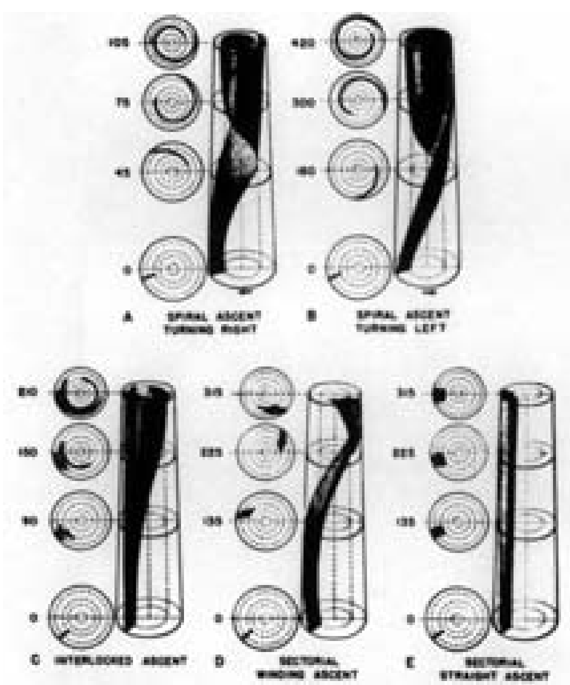

Figure 1. Five types of water-conducting systems in various conifers as shown by the tracheidal channels dyed by trunk injection. The numbers give the height in centimeters of the transverse section above injection. A. Spiral ascent, turning right: Abies, Picea, Larix *and* Pinus *(Rehder's section 3,* Taeda*). B. Spiral ascent, turning left:* Pinus *(Rehder's section 2,* Cembra*). C. Interlocked ascent:* Sequoia, Libocedrus *and* Juniperus. *D. Sectorial, winding ascent:* Tsuga *and* Pseudotsuga. *E. Sectorial, straight ascent.* Thuja *and* Chamaecyparis. *Oaks and many ring-porous species have a pattern similar to E. From Rudinski and Vite, 1959. Reprinted courtesy of the Boyce Thompson Institute for Plant Research.*

Forest in Petersham, Massachusetts, 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. The following description of the growth of tree roots is a synthesis of Lyford's published descriptions, the author's personal observations, and recent books on the subject (Kostler et al., 1968, Bohm, 1979; Torrey and Clarkson, 1975; R. S. Russell, 1977; E. W. Russell, 1973).

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

The first root, the *radicle*, to emerge from the germinating seed of some species, such as pines, oaks, and walnuts, sometimes persists and grows straight down into the soil to depths of 1 to 2 meters (3 to 6 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, such as spruces, willows, and poplars, does not usually persist. Instead, a system of fibrous roots dominates early 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 ground level and are associated with a marked swelling of the tree trunk (Figure 2). These major roots branch and decrease in diameter over a distance of one to

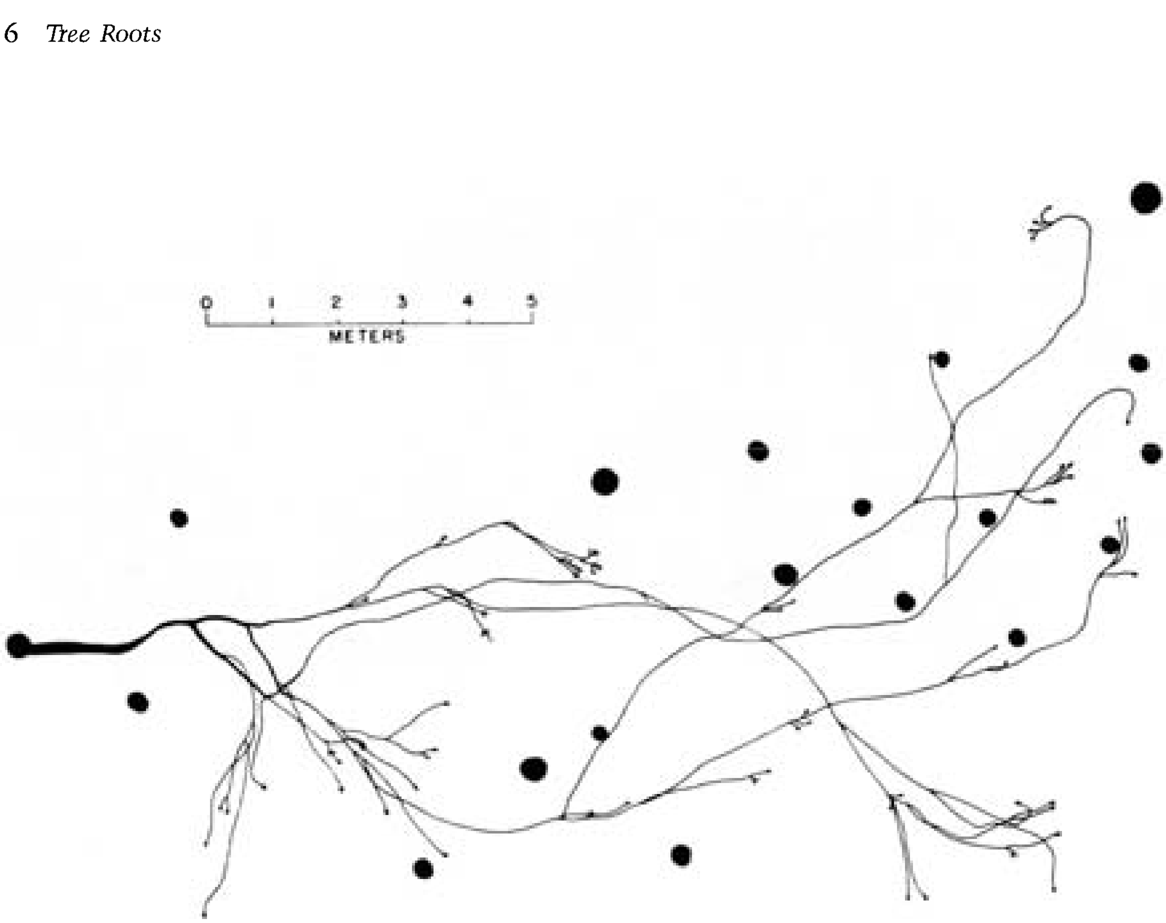

Figure 2. Plan-view diagram of the horizontal woody root system developed from a single lateral root of a red maple about 60 years old. Solid circles show the location of other trees in the stand. Arrows indicate that the root tips were not found; therefore these roots continued somewhat farther than is shown. From Lyford and Wilson, 1964.

