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Rooting Depth of Mature Loblolly Pine (Pinus Taeda L.) as Influenced by Physical Properties of the Soil in Southeastern Louisiana.

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ROOTING DEPTH OF MATURE LOBLOLLY PINE (*Pinus taeda* L.) AS INFLUENCED BY PHYSICAL PROPERTIES OF THE SOIL IN SOUTHEASTERN LOUISIANA

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ABSTRACT

The root systems of mature loblolly pine (Pinus taeda L.) trees in representative Coastal Plain soils in southeastern Louisiana were studied to determine how root distribution was affected by soil physical properties. Soil properties were characterized to depths of 18 ft in some cases and seasonal use of soil moisture by the pine stands was examined from 1968 to 1972.

Eight circular quarter-acre plots were established on six soils at varying topographic positions. Soil moisture was measured weekly for five growing seasons with a neutron probe. Soil oxygen content was measured biweekly during 1970 and 1972. Bulk density was determined with a depth density gauge.

Soil samples were obtained from conventional soil pits and with a hydraulic core sampling machine. Laboratory determinations included percolation rate, porosity, bulk density by three methods, moisture constants, color and mottling, and texture.

Root samples were collected from 20 48-inch soil cores on each plot. Roots were separated by wet-sieving, divided into eight size classes, and dried.

Values of bulk density and moisture content from different methods were compared by analyses of variance.

The degree of association of soil properties was determined by multiple correlation analyses. Soil properties that accounted for the greatest variation in root distribution were examined by step-wise multiple regression analyses.

Mean density values from nuclear measurements were 0.08 g/cm^3 lower than those from undisturbed soil cores. Mean density values obtained by resin-coated and wax-coated clod methods were 0.03 and 0.04 g/cm^3, higher and lower, respectively, than those of soil cores. Density measurements by the nuclear method are probably better than other methods because less soil disturbance occurs.

Measurements of soil moisture with a neutron probe compared favorably with gravimetric determinations in soils having more than 50% sand. The neutron method is excellent for continual measurement of moisture changes in undisturbed soils.

Bulk density values were positively correlated with percent sand and negatively correlated with percent silt, as sand increased and silt decreased with soil depth. Percent clay was highly correlated with wilting point and field capacity, with r values of .947 and .866, respectively.

Depletion of soil moisture was greatest in the upper 4 ft of all soil profiles. Soil moisture was usually at a minimum in June and at a maximum in March or April. Soil moisture was depleted below the wilting point on only one plot, which was located on a steep slope.

Larger roots were found less frequently than small roots, especially with increasing soil depth. On eight of ten plots, 75% of the total root mass sampled was found in the upper 18 inches of the profile, however roots were found at all depths from 0 to 48 inches.

The following significant mean differences in soil properties were found between zones that contained 75% of the root mass and deeper zones where few roots were sampled: increase in bulk density from 1.58 to 1.78 g/cm^3, decrease in soil oxygen from 19 to 13%, decrease in total pore space from 36 to 33%, increase in percent sand from 55 to 78%, and decrease in percent silt from 25 to 9%.

Roots smaller than 2.5 mm were influenced most by silt-plus-clay content, while bulk density had the most influence on roots from 2.5 mm to 1.0 cm. Field capacity had the greatest influence on roots larger than 1.0 cm in diameter.

The combined effects of soil oxygen, moisture, and the above soil properties influenced root distribution of mature loblolly pines studied.

INTRODUCTION

The root system of any plant is essential for the growth and development of the plant. Root systems are important to plants for water and nutrient absorption and for storage of carbohydrate food reserves. They function also for physical support and anchorage of the plant. Water and nutrients, utilized by plants in photosynthesis, transpiration, and other physiological processes, must be absorbed through the root system to replenish quantities used if the plant is to grow.

The extent of root growth in the soil then affects the ultimate growth of the whole plant. According to Kramer and Kozlowski (1960), the effectiveness of the root systems of trees in absorbing water and nutrients depends on their extent and efficiency. Many studies have shown that trees have root systems which are quite extensive (Brown and Woods 1968, Crossley 1940, Diebold 1933, Heyward 1933, and others).

Some roots extend laterally in the soil beyond the spread of branches in the crown and can penetrate quite deeply into the soil profile. The degree of development of a tree's root system is largely, but not exclusively, dependent on soil characteristics. Kohnke (1968) emphasized that the depth of root penetration is determined by the nature of the plant, the mechanical penetrability of

the soil, the water supply, the oxygen supply and the nutrient supply. Kramer (1949) stated that the development of the root system depends first of all on heredity and secondly on environmental factors. He included soil texture, structure, moisture content, aeration, temperature, kind and concentration of solutes, and competition with other roots as environmental factors. For example, in wet soils the penetration of roots into deeper layers is frequently restricted by lack of oxygen. Plants growing in swamps and poorly drained soils tend to be shallow-rooted (Kohnke 1968).

Most studies of the effects of soil physical properties on the development of tree root systems have been done on tree seedlings or young trees. Effects of soil properties are easier to study on smaller trees or herbaceous plants. Numerous researchers have studied the effects of soil properties such as soil texture, bulk density, or moisture-aeration levels on root development and growth of young trees and herbaceous plants (Broadfoot and Bonner 1966, Foil 1965, Meredith and Patrick 1961, Veihmeyer and Hendrickson 1948, Zimmerman and Kardos 1961, and others).

The lack of experimental data on the development of mature tree root systems and the soil properties which have influenced their development has been due primarily to the expense involved in research of this nature. Early studies on rooting depths of mature trees were accomplished with great labor and expense. Relatively little quantitative soils data were collected to determine the relationship

to root distribution or rooting depth of the trees involved (Cheyney 1932, Crossley 1940, Diebold 1933, and Heyward 1933).

Since it is obvious that larger trees continue to grow and increase their value to man in terms of a larger wood product, it is important to learn more about their root systems which enable them to absorb the water and nutrients necessary for this growth.

A major purpose of this study was to determine which soil physical properties, either singly or in combination, affect the distribution of mature loblolly pine (*Pinus taeda* L.) root systems and limit or restrict the penetration of their roots in the soil profile. A second purpose was to characterize representative Coastal Plain soils with respect to their soil physical properties, especially their capacity to retain soil moisture. A third purpose was to study the seasonal use of soil moisture by mature loblolly pine stands on some representative Coastal Plain soils.

One hypothesis which was tested is that the depth of penetration of the root systems of mature loblolly pine is restricted by soil characteristics which can be numerically quantified. Another hypothesis was that for a given species and stand density, the effective depth of rooting of mature trees can be determined by measuring the depth to which soil moisture is substantially depleted. Also, the data provided a measure of the total amount of soil moisture in several different soil types. In addition,

determination of soil bulk density *in situ* with a nuclear depth density gauge was tested and compared with bulk density values obtained by several other methods.

Findings in this work will be valuable in adding to the basic knowledge of the rooting depth of loblolly pine. This will, in turn, improve the understanding of site quality and allow more accurate predictions of the expected productivity of a particular site.

REVIEW OF LITERATURE

Nuclear methods were used in this research both in determining soil moisture and soil density, hence a brief review of both methods will be treated initially. This will be followed by discussions of associated soil physical properties and root distribution.

Measurement of Soil Moisture and Density by Nuclear Methods

Soil moisture by neutron method. -- One of the earliest and best known proponents of the neutron method, van Bavel (1958), defined the method as a measurement of the number of hydrogen nucleii that are present per unit volume of soil. Some advantages of the method were enumerated by Nixon and Lawless (1960) as (1) the determination of moisture under conditions where it is impractical to sample by the gravimetric method, (2) generally the most accurate method, and (3) the relative ease with which readings can be made to necessary depths.

Certain disadvantages of the method were listed by Luebs et al. (1968). One was that the count rate can be affected by hydrogen nucleii from sources other than water. Concentrations of neutron absorbers such as boron, chlorine, and lithium in soils cause a proportionate reduction in counting response (van Bavel et al. 1961).

