STATE OF SOUTH DAKOTA

SOUTH DAKOTA DEPARTMENT

OF ENVIRONMENT AND NATURAL RESOURCES

IN RE: THE MATTER OF THE HEARING FOR RE-ISSUING THE STATE GENERAL WATER POLLUTION CONTROL PERIMT FOR CONCENTRATED ANIMAL FEEDING OPERATIONS	**INTERVENERS' EXPERT WITNESS AND WITNESS DISCLOSURE**

Pursuant to the Procedural and Scheduling Order, dated the 15th day of March, 2016, the Interveners, South Dakota Cattlemen's Association and South Dakota Dairy Producers, designate the following individuals as their expert witnesses and witnesess for the hearing scheduled for September 27-29, 2016.

A. Expert Witnesses

1. Dr. Todd Trooien *curriculum vitae attached*
2. Brad Woerner *curriculum vitae attached*
3. Dr. Erin Cortus *curriculum vitae attached*
4. Dr. John Ball *curriculum vitae attached*
5. John Lentz *curriculum vitae attached*
6. Interveners reserve the right to call additional witnesses to rebut any testimony which has not yet been disclosed.

B. Witnesses

1. Mike Schmidt
2. Eric Loe
3. Bill Wilkinson
4. John Haverhals

5. Lynn Boadwine
6. Jason Feldhaus
7. Wayne Smith
8. Terry Heinle
9. Roger Scheibe

CERTIFICATE OF SERVICE

I, Todd D. Wilkinson, the undersigned, hereby certify that on August 29, 2016, I served a true and correct copy of the foregoing Interveners', South Dakota Cattlemen's Association and South Dakota Dairy Producers, Expert Witness and Witness Disclosure in the above-entitled matter, by mail and electronic means on the following:

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Todd Trooien

Professor

Education

- Ph.D.—Colorado State University
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- M.S.—South Dakota State University
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    - Agricultural Engineering, 1985
- B.S.—South Dakota State University
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    - Agricultural Engineering, 1983

Academic Teaching

- AST 333 Soil and Water Mechanics

Professional Organizations

- American Society of Agricultural Engineers
- Soil Science Society of America
- Irrigation Association
- Subsurface drip irrigation for row crops

Research

- Use of subsurface drip irrigation for utilization of livestock wastewater
- Water movement through glacial till-derived soils
- Irrigation water management
- Subsurface drip irrigation for row crops

Publications

- Lamm, F. R., T. P. Trooien, H. Sunderman and H. L. Manges. 2001. Nitrogen fertilization for subsurface drip-irrigated corn. Trans. ASAE 44(3): 533-542.
- Alam, M. and T. P. Trooien. 2001. Estimating reference evapotranspiration with an atmometer. Applied Eng. in Agric. 17(2): 153-158.
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- Trooien, T. P., F. R. Lamm, L. R. Stone, M. Alam, D. H. Rogers, G. A. Clark and A. J. Schlegel. 2000. Subsurface drip irrigation using livestock wastewater: Dripline flow rates. Applied Eng. in Agric. 16(5): 505-508.
- Trooien, T. P., L. L. Buschman, P. Sloderbeck, K. C. Dhuyvetter and W. E. Spurgeon. 1999. Water use efficiency of different maturity corn hybrids and grain sorghum in the Central Great Plains. J Prod. Agric. 12:377-382.
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- Wienhold, B. J. and T. P. Trooien. 1995. Salinity and sodicity under irrigated alfalfa in the Northern Great Plains. Soil Sci. Soc. Am. J. 59(6): 1709-1714.
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- Trooien, T. P. and G. A. Reichman. 1990. Hydraulic conductivity of till subsoil in North Dakota. Transactions of the ASAE 33(5): 1492-1496.

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BRADLEY S. WOERNER, PE

Project Manager; Eisenbraun and Associates, Inc.

Professional Registration Professional Engineer: South Dakota, Nebraska, Iowa, Minnesota

Education

B.S. Iowa State University, 1996, Agricultural Engineering
M.S. Iowa State University, 1998, Agricultural Engineering

Relevant Experience

Mr. Woerner leads the agricultural engineering team at Eisenbraun and Associates. As a project manager for the firm, he has successfully permitted, designed, and overseen construction of hundreds of livestock facilities throughout the states of South Dakota, Iowa, Nebraska and Minnesota. His projects have included large scale dairies, swine facilities, and cattle feedlots.

Prior to joining Eisenbraun and Associates in 2002, Mr. Woerner has worked on various design and construction projects for a general contracting firm. These projects included stream bank stabilization, bridge and road construction, wetlands restoration, residential housing development, and county and state park construction.

While with the Iowa State University Department of Agricultural and Biosystems Engineering, he managed and conducted several pit additive studies for swine manure management, and collected, analyzed and reported data to companies. He worked on several research projects dealing with air quality control of livestock confinement facilities, wastewater treatment and management systems. His Master's project included the development and design of an odor-reducing cover for swine manure storage facilities.

Mr. Woerner has worked with farmers, livestock producers, rural and urban homeowners, DNR and local government agencies to develop and implement programs and to permit agricultural facilities. He has over ten years of experience in air and water quality, livestock and human housing, wastewater facility design and management, grain storage, drying and handling facilities, and manure management planning.

- Project Manager for nearly 100 SD Association of Conservation District projects.
- Project Manager for SD NRCS, IA NRCS, and MN NRCS IDIQ contracts.

Areas of Study/Academic Interests:

- Livestock housing and environment

Education:

- Ph.D. 2007 Agricultural and Bioresource Engineering, University of Saskatchewan
- B.E. 2002 Agricultural and Bioresource Engineering, University of Saskatchewan

Teaching Responsibilities:

- AST/AS 463 - Agricultural Waste Management

Research/Scholarship Responsibilities:

- Gas and dust emission measurement from livestock facilities
- Modeling gas production in livestock facilities
- Air quality and environment in livestock facilities

Extension Responsibilities:

- Air Quality and Emissions
- Manure Management

Professional Memberships:

- American Society of Agricultural and Biological Engineers
- Canadian Society for Bioengineering
- Air and Waste Management Association

Awards & Honors:

- Canadian Society for Bioengineering Ph.D. Thesis Award

Ball, John J., Professor of Horticulture, Forestry, Landscape and Parks, 1991, 2001; B.S., Michigan Technological University, 1976; M.S., Michigan State University, 1979; Ph.D., 1982.

John C. Lentz

Curriculum Vitae

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Current Position:

Resource Conservationist with United States Department of Agriculture – Natural Resources Conservation Service (USDA-NRCS). Currently serve as team leader of the South Dakota NRCS Ag Nutrient Management Team (ANMT). The team provides both engineering and agronomic technical assistance to producers in development/implementation of Comprehensive Nutrient Management Plans (CNMP).

Education:

B.S. Range Science – South Dakota State University, Brookings SD (1994)
Minors – Soil Science, Agronomy
25+ Years of farming/ranching in eastern South Dakota

Employment:

USDA-Natural Resources Conservation Service

Resource Conservationist (Team Leader),
Agricultural Nutrient Management Team; Mitchell — 2006 – Present

District Conservationist,
Hamlin County USDA Service Center; Hayti — 1996 – 2006

Rangeland Management Specialist,
Aberdeen, Brookings, and Sioux Falls NRCS Field Offices — 1992-1996

Membership/Certifications with Professional Societies:

American Society of Agronomy; Certified Crop Advisor (since 1997)

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INTERVENERS' EXHIBIT DISCLOSURE

Pursuant to the Procedural and Scheduling Order, dated the 15th day of March, 2016, the Interveners, South Dakota Cattlemen's Association and South Dakota Dairy Producers, designate the following list as their exhibits for the hearing scheduled for September 27-29, 2016.

A. Exhibits
   1. *"Water Quality Effects of Winter Application of Manure in SD 2011 to 2015"*
   2. *"Tree Roots: Facts and Fallacies"*
   3. *"Root Distribution of Some Native Trees and Understory Plants Growing on Three Sites Within Ponderosa Pine Watersheds in Colorado"*
   4. *"Natural Windbreak Effect on Livestock Hydrogen Sulfide Reduction and Adapting an Odor Model to South Dakota Weather Conditions"*
   5. *"At the Root of It"*
   6. *Manure Application Site*
   7. *Tree Planting Scenario*
   8. Interveners reserve the right to present any other exhibits to rebut any testimony which has not yet been disclosed.

CERTIFICATE OF SERVICE

I, Todd D. Wilkinson, the undersigned, hereby certify that on August 29, 2016, I served a true and correct copy of the foregoing Interveners', South Dakota Cattlemen's

Association and South Dakota Dairy Producers, Exhibit Disclosure in the above-entitled matter, by electronic means on the following:

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REFERENCES:

Water Quality Effects of Winter Application of Manure in SD 2011 to 2015

Introduction:

This project was initiated in the late 1990's in an effort to quantify the risk associated with manure management practices, particularly regarding winter manure application. SD producer groups, DENR, the EPA, and SDSU came together in order to investigate/develop best management practices. An ongoing watershed project on the effects of winter manure application practices on runoff water quality has been operational since 2011.

Progression of Research:

Bench Top Tests – Laboratory tests were performed to assess the level of dissolved phosphorus runoff correlated to soil type and phosphorus content of the soil. It was found that different soil types retain phosphorus at different rates, and that higher concentrations of soil test phosphorus indicate greater risk of phosphorus loss in runoff. An interesting aside is that soils tend to group into 2 major categories, high loss and low loss.

Field Plot Tests – The laboratory tests were repeated on larger field plots and the same observations were recorded. Figure 2 demonstrates the soils tested and rate of phosphorus loss. The soils are representative of common SD soils across the state. Please note the high slopes represent higher loss soils and lower slopes represent low loss soils.

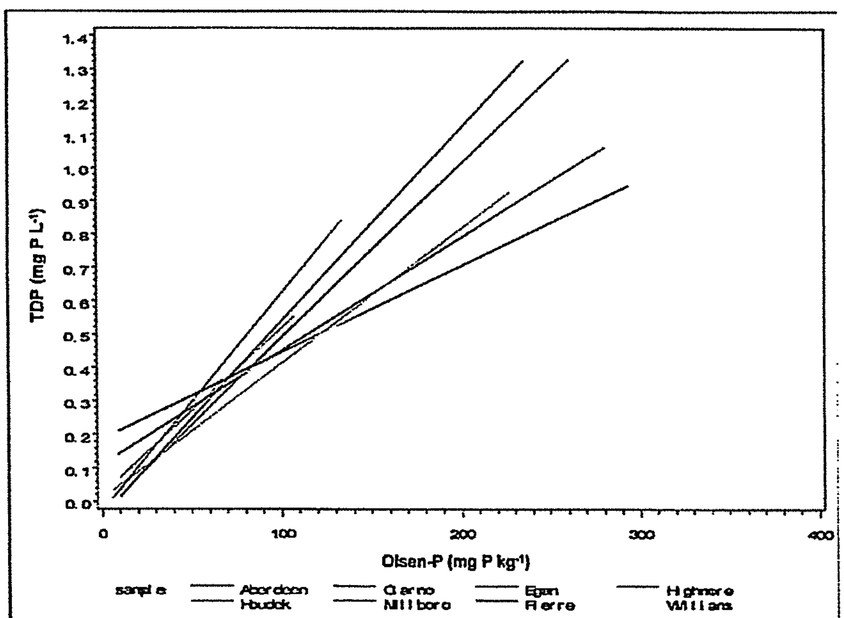

Figure 2. SAS output showing the predicted relationship between total dissolved P (TDP) concentration in surface runoff and Olsen-P (mg kg-1) for the studied soil series at the 0-5 cm soil depth. Evaluation derived via indoor rainfall simulation.

Large Scale Field Test – One ~25 acre field with 3 distinct watersheds was provided by Mike Schmidt, a producer in Moody County. The research aims are to quantify the differences, if any, on runoff quantity and level of runoff nutrient contamination. The South watershed received manure in the winter on the higher 50% of the plot, the North watershed received manure on the lowest 50%, and the third received no manure. All areas without manure were fertilized with conventional fertilizers. Data continues to be collected.

Current Results:

Overall, manuring the low ground results with slightly higher levels of contamination in runoff. There appears to be mostly insignificant differences between manuring the high ground and straight conventional fertilizer.

Table - 1: Average Concentrations of Compounds in Runoff collected over 3 years

Watershed	Total N	nitrate-N	ammonia-N	Total P	Dissolved P	TSS	# of
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	Samples
North	8.60	2.34	2.57	1.30	1.09	157.45	11
95% CI*	(6.8 - 10.4)	(1.2 - 3.5)	(2.1 - 3.1)	(0.7 - 1.9)	(0.8 - 1.4)	(-16.3 - 331.2)	
South	6.36	4.05	1.56	0.85	0.44	143.16	11
95% CI*	(4.5 - 8.3)	(2.2 - 5.9)	(0.9 - 2.2)	(0.1 - 1.7)	(0.2 - 0.7)	(-71.6 - 358.0)	
East	6.50	5.44	1.52	0.50	0.51	38.81	9
95% CI*	(5.1 - 7.9)	(2.1 - 8.8)	(1.1 - 1.9)	(0.4 - 0.6)	(0.4 - 0.6)	(26.5 - 51.1)	

North Watershed - Manured on lower 50% of topography, conventional fertilizer upper 50%

South Watershed - Manured on upper 50% of topography, conventional fertilizer lower 50%

East Watershed - No manure, conventional fertilizer only

* Confidence interval was calculated using Student's t-distribution

Above is the summary of 3 years of collected data. Note that none of the field plots discharged, on average, greater than 10 ppm nitrate, the drinking water standard. Ammonia discharges from all field treatments exceed 1 mg/L (ppm), these levels can be lethal to sensitive fish populations. Only the north watershed with manure application on the lowest 50% of the topography generated total dissolved phosphorus above the critical level of 1 mg/L proposed by Sharpey et al 1966 to limit lake eutrophication.

The study is ongoing. Automatic samplers utilized this year have dramatically increased the number of samples collected. A more complete assessment will be performed after all summer and fall runoff events are collected and analyzed. Currently, samples continue to be analyzed in the lab. This year's data will be compiled and assessed later this fall as analysis becomes available from the lab.

Conclusions:

The first 3 years of data suggest minimal differences between manuring the upper 50% of the topography and conventional fertilizer application. Winter manure application limited to the higher elevations on a field should be considered as a risk limiting management practice within the confines of appropriate nutrient additions to arable land. Limitations of the data to date include exclusion of high flow events due to difficulty in obtaining samples, and rare occurrence of high flow events during the first years'. This year's data should remedy this gap.

Summary prepared by Dr. Joe Darrington.

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 magnitude: 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 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).

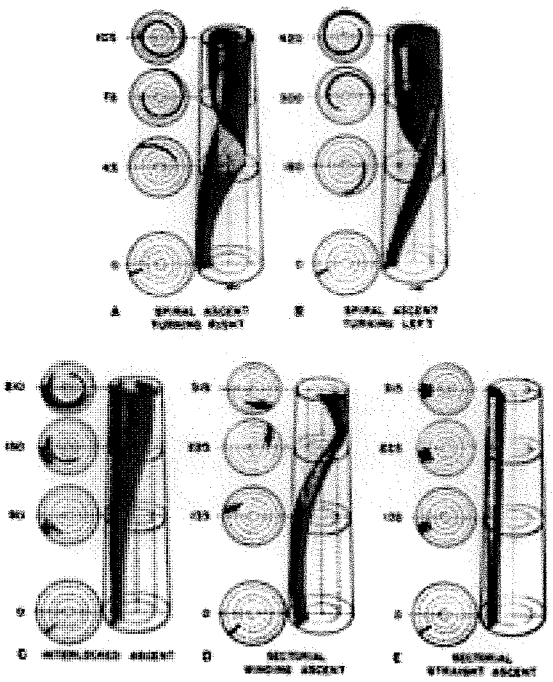

Figure 1. Five types of water-conducting systems in various conifers as shown by the tracheidal channels dyed by trunk injection. The numbers give the height in centimeters of the transverse section above injection. A. Spiral ascent, turning right: Abies, Picea, Larix *and* Pinus *(Rehder's section 3,* 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.*

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

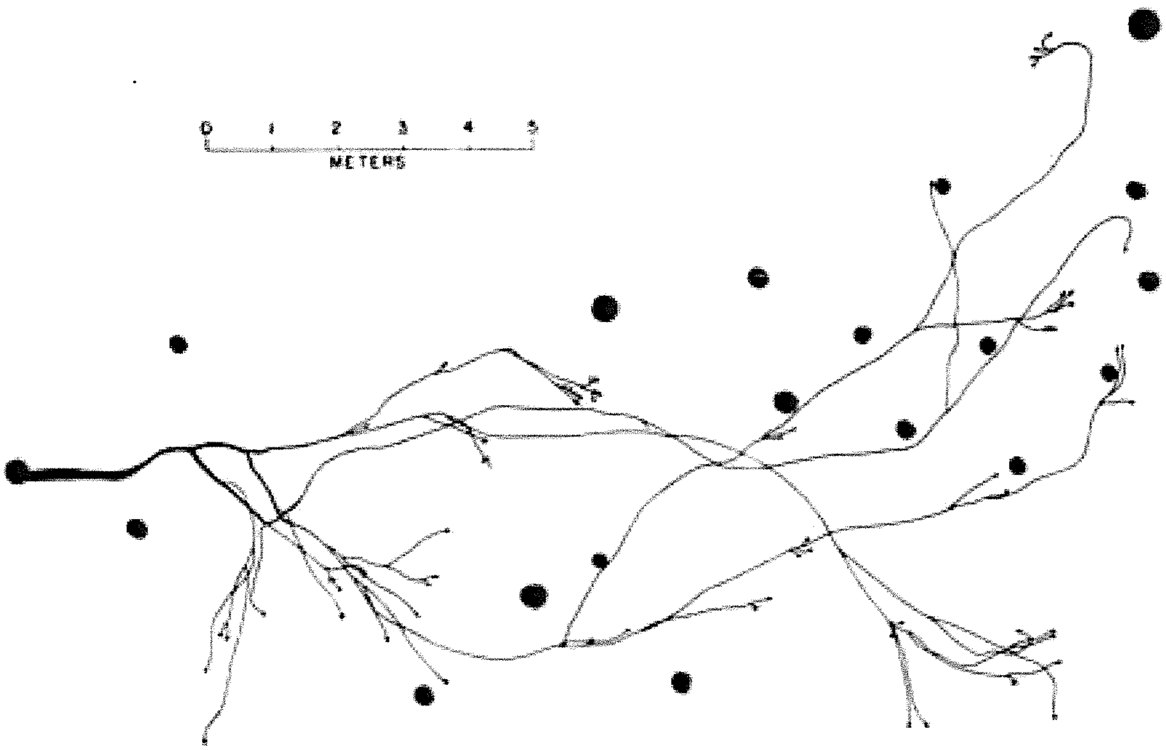

Figure 2. Plan-view diagram of the horizontal woody root system developed from a single lateral root of a red maple about 60 years old. Solid circles show the location of other trees in the stand. Arrows indicate that the root tips were not found; therefore these roots continued somewhat farther than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

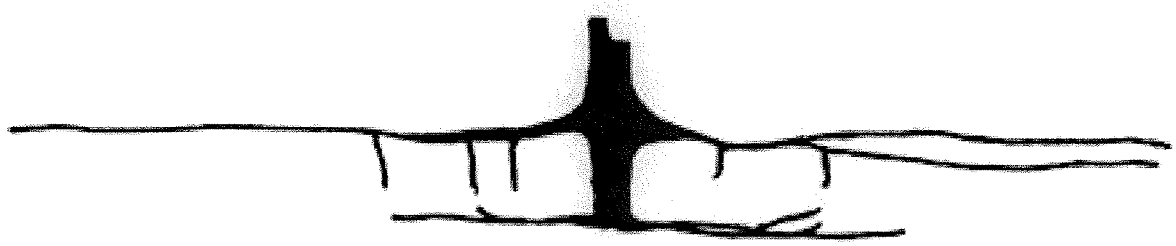

Figure 3. Drawing, not to scale, of framework system of longleaf pine tree grown in well-drained soil with a second layer of roots running in the soil layers where oxygen supplies become limiting.