four meters (3 to 15 ft) from the trunk to form an extensive network of long, rope-like roots 10 to 25 millimeters (.25 to 1 in) in diameter.

The major roots and their primary branches are woody and perennial, usually with 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 centimeters (8 to 12 in) below the surface and grow outward far beyond the branch tips of the tree. This system of framework roots, often called "transport" roots, frequently extends to encompass a roughly circular area four to seven times the area delineated by an imaginary downward projection of the branch tips (the so-called drip line).

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). In drier soils, pines and some other species can form "striker roots" at intervals along the framework system. These striker roots grow downward vertically until they encounter obstacles or layers of soil with insufficient oxygen. Striker roots and taproots 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 (Figures 3 and 4).

The zone of transition between sufficient and insufficient oxygen supply is usually associated with changes in the oxidation-reduction state and color of the iron in the soil

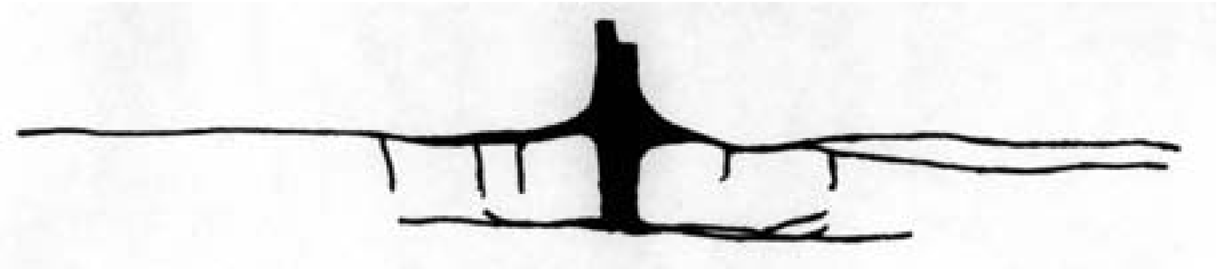

Figure 3. Drawing, not to scale, of framework system of longleaf pine tree grown in well-drained soil with a second layer of roots running in the soil layers where oxygen supplies become limiting.

Figure 4. Photograph of framework roots of longleaf pine including striker roots, 90 percent of the surface root system has rotted and washed away, Kerr Lake, North Carolina.

Figure 5. 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 little or no oxygen is available. Iron oxide deposits are typically associated with such roots

(from reddish-yellow to gray for example). Water can hold less than 1/10,000 the oxygen that air can hold, 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 (Figure 5).

Feeder Roots

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 6, 7, 8, and 9). Many of these smaller roots and their multiple tips are 0.2 to 1 millimeter or less in diameter and less than 1 to 2 millimeters long. These fine, non-woody roots constitute the major fraction of the surface of a tree's root system. Their multiple tips are the primary 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 expand greatly the effective surface area of the root system (Figure 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 fluc-

tuations 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 are frequent and are caused by many agents. New roots form rapidly after injuries, so the population and concentration of roots in the soil are as dynamic as the population of leaves in the air above, if not more so.

The crowns of trees in the forest are frayed away as branches rub against one another in the wind. One can easily observe the frayed perimeter of each tree crown by gazing skyward through the canopy of a mature forest. Such "shyness" is not seen below the ground. Roots normally extend far beyond the branch tips, and the framework root systems of various trees cross one another in a complex pattern. The non-woody root systems of different trees often intermingle with one another so that the roots of four to seven different trees can occupy the same square meter of soil surface (Figure 9). Injuries, rocks, or other obstacles can induce roots to deviate 90 degrees or more from their normal pattern of radial growth. These turnings and interminglings of roots make the determination of which roots belong to which tree extremely difficult. Furthermore, natural root grafts