Luebs et al. (1968) listed as another disadvantage that the depth probe is unsuitable for measurements near

the surface. Pierpoint (1966) stated that the usefulness of neutron depth probes is impaired if accurate readings can not be obtained within the top 12 inches of soil since moisture changes are normally greatest in this area. Marston (1965b) tested subsurface moisture probes and found that the size of the sphere of influence varies with the soil material studied, but generally measurements with subsurface moisture probes at less than 12 inches below the surface should not be made unless a special calibration is made for the particular soil. Lawless et al. (1963) reported that readings taken at shallow depths had the greatest errors. Errors were always negative. This is understandable since some neutrons leave the soil and are lost into the air. Luebs et al. (1968) also stated that the most accurate soil water determinations by the neutron method require calibration for the soil in question, including a consideration of bulk density changes in the profile. Marais and Smit (1962) indicated a reason for the count rate of a subsurface neutron moisture gauge increasing with increasing bulk density. The increase is partly due to an increase in the volume of hydrogen in the soil which has been compacted. Holmes (1966) stated that, because the volumetric content of hydrogen chemically bound to the soil solids and the macroscopic absorption cross-section for slow neutrons both depend on bulk density of the soil, then the calibration curves for neutron probes depend on bulk density. Olgaard and Haahr (1968) reported that the

counting rate of slow neutrons is increased by an increase in soil bulk density.

Another feature of the method which could be considered a disadvantage is the loss of sensitivity at high moisture contents (van Bavel et al. 1956). They stated that the sample size or resolution is of the same order of magnitude as the sphere of influence, which is between 30 and 75 cm in diameter depending on moisture content. Bowman and King (1965) reported that sensitivity was greatest near the probe and decreased to an insignificant amount at a radius of 25 cm for wet soil and 40 cm for dry soil.

Many researchers have contributed to refinement of techniques in the neutron method. Schultz (1964) studied the methods of determining the center of measurement or reference point of probe placement in the soil for different types of probes. Lawless et al. (1963) recognized that the effective center varies with soil moisture content and is not actually a fixed point. McCauley and Stone (1972) used X-ray radiographs to determine the center of sensitive volume or reference point in the detector tube. Stewart and Taylor (1957) determined the center of the sensitive zone by repeated meter readings of known water contents in a soil profile at different probe placement.

Other researchers have studied the timing interval or time of counting. Hewlett et al. (1964) reported that instrument and timing errors are practically negligible, and in most sampling problems there is little advantage

in increasing the time interval. Marston (1965a) indicated that scalers with built-in timers may not be exact but the interval variation is small and the built-in timer is easier and faster in field use. Rogerson (1970) summarized results which showed that, for practical purposes 1/2-minute counts are adequate for late model probe systems with 100-mc Am-Be sources.

Marston (1965b) and other researchers have recommended the use of aluminum as a suitable material for access tubing to facilitate the detection of small changes in soil moisture. Other researchers (Dickey et al. 1964) discovered that there is a tendency for the soil-water content to be slightly higher near the access tubes but, since the errors in either neutron or gravimetric soil-water determinations are about 1%, the differences would be insignificant. Koshi (1966) evaluated the effects of void spaces around the access tubes in a loamy soil and found that readings with voids up to 3/8 inch in size were within the limits of experimental error. Usually the voids created during tube installation would be less than 3/8 inch.

The instrumentation as available seems to be satisfactory in regard to portability, cost, and precision. The method is sufficiently accurate and the time per measurement is not long. One calibration curve probably suffices for all soils (van Bavel 1956).

Soil density by gamma ray back-scattering method. -- Kirkham and Kunze (1962), in a review of isotope research in soil physics, stated that soil density may be measured by methods consisting of either transmission or back-scattering of gamma rays. The back-scattering method was utilized in the current research and hence will be explored further. The wet density measurement using the back-scattering principle involves the absorption and back-scattering of gamma rays by the outer orbit electrons of all atoms present in the soil, atoms of water included. The amount of back-scattering is inversely proportional to the wet density of the material (ASTM 1960).

Kirkham and Kunze (1962) reported that with either the back-scatter or transmission technique one must determine volumetric moisture content and subtract it, expressed as g/cm^3, from the wet bulk density to obtain dry bulk density.

The back-scattering method can be applied to both surface and depth measurements, whereas the transmission method is only used for depth measurements (van Bavel et al. 1957). In the back-scattering method, the source and detector are both placed in the same tube and are separated from each other by a shield of lead. Radiation from the source passes into the soil and a portion of it is scattered back to the detector. In the transmission-type gauges the source and detector are in separate tubes

(Vomocil 1954). Two major difficulties were attributed to the back-scattering method, the gamma background from the source itself and the lack of resolution. In measurement of density, it is even more important than in moisture studies to characterize definite and narrow layers of soil (van Bavel 1956).

The two types of nuclear gauges for measuring soil density both have certain advantages. Taylor and Kansara (1966) concluded that the back-scatter gauge is convenient and fast when compared to the transmission or direct radiation gauge but it is affected by moisture content and soil type. There is a movement of the calibration curve with a change in soil type, whereas the transmission type gives a more direct measurement of the density and is less affected by soil type (Taylor and Kansara 1967). As an example of the resolution possible with the transmission of gamma radiation, van Bavel (1959) produced microprofiles of soil density using measurements at each inch of depth down to 22 inches. He further stated that measurements could be carried out within 1/2 inch of the ground surface.

Bulk Density and Compaction Defined

Buckman and Brady (1962) defined bulk density as the mass (weight) of a unit volume of dry soil which includes both soil solids and pore space. Bulk density is also referred to as volume weight. Lutz and Chandler (1947)

defined volume weight as the ratio between the dry weight of a given volume of undisturbed soil and the weight of an equal volume of water. Thus, density refers to the density of undisturbed soil samples, cores, or a particular horizon in the profile due to the fact that bulk density is inextricably associated with the pore volume on a unit basis and does not refer simply to the soil solids.

Since the bulk density of soils is dependent on the proportion of void space to solid space on a unit volume basis, it is clear that anything which has a tendency to increase or decrease the amount of void space will affect bulk density. Generally speaking, the closer together the soil particles can be fitted, the higher the bulk density will be. Bodman and Constantin (1965) obtained the highest bulk density by compacting soil mixtures of loamy sand texture. As a general rule, there are not many cases in which the bulk density would need to be increased for improved plant growth. This is true because, essentially, increasing bulk density entails decreasing the void space or total soil porosity by compressing the solid particles more tightly together. Usually, only very light (very sandy) soils could have very high soil porosities and, consequently, might be excessively aerated for plant growth.

Most of the investigations dealing with the influence of bulk density on the growth of plants are concerned with soil bulk densities which are too high. Kohnke (1968)

declared that aeration almost always needs to be increased in medium-textured and heavy soils in humid climates. Since an increase in air space or porosity will decrease the solid space per unit of volume, the bulk density will be decreased.

Compaction is one of the major causal agents of high bulk densities. Webster's Dictionary (1956) refers to compaction as the state of being closely and firmly packed; dense; solid. A compacted soil, therefore, would be one which has been packed or pressed and would tend to be more dense and solid. Bodman and Constantin (1965) stated that soil compaction is the process of bringing solid soil particles closer together. When such an arrangement occurs, the bulk volume of the soil is said to diminish and the bulk density to increase.

Fuller (1958) stated that there are two broad classes of soil compaction. These are genetic, compaction formed during natural soil development, and induced, compaction caused by the mechanical pressure of machinery or water. Gill (1961) defined soil compaction as the pressing of soil together to make it more dense. Bodman and Constantin (1965) declared that soil bulk density is commonly used as a measure of soil compaction.

The Relationships of Soil Bulk Density and Compaction to Other Soil Physical Properties

Soil structure. -- One important point that Diebold (1933) emphasized was the importance of structure to depth

of root penetration. In a friable, single-grained fine sand he found good rooting to a depth of 10 ft. In another soil which was a compact, structureless fine sand, there was no root penetration below 3 ft. Cheyney (1932) suggested the possibility that the structure and consistency of the soil layers may have influenced the rooting habits of jack pine (*P. banksiana* Lamb.). Schlots et al. (1956) stated that roots were abundant in the B horizon in Vashon glacial till but formed a mat due to the hard platy C_1 horizon. They reported that many soils in western Washington have fine clay B horizons which limit root penetration. They described Lacamas silt loam as one in which the B horizon was a dense clay with prismatic structure. It was plastic and sticky but became extremely hard when dry so that tree roots formed a mat over the B_2 horizon and very few penetrated. Those roots which did penetrate the B_2 followed prism faces and did not penetrate the peds.

Soil texture. -- The textures of the soils have been mentioned when they were reported by researchers because texture is important in a discussion of compaction and associated bulk densities.

Veihmeyer and Hendrickson (1948) reported that sandy soils can be compacted to higher densities than clay soils. Actually, the more balanced the distribution of the various percentages of soil separates, the better the particles can be made to fit together and the tighter they can all

be compressed. Hatchell et al. (1970) reported that the increase in density after compaction was greater in loamy sand or sandy loam than in clay loam or clay. They stated that this may have resulted from fine-textured soils having nearly saturated pores when wet and an extremely hard and cohesive condition when dry, thus resisting changes in either extreme. Zimmerman and Kardos (1961) described the difficulty they had in achieving a high bulk density in compacting Araby loamy sand. They attributed this difficulty to a lack of sufficient silt and clay particles to fill the spaces between the rounded sand grains. The higher bulk densities obtained with Hubersberg subsoil, a silty clay, were due to more balance among textural units for maximum particle packing.