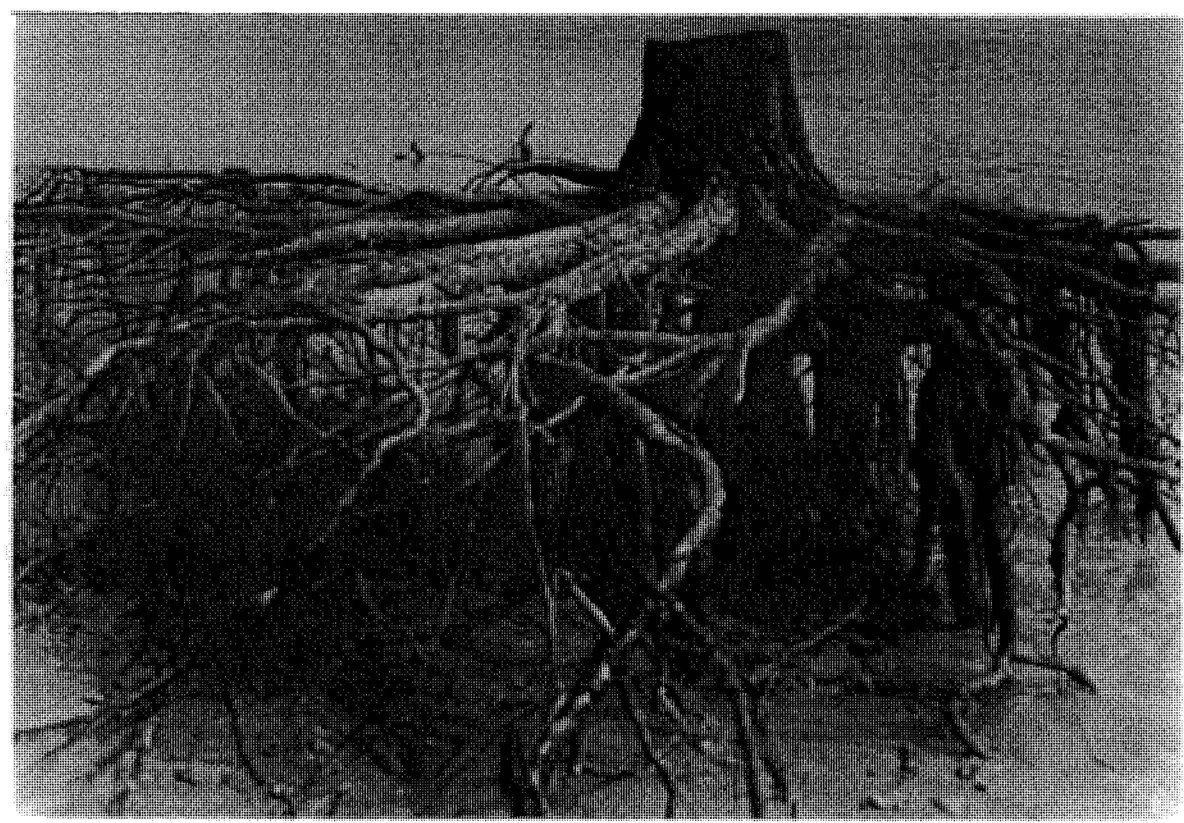

Figure 4. Photograph of framework roots of longleaf pine including striker roots, 90 percent of the surface root system has rotted and washed away, Kerr Lake, North Carolina.

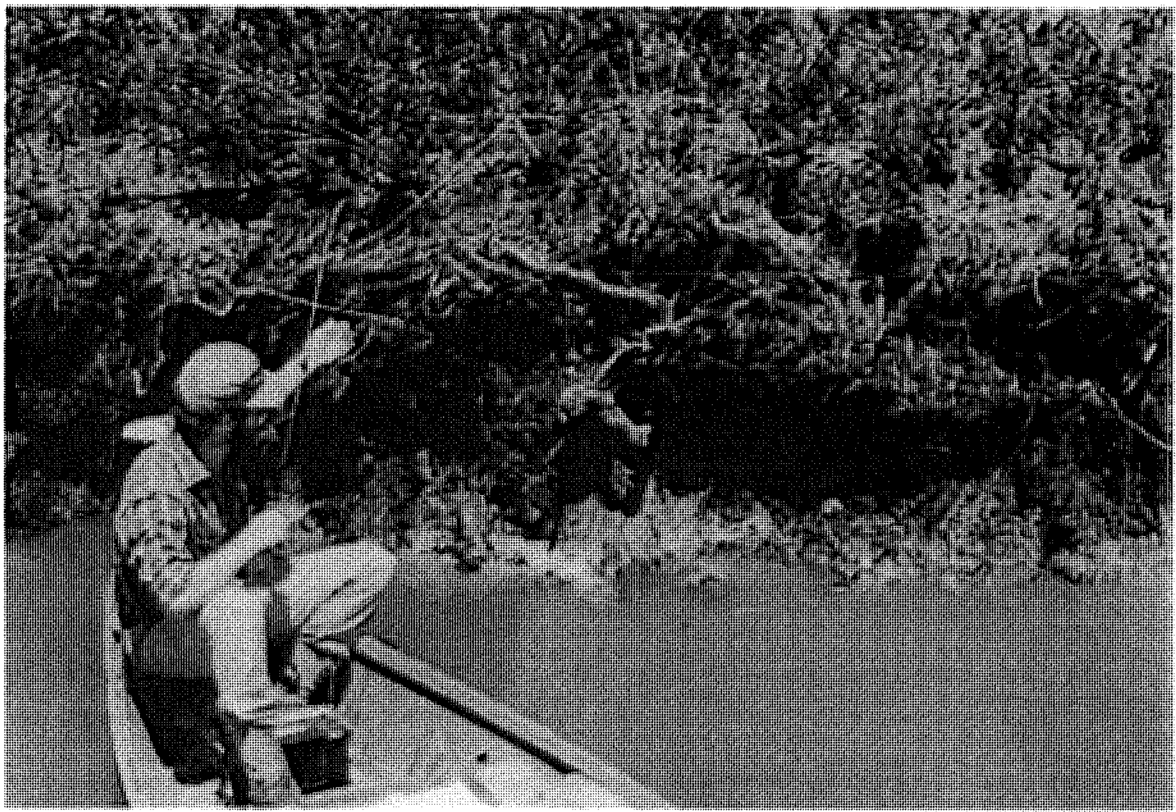

Figure 5. Mat of roots above the permanent water table exposed by digging a drainage canal, Green Swamp, North Carolina. A few species have specialized tissues containing air passages and specialized metabolisms that permit their roots to penetrate several feet below the permanent water table where little 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 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 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

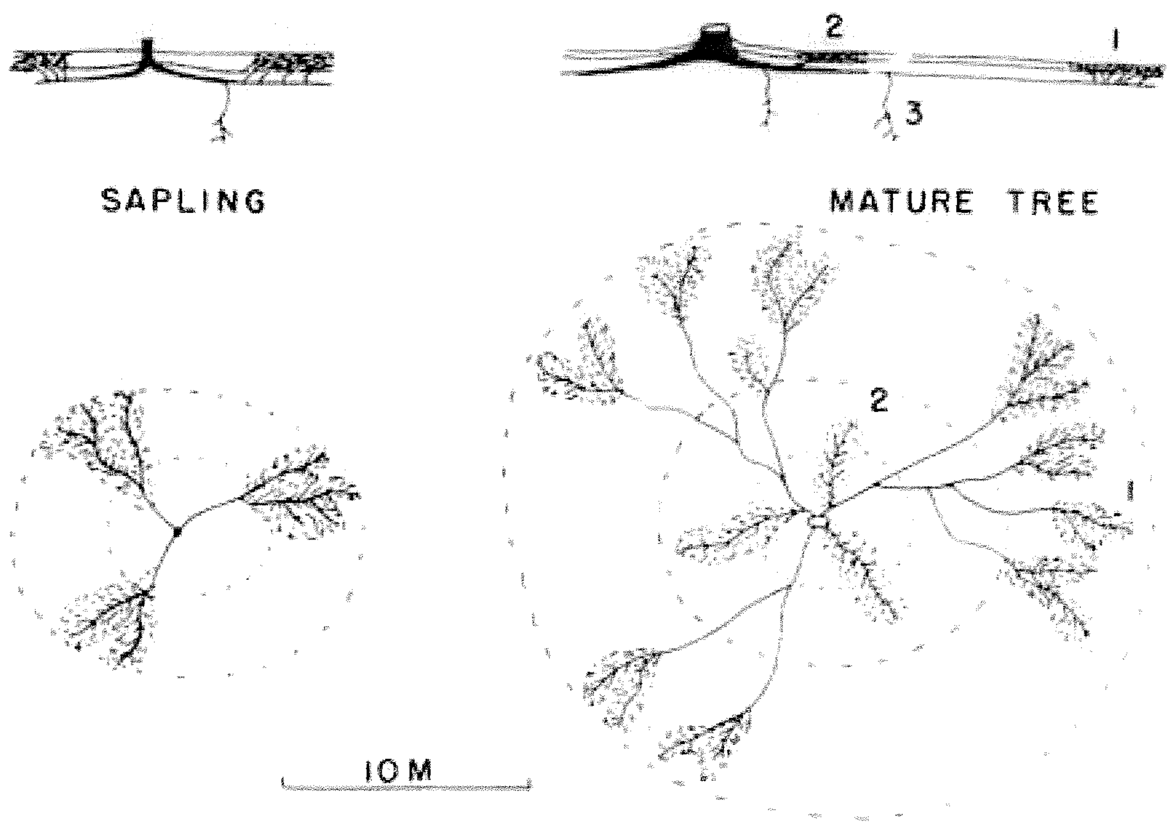

Figure 6. Schematic diagram showing reoccupation of soil area near the base of a mature tree by the growth of adventitious roots. 1) Root fans, growing from the younger portions of the woody roots, have extended to a distance of several meters from the tree 2) Root fans on adventitious roots have only 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.

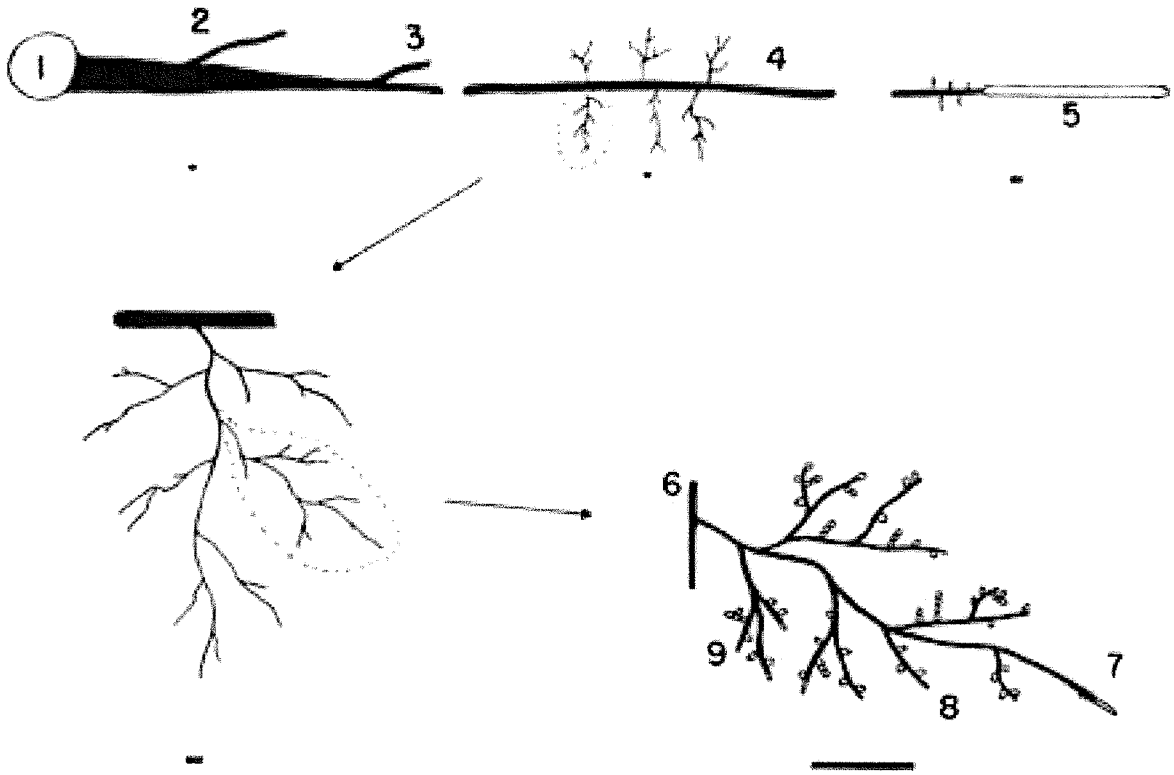

Figure 7. Schematic diagram showing woody and non-woody root relationships. 1) Stem. 2) Adventitious roots in the zone of rapid taper. 3) Lateral root. 4) Non-woody root fans growing from opposite sides of the rope-like woody root. 5) Tip of woody root and emerging first order non-woody roots. 6) Second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

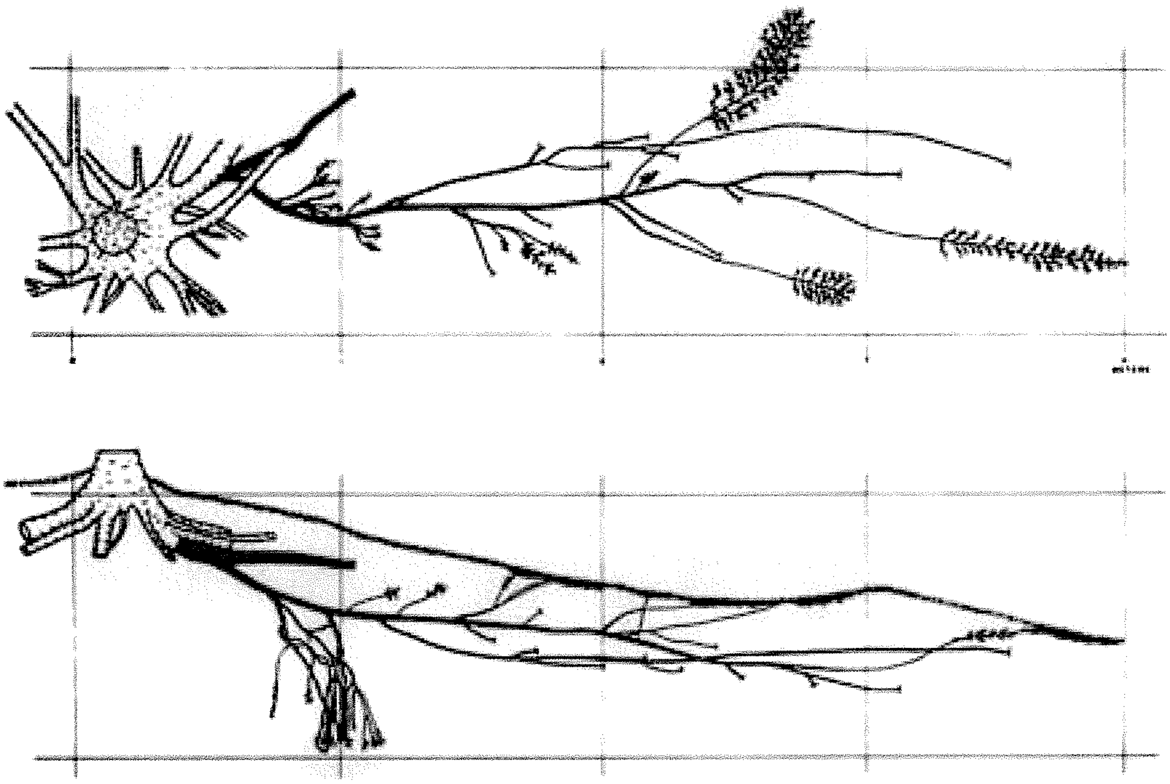

Figure 8. Scale diagrams of horizontal, woody, third order lateral roots of red oak, Quercus rubra. *Emphasis is on the roots that return to the surface and elaborate into many small-diameter non-woody roots in the forest floor. Top view (above), side view (below). The squares are 1 meter on a side.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

