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THE ECOLOGY OF TREE ROOTS AND THE PRACTICAL SIGNIFICANCE THEREOF[1]

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Abstract. Tree root growth is opportunistic and occurs wherever 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.

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, 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 paper 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 sewer lines).

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 paper 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 portion of the roots is 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

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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 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 1/10 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 indicate 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 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.

Patterns of Growth and Development 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, Bohm 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.

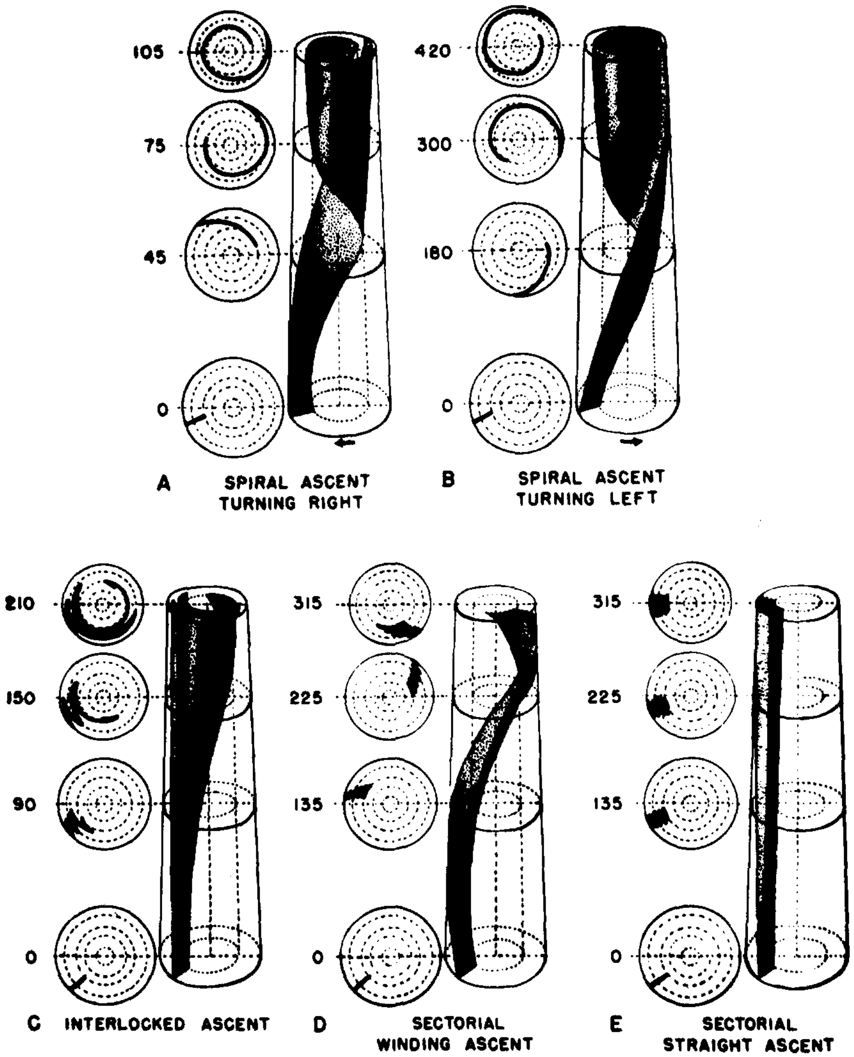

Figure 1. Five types of water-conducting systems in various conifers as shown by the tracheidal channels that were dyed by trunk injection. The numbers give the height in centimeters of the transverse section above injection. A. Spiral ascent, turning right: Abies, Picea, Larix, and Pinus (Rehder's section 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.***

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 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, Russel, 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 from 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 poplars, for example) does