Turner (1936) reported the finer-textured Caddo silt loam to contain more total roots and more large roots of shortleaf pine (P. echinata Mill.) than either of two nearby fine sandy loams.

Soil porosity. -- Lull (1959) stated that compaction increases bulk density, reduces total pore space by the same proportion, reduces noncapillary pore space, and affects infiltration and percolation. Appel (1950) reported compact soil conditions in recreational areas deprived trees of water due to surface runoff, and the roots did not get sufficient oxygen for normal growth due to compaction. Sartz (1961) stated that bulk density was

an indicator of the water relations of soils. The low bulk density signified a porous condition associated with high infiltration and high water-holding properties. He went on to state that low bulk density was influenced by macropore space and organic matter which are themselves under the influence of land use.

The loss in water and air permeability points to the major problem associated with soils of high bulk density. This is the degeneration of good air-water relations so vital to the life processes of all plants. Foil and Ralston (1967) reported that even the smallest pressure which was applied to soils in their study of compaction decreased soil aeration and increased mechanical impedance to root growth to unfavorable levels. Scott and Erickson (1964) suggested that oxygen availability and mechanical impedance both appeared to be physical factors that restricted plant root development in uncemented layers with bulk densities as high as 1.90 g/cm^3. Alfalfa roots penetrated these dense layers but did not proliferate unless extra oxygen was present. Gardner and Danielson (1964) indicated that decreased aeration with measured carbon dioxide content lowered the penetrating ability of cotton roots. Tackett and Pearson (1964a) reported that a decrease in oxygen level caused a decrease in cotton root length, but that oxygen was secondary to mechanical impedance in limiting root growth in soils with a high bulk

density, 1.9 g/cm^3. Tackett and Pearson (1964b) also stated that the mechanical impedance of the soil at a density of 1.7 g/cm^3 overrode the effect of carbon dioxide concentrations.

Veihmeyer and Hendrickson (1948) said that the failure of sunflower roots to penetrate compacted soils may have been due to the small size of pores rather than to the lack of oxygen. This statement has faults in that the smaller capillary pores do not contribute to the soil air as do the larger noncapillary pores. Essentially, the loss of noncapillary pore space, through compaction, creates the higher bulk density values. Schlots et al. (1956) found only relatively few pores in Olympic silt loam with a consequent reduction in good air-moisture relations and root penetration. Lutz (1952) indicated that excessive packing of a montmorillonitic type of clay can reduce pore size to a degree where no water or air is available to the plant roots. Broadfoot and Bonner (1966) stated that compaction of soils with bulk densities above 1.6 g/cm^3 resulted in a decreasing percentage of large pores. At this bulk density, they noted a total porosity of 38% in a sandy loam, which retarded the growth of cuttings. Compaction, in their studies, decreased aeration, moisture infiltration, and the movement of moisture and nutrients. Hill and Sumner (1967) stated that compaction causes a predominance of different pore sizes in different soils. In sands, larger pores predominate, so here the greatest effect of increased

density is in the low water-tension range. In clays, there are many more small pores and increased bulk density from compaction affects the higher water-tension range more. Hatchell et al. (1970) found that compaction caused a greater reduction in noncapillary porosity in wet soils than in drier soils.

Perry (1964) studied loblolly pine growing in North Carolina. He found that, after 26 years, pines in the field yielded about twice as much cubic volume as those trees planted in an old road which was badly compacted years before. One of the reasons for this was evident in the lower percolation rates for soil of an abandoned road, 18.5 minutes compared to a rate of 3.5 minutes for soil in the field. The higher bulk density and lower noncapillary porosity was responsible for the slower percolation rate in the road.

Soil strength. -- Mathers et al. (1966) stated that a high soil strength condition is simply a resistance to penetration or cleavage which develops due to compaction. High strength conditions can limit root penetration and radial root extension. They found that when the compaction occurred in conjunction with high moisture contents, the bulk density would be higher. Taylor et al. (1966) found that soil strength varied greatly at the same bulk density and moisture tension for different soils. They presented the following data of soil strength in bars with

soil moisture constant at field capacity (1/3 atm.):

Soil type	Soil strength: Bulk density of 1.55	Soil strength: Bulk density of 1.80
Miles loamy fine sand	6	17
Columbia loam	19	-
Naron fine sandy loam	7	21
Quinlan very fine sandy loam	9	30

They found that the percentage of root penetration decreased as soil strength increased and that there was no root penetration above 25 bars.

Barley (1962) also reported that the soil's strength depends on its water content. He found that changes in root growth in soil at different moisture contents can be interpreted in terms of the amount of resistance offered to the growing root. It should be noted that there may be differences in mechanical measurements of soil strength and in the actual resistance of compact layers offered to growing roots. Stolzy and Barley (1968) stated that differences in resistance were due to the tapered shape of the root and to the ability of the root tip to grow along planes of weakness. This would reduce the resistance encountered by the root as compared to that encountered by a rigid measuring device.

Soil moisture. -- Reinhart (1954) reported that bulk density is affected by texture, organic matter, and

structure over a long time period. It is also affected by changes in moisture content of the soil because of swelling and shrinking caused by the addition and loss of water. This causes changes in bulk density within short time periods.

Taylor and Gardner (1963) found that the bulk density at which no roots penetrated Amarillo fine sandy loam depended upon the soil moisture content.

Soil horizons with high bulk densities or compacted soil layers also affect moisture-root relations. Van Eck (1958) discovered that low site indices for red pine (P. resinosa Ait.) were correlated with the presence of groundwater and compacted subsoils. His root studies showed that these characteristics apparently limited the effective depth to which the root system could penetrate and branch out. Croker (1958) also reported shallow rooting in longleaf (P. palustris Mill.) pine where the soils were shallow with a clay or sandy clay layer in the top 2 ft.

One advantageous effect of a compacted soil with a high bulk density concerns better utilization of soil moisture. Gessel and Lloyd (1950) reported that the site index, as a measure of tree growth potential, on soils underlain by an impeding soil layer was increased with increasing precipitation up to 60 inches. This is in contrast to site index not increasing with increasing precipitation past 40 inches on fine-, medium-, and coarse-textured soils not underlain by a compacted layer.

Soil organic matter. -- Sartz (1961) found a lower soil bulk density under forest stands in the 0- to 3-inch zone due to humus accumulation. Buckman and Brady (1962) stated that bulk density is usually less in the surface due to a higher organic matter content of lower weight. May and Blackmarr (1965) found that the average bulk density increased with increasing depth in the profile in two typical bottomland soils in Georgia, the Congaree and Wehadkee series. They also found that bulk density varied inversely with the organic matter content of the soil. One point brought out by Lull (1959) is that in most forest soils density increases when a reduction in organic matter content occurs.

The Relationships of Other Soil Physical Properties to Soil Moisture and Aeration

Soil texture. -- Coile and Schumacher (1953) stated that the amount of fine material -- silt and clay -- in the soil is directly related to water-holding capacity and water availability. Salter and Williams (1965) found that moisture contents at field capacity and at the permanent wilting point increased as the soils became finer in texture, but the medium textured soils held the greatest volume of available water. They found that available water capacities of soils ranged from 0.77 inches per foot of depth in a sand to 1.95 inches in clay to 3.12 inches per foot in a silt loam. Turner (1938) reported that the sand-silt-clay proportion of horizons affects

internal drainage and aeration of soils. Curlin (1960) stated that the proportion of sand influences the noncapillary porosity of the soil and the rapidity and degree to which the soils will drain due to gravity. Curlin found that available water between field capacity and wilting point is a function of the silt fraction or the sand-clay interaction. Jamison and Kroth (1958) also concluded that silt particles were of primary importance in controlling available moisture in soils. Ike (1969) related that the effect of texture on growth of American sycamore (Platanus occidentalis L.) was probably attributable to some other soil property influenced by soil texture such as soil moisture supply.

Turner (1938) reported a definite correlation between the rate of height growth of shortleaf and loblolly pine and the clay content of the B_2 horizon. Coile and Schumacher (1953) found that site index of loblolly and shortleaf pines is partially determined by the ratio of silt-plus-clay content to the moisture equivalent. Barnes and Ralston (1955) indicated that one of the soil factors significantly related to height growth in slash pine was silt-plus-clay content of the heaviest horizon in the profile. Linnartz (1963) reported that percent sand in the subsoil was significantly related to site index of loblolly pine; the site index decreased with increasing sand content in the subsoil. Weissen and André (1970)

found that forest productivity (expressed as mean total stand height) was significantly correlated with soil texture when texture was expressed as a function of moisture parameters.