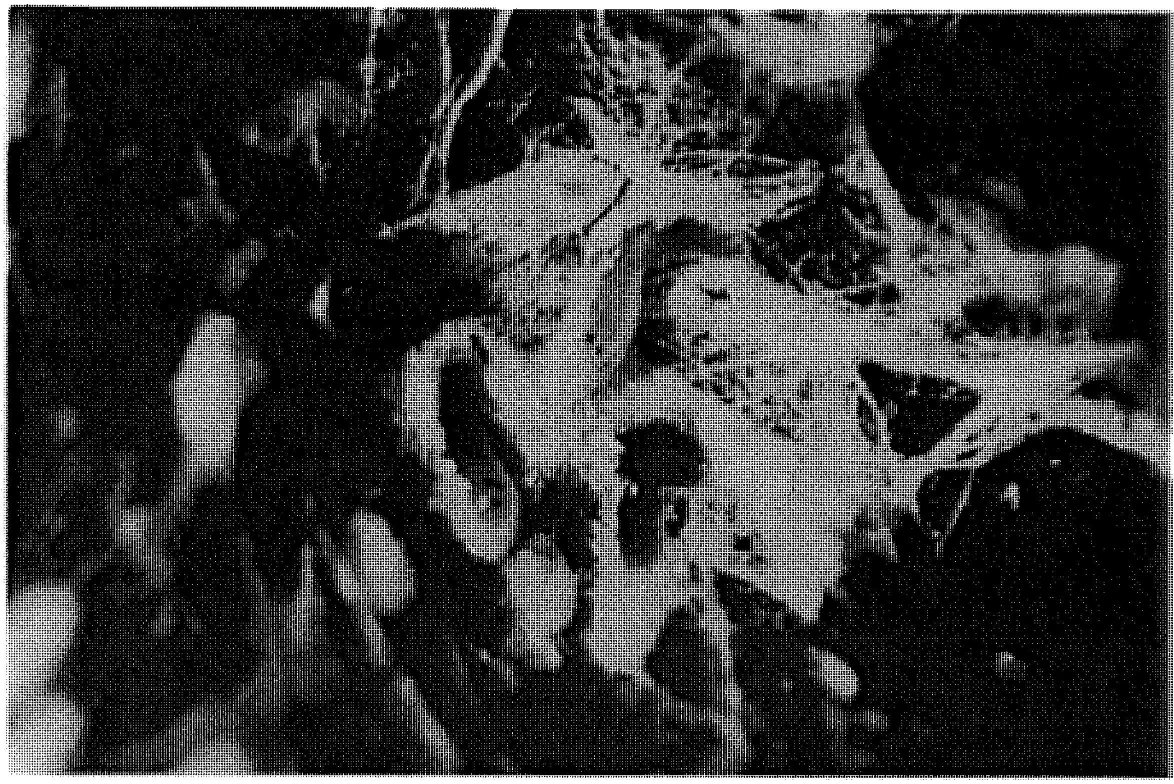

Figure 10. Photograph of root tips growing in the litter of a mixed hardwood forest. The mycorrhizae extend out from the root tips to expand greatly the functional absorptive surface area of the roots they are attached to. Root diameters about 0.5 mm. Photo by Ted Shear, North Carolina State University.

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 trcc. 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

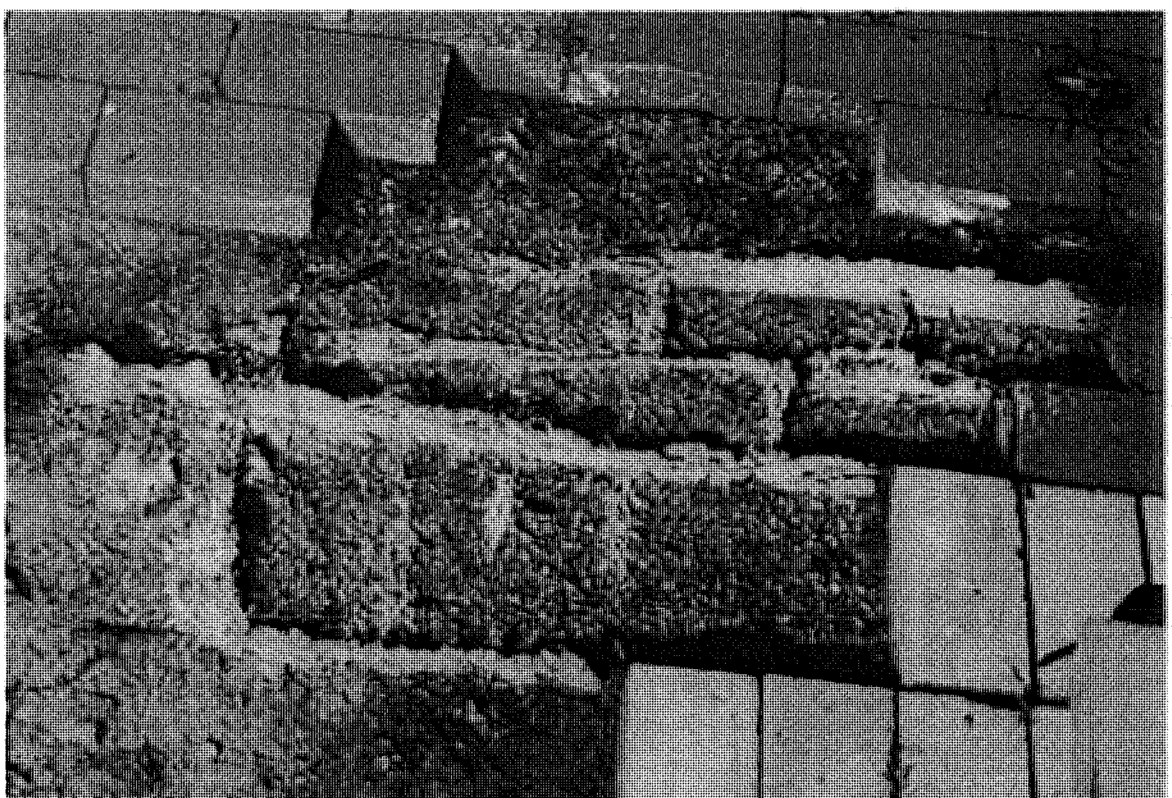

Figure 11. Roots growing in the crevices between bricks. There was no oxygen below the bricks that overlaid a compacted clay soil on the North Carolina State University campus. Tree roots commonly follow cracks, crevices, and other air passages underneath pavement. Photo by T. O. Perry.

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

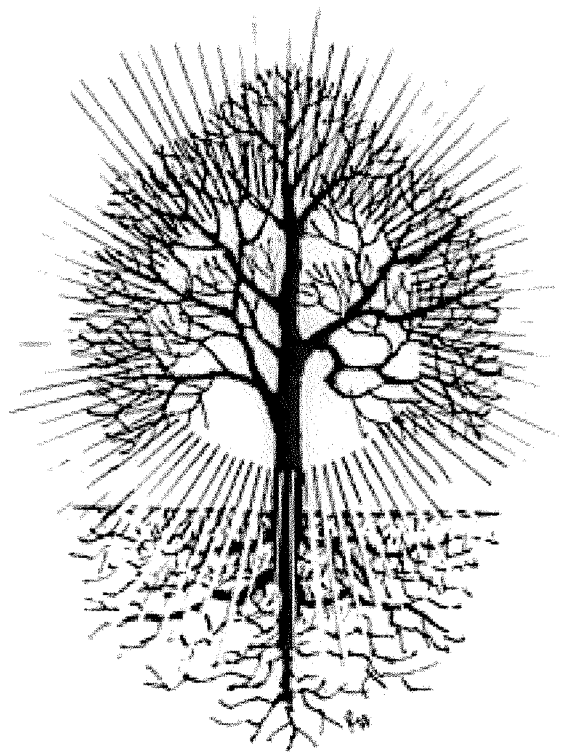

Figure 12. Roots do not grow as this artist's conception indicates. Inaccurate illustrations like this one have led to harmful practices in the management of trees in both forest and urban situations. Illustration from a brochure produced by the Society of American Foresters.

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 dieback 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

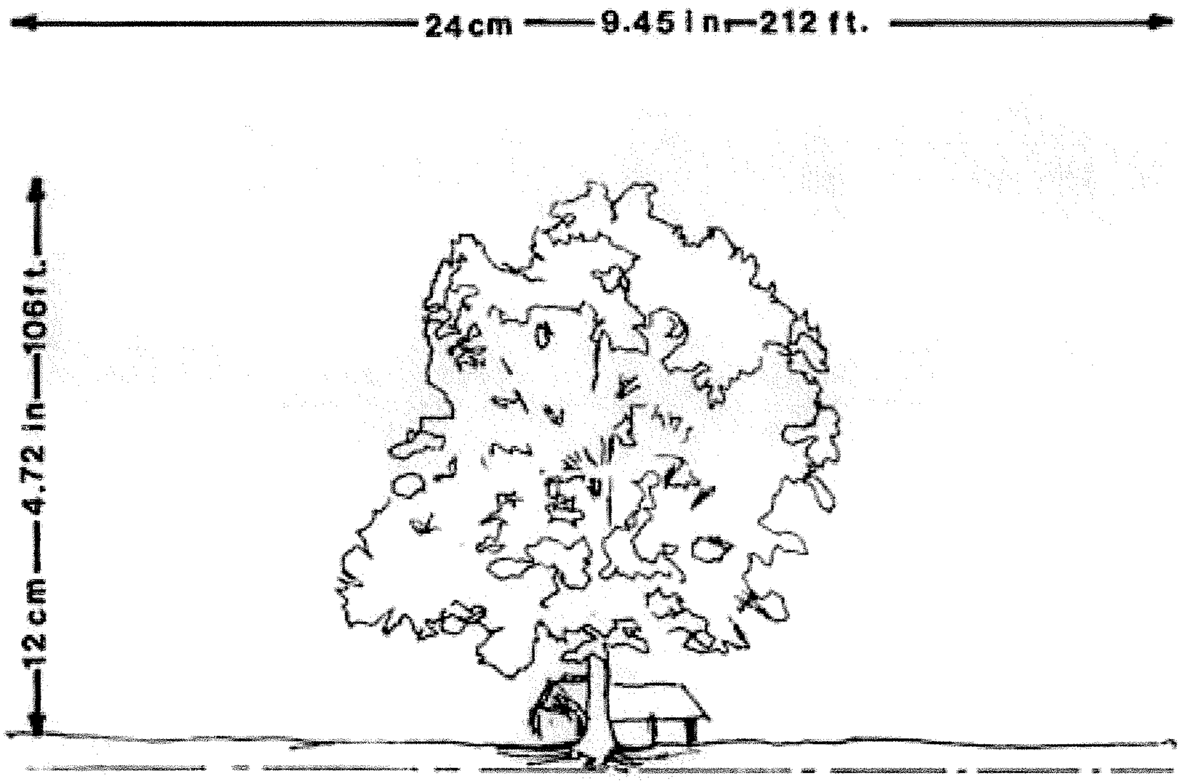

*Figure 13. Scale drawing of Memorial Oak Tree (*Quercus alba*), Schenck Forest, North Carolina State University. The original drawing was made by tracing the projected image of the tree (Figure 14) onto a piece of paper with a pen that produced a line 0.2 millimeters thick, the thinnest line that can 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.*

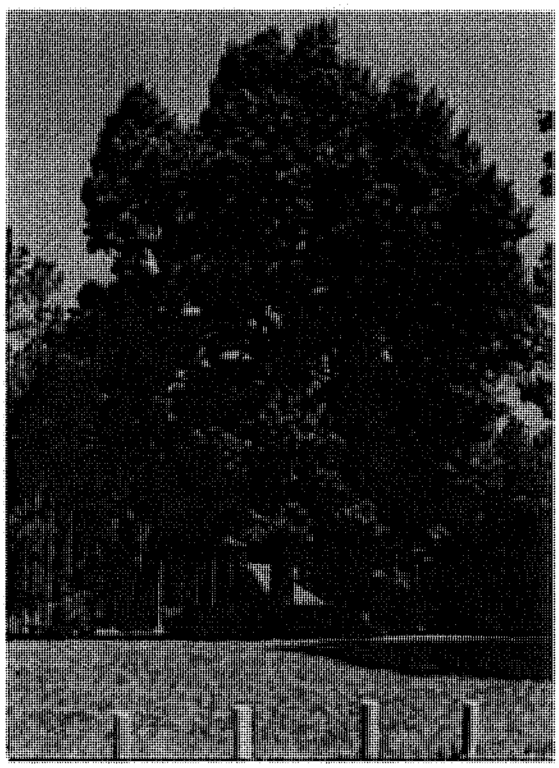

*Figure 14. This photograph of the Schenck Memorial Oak (*Quercus alba*) was projected and traced to produce Figure 13. The Schenck Memorial Oak is 32.3 meters tall (106 ft) and has a crown spread of 29 meters (94 ft) and a diameter at breast height of 1.07 meters (42 in).*

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

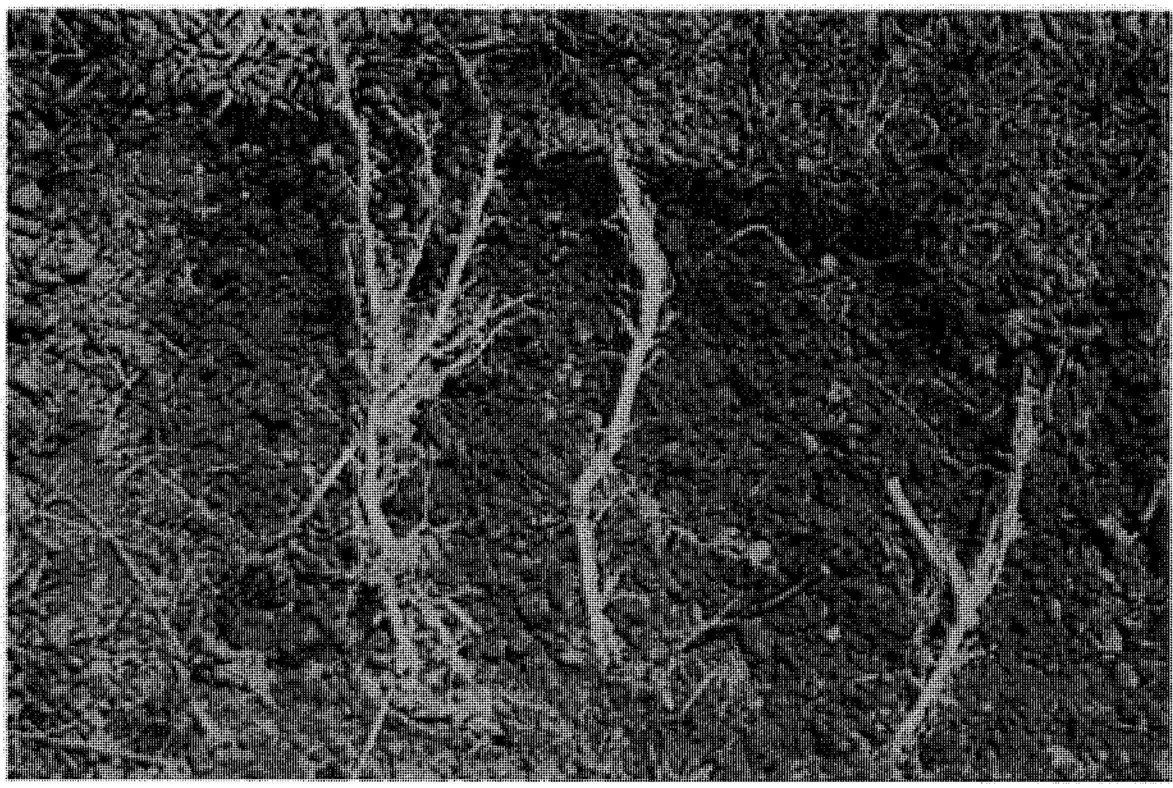

Figure 15. Many roots of trees grow closely intermingled with grass roots in the few top centimeters of a lawn. Therefore fertilizers and herbicides do not have to move down into the soil in order to affect trees.