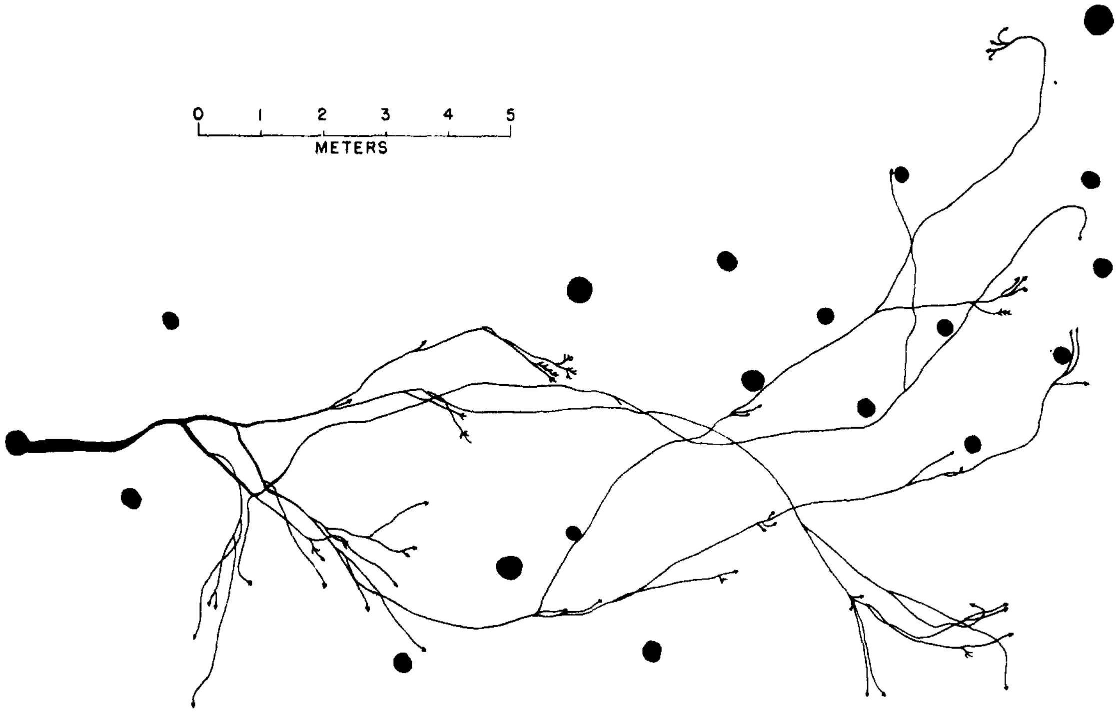

Figure 2. Plan view diagram of the horizontal woody root system developed from a single lateral root of red maple about 60 years old. Solid circles show the location of other trees in the stand. Arrows indicate that the root tips were not found and therefore these roots continue somewhat farther than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