Soil permeability. -- The rate of water movement into a soil, i.e. infiltration, and movement of water through the soil, i.e. percolation, are very important to the growth of plants. The degree of permeability of the soil is related to the other soil physical properties of texture, porosity, bulk density, and soil structure.

Parr and Bertrand (1960) reviewed the methods of studying water infiltration into soils. The best measurements are made on undisturbed soils in the field but most methods are cumbersome. Slater and Byers (1931) determined percolation rates on "undisturbed" soil cores in the laboratory, but their rates varied too widely on cores from the same soil to establish absolute percolation rates from the study. They concluded that the field percolation rate of the soil is governed more by the water passageways it contains (root channels or structural cleavages) than it is by the character or volume of the soil mass. Coile (1935) indicated, from a study including 288 observations, that water-ways formed by soil animal activity and decayed roots are more important in determining the rate of water percolation than cleavage planes and pore space.

Soil porosity. -- Descriptions of the pore system of soils are usually presented in terms of total porosity, volume of large pores, or pore-size distribution. Most effects of the pore system on root distribution are interdependent with soil texture, bulk density, permeability, degree of compaction, soil oxygen and soil moisture percentages. Some effects of porosity have already been discussed in other sections of this literature review.

Vomocil (1965) stated that characterizations of the pore system are important to investigations of the storage and movement of water and gases and to studies of the development of root systems by plants. His work includes an excellent summary of methods for determining soil porosity. Vomocil and Flocker (1961) reported that, when a soil is compressed, pore size distribution generally suffers greater relative change than bulk density or total porosity. Dyrness (1969) indicated that the observed decrease in water movement rates through the subsoil is not due so much to decreases in total porosity as it is to shifts from predominantly noncapillary porosity to capillary porosity. Dyrness went on to describe a relationship between water storage and pore sizes. He termed retention storage water as that held in capillary-sized pores or that portion of total soil moisture at moisture contents of field capacity or less. Detention storage water was the water located in the large, noncapillary-size pores or that water from field capacity to saturation and subject to

gravitational pressures. Steinbrenner and Gessel (1955) studied changes in soil properties associated with changes in porosity. They found that soils compacted due to tractor logging were changed so that macropore space decreased in cutover areas by an average of 11% but on skid roads by 53%. On the cutover areas bulk density was increased only 2.4% but was increased by 35% on skid roads. The reduction in permeability rate in cutover areas was 35% compared to a tremendous reduction of 92% on the skid roads.

Importance of Soil Bulk Density and Compaction to the Development of Root Systems

Effect on root and seedling growth. -- Rosenberg (1964) stated that excessive compaction is related to decreases in the productivity of many soils. Levy (1968) described rooting density as the number of roots per unit of area in a horizon. He correlated rooting density with instability of soil structure, high bulk density, and low noncapillary porosity. He found that rooting density for Norway spruce [*Picea abies* (L.) Karst] was much greater than that for Scotch pine (*Pinus sylvestris* L.) down to a depth of 35 cm. Trouse (1964) reported morphological distortions of roots in subtropical soils in Hawaii. He related these to increases in bulk density after compression. Korstian (1927) observed that acorn radicles were unable to penetrate excessively compacted soils.

Foil (1965) reported that compaction, from pressures as low as 50 $lb/inch^2$ of surface, greatly reduced size and weight of loblolly pine seedlings grown in artificially compacted soil cores. Soil density, in his study, was increased by an average of 0.3 g/cm^3 due to the decrease in aeration, or noncapillary, pore space. Aeration porosity was reduced to below 10% of the soil volume. Infiltration capacity was reduced to 12% of that in non-compacted, adjacent soils. Foil stated that the application of the smallest surface pressures reduced soil aeration and increased mechanical impedance to root growth to unfavorable levels. Significant relationships were obtained between root length and soil densities and root weight and soil densities ranging from 0.8 to 1.4 g/cm^3. Campbell et al. (1973) stated that the height growth of loblolly pine seedlings planted in skidding ruts did not show any significant response to the increases in bulk density caused by skidding. Hatchell (1970) found a highly significant reduction in dry root weight of loblolly pine seedlings grown in soil compacted in pots.

Soils with high bulk density probably impede the smaller roots more than the larger ones. Patt et al. (1966) declared that the lack of fine roots on citrus trees reduced their growth and yield. They felt that the fine root growth was inhibited in tight or heavy soils.

Effect on rooting depth. -- Fairly deep rooting depths have been observed in soils where some sort of compact layer did not prevent deeper penetration. Heyward (1933) found taproots on mature longleaf pine over 14 ft long and 9 ft long on longleaf seedlings. He added that the seedling taproots in poorly drained soils extended down to the water table. Many species growing on wet sites have shallow root systems where deeper root penetration for soil moisture is not required. Schlots et al. (1956) found that, in Wahkiakun silt loam where the soil peds are porous, root penetration goes on without restriction to depths of 60 inches or more. Water and aeration characteristics are also good. Since the peds are porous, a somewhat lower bulk density is implied.

Compacted subsoils with associated higher bulk densities can restrict root penetration. Veihmeyer and Hendrickson (1948) stated that plants on soils having dense subsoils may be as shallow rooted as those on typical hardpan soils. Crossley (1940) worked with bur oak (*Quercus macrocarpa* Michx.) on a compact stony glacial till which affected the penetration of roots, especially when hardened due to drying. In another soil nearby, Hubbard loamy fine sand, taproots were found as far down as 11 ft. Crossley also stated that fine feeding rootlets were not found at this depth but he felt this was due to limitations in excavating roots to the growing tip.

The ability of tree roots to follow cracks, fissures, or cleavage planes is important in some cases where hardened layers, compacted zones, or pans underlie shallow soils. Taylor and Burnett (1964) found that plant roots did not penetrate compacted soil except in cracks, and roots grew laterally with many 90-degree turns. Fisher (1968) described a shallow soil, Channery silt loam, which was overlying silt stone bedrock. In this soil, some roots of red pine penetrated to a depth of 1.5 m when the soil averaged only 60 cm in total depth. He stated that small roots were numerous in the silty layers that coated the bedrock fragments and that penetration of the fractured bedrock was important for the trees' survival. Diebold (1933) found apple tree roots at depths of 9 ft following cleavage lines in a Lucas silty clay loam with a blocky structure which was compact.

Since the development of the radioisotope tracer techniques, the extent of shallow root systems can be studied more easily. Brown and Woods (1968) used Iodine-131 and reported maximum lengths of horizontal root extensions of 31.8 ft for dogwood (Cornus florida L.) and 54.6 ft for hickory (Carya sp.). The soil consisted of silt loam to stony silt loam surface horizons overlying friable red clay which had bulk densities ranging from 1.58 down to 1.22 g/cm^3.

The actual physical impedance to tree roots is related to high bulk density generally caused by compaction. Some impedance is due to the structural differences of soil in addition to the actual degree of compaction.

Maximum bulk density values critical to root penetration. -- Critical maximum bulk densities of 1.6 g/cm^3 for cottonwood (Populus deltoides Bartr.) in sandy loam (Broadfoot and Bonner 1966) and 1.9 to 1.7 for sunflowers, depending on texture (Veihmeyer and Hendrickson 1948), have been determined. Broadfoot and Bonner (1966) reported that cottonwood cuttings developed best at a bulk density of 1.4 g/cm^3 in a sandy loam. Gessel and Cole (1958) stated that the critical density for root penetration depends on the species involved and the moisture conditions of the soil. They said that most forest soils have fairly low bulk densities but also cited work which placed the limiting bulk densities for root penetration in the range 1.6 to 1.8 g/cm^3. It should be noted that they worked with western North American species, mainly conifers. Forristall and Gessel (1955) had observed earlier that critical densities differed with species. Western red cedar (Thuja plicata Donn.) grew on a wet site with a bulk density of 1.80 g/cm^3, whereas a density of 1.50 stopped the growth of red alder (Alnus rubra Bong.) roots. Douglas-fir [Pseudotsuga menziesii (Mirb.) Franco] and western hemlock [Tsuga

heterophylla (Raf.) Sarg.] root growth was restricted when the bulk density approached 1.25 g/cm^3.