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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Station Paper No. 37

July 1958

ROOT DISTRIBUTION OF SOME NATIVE TREES AND UNDERSTORY PLANTS GROWING ON THREE SITES WITHIN PONDEROSA PINE WATERSHEDS IN COLORADO

by

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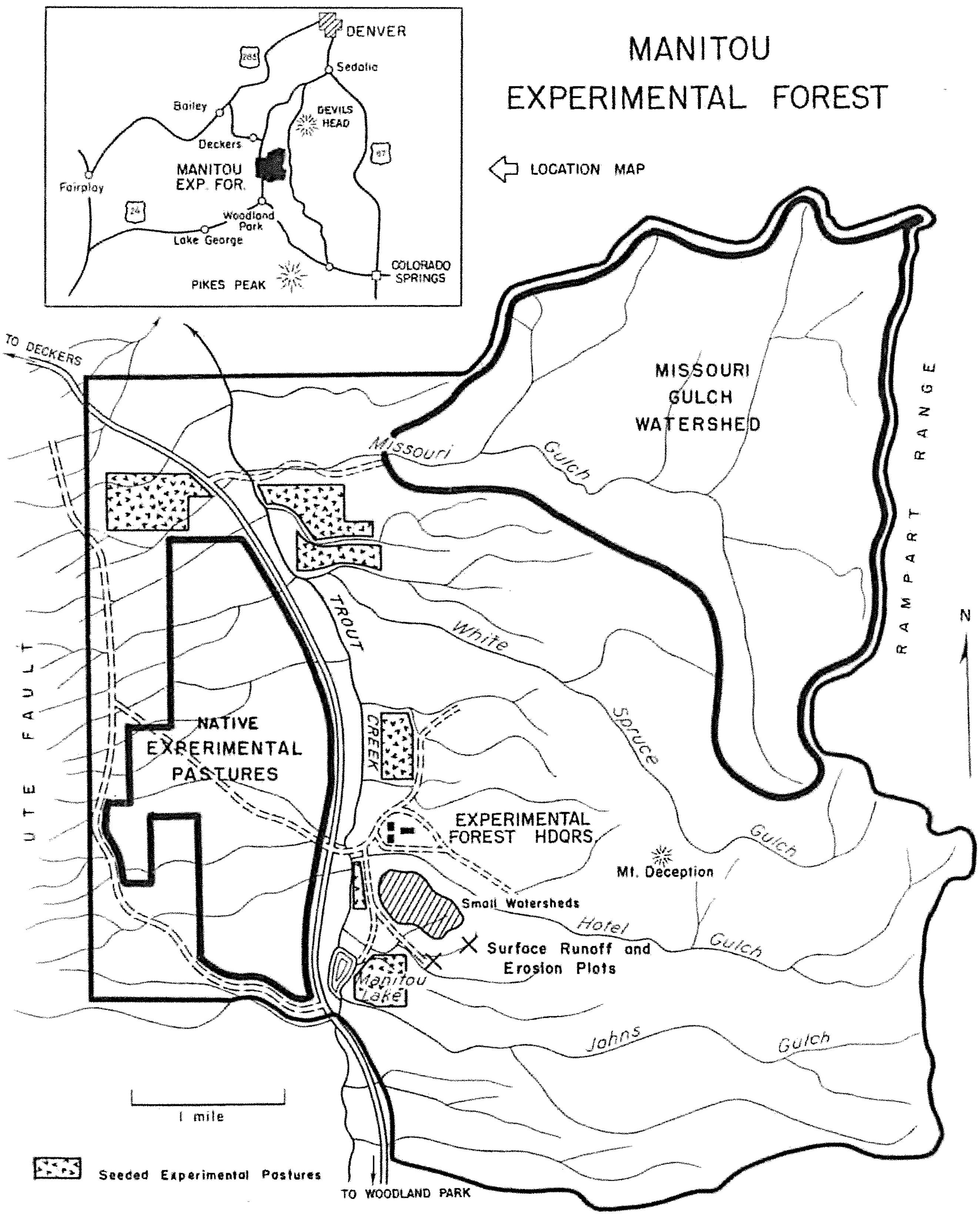
Rocky Mountain Forest and Range Experiment Station
Fort Collins, Colorado

Raymond Price, Director

Forest Service U. S. Department of Agriculture



MANITOU
EXPERIMENTAL FOREST
LOCATION MAP
DENVER
Sedalia
Bailey
DEVILS HEAD
Deckers
MANITOU EXP. FOR.
Fairplay
Woodland Park
Lake George
COLORADO SPRINGS
PIKES PEAK
285
24
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TO DECKERS
MISSOURI GULCH WATERSHED
Missouri
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RAMPART RANGE
N
TROUT
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UTE FAULT
NATIVE EXPERIMENTAL PASTURES
EXPERIMENTAL FOREST HDQRS.
Mt. Deception
Small Watersheds
Hotel
Gulch
Surface Runoff and Erosion Plots
Manitou Lake
Johns
Gulch
1 mile
Seeded Experimental Pastures
TO WOODLAND PARK

ROOT DISTRIBUTION
OF SOME NATIVE TREES AND UNDERSTORY PLANTS GROWING ON THREE SITES WITHIN PONDEROSA PINE WATERSHEDS IN COLORADO

by

Herbert W. Berndt and Robert D. Gibbons, Foresters

ROCKY MOUNTAIN FOREST AND RANGE EXPERIMENT STATION

FOREST SERVICE U. S. DEPARTMENT OF AGRICULTURE

The station maintains central headquarters at Fort Collins, Colorado, in cooperation with Colorado State University.

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INTRODUCTION

Knowledge of the depth and extent of plant root systems is basic to watershed management. From such knowledge it may be possible to select plants most useful for soil stabilization, flood control, or for minimum transpiration.

This report presents information on root distribution of eight native plant species studied at the Manitou Experimental Forest.

The experimental forest lies northwest of Colorado Springs, Colorado, on the west side of the Rampart Range, and has a forest of ponderosa pine, Douglas-fir, and aspen, with an understory of shrubs and grasses. Lodgepole and limber pine grow near the mountain crests. Base rock of the area is Pikes Peak granite, overlain by the three sedimentary formations: Sawatch quartzite, Madison limestone, and Fountain arkose. Residual soils have developed from weathering of the parent formations, and along the streams there are alluvial deposits derived mainly from granites.

METHODS OF STUDY

Root systems of eight species were examined at three study sites selected to represent three residual soils[1/] -- Edloe gravelly sandy loam, Chubbs stony loam, and skeletal soil from sandstone.[2/] Roots were exposed by digging back with hand tools from a trench excavated by a tractor-mounted back hoe. Species studied were:

1/ Soil names used are tentative and subject to final correlation.

2/ These skeletal or lithosol soils have many characteristics of the Travessilla soils.

1. Lodgepole pine (*Pinus contorta* Dougl.)
2. Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco)
3. Quaking aspen (*Populus tremuloides* Michx.)
4. Ponderosa pine (*Pinus ponderosa* Laws.)
5. Mountainmahogany (*Cercocarpus montanus* Raf.)
6. Kinnikinnick (*Arctostaphylos uva-ursi* (L.) Spreng.)
7. Arizona fescue (*Festuca arizonica* Vasey)
8. Mountain muhly (*Muhlenbergia montana* (Nutt.) Hitchc.)

At each study site two trenches were dug--one to observe tree roots and the other to study roots of understory species. Tops of the plants were removed, and root crowns were anchored to retain their positions throughout the hand digging (fig. 1). The exposed roots were sketched periodically as the digging progressed.

Figure 1.--Exposed root systems at Edloe gravelly sandy loam site.

Information gathered for each site included: (1) soil character and depth; (2) age and condition of tree species; (3) condition of understory species; and (4) length, depth, and configuration of root systems.

RESULTS

Findings from each site are presented by means of drawings of root distributions, with a discussion of the individual root systems and a tabular comparison.

EDLOE GRAVELLY SANDY LOAM

The single site for excavation of lodgepole pine was chosen at 9,300 feet elevation on a 15-percent northwest slope. A well-developed 2-inch needle litter covered the soil surface. The grayish-brown surface soil was a coarse, gravelly loam 8 inches deep. Fine clays were not noticeable in this layer. Subsoil exhibited no profile development. Parent material was a coarse gravel resulting from disintegration of granite bedrock from which the Edloe soils have developed. This layer was penetrable to a depth of 4 feet. Dense overstory consisted of lodgepole pine, with scattered aspen. Sparse understory was mainly kinnikinnick, with a few grasses.

The site where the other species were studied was at 8,400 feet elevation on a 25-percent north slope. The soil was similar to that described above. The surface layer was noticeably darker and the subsoil was unconsolidated gravels. Hard granite was found at 4.5 to 6 feet. Timber overstory was an open stand of ponderosa pine and Douglas-fir, with scattered aspen. Mountainmahogany occupied most openings. Dense understory was made up of kinnikinnick, low juniper (Juniperus communis L.), Arizona fescue, mountain muhly, and numerous annual forbs.

These extensive Edloe soils have only a weak profile development. Made up of only about 20 to 30 percent silt plus clay, they are, nevertheless, highly erosive. Relatively low fertility retards plant growth.

Root distribution of the species studied on the Edloe soil are shown in the figures that follow (figs. 2, 3, 4, 5, 6, 7). Grid scale equals 1 foot.

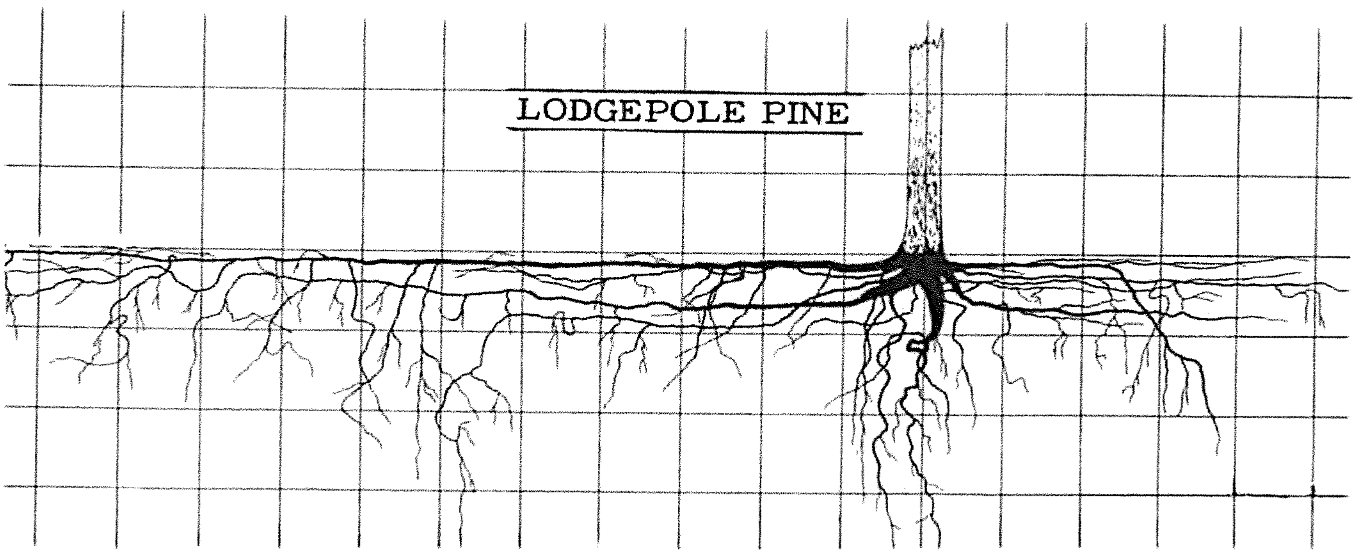

Figure 2. --This root system is from a tree that was 90 years old, 23 feet high, and 5 inches d.b.h. Maximum root penetration was 4 feet and maximum lateral spread was 16 feet. Although roots frequently penetrated 4 feet, most of the system was in the upper 2 feet of soil. The main laterals branched frequently into feeder roots and formed a matlike system (see fig. 3).

Figure 3. --View of exposed lodgepole pine roots, Edloe gravelly sandy loam.

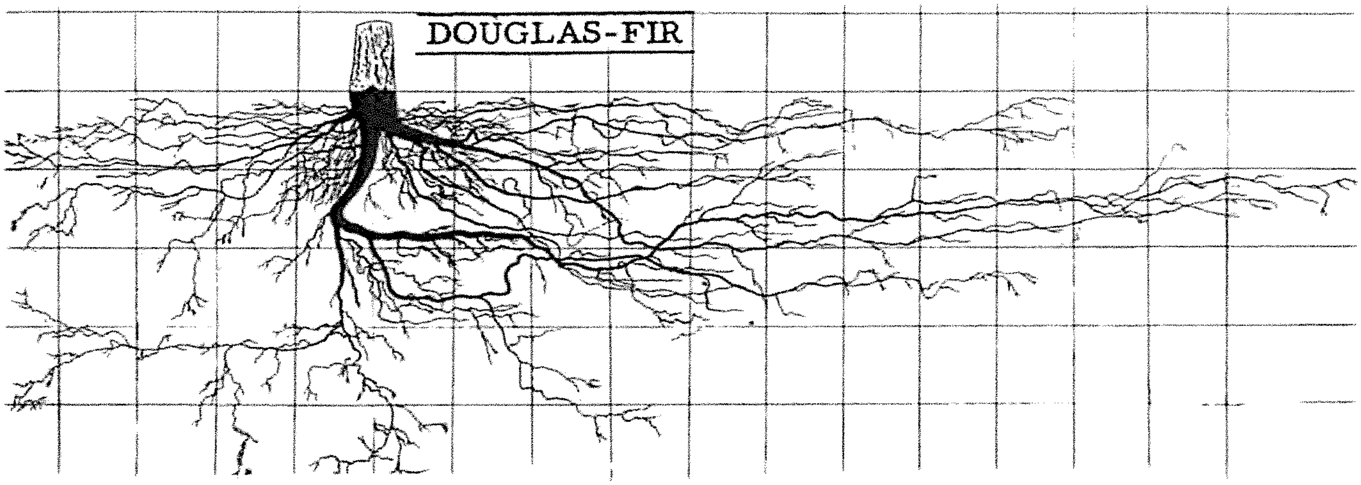

Figure 4.--This root system is from a tree that was 80 years old, 21 feet high, and 5.5 inches d.b.h. Maximum root penetration was 5 feet and maximum lateral spread was 13 feet. This root system had isolated concentrations of fine roots. None were more than 0.2 inch in diameter; many were 0.1 inch or less. The pit used to excavate this tree was oriented up and down the slope (see fig. 1). Most of the roots were downslope from the base of the tree.

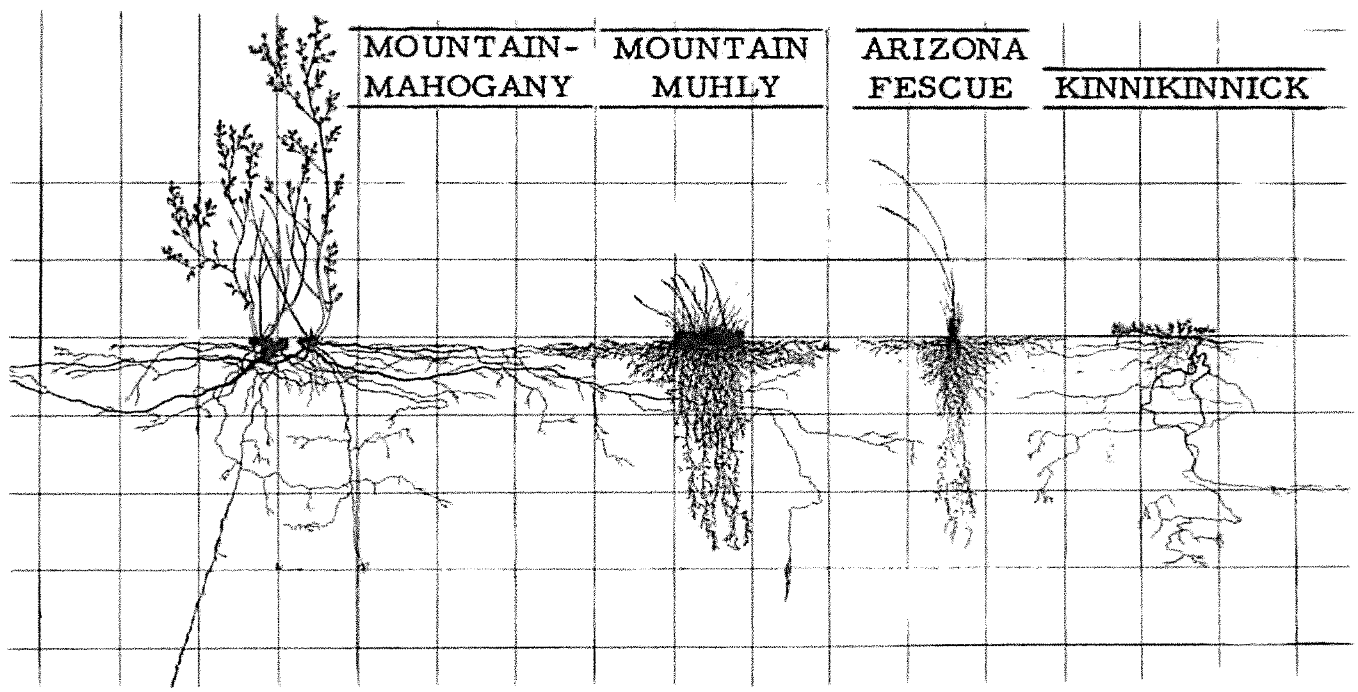

Figure 5.--The mountainmahogany, mountain muhly, and Arizona fescue root systems were from the same pit, while the kinnikinnick system was from a separate trench. The mountainmahogany was 4.5 feet high; maximum root penetration was 5 feet and maximum lateral spread was 8 feet. Mountain muhly had a fibrous root system consisting of 316 individual roots. The grass was 1 foot high, 10 inches in diameter, and its roots had a maximum penetration of 2.8 feet and a maximum lateral spread of 1.7 feet. Arizona fescue also had a fibrous root system, consisting of 290 individual roots. The grass was 2.3 feet high, 4 inches in diameter, and its roots had a maximum penetration of 2.8 feet and a maximum lateral spread of 1.5 feet. Only part of the root system of kinnikinnick was excavated. The main root was a meandering runner just below the surface of the soil. From this runner the plant sent aerial shoots upward and feeder roots downward. Plants forming a dense mat up to 7 feet in diameter were found. Conceivably, these plants could have originated from one rootstock.

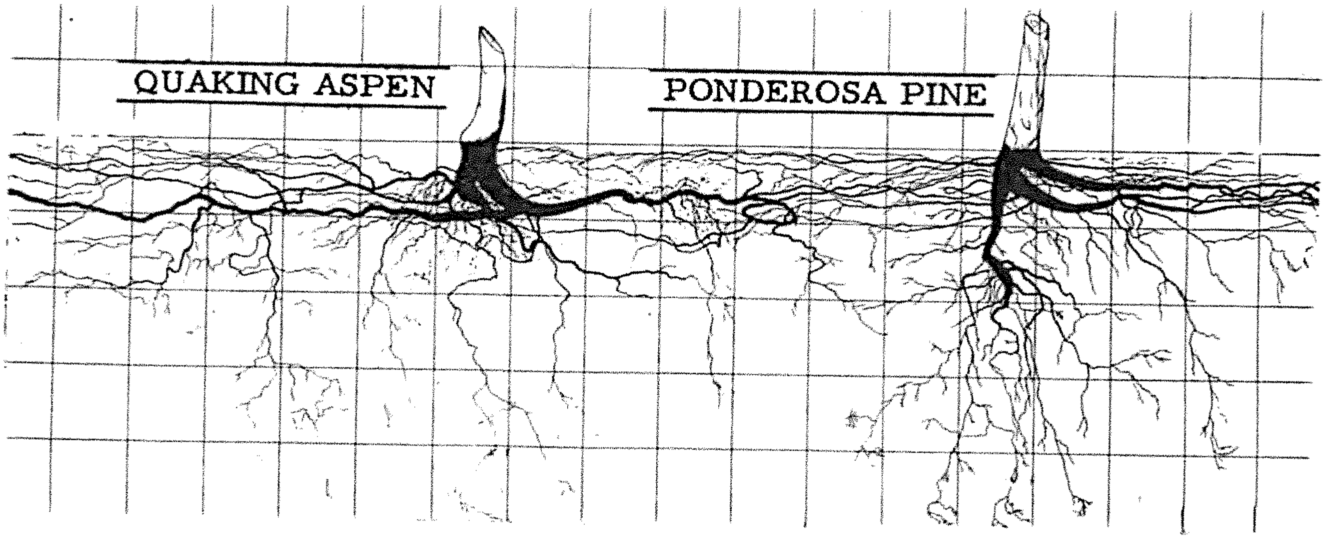

Figure 6. --These root systems were from the same pit as that of Douglas-fir (see fig. 4). The drawing shows the intertwining of the root systems. The aspen root system is from a tree 70 years old, 26 feet in height, and 4.5 inches d.b.h. Maximum root penetration was 5 feet and maximum lateral spread was 31 feet. These aspen roots were rather contorted, often changing direction without apparent cause. Concentrated masses of fine roots, similar to those found in Douglas-fir, were noted (see fig. 7). Root development was mainly downslope. The ponderosa pine was 85 years old, 19 feet high, and 4.5 inches d.b.h. Maximum root penetration was 5 feet and maximum lateral spread was 10 feet. The roots showed downslope development. No fine roots were found as in the systems of Douglas-fir and aspen, nor was the pine root system as finely branched.