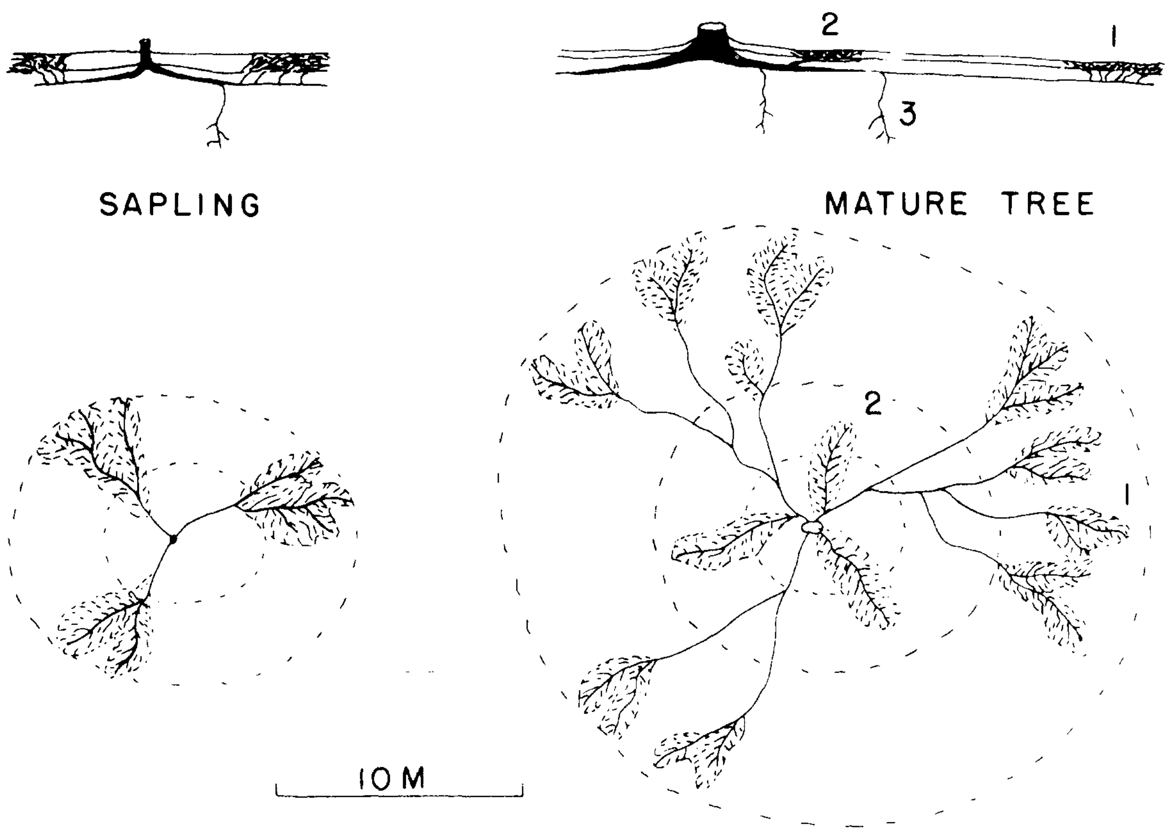

Figure 3. Schematic diagram showing reoccupation of soil area near the base of a mature tree by the growth of adventitious roots. 1. Root fans growing from the younger portions of the woody roots which have extended to a distance of several meters from tree. 2. Root fans on adventitious roots only recently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

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). 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 deliniated 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).

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 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 (see Figures 4 and 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 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, 3, 7, 8, 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 sites of absorption of water and minerals. Hence they are often called "feeder roots."

Figure 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 5. (Upper) 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*). (Lower) Roots of loblolly bay tree *Persea borbonia L.* One of hundreds of trees of various species exposed by beach erosion associated with Hurricane David — Seabrook Island, S.C. All specimens show a two layered root system — see figures 2-4 and 2-5.

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 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. Roots normally extend far beyond the branch tips and the framework root systems of various trees cross each 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 9).

Injuries, rocks, and other obstacles can induce roots to deviate 90° or more from their normal *pattern of radial growth. These turnings and inter*minglings 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 horizontal*ly 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 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

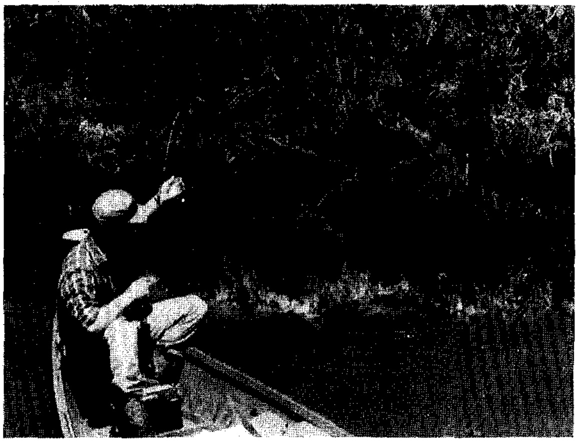

Figure 6. Mat of roots above the permanent water table exposed by digging a drainage canal. Green Swamp, North Carolina. A few species have specialized tissues containing air passages and specialized metabolisms that permit their roots to penetrate several feet below the permanent water table where there is inherently little or no oxygen. Iron oxide depoits are typically associated with such roots.

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 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