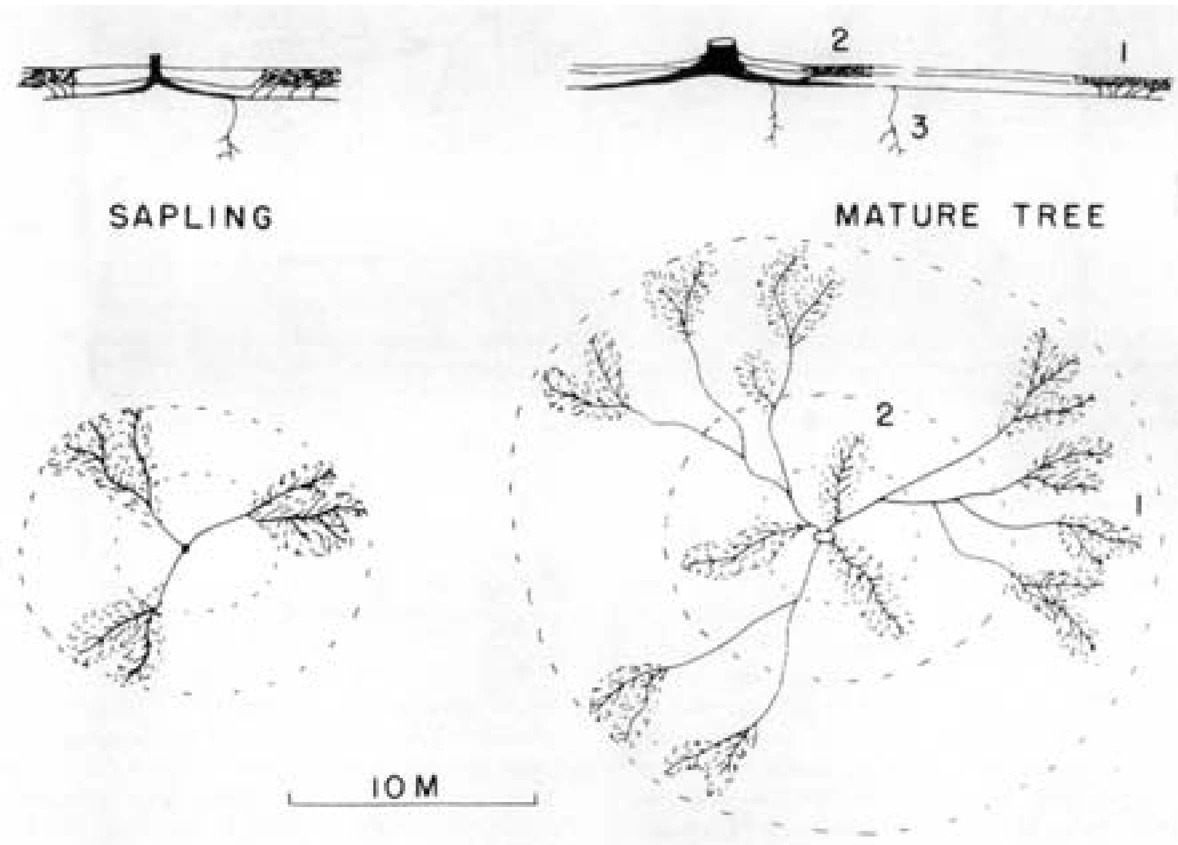

Figure 6. Schematic diagram showing reoccupation of soil area near the base of a mature tree by the growth of adventitious roots. 1) Root fans, growing from the younger portions of the woody roots, have extended to a distance of several meters from the tree 2) Root fans on adventitious roots have only recently emerged from the zone of rapid taper or root collar and now occupy the area near the base of the tree. 3) Vertical roots. From Lyford and Wilson, 1964.

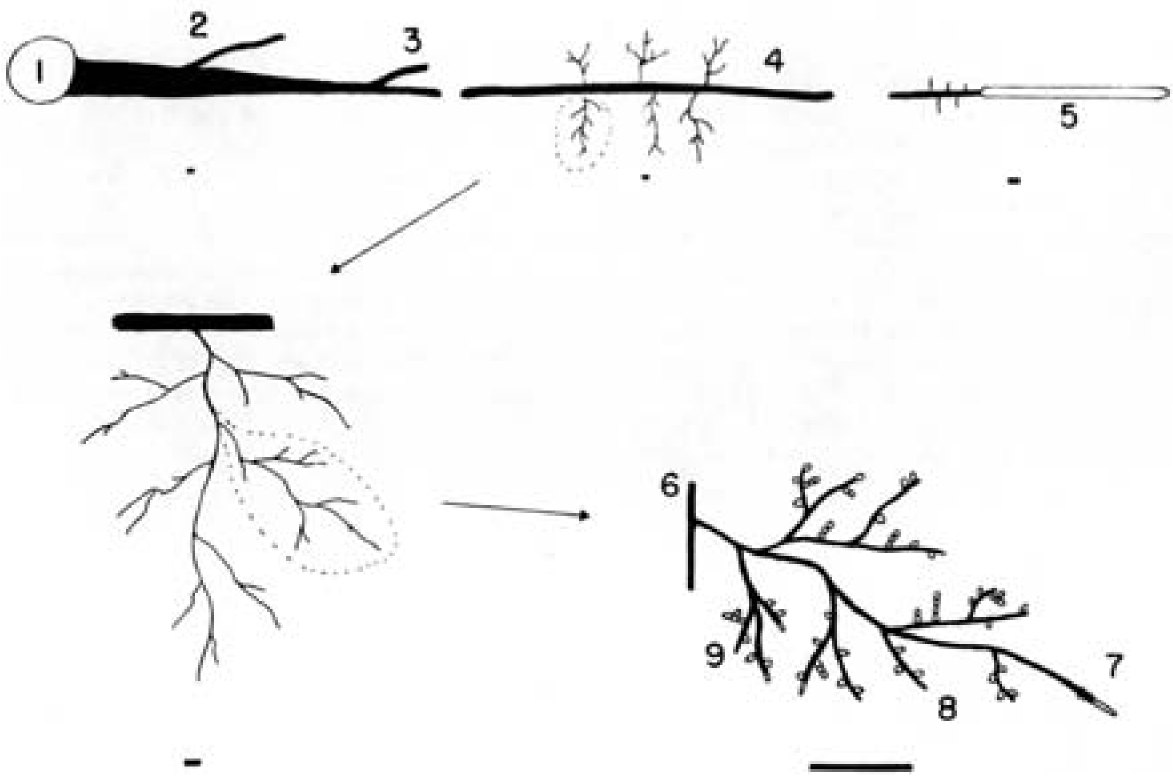

Figure 7. Schematic diagram showing woody and non-woody root relationships. 1) Stem. 2) Adventitious roots in the zone of rapid taper. 3) Lateral root. 4) Non-woody root fans growing from opposite sides of the rope-like woody root. 5) Tip of woody root and emerging first order non-woody roots. 6) Second 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 centimeter. From Lyford and Wilson, 1964.

commonly occur when many trees of the same species grow together in the same stand.