Figure 7. --View of exposed aspen roots, illustrating concentrations of small roots and downslope development; Edloe gravelly sandy loam.

CHUBBS STONY LOAM

The Chubbs stony loam site was selected on a 20-percent slope facing north at 7,800 feet elevation. This residual soil was developed from Madison limestone. Litter was 1 to 2 inches deep. The dark, reddish-brown surface soil, extending to a 10-inch depth, was a loose, stony loam. Horizon development was pronounced. Subsoil was a reddish-brown loam, lighter in color than the surface soil. Texture graded from a rather heavy clay loam near the top of the layer to a very stony loam near the bottom. Both layers contained great amounts of limestone rock. Parent material, lying 5 to 7 feet deep, consisted of fragmented limestone rock with fine soil material in the fissures.

The dense overstory was predominantly ponderosa pine, with scattered Douglas-fir and aspen. Mountainmahogany occurred in most openings. Dense understory consisted of kinnikinnick, mountain muhly, Arizona fescue, low juniper, and many annual forbs.

Chubbs soils developed from Madison limestone are calcareous, loose, and fertile. They have excellent moisture relations and good plant growth.[3/]

Root distribution of species studied on the Chubbs soil are shown in the figures that follow (figs. 8, 9, 10, 11, 12). Pits for this site were oriented across slopes; hence, no comparisons between upslope and downslope root development could be made. Grid scale equals 1 foot.

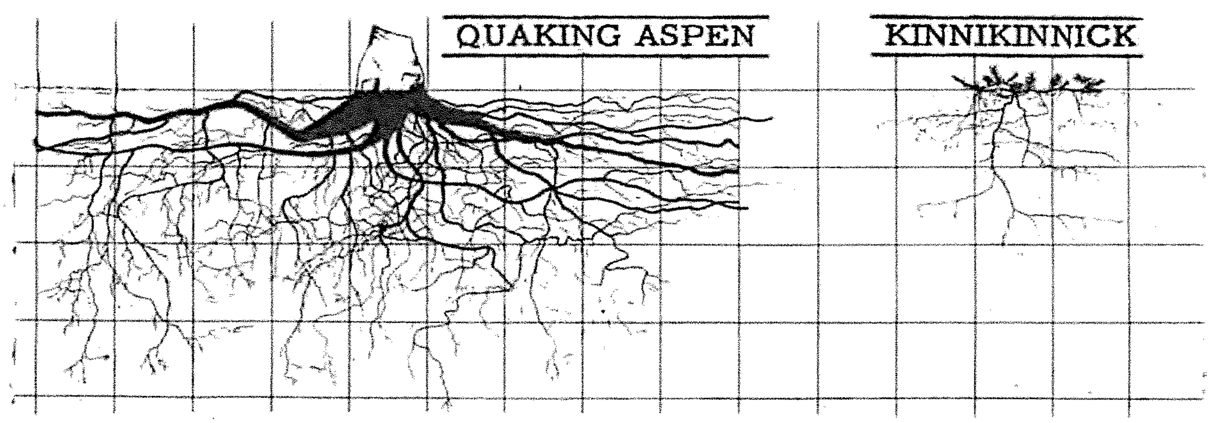

Figure 8.--This root system was from an aspen tree 97 years old, 38 feet high, and 8.5 inches d.b.h. The system was one of the more dense and widespread systems studied. Maximum penetration was 4.2 feet and maximum lateral spread was 48 feet. The small kinnikinnick plant had a root system that penetrated the soil to 2 feet and a lateral spread of 2.6 feet. Most of the roots were close to the surface.

3/ Retzer, J. L. Soil and physical conditions of Manitou Experimental Forest. U. S. Forest Serv. Rocky Mountain Forest and Range Expt. Sta. 1949. [Processed.]

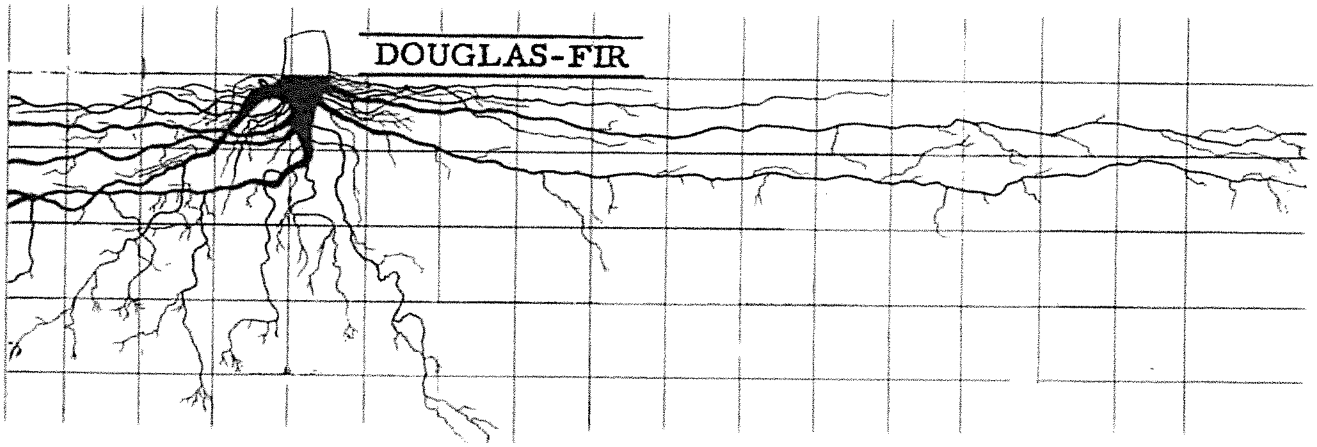

Figure 9. --This tree was 72 years old, 24 feet high, and 5 inches d. b. h. The root system had a maximum penetration of 4.8 feet, and a maximum lateral spread of 21 feet. The tree had a many-branched root system with several lateral roots originating from the root crown (see fig. 10).

Figure 10. --View of Douglas-fir roots, Chubbs stony loam.

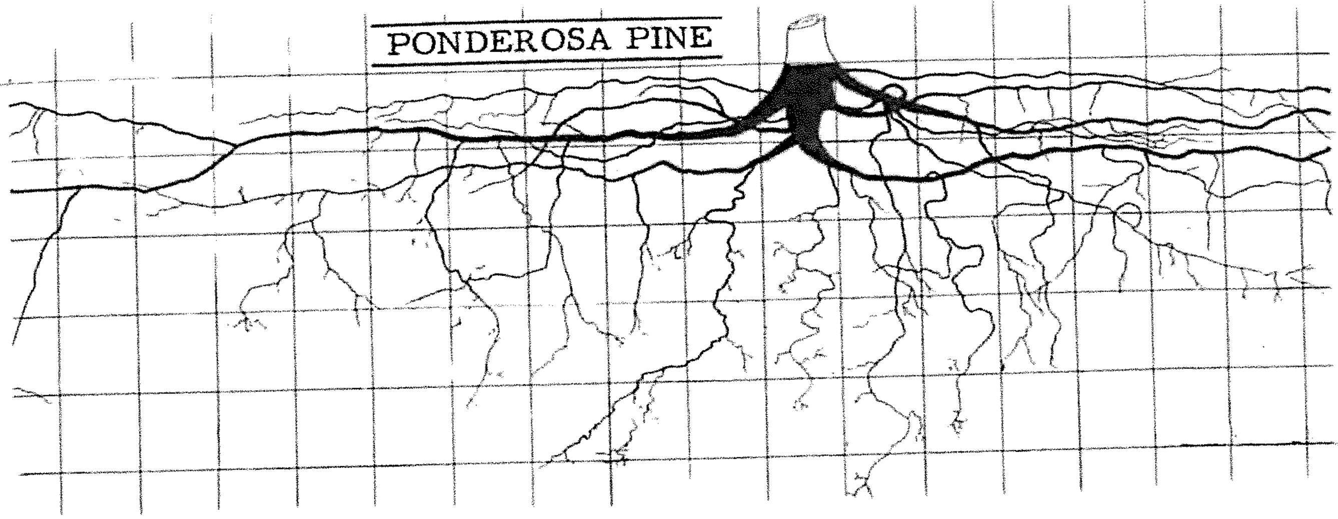

Figure 11.--This root system was from a tree that was 63 years old, 25 feet high, and 5 inches d.b.h. The system exhibited little branching and had a maximum penetration of 5.6 feet and a maximum lateral spread of 20 feet.

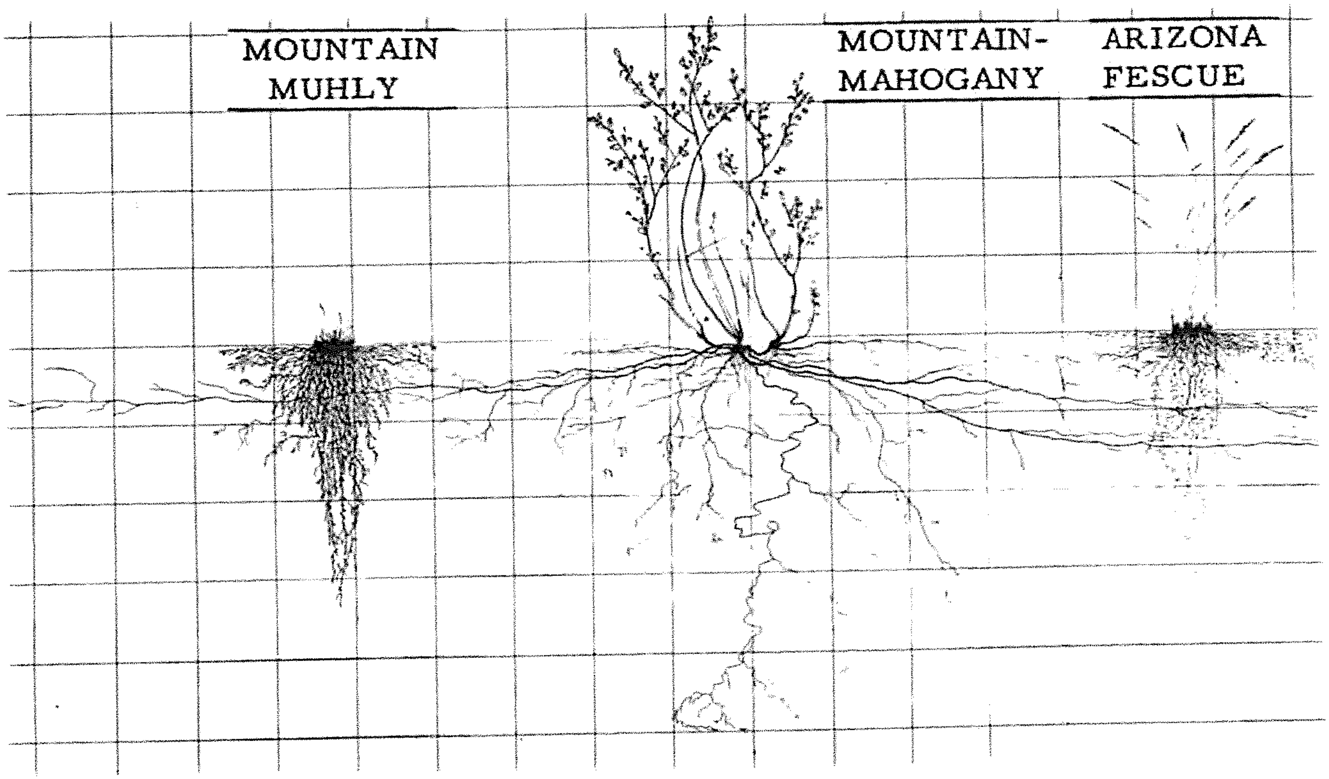

Figure 12.--The fibrous root sytem of mountain muhly consisted of 308 individual roots. The plant was 0.5 foot high and 6 inches in diameter. The maximum penetration of the roots was 3.4 feet and the maximum lateral spread was 1.3 feet. The mountainmahogany plant was 4 feet high. Its root system had a maximum penetration of 5 feet and a maximum lateral spread of 10 feet. The fibrous root system of Arizona fescue consisted of 780 individual roots. The plant was 2.7 feet high and 6 inches in diameter. Maximum penetration of its roots was 3.1 feet and maximum lateral spread was 1.7 feet. All three root systems were excavated from the same trench and the diagram shows the intertwining of the roots.

SKELETAL SOIL FROM SANDSTONE

The site was located on a northwest exposure at 8,350 feet elevation. Slopes ranged from 7 to 14 percent. The surface soil was a loose, fine, gray sand resting directly on disintegrating sandstone. Topsoil depth varied from 4 to 6 inches. Parent rock was a hard, light gray sandstone in the Sawatch Formation, fractured into a massive block pattern.

Overstory was predominantly Douglas-fir, with scattered ponderosa pine and aspen. Dense stands of mountainmahogany occupied all openings. The sparse understory consisted of kinnikinnick, aspen root-suckers, low juniper, Arizona fescue, mountain muhly, and some low annuals.

These skeletal soils are little more than disintegrated parent rock and are of limited extent. Their fertility is extremely low.[4/]

Root distribution of plants studied on skeletal soils are shown in the figures that follow (figs. 13, 14, 15, 16, 17). All systems had roots that penetrated the shallow soil mass, trailed along the parent rock, and penetrated fissures. All root systems were contorted by the many barriers. Grid scale equals 1 foot.

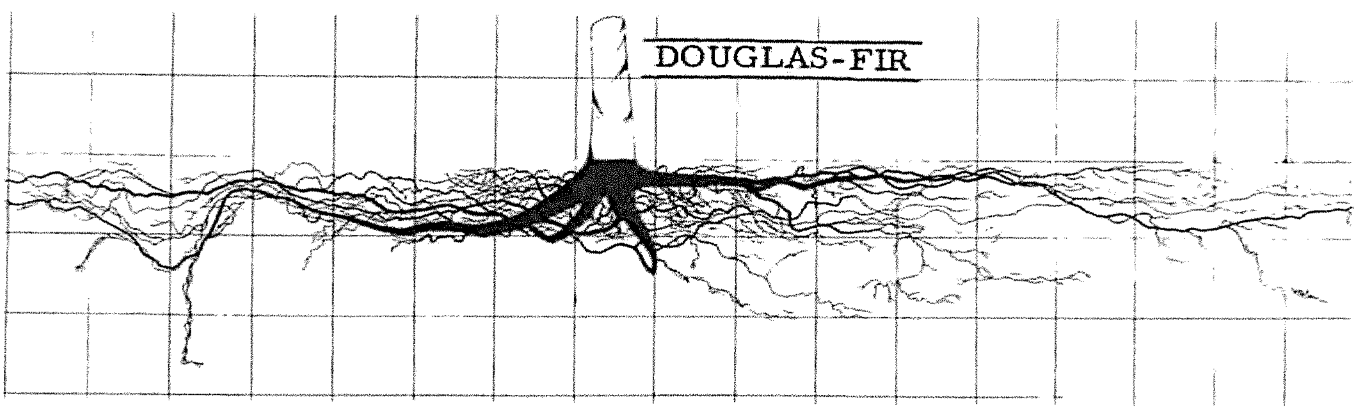

Figure 13.--This tree was 60 years old, 22 feet high, and 4 inches d.b.h. Its root system had a maximum penetration of 2.7 feet and a maximum lateral spread of 10 feet.

4/ Retzer, J. L. Soil and physical conditions of Manitou Experimental Forest. U. S. Forest Serv. Rocky Mountain Forest and Range Expt. Sta. 1949. [Processed.]

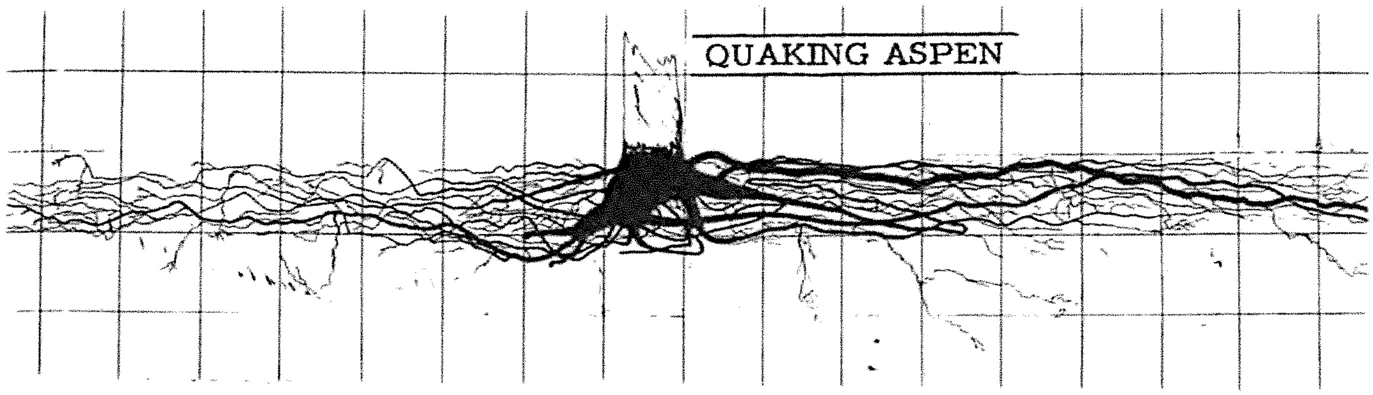

Figure 14. --This root system was from a tree that was 110 years old, 22 feet high, and 7 inches d.b.h. Maximum penetration of the system was 2.4 feet and maximum lateral spread was 20 feet.