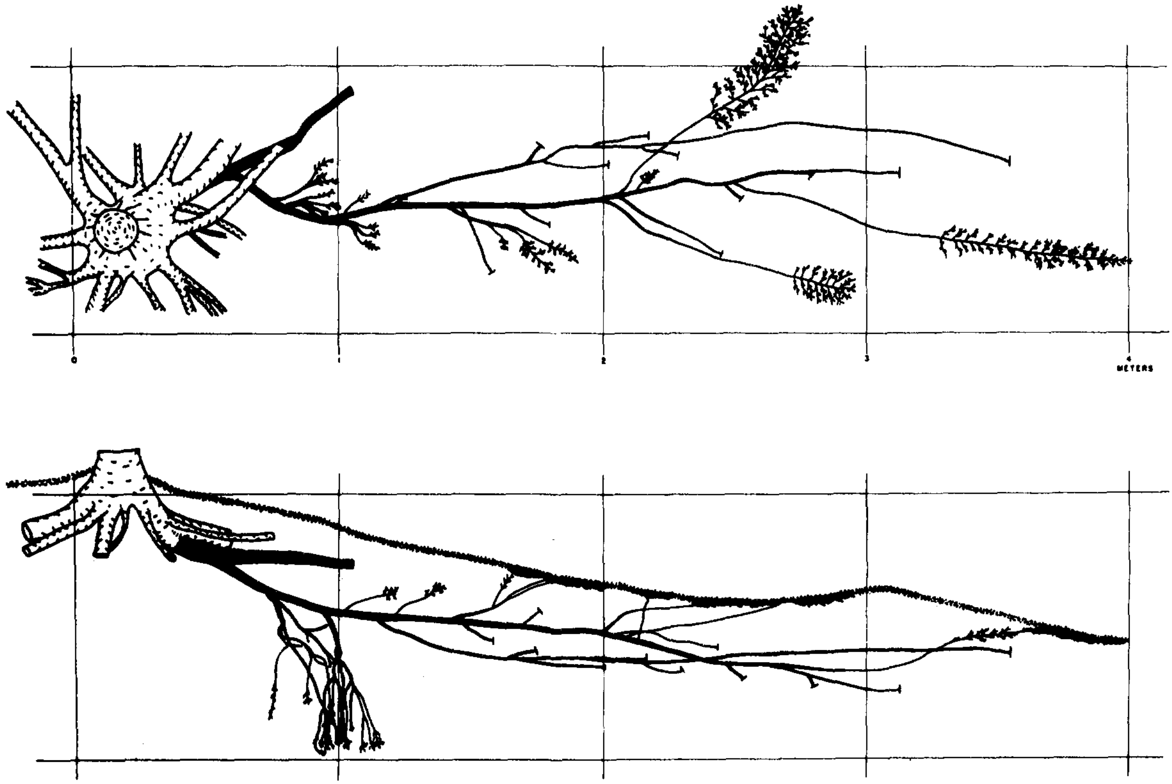

Figure 7. Schematic diagram showing woody and non-woody root relationships. 1. Stem. 2. Adventitious roots in the zone of rapid taper. 3. Lateral root. 4. Non-woody root fans growing from opposite sides of the rope-like woody root. 5. Tip of woody root and emerging first order non-woody roots. 6. Second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

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 drouth.

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 bed rock. 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"