Minore et al. (1969) used three degrees of compaction, 1.32, 1.45, and 1.59 g/cm^3, in pot studies. They reported that the average root depths showed that Douglas-fir, lodgepole pine (*Pinus contorta* Dougl.) and red alder could penetrate soil densities that inhibited roots of Sitka spruce [*Picea sitchensis* (Bong.) Carr.], western hemlock and western red cedar. Faulkner and Malcolm (1972) found that root extension ceased at soil densities of about 1.5 g/cm^3.

Meredith and Patrick (1961) found no critical bulk density for root penetration of cotton. They did find a loss in noncapillary porosity due to compaction and also a decrease in the amount of root penetration. Doneen and Henderson (1953) found that corn roots were unable to penetrate compact subsoil of Yolo clay loam with a bulk density of 1.5 g/cm^3.

Zimmerman and Kardos (1961) used sudan grass and soybeans and found that bulk densities of 1.8 to 2.0 virtually excluded root penetration. They stated that visual examinations of root growth penetrating soil cores showed noticeable limitations at a bulk density of 1.6 and pronounced limitations at 1.8 g/cm^3. Veihmeyer and Hendrickson (1948) found no penetration of sunflower roots in soils where the bulk density was above 1.9. They found, in addition, that there was no root penetration in sandy soils above 1.8

g/cm^3 or in clay soils above bulk densities of 1.6 to 1.7. They stated that the critical density for root penetration varied with soils.

Relationship of Other Soil Physical Properties to Root Growth and Distribution

Soil texture. -- Many researchers have studied the effects of soil texture on root penetration and development. Pomeroy (1949) reported that root penetration of roots of loblolly pine seedling radicles was significantly less in a clay loam soil than in a loam or sandy soil. Raney et al. (1955) stated that root growth was restricted in fine textured soils.

An important effect of texture on root growth may be due to its influence on moisture and aeration. Coile and Schumacher (1953) concluded that physical properties of Piedmont subsoils or B-horizons which condition water absorption, retention, movement, and availability are important factors affecting growth of tree roots. Wenger (1952) found that the effect of soil texture on sweetgum (*Liquidambar styraciflua* L.) and pine seedling mortality was highly significant, since many more seedlings failed to develop in sandy soil than in clay or silty clay loam soils. Jorgensen (1968) reported that low moisture availability in sandy soils may account for loblolly pine seedlings having few and short secondary roots in contrast to the multiple laterals on seedlings grown in finer soils. Root growth in sand was only half of that in clay and loam

soils. Armson and Shea (1970) found that root development of jack pine (Pinus banksiana Lamb.) was very restricted in coarse sand and essentially unrestricted in the fine-textured medium whereas in black spruce [Picea mariana (Mill.) B.S.P.] the difference was only slight. Seedling growth was best in the fine-textured medium and the oxygen supply was never a limiting factor.

However, fine-textured soils can present problems to root development. Stransky and Wilson (1967) indicated that texture produced significant differences in shoot weight in both loblolly and shortleaf pine seedlings, with the heaviest shoots on plants grown in loamy sand and the lightest on those grown in clay. Root development was also similar, with the biggest roots being developed in loamy sand followed by sandy loam and clay in that order. They stated that the decreases in root size with increasing clay content of the soil were probably caused by restriction of root extension. Blevins (1968) found that finer-textured soil adjacent to the root is less permeable to water and air. Hatchell (1968) reported that any soil disturbance, especially on medium to fine textured soils, can seriously reduce the establishment and early growth of loblolly pine seedlings.

Soil permeability. -- Percolation of water in the soil is important to tree growth. Zahner (1957) reported that small stream floodplains were the best loblolly sites,

having site indices of 95 and better, where internal drainage was good. Gaiser (1950) found that the lower permeability of Piedmont soils (compared to Coastal Plain soils) may seriously limit the development of roots in subsoil horizons. He stated that the depth to impermeable subsoil horizons and the imbibitional water value of the least permeable subsoil horizon affect the growth of loblolly pine.

Soil porosity. -- Pendleton (1950) found that root development of sugar beets was restricted at noncapillary porosities of 3.5% in sandy loam and 11.7% in silt loam. Root development was good at porosities of 14 and 18%, respectively. Beavington and Adu (1971) reported that total pore space was reduced from 50 to 35% in a compacted horizon. In the forested sites the compacted horizons occurred from 14 to 126 cm deep and were at least 0.75 m thick. These compacted horizons formed a barrier to roots. The depth of root penetration was the same as the depth of the upper surface above the compacted layers.

Soil oxygen. -- Wiegand and Lemon (1958) stated certain basic concepts. First, the supply of oxygen reaching the root surfaces of plants growing in the soil is largely controlled by (a) the rate of gaseous exchange between the air in the soil and the air above the soil and (b) the conditions in the immediate root environment which influence

the transfer of oxygen from the soil pores to the root surfaces. Second, the dependence of oxygen and carbon dioxide exchange between respiring cells and the immediate environment on diffusion emphasizes the importance of aeration conditions in the immediate vicinity of the roots. Thirdly, the requirement of plant roots for oxygen is not lessened even though soil conditions prohibit an adequate supply of oxygen to them.

Patrick (1971) stated that two of the most important soil properties governing the development of plant roots in the soil are compaction of the soil (the extent to which soil particles are packed together) and soil aeration (the supply of oxygen in the soil). In some soils both may act to limit root development. Patrick went on to conclude that conditions of high rainfall, low water run-off, high soil compaction, high clay content, poor soil structure, and a high water table can create unfavorable internal soil drainage and result in low soil oxygen content. Hopkins and Patrick (1969) found that soil compaction and oxygen content interacted in their effect on sudangrass root penetration. At the highest compaction levels or at the lowest oxygen content little or no penetration occurred, but at intermediate levels of compaction and oxygen both factors were operative in determining root penetration. At optimum levels of either factor the amount of root penetration was governed by the other

factor. Gill and Miller (1956) reported that growth of corn seedling roots did not cease at concentrations as low as 1% oxygen in the absence of mechanical impedance to growth.

Patrick, Turner and Delaune (1969) reported a close relationship between oxygen content in the 2-ft depth in alluvial soils and the amount of sugar cane root development in the 6-inch to 2-ft zone. Patrick (1973) worked with cotton roots and obtained similar results to the previous sugar cane study. Huck (1970) stated that the distribution of roots through a volume of soil may be influenced by oxygen availability.

Bertrand and Kohnke (1957) studied corn roots and found that dense subsoils may act as effective barriers to normal root penetration. They indicated that the nature of the barrier is not entirely mechanical, but it also causes a lack of oxygen. Aubertin and Kardos (1965) reported best root growth of corn seedlings when oxygen levels were at 10% and that root growth was similar at 5 and 21% but decreased at 2.5% oxygen content.

Armson and Millward (1970) grew seedlings of black spruce and jack pine at controlled oxygen concentrations in the rooting medium. At the high concentration, 18.8 ± 1.8%, both species produced large increases in root surface area with jack pine showing greater lateral root development. Results from another study showed that root

development of lodgepole pine was reduced at concentrations between 10 and 3% and at less than 3% root growth was greatly reduced, whereas shoot growth was maintained even at low oxygen contents.

A comprehensive review of the literature on soil oxygen and its effects on forests was given by Hu and Linnartz (1972) from the senior author's dissertation on the same McIntire-Stennis project as involved in the current research. They summarized Hu's (1971) results as follows:

(1) Oxygen content in the soil varied during the year. It was usually lower in winter and higher in the growing season, especially on low sites.

(2) Oxygen content decreased with soil depth.

(3) Oxygen content varied inversely with soil moisture content.

(4) Oxygen content immediately adjacent to the often fluctuating water table was sharply reduced.

(5) Oxygen content decreased with slope position when measured at similar soil depths.

(6) A significant relationship was found between soil oxygen content and capillary and noncapillary porosity. As the capillary porosity increased, the soil oxygen content decreased; as the noncapillary porosity increased, the oxygen content in the soil increased.

(7) Soil oxygen content was not significantly related to soil texture or bulk density.

(8) Mature loblolly pine trees are probably tolerant to low soil oxygen content. Low soil oxygen in the winter and early spring or in subsoils (below 4 ft) apparently was not detrimental to tree growth. Optimum growth perhaps depends more on the proper balance of soil oxygen and soil moisture content throughout the growing season than on a minimum level alone.

Relationship of Soil Moisture to Tree Growth and Root Development

Importance of available moisture. -- Lutz and Chandler (1947) stated that the moisture supply is probably the most important of all the factors that determine the productivity of a forest site. Kramer (1949) wrote that water is not equally available throughout the available range -- in light soils most of the available water is held by a force of less than 1 atm while in heavy clays 50% or more of the available water is usually held by a force of more than 1 atm. Chesters and Wilde (1972) indicated that usually the length of the growing season is associated with temperature but actually the active growth period of forest stands is probably determined as much by available water supply as by temperature.