In summary, large woody tree roots grow horizontally through the soil and are perennial. They are predominantly located in the top 30 centimeters (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 larger than the projected crown area. Typically, the fine, non-woody tree roots grow upward into the litter and into 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 toward anything. Generally they cannot grow where there is no oxygen or where the soil is compacted and hard to penetrate. In most soils, the number of soil pores, and the consequent availability of oxygen, decreases exponentially with depth below the surface, the amount of clay, and the resistance to penetration (hardness).

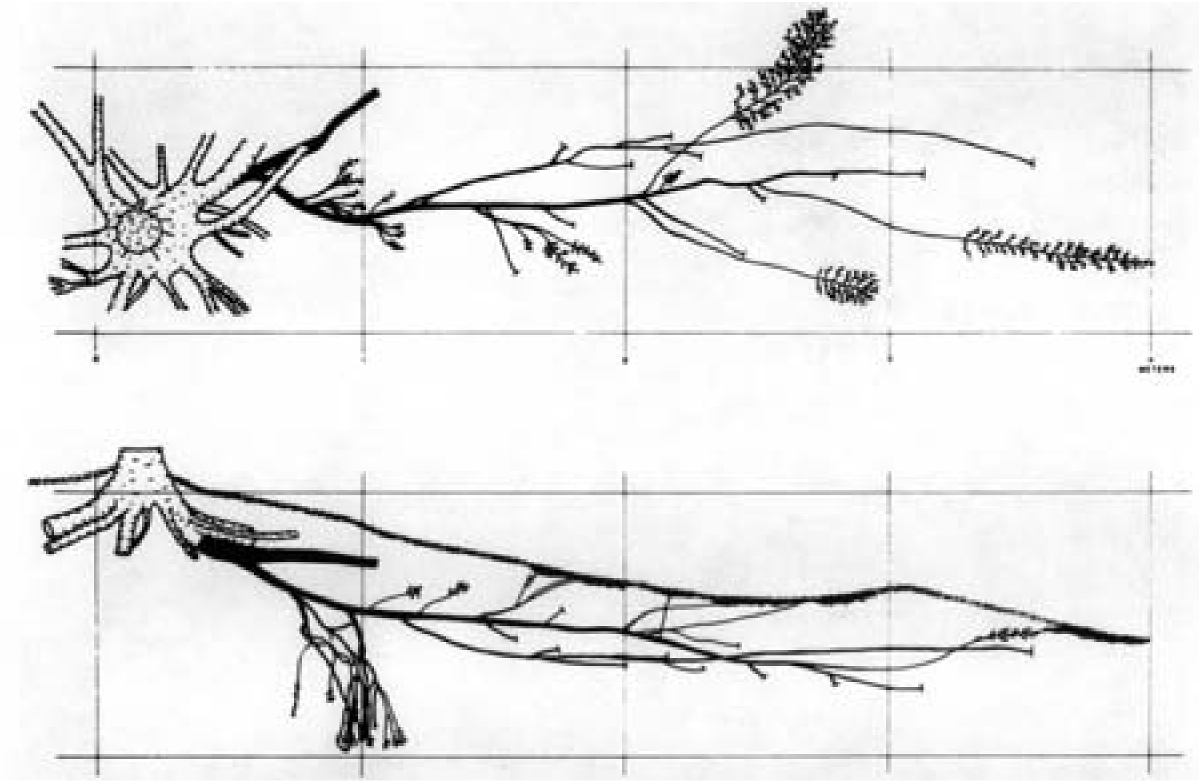

Figure 8. Scale diagrams of horizontal, woody, third order lateral roots of red oak, Quercus rubra. *Emphasis is on the roots that return to the surface and elaborate into many small-diameter non-woody roots in the forest floor. Top view (above), side view (below). The squares are 1 meter on a side. From Lyford, 1980.*

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 percent 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 positively charged cations (e.g., Ca^{++}, K^{+}, Mg^{++}) and functions to trap plant nutrients and prevent their leaching into the deeper layers of soil. Soil analyses show that the greatest supplies of materials essential to plant life are located in the very surface layers of the soil, and, predictably, this is where most of the roots are located (Woods, 1957; Hoyle, 1965).

Variations in Soil Conditions

Roots are most abundant and trees grow best in light, clay-loam soils about 80 centimeters deep (3 ft) (Coile, 1937, 1952). Conversely, 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 (33 ft) or more—when oxy-

Figure 9. Photograph of roots intermingling in the soil. Mixed hardwood stand, Harvard Forest, Petersham, Massachusetts. The roots in front of the trowel were exposed by careful brushing and pulling away of the litter. 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. Photo by T. O. Perry.

gen, 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.

Adapting to their situation, pines and other trees tend to develop a two-layered root system in the deep sands of the Southeast and other similar sandy locations. They form 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 drought conditions.

Some soils of the western United States are geologically young and unstructured, originating primarily from the downward movement of eroded particles of rock. Such deposits can form a layer 10 meters (33 ft) or more deep and are extremely dry, especially on the western