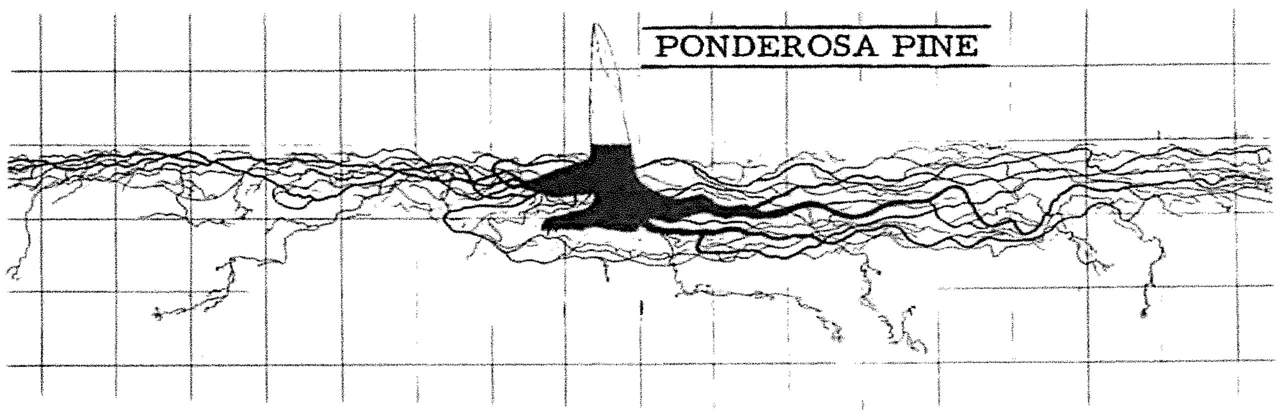

Figure 15. --The pine tree was 75 years old, 19 feet high, and 5 inches d.b.h. Its root system had a maximum penetration of 2.8 feet and a maximum lateral spread of 19 feet. The tree was anchored by a tap root, penetrating a crevice to an undetermined depth (see cover photo).

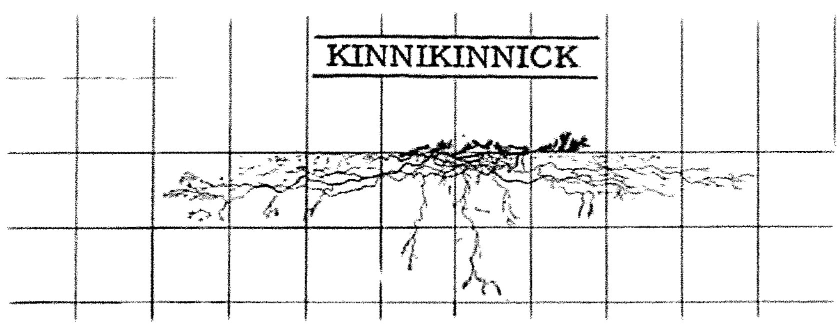

Figure 16. --This plant had a very shallow root system with maximum penetration of 2 feet. Most of the roots were in the top 6 inches of soil, and many could be exposed by simply turning back the thin humus layer.

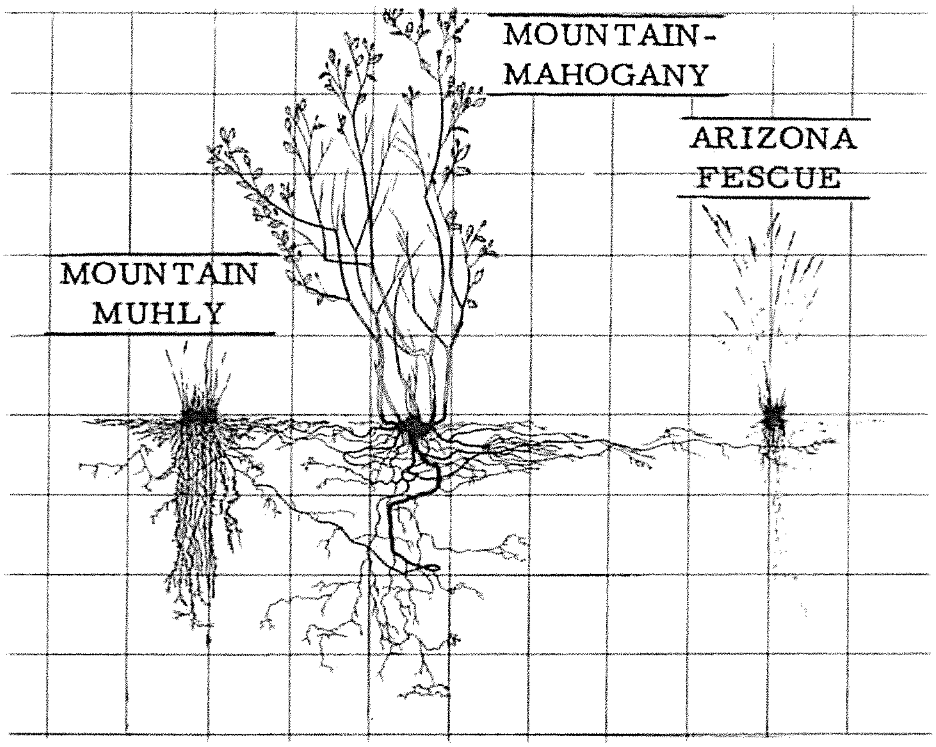

Figure 17.--The root systems of these three plants were excavated from the same trench and the diagram shows the intertwining of the roots. The mountain muhly plant was 0.9 foot high and 6 inches in diameter. Its roots penetrated to a maximum depth of 2.7 feet and had a maximum lateral spread of 1.3 feet. The fibrous root system consisted of 324 individual roots. The mountainmahogany plant was 5 feet high. Maximum penetration of the roots was 3.5 feet and the maximum lateral spread was 5 feet. The fibrous root system of Arizona fescue consisted of 308 individual roots. The plant was 2.6 feet high and 2.5 inches in diameter. Maximum penetration of its roots was 2.6 feet, and maximum lateral spread was 1.2 feet.

The three residual soils studied exhibited different characteristics and provided different sites for plant growth. In table 1, comparisons are made of the plants studied on the three soils. For the trees and shrubs, root penetration and lateral spread was least for the skeletal soil and about equal in depth for the Edloe and Chubbs soils, but of greater lateral spread in the Chubbs soil. Root penetration of the grass roots was about equal in the Edloe and skeletal soils, but of greater depth in the Chubbs soil. Lateral spread was greatest in the Edloe soil, somewhat less in the Chubbs soil, and least in the skeletal soil.

Table 1.--Comparisons of native plants studied on three soils of the Colorado Front Range

Species	Age	Height	Diameter	Maximum root depth	Maximum spread
	Years	Feet	Inches	Feet	Feet
			EDLOE SOIL		
Lodgepole pine	90	23	5	4	16
Douglas-fir	80	21	5.5	5	13
Aspen	70	26	4.5	5	31
Ponderosa pine	85	19	4.5	5	10
Mountainmahogany	--	4.5	--	5	8
Kinnikinnick	--	--	--	3	--
Mountain muhly	--	1	10	2.8	1.7
Arizona fescue	--	2.3	4	2.8	1.5
			CHUBBS SOIL		
Lodgepole pine	--	--	--	--	--
Douglas-fir	72	24	5	4.8	21
Aspen	97	38	8.5	4.2	48
Ponderosa pine	63	25	5	5.6	20
Mountainmahogany	--	4	--	5	10
Kinnikinnick	--	--	--	2	--
Mountain muhly	--	0.5	6	3.4	1.3
Arizona fescue	--	2.7	6	3.1	1.7
			SKELETAL SOIL		
Lodgepole pine	--	--	--	--	--
Douglas-fir	60	22	4	2.7	10
Aspen	110	22	7	2.4	20
Ponderosa pine	75	19	5	2.8	19
Mountainmahogany	--	5	--	3.5	5
Kinnikinnick	--	--	--	2	--
Mountain muhly	--	0.9	6	2.7	1.3
Arizona fescue	--	2.6	2.5	2.6	1.2

SUMMARY

Lateral extent and depth of root systems for 8 plant species on 3 different soils of the Colorado Front Range were examined on the Manitou Experimental Forest near Colorado Springs, Colorado. The trees studied were between 60 and 110 years in age, 19 and 38 feet in height, and 4 to 8.5 inches in d.b.h.

Ponderosa pine, Douglas-fir, lodgepole pine, and mountain-mahogany roots reached maximum depths between 4 and 5.6 feet, except where downward penetration was limited by bedrock. Mountain muhly, Arizona fescue, and kinnikinnick roots grew to depths of between 2 and 3.4 feet.

Quaking aspen roots had the greatest lateral extent, with some laterals growing 48 feet from the parent stump. Other tree species had laterals less than one-half this length.

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Natural Windbreak Effect on Livestock Hydrogen Sulfide Reduction and Adapting an Odor Model to South Dakota Weather Conditions

R.E. Nicolai, S.H. Pohl, R. Lefers, and A Dittbenner

Introduction

The University of Minnesota has developed a tool to establish setback distances from a livestock production facility that utilizes scientific methods to predict odor impacts on the community (Jacobson et al., 2000). The tool, "Odor From Feedlots Setback Estimation Tool" (OFFSET), is designed to predict the odor impact from livestock and poultry facilities on the neighboring community. One feature in the OFFSET model is to give credit for odor control technology that is incorporated in a livestock producing system. Odor reduction factors have been determined for biofilters, manure storage covers (geotextile, straw, and natural) and oil sprinkling in a building. The use of natural windbreaks is often given as an odor reducing technology (Koelsch, 1999; WED, 1999; NPPC, 1999; Lorimer et al., 1998; OCTF, 1998; Jacobson et al., 1998). Planting trees downwind of manure handling facilities has been recommended in ASAE Standard 379.2 (ASAE, 2003) to intercept odor transport off-site and improve aesthetics. However, odor reduction factors still need to be determined for that technology to be used in an odor reduction model. Gassman (1995) concluded in a literature review that shelterbelt effect on odor movement and abatement has yet to be studied in detail.

Proper shelterbelt and shelterbelt systems designs should be able to decrease the concentration levels of odor plumes leaving production sites. When combined with legal separation distances they have been reported to effectively reduce the odor perception levels reaching populated areas, reduce the number of people affected by odors, reduce the time duration of exposure to odors, and allow for reductions in the number of occurrences of odor events. Unfortunately, while several sources (Koelsch, 1999; WED, 1999; NPPC, 1999; Lorimer et al., 1998; OCTF, 1998; Jacobson et al., 1998) list shelterbelts as odor control devices, they provide little physical, biological, or economic quantification as to effectiveness.

Natural Windbreaks – Odors can also be controlled by diluting and/or enhancing the dispersion of the odorous gases leaving the livestock facility. Rows of trees and other vegetation known as shelterbelts may have value as odor control devices by increasing odor dispersion. Shelterbelts are vegetation systems that typically use trees and shrubs to redirect wind and reduce wind speeds, thereby modifying environmental conditions within the upwind and downwind sheltered zones.

Shelter belts have the potential to reduce odor by four different mechanisms. On windy days a shelterbelt will create turbulence forcing the odorous air to mix with clean air at higher elevations. Shelterbelts may also encourage settling of dust and particulates by reducing wind speeds. These particulates are often odorous or carry odors. The third mechanism for odor control is the physical interception of dust and particulates. As the odorous air moves through the shelterbelt the odorous particles collect on leaf surfaces thus reducing the odor. The last potential means by which shelterbelts control odor is through adsorption and absorption of the odorous chemicals on the foliage and the subsequent breakdown of these chemicals via microbial activity.

Thernelius (1997) and Laird (1997) estimated a 56% reduction in odor concentration at or very near the source. The reduction estimate was achieved in a wind tunnel experiment modeling a natural ventilated production building with minimal shelterbelt design considerations. There are no studies available that directly address the total impact of vegetative barriers on odor reduction from animal farms, but many people give testimonials to their benefit. However, in order for this technology to be accepted by the general public and to be included into the OFFSET model, the background data needs to be measured and confirmed in a scientific approach.

Frequency Curve adaptation for South Dakota – In developing the original setback curves for the OFFSET model, Minnesota weather data was used to determine the frequency and intensity for the dispersion of the odor plume. This process involves combining the wind data from various weather stations around Minnesota with the frequencies of atmospheric stability classes D, E, and F.

The University of Nebraska – Lincoln has developed a second-generation of the OFFSET model called Odor Foot-print Tool (OFT). This model is very similar to the OFFSET model except that it includes information about wind direction frequency. The OFFSET model assumes a worst-case wind frequency applies to all directions.

Both the models were developed using weather data from their respective state, i.e. Minnesota weather data for the OFFSET model and Nebraska data for the OFT model. For a model to be used in South Dakota, weather data (wind direction and frequency) from various areas in the state must be incorporated in the model. To apply the models to South Dakota, new odor annoyance frequency curves need to be developed that are based on South Dakota weather data.

Objectives:
The objectives of this research are:
(1) To develop an odor control factor for natural windbreaks to be used in the OFFSET and the OFT models, and
(2) To develop odor annoyance free curves based on South Dakota weather data which will be used in determining set-back distances in the OFT model.

Material and Methods

Windbreak study
Swine finishing facility emissions reduction compared to no windbreak were measured using two types of natural windbreaks. Figure 1 illustrates the site of two 1000 head barns (41 ft X 200 ft each) and an earthen basin manure storage structure (110 ft X 375 ft). Sixty feet west of the manure storage structure is a 140 ft thick windbreak of mature large trees. A small tree windbreak is located 120 ft north of the manure storage.

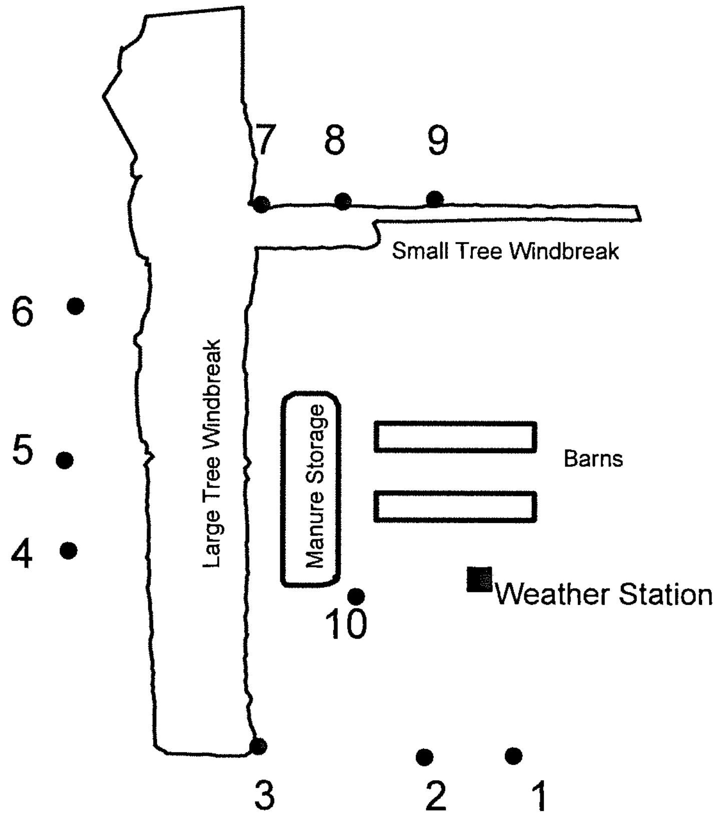
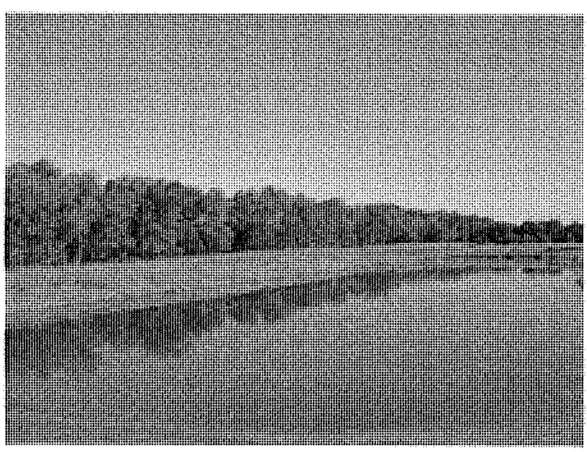


Figure 1 Site layout showing 10 H_2S monitoring stations.

The large tree windbreak (Figure 2) was 140 ft thick and began 260 ft south of the manure storage and extended about 1500 feet north. It consists of eight rows of deciduous trees averaging approximately 30 feet high. The foliage density is less near the ground and increases above 6 to 10 feet.



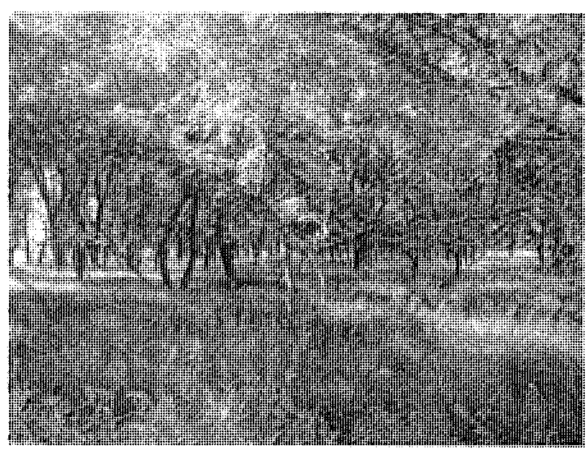


Figure 2 Large tree windbreak west of manure storage and showing density.

The immature tree windbreak to the north of the manure storage is 10 years old with a second planting 2 years ago (Figure 3). The original planting consists of two rows of deciduous and one row of conifer.