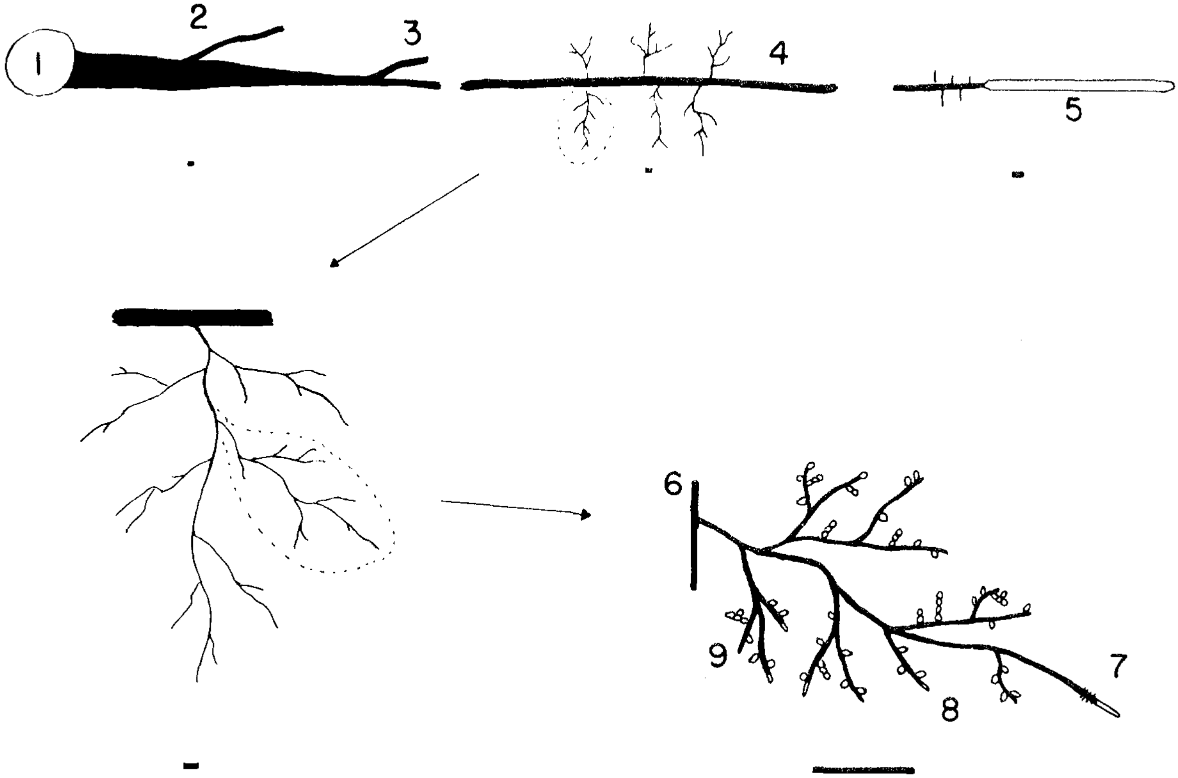

Figure 8. Scale diagrams of a horizontal woody third order lateral with particular emphasis on the roots that return to the surface and elaborate into many small diameter non-woody roots in the forest floor. Top view (above), side view (below). The squares are 1 m on a side. Species: red oak (*Quercus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

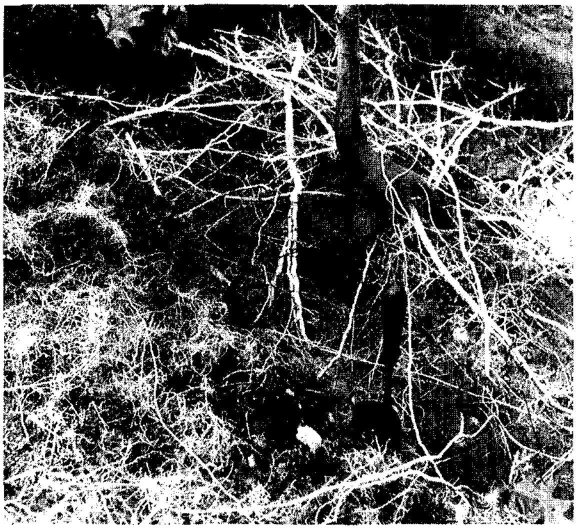

Figure 9. Photograph of roots intermingling in the soil. Mixed hardwood stand. Harvard Forest, Petersham, Mass. The roots in front of the trowel have been exposed by careful brushing and pulling away of the litter. Many hours were required. The roots in the background were exposed by digging down and 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.

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.

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 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 11). Roots commonly grow down cracks between fracture columns ("peds") in heavy clay soils that they could not otherwise penetrate.

Misconceptions about Tree Roots

The rope-like roots at or near the surface of the soil have been obvious to diggers of holes for

Figure 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.

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 12 for example).

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 Figure 13 and 14. 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).

Figure 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.

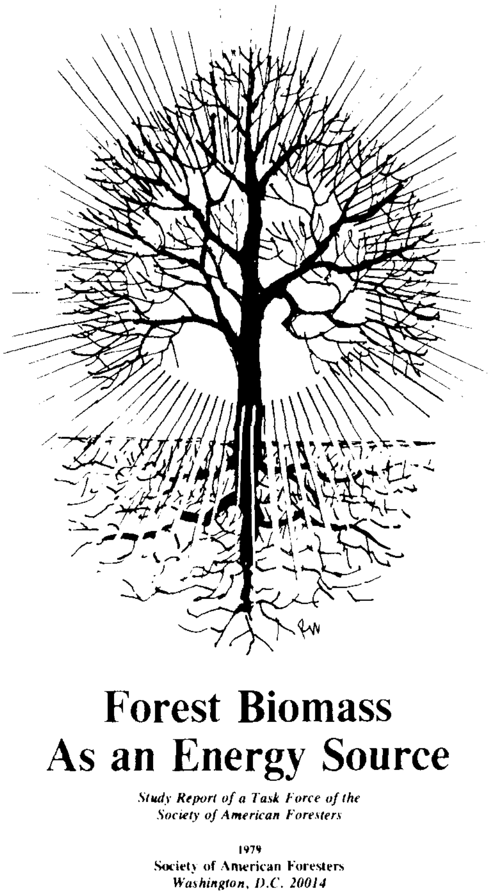

Figure 12. Roots do not grow as this artist's conception indicates. Inaccurate illustrations like this one have led to harmful practices in the management of trees in both forest and urban situations. *Illustration from a brochure of the Society of American Foresters.*

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 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.