McClurkin (1961) indicated that, between highs of 40 to 60% available moisture and lows of 15 to 25%, growth was affected both by the amount and rate of change in

available moisture content. Below the lower limit, diameter growth ceased regardless of the rate of moisture loss. Covell and McClurkin (1967) stated that site index of loblolly pine may be closely predicted from April through September rainfall which influences the soil moisture supply. Zahner and Donnelly (1967) discovered that water deficits accounted for 70 to 75% of the variation in red pine radial growth. Eighty percent of the variation was accounted for when rainfall was included in the equation. Bassett (1964) emphasized that tree diameter growth is closely associated with soil moisture availability. Garrett (1969) worked with red pine and found diameter growth to be closely correlated with current moisture treatments since irrigated trees produced more than twice as much diameter increment as trees under drought stress. Moehring and Ralston (1967) reported that loblolly pine diameter growth was related to the amount and weekly rate of change in available soil moisture from June through August in six sawtimber stands in northeastern Louisiana. They found that, regardless of the amount of moisture available during the summer, growth was curtailed when soil moisture loss was rapid. Consequently, the soil moisture content at which tree growth ceased was highly variable.

Effects of moisture excesses. -- Numerous researchers have studied the harmful effects of high water tables on

the development of root systems and tree growth. Zahner (1955) reported that aeration was limiting to root growth in a Leshe soil at Crossett, Arkansas, because of periods of excess water in the spring. Consequently, tree roots were not extensively developed in and below a silt loam pan. Klawitter (1966) indicated that high soil-water levels appeared to impede growth of scattered sapling- and pole-sized typical slash pine (Pinus elliottii var. elliottii). Moehring (1967) stated that converting pin oak flats to pine is difficult because root development of planted seedlings is often impeded by prolonged periods of flooded or water-logged soil in the spring. As a result seedlings that survive a wet spring may succumb to later summer droughts. Burton (1971) discovered that flooding 2-year-old loblolly pine seedlings for 14 and 21 weeks adversely affected stem height, dry weight of roots and new stems, average needle length, and number of growth flushes. McMinn and McNab (1971) studied the effects of flooding on typical slash pine. Flooding created a marked reduction in production of secondary roots and mycorrhizal occurrence.

Other researchers have found helpful effects of high water tables. Broadfoot (1973a) reported that planted cottonwood grew best when the water table was about 2 ft deep, but a surface water table restricted the growth of cuttings. White and Pritchett (1970) indicated the best

growth of pine was obtained with the water table at 46 cm. Better growth was also obtained with the water table at either 46 or 92 cm rather than with a fluctuating water table. Watterston (1966) stated that the ground water table located in a siliceous sand at a depth of 8 ft augmented the content of moisture about 2 ft above the water table.

Changing the distance to the water table can have definite effects on tree growth. Broadfoot (1973b) reported average radial growth of various hardwood species increased 50% after the water table near a reservoir was raised to within reach of the tree roots.

The practice of raising the planting site above the water table through bedding or drainage also effects growth. Fedkenheuer (1970) stated that soil analysis indicated that the improved growth of eastern white pine (P. strobus L.) and red pine planted on prepared ridges of lacustrine clay soils in Wisconsin was attributable chiefly to greater soil porosity, aeration, and infiltration capacity in the root zone. The soil pores in the furrows were filled with water for half of the growing season. McKee and Shoulders (1970) found that bedding significantly increased tree heights by increasing depth to the water table and raising the redox potential.

Effects of moisture deficiencies. -- McMinn and McNab (1971) reported that South Florida slash pine (P. elliotii

var. densa Little and Dorman) responded to drought conditions by developing a longer taproot and a marked decrease in needle size. Moehring (1967) indicated that pine seedlings with poorly developed root systems cannot survive drought due to inability of the root system to expand fast enough to maintain contact with the receding moisture in the soil.

Soil Moisture Depletion and Storage in Forested Soil Profiles

Moisture depletion. -- The depletion of soil moisture has been studied by many researchers. Hoover, Olson, and Green (1953) reported that soil water is extracted by vegetation from the zone in which it is most readily available regardless of depth within the zone of rooting. They found that an 11-year-old loblolly pine plantation in South Carolina removed water from the 54- to 66-inch depth at the same rate as from shallower depths. However, this plantation was on a well-drained Piedmont soil where aeration was not limiting to root growth. Moyle and Zahner (1954) measured soil moisture depletion where the well stocked forests removed 4 inches of available water in the top 48 inches in early June and up to 7 inches in only four weeks. Schneider, White, and Harlan (1966) reported the estimated average annual water loss from storage in the profile to be 23 inches. Brown and Thompson (1965) provided data on water use which relates to water lost from the soil. They stated that average values for

annual water use were 19.2 inches for quaking aspen (*Populus tremuloides* Michx.) stands, 14.9 inches for Engelmann spruce (*Picea engelmannii* Parry) and 8.9 inches for grassland. Taylor and Haddock (1956) indicated that soil water was withdrawn from zones where it was most readily available. Harlan and White (1968) reported that depletion occurred at all depths within a measured 9-ft profile but not at equal rates. The most readily available water was depleted at the greatest rate regardless of depth in the profile. Generally, they found that the rate of soil moisture depletion decreased with decrease in available moisture. Stransky and Wilson (1966) simulated drought conditions using pine seedlings and sod ground cover. They found that moisture depletion rates were greatest in the upper soil layers. Schneider et al. (1966) measured distinct differences in moisture accumulation and depletion between the 1- to 3-ft, 4- to 6-ft and 7- to 9-ft depths under old growth sugar maple (*Acer sacharum* Marsh.) and beech (*Fagus grandifolia* Ehrh.) stands in Michigan. They reported seasonal moisture contents higher in the 1- to 3-ft level than at lower levels where little re-accumulation of moisture occurred. Bubalola and Samie (1972) used a neutron moisture meter to record changes in soil moisture down to a depth of 228 inches under a natural woodland and eucalyptus plantation in Nigeria. They found soil moisture storage to be higher under the natural woodland because canopy interception was higher in the plantation

and the plantation drew more moisture from a lower level in the profile. Sopper (1960) obtained results similar to those of Bubalola and Samie. He stated that 29% of the rainfall was intercepted by the canopy in a red pine plantation. Soil moisture depletion was greater under the pine plantation than under old-field vegetation nearby.

Moisture storage. -- Rutter and Fourt (1965) reported that available water varied from 17 to 37 cm depending on the texture of the soil on forested sites. Here Scotch pine roots penetrated to depths of about 2 m. Troendle (1970) found that the 24-inch depth of Calvin silt loam contained close to 8 inches of water at full recharge. Moyle and Zahner (1954) stated that a Leshe silt loam in Arkansas still had about 11 inches of available water stored in the surface 48 inches at the beginning of June.

Researchers have characteristically reported soil moisture use and storage values in various units with little standardization.

Research on Tree Root Systems

The study of root systems of trees is both very important and difficult. Staebler and Rediski (1958) listed some of the needs in additional root studies as follows: (1) knowledge of the extent of root systems in research on tree competition, (2) determination of areas of root systems of trees at specified ages to aid in

optimum spacing between trees, and (3) determination of the rate of spread of root systems.

Methods of study. -- Kolensnikov (1972) listed some main methods of studying root systems: (1) dry excavation and drawing, (2) monolith methods, (3) section or profile method, (4) excavation by hosing with water, and (5) permanent observation methods, using glass and observation pits.

The earliest method consisted of dry excavation by digging as done by Cheyney (1932), Heyward (1933), Reed (1939), and Bishop (1962). Also, many earlier researchers used trenches or soil pits where sections of the profiles were exposed and roots could be counted or their positions diagramed (Toumey and Kienholz 1931, McQuilken 1935, Yeager 1935, Turner 1936, Coile 1937, Billings 1938, Kalela 1949, Gaiser and Campbell 1951, and Dingle and Burns 1954). Washing the soil away from the roots with water under pressure was utilized by Curtis (1964), Singer and Hutnik (1965) and numerous other researchers. Merritt (1968) determined the growth pattern of seedlings by growing the roots against glass windows for observation.

More recent methods of root study include the use of radioisotopes (Ferrill 1964, Ferrill and Woods 1966, and Hough et al. 1965). Weir (1966) reported the use of a trailer-mounted air compressor that could be used with compressed air to blow away the soil where water was not available.

Another new technique in root sampling is through the use of trailer-mounted or truck-mounted soil coring machines to obtain soil cores (Mielke 1973 and others).