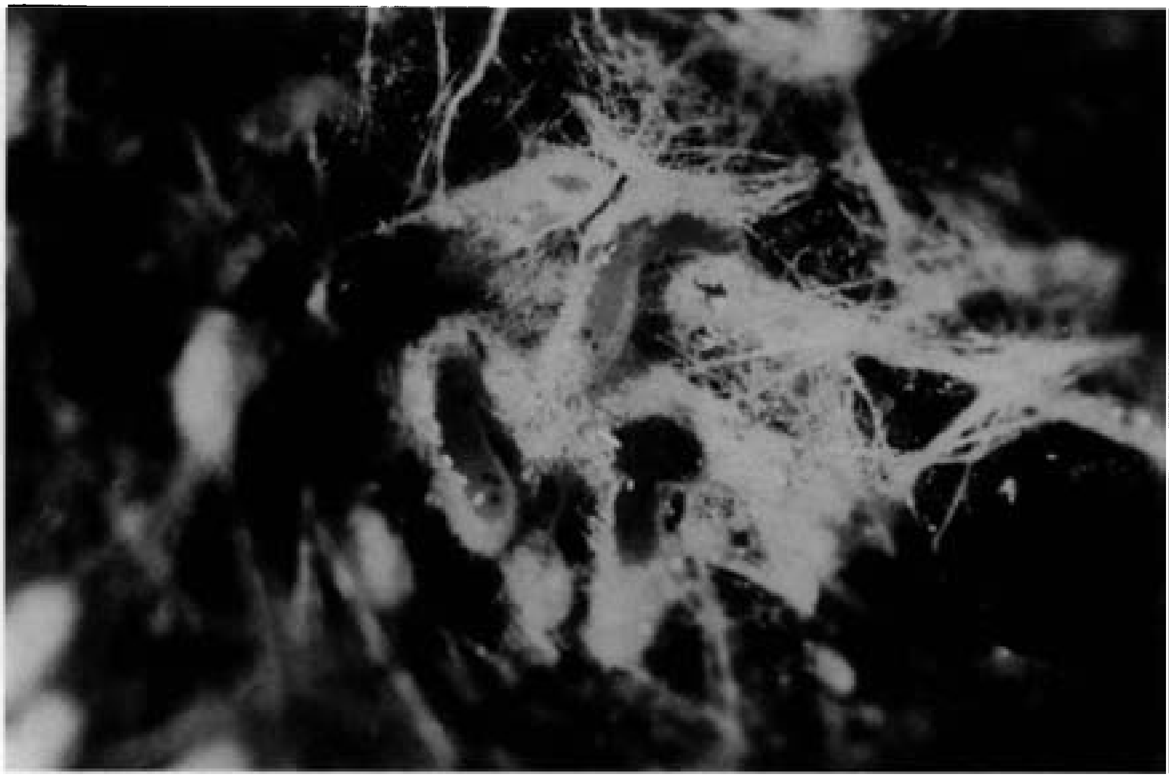

Figure 10. Photograph of root tips growing in the litter of a mixed hardwood forest. The mycorrhizae extend out from the root tips to expand greatly the functional absorptive surface area of the roots they are attached to. Root diameters about 0.5 mm. Photo by Ted Shear, North Carolina State University.

slope of the Sierras where summer rains are light and infrequent. Most water in the soils of this region originates from winter rains and snowmelt that travel along the surface of the unbroken bedrock that lies below the soil layer. 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 taproot system that plunges down and runs along the soil-rock interface. Deep cuts for superhighways sometimes reveal these roots 15 meters (50 ft) or more below the surface.

Some trees, like longleaf pine (*Pinus palustris*), have made 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 tend to be shallow and multi-branched. Tupelo, cypress, and other species of the swamps and flood plains have evolved specialized anatomies that permit conduction of oxygen 30 centimeters (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 flood-plain species can survive the conditions of low soil oxygen that result from several months of flooding (Hook et al., 1972).

Other species, particularly cherries and other members of the rose family, are especially sensitive to conditions where oxygen supplies limit growth. Cherry roots contain cyanophoric glucosides, which are hydrolized to form toxic cyanide gas when oxygen supplies are limited (Rowe and Catlin, 1971). Flooding that lasted less than 24 hours killed most of the Japanese cherry trees around Hains Point in Washington, D.C., following Hurricane Agnes in 1973. Sediment buildup, which in some locations exceeded 20 centimeters (8 in), also contributed to this mortality.

There are important genetic differences in the capacity of tree species and varieties to tolerate variations in soil chemistry, soil structure, or oxygen supply (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. On the one hand, the roots of flood-plain species such as cypress, tupelo, maple, and willow, which are generally thought of as "shallow," will grow deep into the soil and down sewer lines if oxygen and water supplies are adequate. On the other hand, the roots of pines, hickories, and other upland species, which are generally thought of as "deep," will stay close

Figure 11. Roots growing in the crevices between bricks. There was no oxygen below the bricks that overlaid a compacted clay soil on the North Carolina State University campus. Tree roots commonly follow cracks, crevices, and other air passages underneath pavement. Photo by T. O. Perry.

to the surface if the soil is too compact, or if oxygen supplies below the surface are limited.

Roots grow *parallel* to the surface of the soil so that trees on slopes have sloping root systems that actually grow uphill. In search of nutrients, roots often grow along cracks, crevices, and through air spaces for unbelievable distances under the most impermeable pavements and inpenetrable soils (Figure 11). Roots commonly grow down the cracks between fracture columns ("peds") in heavy clay soils they could not otherwise penetrate.

Temperatures and Tree Roots

The roots of trees from temperate climates, unlike their shoots, have not developed extreme cold tolerance. Whereas the tops of many trees can survive winter temperatures as low as -40 to -50 degrees C (-40 to -60 F), their roots are killed by temperatures lower than -4 to -7 degrees C (20 to 25 F) (Beattie, 1986). In areas that experience severe cold, such as northern Europe or Minnesota, a good snow cover or a layer of mulch can often prevent the ground from freezing completely during the winter (Hart, Leonard, and Pierce, 1962). By repeatedly digging up, measuring, and then reburying them, researchers have observed that roots can grow throughout the winter—whenever soil temperatures are above 5 degrees C (40 F) (Hammerle, 1901; Crider, 1928; Ladefoged, 1939).

One of the subtle impacts of raking leaves in the fall is that it exposes roots to destructive winter air temperatures that they would ordinarily be insulated from by the layer of leaves. Similarly, the potted trees so common in the central business districts of northern cities seldom survive more than a few years because their roots are exposed to air temperatures that are substantially lower than those of the soil. Skilled horticulturists are careful to move potted perennials to sheltered locations where they will be insulated from the full blast of winter.

Contrariwise, soil surface temperatures in summer are often hot enough to "fry an egg," as newspapers boastingly report. Such temperatures, which can be as high as 77 degrees C (170 F), also fry plant roots. Fortunately, most soil temperatures decrease rapidly with depth, and roots only a few millimeters below the surface generally survive, particularly if an insulating layer of mulch is present. As in the case of freezing temperatures, plants growing in containers are more susceptible to heat damage because of the lack of insulation. Roots, like shoots, grow most rapidly when temperatures are moderate—between 20 and 30 degrees C (68 and 85 F) (Russell, 1977).