Figure 3 Small tree windbreak north of the manure storage

Single Point Monitors (SPMs) (Model 7100, Zellweger Analytics, Inc., Lincolnshire, Ill.) at the ten locations around swine facilities were used to monitor H_2S levels. The SPM measures gas levels based on the rate of color change of a chemical cassette tape that reacts with the target gas. The color intensity change of the tape is sensed by a photocell whose output is then converted to analog output and digital display of the gas level. Liang and Xin (2005) compared the performance of a SPM to a know gas concentration and found that the SPM readings for H_2S measurement can achieve 90% to 107% agreement with an analyzer. A H_2S/L "chem-key" on the SPM sets the range span (1 to 100 ppb) for the hydrogen sulfide. The SPMs were set to record a H_2S concentration every 17 minutes.

The location of the monitors and the perimeter of the windbreaks relative to the manure storage and swine barns were determined by a GPS system. A weather station was located in an open area approximately 100 ft from the barns. Wind direction and speed were recorded every 10 min.

All data was first examined using a two-way analysis of variance. Secondly a pairwise multiple comparison procedure was applied to test for significant differences in H_2S among the three wind speed categories and the three shelterbelts. All tests were evaluated at a significances of $p = 0.05$.

SDOFT model

Using the OFFSET model as a basis, a revised tool was developed for South Dakota climate conditions. The new tool is divided into two parts. The first determines the total odor emissions that a site is emitting. This part is identical to the OFFSET model. The second part determines the rate of odor dispersion. Because dispersion is directly related to local weather conditions, this part was modified for South Dakota weather.

Surface wind direction and frequency (wind rose chart) were obtained from the South Dakota Office of Climatology for 19 sites across South Dakota. Upper air (1000 ft to 3000 ft) wind direction and frequency was obtained for three locations (Sioux Falls, Aberdeen, and Rapid City) from the US Weather Service. The state was divided in three regions with similar wind patterns. Odor annoyance free curves were determined using the Airmod dispersion model based on wind direction and velocity for three regions in South Dakota.

The two parts were assembled into the South Dakota Odor Footprint Tool (SDOFT).

Results and Discussion

Windbreak study

Figure 4 shows the locations of the SPMs used in the study. Because of electronic problems with SPM #2 and #3 the results were not usable. Therefore, hydrogen sulfide levels at SPM 1 were the only data used in the no windbreak results.

The mean hydrogen sulfide concentration data from SPM 4, 5, and 6 were compared at all wind speed. There is not a statistically significant difference ($P = 0.233$) between each of the monitors. Therefore all three monitors were averaged to give mature windbreak results.

Likewise, H_2S concentration data for the immature windbreak at locations 7, 8, and 9 were analyzed. A two-way analysis of variance found a statistically significant difference ($P = <0.001$) between the three monitors that could not be explained by random sampling variability alone. There is a statistically significant interaction between the three monitors and wind speed ($P = < 0.001$). Thus a multiple comparison procedure was used to isolate which monitor differs from the others and to determine which, if any, wind speed differed. The results of the comparisons were inconclusive. One possible explanation for these results is the size of the windbreak. Since the trees averaged 10 to 12 feet tall, air movement across the tops causes an eddy effect just beyond the last row and more turbulence. Thus the SPM monitor location may effect the sampling concentration and averaging all monitors together to obtain a value for immature windbreak would be justified.

The data from each SPM monitor was modified to only include H_2S and wind speed during the time when the barns and manure storage were upwind from the monitor. For example, the data selected for SPM location #1 included a wind direction between 325° and 360° (Figure 4).

In addition to shelterbelt type, wind speed was also considered to be a factor in H_2S reduction. H_2S concentration was categorized for three wind speeds: under 5 mph, from 5-10 mph, and above 10 mph. Figure 5 shows the average H_2S concentration for the three wind speed categories and windbreaks.

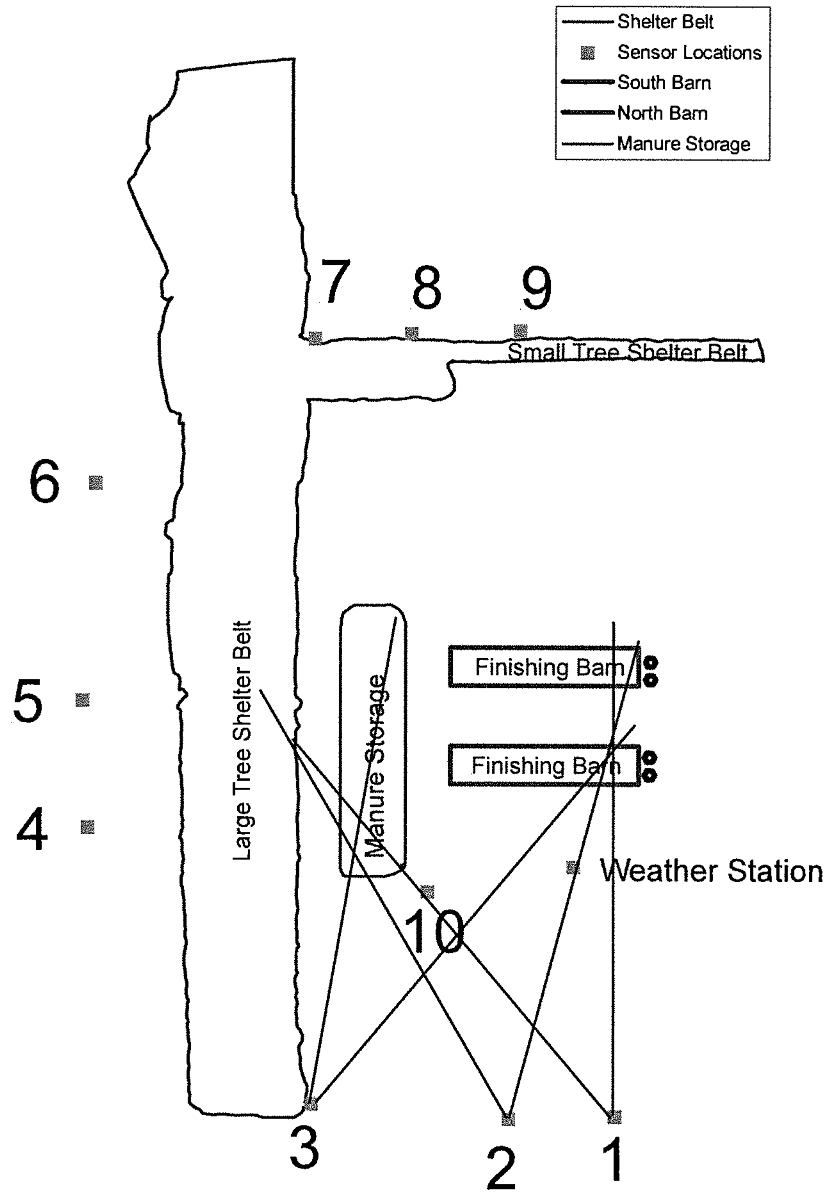


Figure 4: Singe Point Monitor station locations.

There is a significant reduction (P = <0.001) between no windbreak and either a mature or an immature windbreak at all wind speeds (Table 1). However, there is not a significant difference (P = 0.11) between H_2S levels at all wind speeds between an immature windbreak and no windbreak. For all wind conditions, a mature windbreak will provide significant H_2S reduction while an immature windbreak will not.

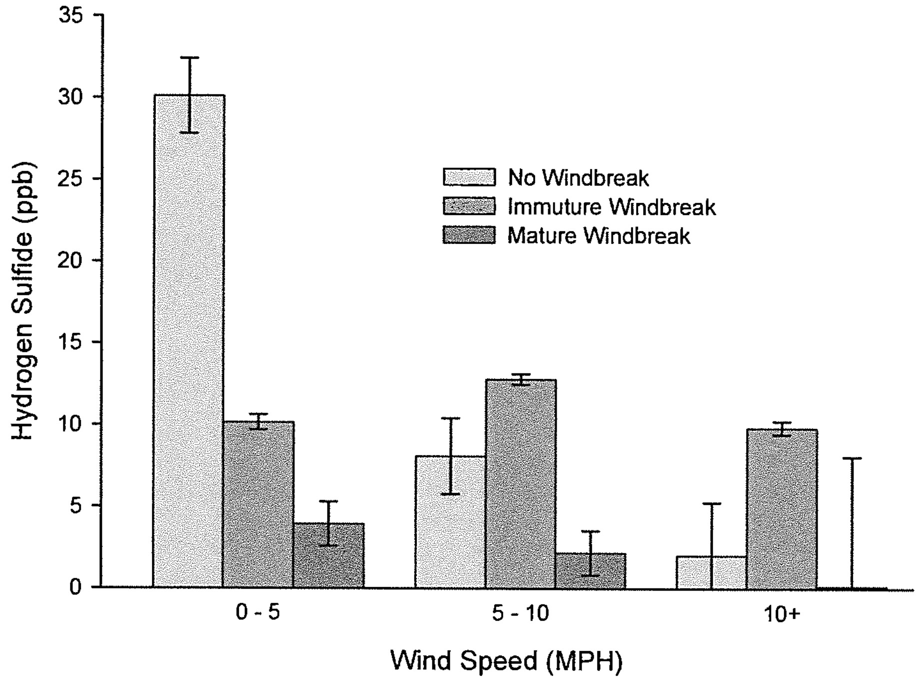


Figure 5. Hydrogen Sulfide change for various wind speeds and windbreak. The error bars indicate one standard deviation.

Table 1: Average H_2S and H_2S reduction for all wind speeds after the two windbreak.

	No Windbreak	Immature Trees	Mature Trees
Average Hydrogen Sulfide (ppb)	13.4	10.9	2.0
Percent Reduction		(no statistical difference)	85%

For the mature windbreak, wind speed did not significantly effect ($P = 0.613$) the average H_2S concentration measured beyond the windbreak. This means that at any wind speed the H_2S would be similar beyond a mature windbreak.

At wind speeds below 5 mph, data results showed that both the mature and immature windbreaks are better than no windbreak (Table 2). The immature and mature windbreak both provided significantly ($P = <0.001$) lower H_2S concentration levels than no windbreak.

Table 2: Average H_2S and H_2S reduction from wind speeds less then 5 mph.

	No Windbreak	Immature Trees	Mature Trees
Average Hydrogen Sulfide (ppb)	30.1	10.2	3.9
Percent Reduction		66%	87%

However, at wind speeds above 10 mph, the results showed that average H_2S levels were not significantly different between no windbreak and mature trees ($P = 0.803$) and immature trees and mature trees ($P = 0.211$). Therefore at wind speeds greater than 10 mph there is no significant additional hydrogen sulfide change that can be contributed to the windbreaks. A possible explanation is that over 10 mph, there is additional wind turbulence to cause sufficient dispersion of the H_2S.

SDOFT model

Input for the model requires information about the type of species housed at the site, type of facility used to house the livestock, and the area of emitting surface, i.e. size of barn and surface size of the manure storage. From these inputs the model then predicts the emissions coming from a barn exhaust fans, vents, and manure storage surfaces. All of the sources at a site are combined into an overall emission factor.

Air quality down-wind is determined by applying the AERMOD dispersion model. It uses meteorological data such as temperature, wind direction, and wind speed to calculate concentrations. The AERMOD dispersion model can predict where air emissions go after being released and then determines how the emissions will move and spread throughout the area. Air dispersion models are not perfect. A model's prediction for one day may not exactly match the measurements at air quality monitors for that day but instead indicate what an average day might produce.

The results from the modeling are presented in an annoyance-free graph. For the purposes of SDOFT, annoyance-free odors are defined as those odors with intensity less than 2 on a 0 to 5 scale (SDSU Extension Fact Sheet 925-A). Odors with an intensity of less than 2 are weak or mild odors that are not annoying to the majority of the population.

The setback distances from a livestock site for various percent of time an observer will be annoyance-free is then illustrated by contour lines circling that site.

Conclusions

- For all wind speeds, a mature windbreak reduces H_2S concentration levels at all wind speeds an average of 85%.

- When averaged for all wind speeds, an immature windbreak did not statistically significantly reduce H_2S concentration levels.

- At very slow wind speeds (0 to 5 mph) both immature and mature windbreaks reduced H_2S concentration levels.

- Above ten mph wind speeds, the H_2S concentration levels were not significantly different between no windbreak, an immature windbreak, and a mature windbreak.

- A model for predicting the impact livestock odor has on the surrounding community was developed for South Dakota.

Future research

It must be cautioned that there is still much to learn concerning windbreaks. For example, what are the relative benefits of placing windbreaks on the upwind and downwind sides of odor sources? What tree and shrub species are best and what planting densities and intervals are needed? What impact does a windbreak have on H_2S and odor reduction measured at various distances downwind of the windbreak?

The predicted intensity and frequency of the odors as modeled by SDOFT must be verified using field odor measurements.

Acknowledgment
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AT THE ROOT OF IT

Susan D. Day and
P. Eric Wiseman

Take a look at any tree and you will find yourself doing one of two things: either staring up into the canopy or looking down at the ground. You might readily see what you are looking for in the canopy, but when you look at the ground, chances are your brow will furrow, you'll look this way and that, you'll contemplate, maybe poke the ground with a stick or pull a soil sample. Watch any tree expert inspecting the root zone and you will see that look: surmising what is going on below ground, looking for clues.

Some of us have always felt the root system is the most important part of the tree—the key to health and longevity. Yet, roots have always been difficult to study. New technologies such as air excavation tools and ground-penetrating radar (GPR) are making root inspection easier than in the past, but learning about roots is still a tedious and imperfect process. These tools, especially GPR, are suitable for visualizing larger roots, as thick as your little finger or so. Fine roots are another animal entirely. As one commentary in a prestigious academic journal put it, "the fine roots ... are a royal pain to study ... to promote sanity, this complex network has often been sampled in ways that fail to relate the structure of the intact system to resource acquisition" (Pregitzer 2002). Even tireless and ambitious graduate students have been felled by the difficulty of studying fine roots.

The fine root system is complex, and its study is still an area of emerging research. The structure, function, birth, and death of fine roots, as well as interactions with symbiotic fungi and other soil biota, are revealing themselves to be more complicated than previously imagined.

Those in the tree care profession have additional complications to add to the mix: pavement, utilities, heat, contamination, and other typical impediments of the built environment. "Now where are the roots?" we ask ourselves. The question cannot be avoided if we are to provide the best diagnosis, treatment, and protection for existing trees as well as the best growing conditions for future trees. Through considerable research effort, entire root systems of trees have been excavated and their allometry (relationship between size and shape) described with the data at hand. We have thus been able to make broad statements about root extent, leading to significant changes in how we view and manage the belowground portion of the tree. These statements take form in arboriculture classes and educational publications as rules of thumb: (1) Tree root systems extend out 2–3 times the dripline, (2) most roots are in the top foot (30.5 cm) of soil, (3) roots extend out about 1.5 times the height of the tree, and (4) more than 60 percent of the absorbing root system is beyond the dripline.

Many times we have taken our students out to estimate root location with these techniques—forming circles around trees, watching amazed students ponder the extent of root systems. Are these rules of thumb wrong? No, they were certainly correct for the excavated research trees, and experience tells us they are not far off for many other trees. Yet it is time to take a fresh look at their estimating techniques. Many of these experiments were conducted with forest trees or young nursery trees, predominantly in the eastern United States. Research on mature urban and landscape trees is still very difficult to come by, especially on root systems, but enough new information is available to merit taking another look at tree roots. Recently we took part in a comprehensive review of scientific literature from around the world related to urban and landscape tree roots. There remains a lot we do not know about tree roots, especially urban and landscape trees, but there is more scientific information now than ever before.

Do Roots Really Go Out That Far?

They can and they do. It continues to surprise most of us when we excavate and follow an individual tree root to see how far it goes. But in our analysis of existing research, we uncovered a few concepts that changed the way we look at roots:

Canopy width and tree height aren't very useful for estimating spread of the root system, even on open-grown trees with few or no belowground obstacles. Most studies we analyzed found a consistent relationship for a particular tree species of a particular size and in similar growing conditions—but when different types of trees were grouped together, predicting root spread from canopy width or tree height produced estimates that were equally incorrect among analysis as one might otherwise be correct.

Trunk diameter is a much better predictor of root spread. Trunk diameter is about as good as it gets for estimating root spread of unobstructed trees. For young trees [less than approximately 8 in (20 cm) in diameter], the ratio of root radius to trunk diameter in the documented studies was about 38 to 1. That is to say, a 6 in (15 cm) diameter tree can have a root system that extends nearly 6 m, or 19.7 ft out from the trunk (about 19 ft per 6 in). There were not enough data to determine the relationship for conifers. Furthermore, the trunk diameter of palms does not increase with age or size, so this relationship cannot be applied to palms.

This relationship probably changes for older trees. First the caveats: there are a lot less data on large and mature trees for obvious reasons—and there are instances of roots extending great distances (but unfortunately the researchers who excavated them didn't record how big the tree was—data collection is not yet standardized in this arena). Nonetheless, existing studies of more mature trees suggest that root spread levels off to some extent as trees age. Thus, a tree with a 90 cm (35 in) diameter will probably have only a marginally larger root system than a tree that is 30 cm in diameter; the root system certainly won't be three times as large. In general, older trees spend a greater proportion of their resources on maintenance of tissue and less on growth. Studies have shown that older trees put more resources into the metabolically costly production of fine absorbing roots and fewer into large structural roots. This makes sense according to some current theories of plant allometry (e.g., West et al. 1999), which predicate the maximization of surface area (which determines resource uptake) and the minimization of the distance resources have to be transported.

Roads, sidewalks, and other surfaces can restrict root extension. Admittedly, there are just a handful of studies where adventurous root investigators have excavated tree roots under pavement. However, these indicate roots generally don't extend very far under intact pavement, and sometimes taper off in as little as 4 in (10 cm). In irrigated sites, root extent is sometimes confined to soil areas receiving irrigation. Other management practices, such as mulch, may also influence root spread, but such effects are not documented.

Root systems are not uniformly distributed around a tree. When entire root systems are excavated and mapped, the irregularity of root distribution can be quite striking. In addition, roots can proliferate in pockets where water and nutrients are plentiful (such as near a leaky sewer line). From our vantage point above ground, we often cannot see changes in water tables or soil that might influence root distribution. However, root extent does tend to be greater on the uphill side of trees planted on a slope, or in the case of a leaning tree, on the side away from the lean.