Root distribution. -- Toumey and Kienholz (1931) found 71.5% of white pine roots in the upper foot, 25.8% in the second, and only 2.7% in the third foot of soil. Stevens (1931) reported that most of the white pine roots were found in the upper 6 inches of soil or the A horizon. Yeager (1935) discovered 97% of the roots of prairie trees to be in the top 4 ft of the soil. McQuilkin (1935) found that fine roots of pitch pine (*Pinus rigida* Mill.) were profuse in the upper soil layers, often even in the humus.

Hopkins and Donahue (1939) worked with yellow birch (*Betula alleghaniensis* Britton), beech, sugar maple, balsam and spruce. They indicated that 70 to 80% of the roots of all tree species were distributed in the A horizon. Kalela (1949) reported 25% of the roots of spruce stands were in the humus layer, and 75% of all the horizontal roots were in the top 10 cm of the profile. He further reported that 87% of the roots of Scotch pine and spruce trees were within the top 20 cm.

Gaiser and Campbell (1951) found the weights of roots in the A_1, A_2, and first two subsoil horizons to be 7.8, 3.2, 1.8 and 1.4 tons per acre, respectively. Gaiser (1952) stated that 91 roots (less than 1/4 inch in diameter)

were in the top 8 inches compared to 26 in the 18- to 36-inch horizon in Wellston soil. White oak (Q. alba L.) roots in Zaleski soil numbered 260 in the top 2 inches compared to only 62 roots (less than 1/4 inch in diameter) in the 8- to 31-inch zone.

Dingle and Burns (1954) studied roots of shortleaf pine and indicated that the number of fine roots in a section of the A horizon 2 ft wide averaged 172, varying from 59 to 335. For each 1-inch increase in thickness of the A horizon, the number of fine roots increased by nine. A 2-ft wide section of the B horizon contained only an average of 13 fine roots compared to the 172 in the A horizon. Koshi (1959) found that post oak (Q. stellata Wangenh.) roots drew water consistently from the 12- to 25-inch depth in Texas. Bishop (1962) found most of the roots of lodgepole pine to be confined to the upper foot of soil.

Curtis (1964) excavated the entire root system of a 60-year-old ponderosa pine (P. ponderosa Laws.). He found that more than 73% of the primary and secondary laterals were located in 18 inches (between 6 and 24 inches beneath the ground surface) of soil. He also reported more than 92% of the primary and secondary laterals were found in the first 24 inches of mineral soil. Nearly 85% of all the secondary roots were in the

0.10- to 0.25-inch diameter class and 98% were less than 1 inch in diameter.

Gifford (1966) studied aspen root systems in Utah. He found that the majority of roots in all soils were concentrated in the upper 4 ft. Leaf et al. (1971) found that downward penetration of red pine roots ceased in a fine layer with a very high silt content at a depth of 2.3 to 2.7 m.

Safford and Bell (1973) estimated the biomass of fine roots (of diameter less than 3 mm) in a white spruce plantation to be 696 ± 224 g/m^2. Variation among individual samples (total of ten samples) was great but was independent of distance to and size of closest tree. Armson (1972) labelled fine roots as those less than 1 mm in diameter. Moire and Bachelard (1969) stated that their results in studies of Monterrey pine (P. radiata D. Don) plantations confirmed the findings of others that fine roots are most concentrated in upper soil volumes.

Lorio et al. (1972) found roots between 0.5 and 2.0 cm in diameter to be twice as numerous on flat sites as on the mounds in southwestern Louisiana. When all size classes were combined, the count on flat sites exceeded that on mounds in the 0- to 10-cm and the 0- to 60-cm layers by about 41 and 22%, respectively.

METHODS AND PROCEDURES

Location and Description of Study Area

The research conducted for this thesis was accomplished under McIntire-Stennis Project 1276 established under the auspices of the Louisiana Agricultural Experiment Station. The study was located on the J. G. Lee, Sr. Memorial Forest in southeastern Louisiana.

The major objectives of the project were to study the depth of rooting of mature southern pine trees and to determine soil characteristics which limit deeper penetration of roots within the soil profile. Some of the secondary objectives were to examine the seasonal use of soil moisture by pine stands in the various soils under study and to study variations in oxygen content in the soil profile. The major objective of this study, and hence the subject of this thesis, was the determination of which soil physical properties, either singly or in combination, limit or restrict the penetration of loblolly pine roots in the soil profile. Data on the seasonal fluctuations in soil moisture will be incorporated in the thesis because soil moisture is extremely important and is interdependent with other soil physical properties.

The Lee Memorial Forest encompasses about 1000 acres of land characteristic of the southern Coastal Plain. The

land is located in T2S, R2E, St. Helena Meridian, Washington Parish, Louisiana (30°52' N latitude and 89°59' W longitude). The topography is gently rolling with ground elevation ranging from 200 to 290 ft above sea level. Two small streams are found on the Forest, the largest being Bogue Lusa Creek which drains a major portion of the Forest land area. It, and the smaller Thomas Creek, are typical of the minor streams found throughout the Coastal Plain.

The soils on the Forest are quite diverse due to the varied topographic situations. Soils range from the poorly drained Bibb (Typic Fluvaquent) in the flood plains and terraces of the streams to the well-drained Ruston (Typic Paleudult) on the slopes and ridge tops.

The original forest on this land was probably predominantly longleaf pine on the well-drained slopes and ridges. On the lower sites, in the small headers and stream bottoms, a variety of hardwoods such as American beech, yellow poplar (<u>Liriodendron tulipifera</u> L.), and black gum (<u>Nyssa sylvatica</u> Marsh.) were found in mixture with loblolly pine. The original timber was cut in the 1920's by the Great Southern Lumber Company. The forest subsequently seeded back naturally to a mixture of loblolly, shortleaf, and longleaf pines with loblolly predominating on the slopes and ridges. Loblolly is also the major pine species of the stream bottoms. It occurs in

all but the small, excessively wet areas of pure hardwood swamps. All of the pine sites, upland and lowland, exhibit the usual hardwood species component typical of the Coastal Plain region.

Establishment of Plots

In 1967, twenty circular quarter-acre plots were selected in well-stocked, even-aged, mature loblolly pine stands in different portions of the Forest. They were established close to all-weather roads to facilitate weekly measurements. The locations were picked to provide as much variation as possible in the soils found on the Forest. Plot locations are shown in Figure 1. The soil on each plot was classified by a soil scientist.

After selection, all plots were cleared of hardwood trees and brush by cutting, injection, or spraying with a mist blower in order that soil moisture would be utilized by only the pine trees and herbaceous vegetation. All pines were located by distance and direction from the center of each plot and numbered with aluminum tags at diameter breast height (dbh).

Initial measurements on all pines in the early fall of 1967 included: age, crown classification, total height, dbh, and radial growth for the past 5- and 10-year periods. Total basal area per acre and average site index were then computed for each plot.

Aluminum access tubes were installed at each plot center for nuclear moisture measurements. Most tubes were