Misconceptions about Tree Roots and the Practical Consequences

The rope-like roots at or near the surface of the soil have been obvious to diggers of holes for fence posts and ditches for thousands of years, as obvious as Galileo's "shadow of the earth on the moon." However, trees can become huge—larger than the largest whale—and very few human beings have had the privilege of actually seeing even a small fraction of the root system of an entire tree. Illustrations in textbooks, in natural history books, and in manuals of landscape architecture or of tree care are usually the creations of artistic imaginations and highly inaccurate (Figure 12).

An insurance company, hearing of Walter Lyford's work on tree roots, wanted to develop an idealized picture of tree roots, penetrating the depths of the soil and securely anchoring the tree in an upright position, as the symbol of the security its customers would achieve by purchasing its insurance. The company commissioned an artist to visit Lyford and examine his findings in order to prepare a logo of tree roots for its advertising campaigns. The projected logo and advertising scheme were never started because it is impossible to portray an entire tree with its roots accurately on the page of a typical textbook.

As an example, take a healthy, open-grown oak tree, 40 years old, with a trunk 21 meters (70 ft) tall and 0.6 meters (2 ft) in diameter. The spread of the branches of such an open-grown tree is rarely less than two-thirds of the

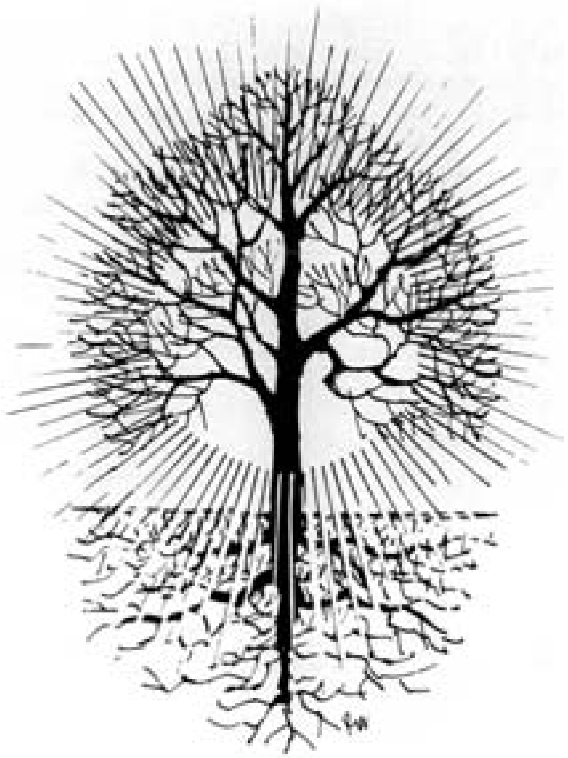

Figure 12. Roots do not grow as this artist's conception indicates. Inaccurate illustrations like this one have led to harmful practices in the management of trees in both forest and urban situations. Illustration from a brochure produced by the Society of American Foresters.

height of the tree and is often equal to or greater than the height. The root system of such a tree usually extends more than 9 meters (30 ft) beyond the tips of the branches, generally forming a circle with a diameter two or more times the height of the tree. The problems of scale are overwhelming and can be appreciated by examining Figures 13 and 14.

A significant portion of the root system of all trees in all soils is concentrated in the top few centimeters of soil. Tree roots grow right into the litter layer of the forest, in among the grass roots of suburban lawns, and in the crevices of the bricks, concrete, and asphalt of the urban landscape (Figures 11 and 15). For this reason, 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 readily available to tree roots. Careful research has failed to show any differences in the response of trees to fertilizer placed in holes versus that broadcast on the soil surface (Himelick et al., 1965; van de Werken, 1981).

Foresters broadcast fertilizers on millions of acres of land and achieve rapid and large returns on their investments. *Except for 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 fertilizer injected into the soil.* The root systems of one-year-old seedlings can take up nutrients ten or more feet from their trunks. The absorbing roots of larger trees commonly extend from their trunks to twenty feet beyond their branch tips. The tree will benefit from having fertilizer broadcast over this entire area.

Herbicides and other chemicals should be used only with extreme care near trees and shrubs since their roots extend far beyond the tips of the tree's branches. When they grow in a lawn, trees can be thought of as "broad-leaved weeds" and application of the common lawn herbicide dicamba (also called "Banvel®") by itself, in combination with other herbicides, or in combination with fertilizers can 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 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®" (glyphosate) herbicide and its formulations are supposedly inactivated when they hit the soil or dirty water, but they do not have to actually penetrate the soil to interact with tree roots growing in a litter layer, lawn, or mulch. Dogwoods and other trees can show extreme leaf distortion and crown die-

back even when herbicides do not strike the green portions of their trunks or their foliage. Since tree roots often grow in cracks and crevices of pavement, applications of sterilants and herbicides to kill weeds in these situations can inadvertently kill trees 20 meters (60 ft) or more away from where they are applied (Figure 15).

Remember, natural root grafts are common among trees of the same species, meaning that herbicides applied to kill one tree can flash back along root grafts to kill trees that were not treated. In addition, many trees, such as poplars, sweet gum, and American beech, send up sprouts from their roots that can be damaged when an herbicide is translocated from a treated stem through the root system to an untreated stem.