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 6×10^{-4}mm or 0.6 μm (0.2 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 mm × 317 = 63.4 mm (2.5 in) in order to be visible on a printed page with a

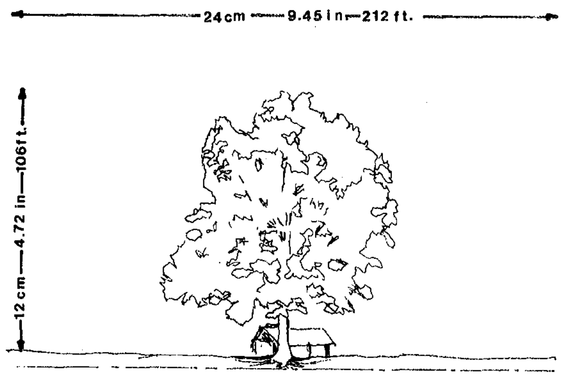

Figure 13. Scale drawing of Memorial Oak Tree, Schenck Forest, North Carolina State University. The original drawing was made by tracing the projected image of the tree (Figure 14) onto a piece of 8.5″ × 11″ paper. A #2 Rapidograph pen point was used to produce a line 0.4 mm thick. This is the thinest 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 or 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.

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 into 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 11 and 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 available to tree roots. That is why Himelick *et al.* (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

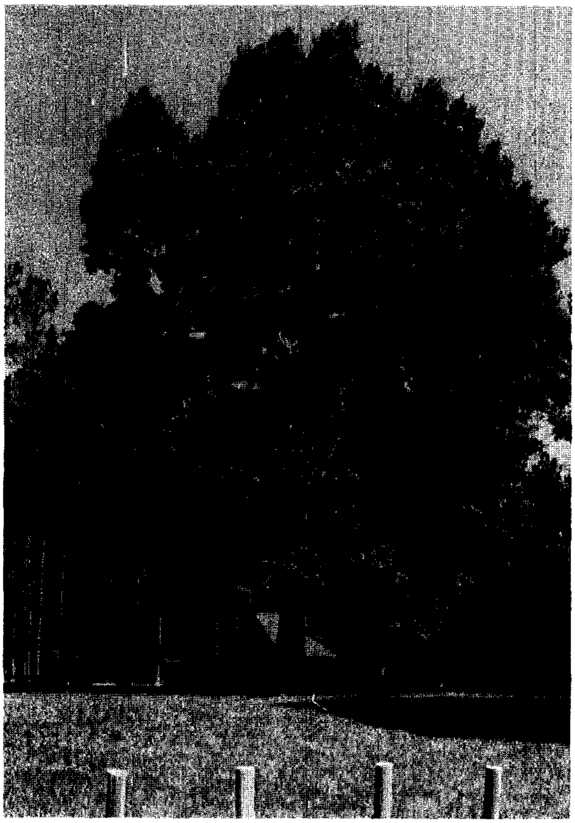

Figure 14. This photograph of the Schenck Memorial Oak was projected and traced to produce Figure 13. The Schenck Memorial Oak is 106′ tall and has a crown spread of 94 ft. and a dbh of 42″. The tree is a white oak.

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 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 to penetrate the soil to interact with tree roots growing in a litter layer,

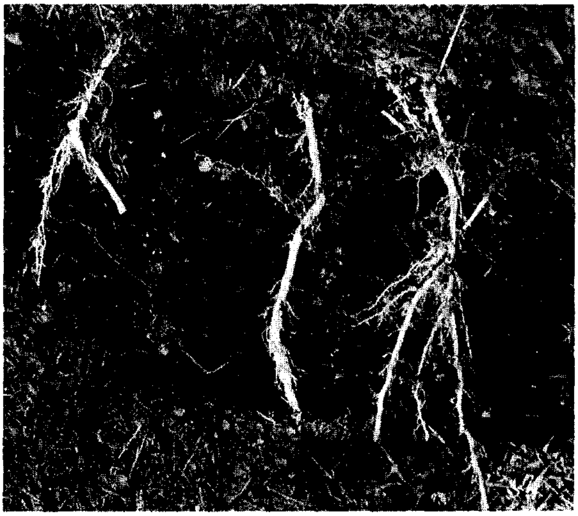

Figure 15. Many roots of trees grow closely intermingled with grass roots — right in the surface millimeters of a lawn. Fertilizers and herbicides do not have to move in the soil in order to affect trees.

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 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 and improper disposal of chemicals and improper use of herbicides is one of the most common causes of tree death 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. 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.

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, mistreated 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 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 accidential 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 obviously 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.

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