These findings largely affirm current practices in tree root zone protection. For example, the guideline for tree protection zones (TPZs) described by Harris, Clark, and Matheny in their text *Arboriculture: Integrated Management of Trees, Shrubs, and Vines* (2004), is based on trunk diameter. Applying this metric to the growth patterns described above, larger trees will have more of the root system protected than smaller trees. This is exactly what we want in most cases because young, high-vitality trees can withstand considerably more injury than mature trees. Tree stature varies considerably of course. Consider that a mature flowering dogwood (*Cornus florida*) may have approximately the same trunk diameter as a young, rapidly growing elm (*Ulmus* spp.). Our TPZ metrics partly account for this by using higher ratio of TPZ radius to trunk diameter for more mature trees.

What About Root Depth?

Tree roots seem to be able to grow everywhere. There are documented instances of roots penetrating cracks in rock 100 microns wide (that's one-tenth of a millimeter). They grow into sewers, buildings, basements, and even through large expanses of open air space. But somehow they rarely grow through compacted urban soils. There are exceptions though. For example, some tree species can elongate roots through compacted soil when it is softened by moisture. Also, some coarse-textured soils are less compactable than fine-textured clays, and roots may penetrate more deeply (Figure 1). Some considerations when estimating rooting depth:

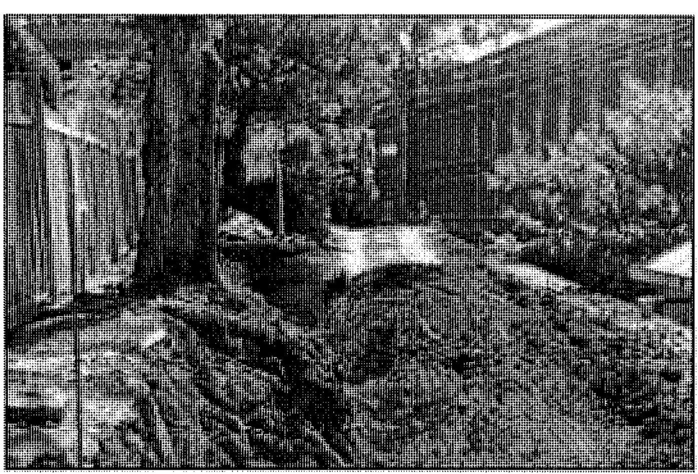

Figure 1. Root depth varies by site. At the construction site pictured here (University of Costa Rica; San José, Costa Rica), nearby trees root systems can be seen to penetrate several meters deep.

There are many barriers to deep roots. Root depth is restricted by pavement, dense rock layers, compacted soil layers, and poor drainage—all common in urban sites (Figure 2). In addition, propagation techniques, nursery production, and transplanting may influence root depth. Adventitiously formed roots are more likely to grow outwards than down, but that is not always the case (Figure 3).

Species matters, but common urban tree species can grow deep roots. Root depth is species dependent, but common urban tree species such as hackberry (*Celtis occidentalis*) can grow very deep root systems if soil conditions permit. Roots for hackberry have been documented to reach a depth of 7 m, or 23 ft.

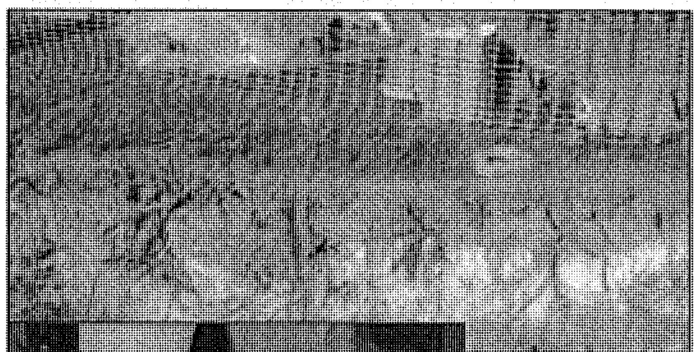

Figure 2. Root depth can be influenced by localized soil changes. ▲ (a) A layer of dense mineral material, likely an artifact of previous construction, has confined roots of this black maple (*Acer nigrum*) very close to the surface. ◄ (b) These loblolly pine (*Pinus taeda*) roots encountered a shallow water table and abruptly changed direction.

What Else Can Roots Do?

We know roots supply water and nutrients to the tree and serve a host of other physiological functions, but roots have some other tricks up their sleeves. For example, fine roots turn over quickly, meaning roots die and new ones grow on a weekly and even daily basis. Roots push their way through the soil as well. Together this means tree roots build soil structure, creating tunnels and macropores as they elongate through the soil and deposit organic matter as they die. Roots can improve drainage too, not only through improving soil structure, but the tunnels created by live and dead roots allow water to move through the soil belowground. With current interest in distributed stormwater management and bioretention systems, these characteristics of tree root systems become very important. Root systems may also develop special features to aid in mechanical stability of the tree. Buttress roots, for example, distribute mechanical stress for the tree. Pronounced buttress roots are most common on tropical trees and are sometimes associated with shallow soils (Figure 4). Tree roots can also play a role in remediation of contaminated soils, stormwater

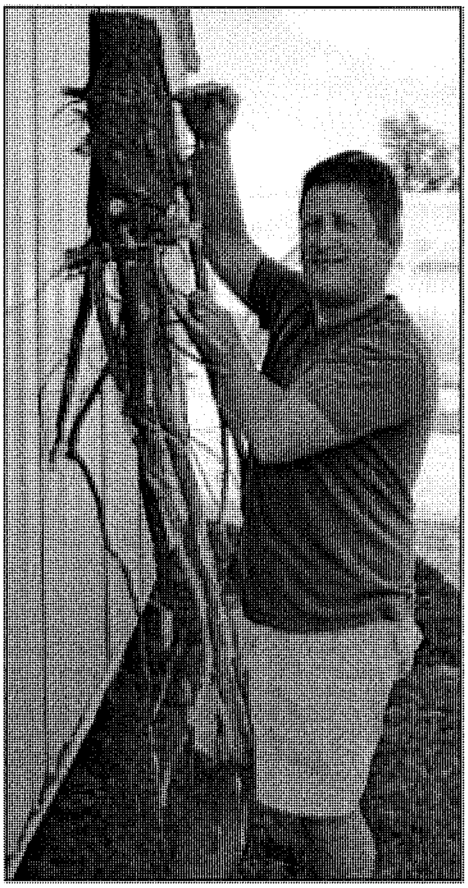

Figure 3. The roots of this tap-rooted species grew deep, despite heavy clay soils. These clonal loblolly pine (*Pinus taeda*) were grown from rooted cuttings and planted in the Piedmont region of the southeastern United States. John Peterson of Virginia Tech's Forest Resources & Environmental Conservation department indicates the original soil surface with his right hand. Note the lateral roots have been removed, but the cut ends are beyond the photo's lower frame.

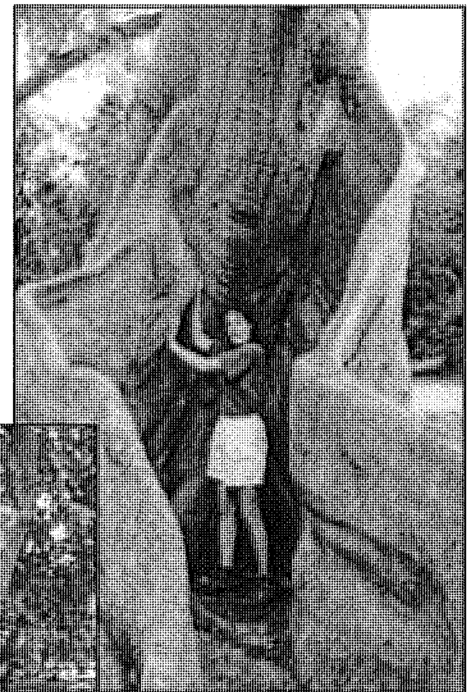

Figure 4. Buttress roots play a role in distributing mechanical stresses. ► (a) This kapok tree (*Ceiba pentandra*) growing in a frequently flooded zone in the Virgin Islands (U.S.). Kapok is known for its pronounced buttress roots, but they may be more well developed in wet areas or areas with shallow soils. ► (b) In temperate climates, buttress roots tend to be less pronounced as illustrated by this European beech tree (*Fagus sylvatica*) in South Dartmouth, Massachusetts, U.S.

filtration, carbon sequestration, and other ecosystem services. This is impressive when you think that we are not even considering the benefits we gain from the canopies supported by all of these roots!

Our society is becoming more urbanized, and trees will play a critical role in the sustainability and quality of life in these environments. To integrate trees into sustainable cities, we must understand how and where tree roots grow. We must also understand how to manage tree roots to ensure safe, healthy trees, and to minimize conflicts with the built environment. How we can manage roots to benefit trees and ourselves is the topic of the next ISA literature review.

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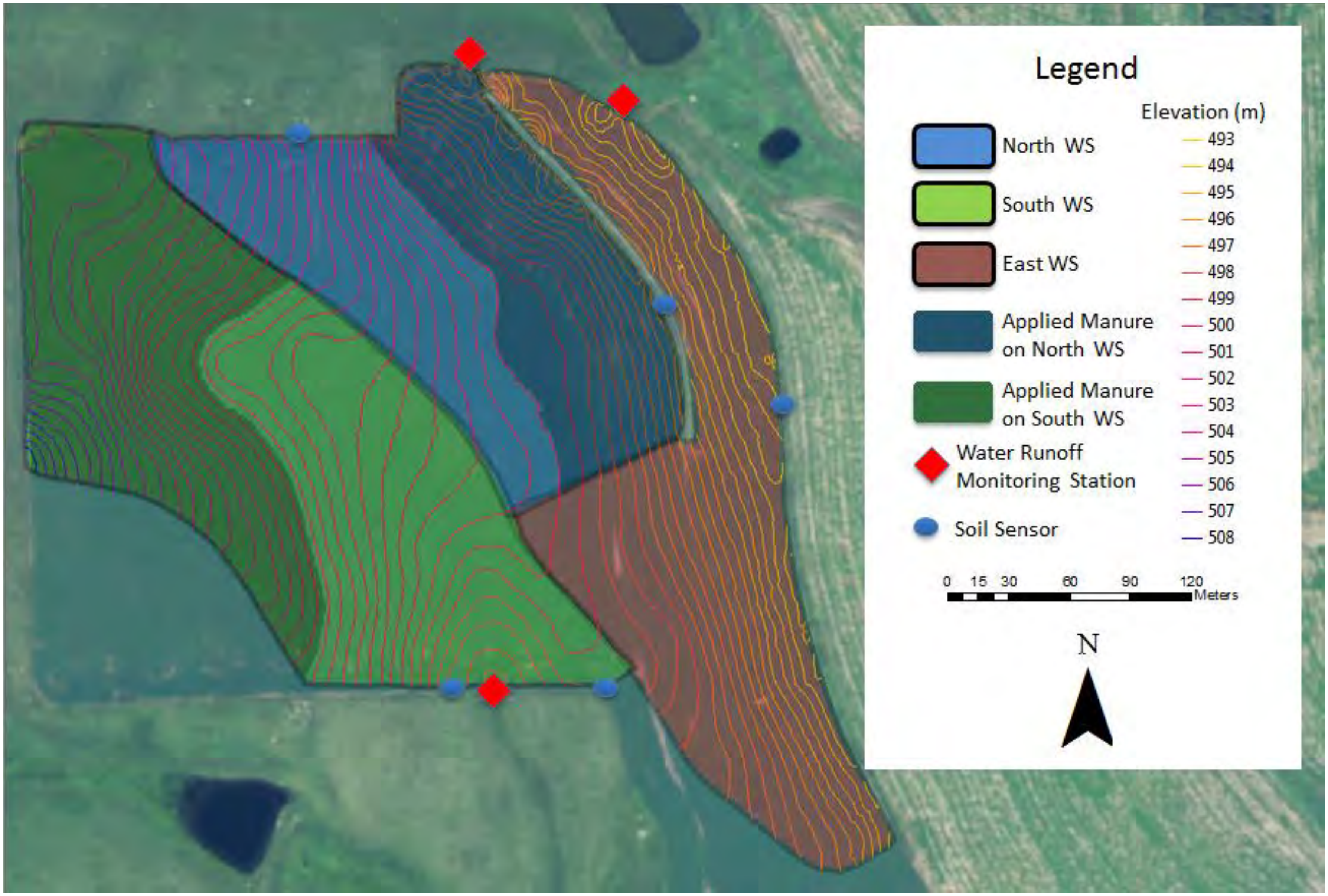
Susan D. Day and P. Eric Wiseman are both faculty in the urban forestry program at the University of Virginia Tech's Department of Forest Resources and Environmental Conservation. With co-authors S.B. Dickinson and J.R. Harris they have recently completed an in-depth review of root development and physiology in urban trees for publication in Arboriculture & Urban Forestry. The full article can be viewed online (auf.isa-arbor.com).

A complete "Roots Bibliography" will be posted on the research portal at the ISA website in early 2010.

The authors thank Jeremy Stovall of Virginia Tech for sharing his loblolly roots.

Photos courtesy of Susan D. Day, James Roger Harris (Figure 4b), and P. Eric Wiseman (Figure 2a).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STOCKWELL

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215 WALNUT ST.
YANKTON, SD 57078
PH: 605.665.8092
FAX: 605.665.0523

This Scenario Provides:

1. Minimal Wind Protection
2. Minimal Erosion Protection
3. Minimal Odor Benefit
4. Minimal Decrease in Wave Action

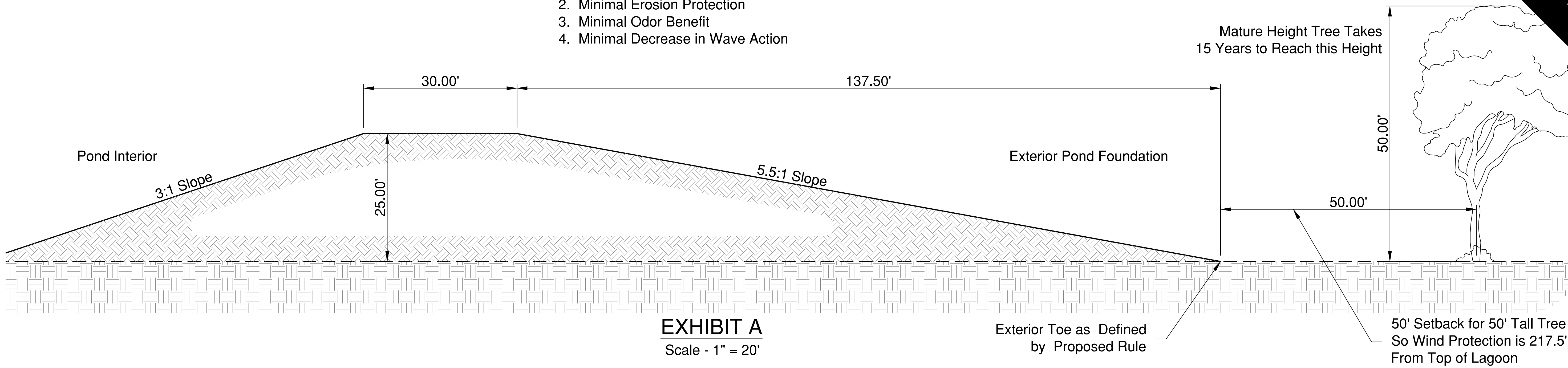

EXHIBIT A

Scale - 1" = 20'

This Scenario Provides:

1. Wind Protection
2. Erosion Protection
3. Odor Benefit
4. Decrease in Wave Action

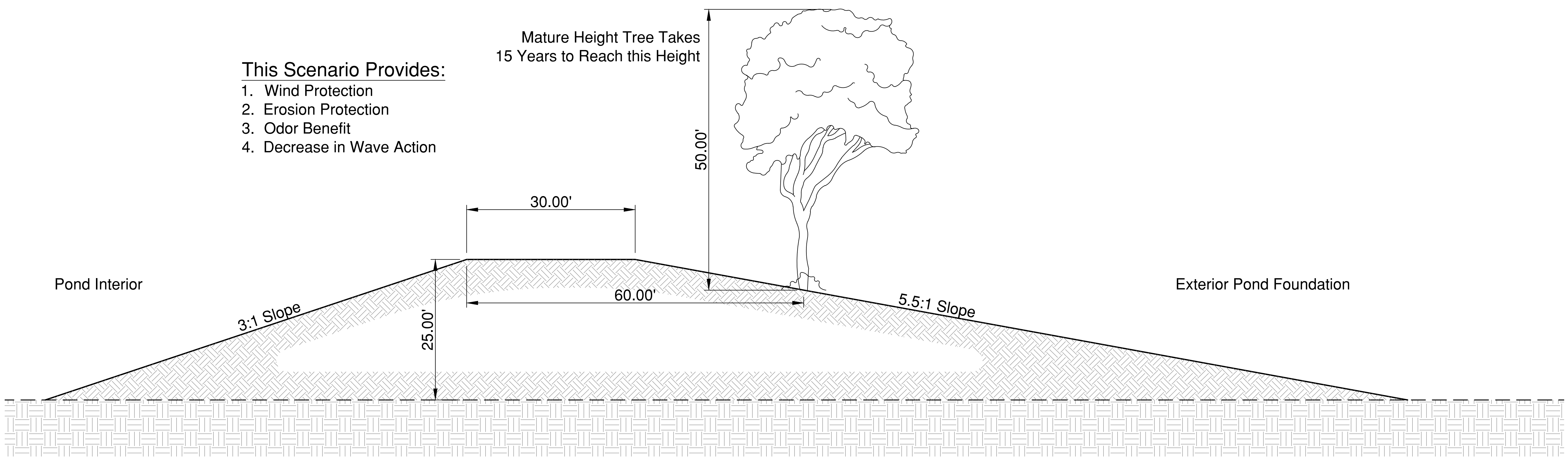

EXHIBIT B

Scale - 1" = 20'

Tree Planting Exhibit

REVISION SCHEDULE

ISSUE/REVISION	DATE

SEI PROJECT #: 15200

EXHIBIT