In larger residential lots, say roughly 32 meters wide by 45 meters deep (105 ft by 150 ft), the roots of a large tree will commonly occupy the entire front or back yard and

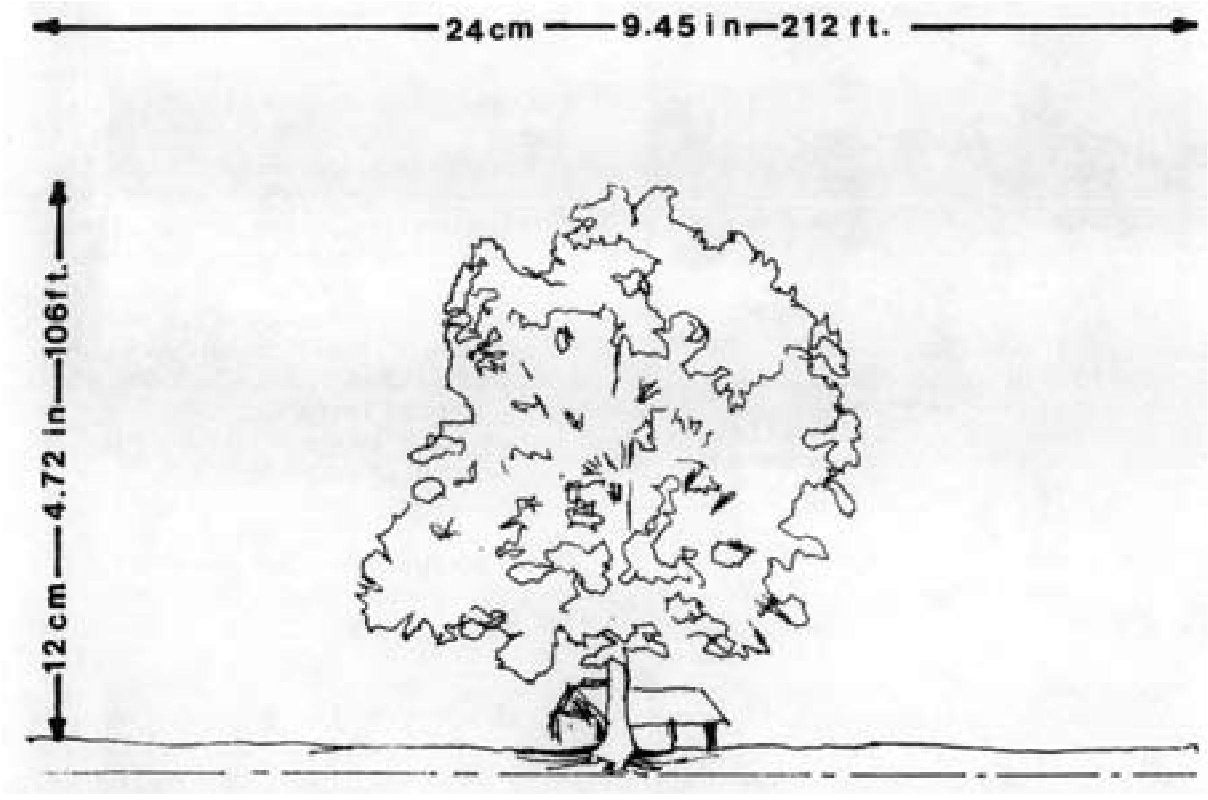

*Figure 13. Scale drawing of Memorial Oak Tree (*Quercus alba*), Schenck Forest, North Carolina State University. The original drawing was made by tracing the projected image of the tree (Figure 14) onto a piece of paper with a pen that produced a line 0.2 millimeters thick, the thinnest line that can be reproduced in most publications. The original drawing was 24 centimeters wide (9.5 in) and represents a typical root spread of 65 meters (212 ft). The Schenck Oak is about 33 meters tall (106 ft) and is represented on the vertical axis as 12 centimeters (4.7 in). The original drawing represented a 274-fold reduction in the actual height of the tree. Most branches and 90 percent of the tree roots would not be visible if drawn to this scale. Indeed the width of a typical white oak leaf would be about the thickness of the lines in the drawing, and most of the roots would be located in the soil layer represented by the thickness of the line representing the soil surface. The dash-dot line is located 1.5 meters (5 ft) below the surface and very few if any roots would penetrate beyond this depth in a representative soil.*

*Figure 14. This photograph of the Schenck Memorial Oak (*Quercus alba*) was projected and traced to produce Figure 13. The Schenck Memorial Oak is 32.3 meters tall (106 ft) and has a crown spread of 29 meters (94 ft) and a diameter at breast height of 1.07 meters (42 in).*

trespass into the neighboring property. No part of an urban yard can be treated carelessly with herbicides. Care must also be taken in disposing of toxic chemicals, deicing salts, old crankcase oil, and high-strength detergents. Careless disposal of chemicals and improper use of herbicides are among the most common causes of tree death in urban areas.

Soil Compaction

The largest single killer of trees is soil compaction—compaction from excessive use of city parks by people, from excessive grazing by livestock (including zoo animals)—and even from the feeding activities of pigeons, whose small feet exert more pressure per square centimeter than heavy machines. Trees are also killed by compaction from construction equipment and by compaction from cars in unpaved parking areas. Compaction closes the pore spaces that are essential to the absorption of water and oxygen and hardens all but the sandiest of soils so that roots cannot penetrate them, even when oxygen supplies are adequate (Patterson, 1965).

Excessive use of mulch can induce fermentation, immobilize nutrients, and cut off the oxygen supply, thereby killing trees. Use of broad expanses of plastic, either as a surface covering or under a layer of organic mulch or stone, is a sure way to cut off oxygen and kill trees. As an alternative, porous landscape fabrics, which permit water and air to penetrate the soil, are a vast improvement over plastic.

The maximum leaf area index that a normal ecosystem can support is about 12, when both surfaces of the leaf are counted. The corresponding maximum root area index is between 15 and 30. A large planting of lawn, annuals, or shrubs underneath existing trees often results in a reduction in the root and leaf area indexes of the trees. 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. Surprisingly, turning over the soil when gardening is another common cause of tree death in urban situations. Gardeners should be aware of the biological compromises that need to be made in order to achieve the proper balance between trees and garden plants.

It should be obvious by now that any earth moving or regrading that cuts or buries tree roots will result in the death of a corresponding portion of the branches in the tree. Unfortunately, this simple fact is often ignored when utility lines, parking lots, or even irrigation lines are being installed. Smearing six inches of clay from the mineral soil layer over the root system of an established tree or covering its roots with pavement can be as lethal as cutting it down with a chain saw.

When a new house is constructed, the yard may have six different trench lines cut from

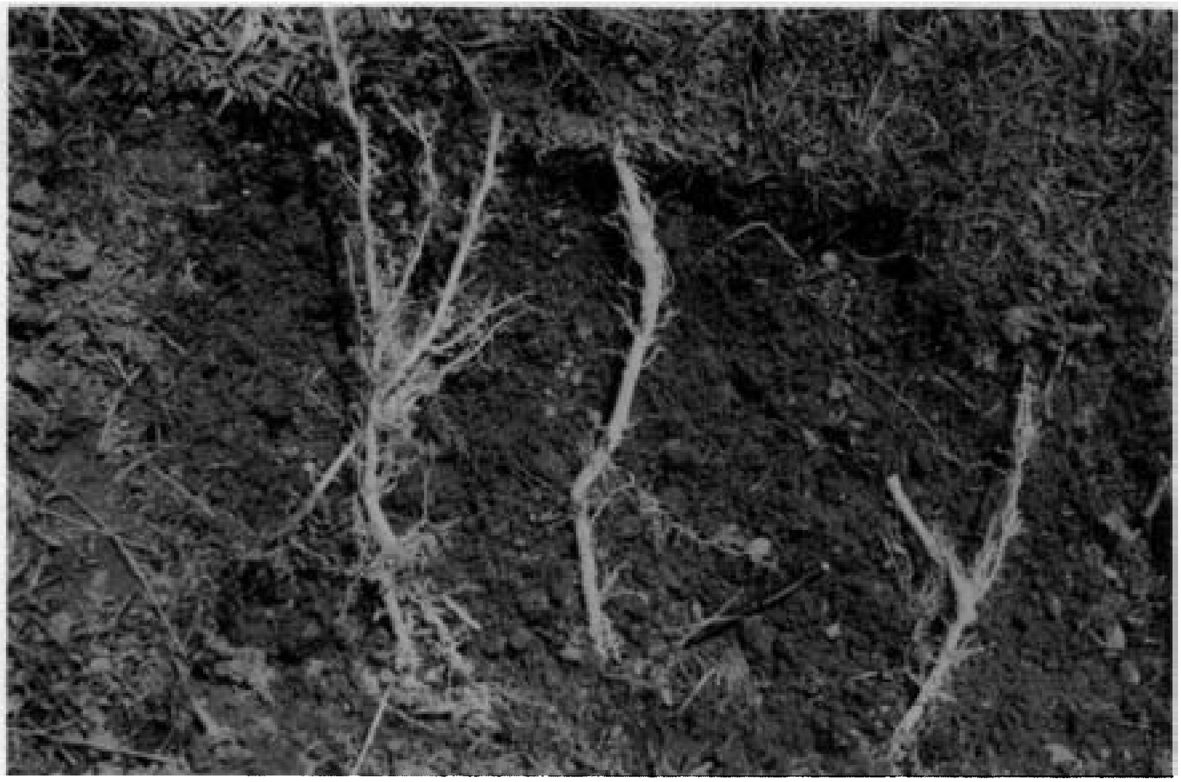

Figure 15. Many roots of trees grow closely intermingled with grass roots in the few top centimeters of a lawn. Therefore fertilizers and herbicides do not have to move down into the soil in order to affect trees.

the street to the house—for water, sewer, electricity, telephone, gas, and cable television. Over 90 percent of the pre-existing tree roots in the front yard are destroyed during construction and utility-line installation. In addition, the soil structure of the entire lot is usually completely destroyed by heavy equipment and the spreading of excavated heavy soil on top of undisturbed soil. The proud new homeowners are left to figure out for themselves why all their trees have severe crown dieback and continue to decline (or die) for a decade or more after they have moved in.

Saving Trees

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 construction without damaging some or all of its roots. By tunneling or concentrating utility-line installations in a single trench, this damage can be minimized. Careful watering and thinning of the tree crowns to compensate for root losses can buy time until new roots can be produced.

It is often wiser and cheaper to accept a bad situation and cut down a tree before construction begins rather than to try to preserve a large specimen in the middle of a construction site. Performing tree surgery after construction is complete—and crown dieback is obvious—will be more expensive and may be too late to save the tree. Planting a young, vigorous sapling after construction is completed not only may be more cost effective but also may provide greater long-term satisfaction.

In urban situations, soil compaction and limited oxygen supplies are the major restraints to growing trees in city parks and in

highly paved areas. Inadequate supplies of water are usually secondary to these two fundamental problems. In terms of surviving these conditions, trees adapted to swamps and flood-prone areas, where soil oxygen tensions are normally low, often perform the best. Indeed, most of our common street trees, including pin oak, willow oak, sycamore, silver maple, and honey locust are flood-plain species that can thrive in compacted, urban soils. Different trees grow on different sites in nature, and it is unreasonable to expect species adapted to well-drained upland or sloping topography to possess roots that would grow well in the compacted soils of a heavily used recreation area or in areas with extensive pavement.

There are hundreds of ways to kill or injure trees. They range from zapping them with laser beams (as in the Omni shopping mall of Atlanta) to girdling them with the grinding tugs of dogs chained outside of college classrooms. Many tree deaths are accidental and involve misconceptions about the structure and function of 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 in Washington, D.C., allow rows of newly planted, eight-inch-caliper trees in front of the new Aerospace Center to remain unwatered while the need for irrigation was recognized and supplied to trees on the mall across the street?

People must know where tree roots are located and what they require if healthy trees are to become a gratifying part of the urban environment.

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