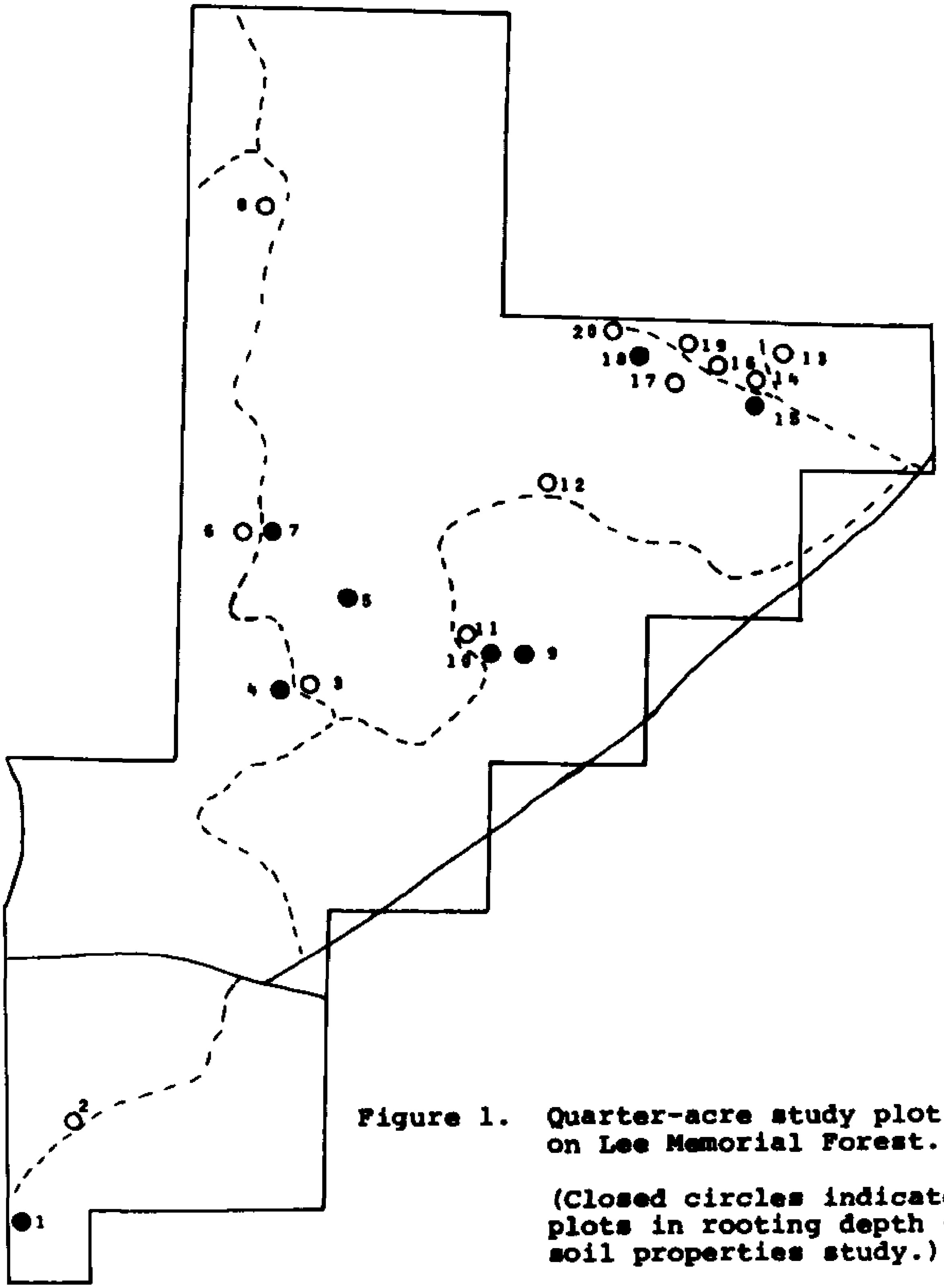

Figure 1. Quarter-acre study plots on Lee Memorial Forest.

(Closed circles indicate plots in rooting depth - soil properties study.)

installed to a depth of 19 ft, but on some wet sites this was not possible. One plot, No. 10, was established with two additional access tubes positioned 33 ft upslope and downslope from the center access tube to study the effect of the 17% slope on this plot.

The procedure for the installation of the access tubes was described by Harold Champagne, a Graduate Research Assistant involved in the initial stages of the project, as follows:

> A heavy duty, 18-foot wooden ladder was used as a framework for support from which the crew drilled. To prevent soil compaction, the drilling took place through a 2-inch hole in a 3/4-inch-thick sheet of plywood. A hole was first dug with a 1 3/4-inch Erwin derrick auger, using 5-foot sections of 1/2-inch water pipe as extensions. Second, 2-inch outside diameter aluminum irrigation pipe was driven down the hole as far as possible without causing damage to the pipe. A 2 x 6-inch board was used as a hammer whenever needed. Third, the soil inside the tube was removed with the auger. The last two steps were repeated until the desired depth was reached, or until further drilling was prevented.
>
> The bottom of the access tube was sealed with a size 10 1/2 rubber stopper, which was pushed down the tube with a homemade device. This plunger was made from half of a 3/4-inch pipe union with a 3/16-inch hole drilled through the larger section. A 16-penny nail was secured in the hole and bent 90 degrees toward the larger opening. As a precautionary measure, the stopper was moistened and the nail oiled. A can slightly larger than 2 inches in diameter was used to cover the 3 inches of access tube that remained exposed above the soil surface.

The original project involved weekly measurements of soil moisture at each foot of depth in all access tubes through five growing seasons, from about April through November. Measurements were taken less often during the

winter months. Soil moisture measurements were taken in this manner from 1968 through 1972.

Early in the growing season of each year, hardwood sprouts were sprayed by back-pack mist blower with an emulsion of 1/2 gal of 2,4,5-T, 1 gal of No. 2 diesel fuel, and 3 1/2 gal of water. Diameter measurements of all pines were taken in January after each growing season during the study period. In January 1973 measurements of total height and past 5- and 10-year radial growth increments were made in addition to diameter measurements.

Variations in oxygen content were studied on nine of the plots (No. 1, 4, 5, 7, 9, 10, 17, 18, and 20) from April 1970 to April 1971 by Hu (1971). Plots No. 1, 4, 5, 9, 10, 15, 18, and 20 were used in a similar study by Ward (1972) from October 1971 to September 1972.

Only eight of the original 20 plots were selected for the study of rooting depth as limited by soil properties. Plots No. 1, 4, 5, 7, 9, 10, 15, and 18 were chosen because soil oxygen data were available and because they represent the maximum variation obtainable in the soils of the original study. The initial stand characteristics of these plots are listed in Table 1. The soils, topographic position, and depth of access tubes are listed in Table 2.

Soil Moisture Measurement in the Field

Soil moisture measurements were made at all 1-ft intervals in the access tubes weekly or biweekly for the

Table 1. Initial stand characteristics for plots in the study

Plot number	Stand density (per acre): Crown classes[a] D	CD	I	S	Total	Basal area	Average stand characteristic (per plot): Age	Total height	Dbh	Site index[b]
	Number of trees					Square feet	Years	Feet	Inches	Feet
1	12	20	52	12	96	64.56	39	73	10.6	98
4	12	76	12	32	132	101.04	38	82	11.4	98
5	16	40	28	28	112	113.28	45	93	12.8	107
7	20	96	28	20	164	126.60	39	85	11.6	100
9	16	88	0	16	120	117.84	36	84	13.1	100
10	4	52	16	20	92	97.56	36	86	13.4	98
15	20	76	28	28	152	134.72	34	73	12.2	94
18	32	32	20	16	100	114.24	36	93	14.0	113

[a]Crown classes: D = dominant, CD = codominant, I = intermediate, S = suppressed.

[b]Based on mean height of dominant and codominant trees at age 50.

Table 2. Soil classification, topographic position, and depth of access tubes

Plot number	Soil classification[a]	Topographic position	Depth of access tube
1	Stough vfsl (Fragiaquic Paleudult)	Flat, terrace near stream	15
4	Kalmia vfsl (Typic Hapludult)	Flat, terrace near stream	11
5	Bibb sil (Typic Fluvaquent)	Flat, terrace near stream	9
7	Lexington sil (Typic Paleudalf)	Ridge, slight slope	19
9	Ruston sl (Typic Paleudult)	Ridge top, flat	19
10	Ruston sl (Typic Paleudult)	Ridge, steep slope	19
15	Ruston sl (Typic Paleudult)	Ridge, slight slope	19
18	Myatt-Mashulaville complex	Flat, terrace near stream	19

[a]Letters after soil series name represent soil texture: sil=silt loam, sl=sandy loam, fsl=fine sandy loam, vfsl=very fine sandy loam. The descriptions of these soils may be found in Appendix A.

project period for five years. Some soil moisture data were utilized by Hu (1971) and Ward (1972). A detailed description of the instruments and of the calibration technique is included here, since the soil moisture equipment was utilized in later tests of the other soil physical properties.

A Troxler Model 104-A depth moisture gauge with a 100-mc americium:beryllium source, manufactured by Troxler Electronic Laboratories, Inc., Research Triangle Park, N.C., was used to measure soil moisture. The moisture probes are thermal neutron detectors. As described by Troxler Laboratories' Operation and Maintenance Manual, the gauges detect moisture by detecting thermal (slow) neutrons which are generated by the slowing-down effect which the hydrogen in the water has on fast neutrons emitted by a radioactive source. The probe signals are registered on the scaler or counter. A Model 200-B Scaler manufactured by Troxler Electronic Laboratories, Inc., was used. The probe is transported and stored in a shield or standard which is also used for a reference reading or for standardization of the probe. The standard with probe in use, portable scaler, and connecting cable are shown in Plate 1.

In use, the probe is released from the standard by placement of the standard over the access tube thereby disengaging the cam locks. The probe is then lowered to the desired level with the measured cable. The scaler or counter is started and counts are obtained. Half-minute

Plate 1. Measurement of soil moisture with nuclear equipment showing standard with probe in access tube, portable scaler and connecting cable.

counts were made in all cases unless otherwise specified. Counts made with the probe in the access tube must be divided by a standard count. Five 30-sec counts were made with the probe in the standard or shield and then averaged to get a single standard count. Standard counts were made each day that measurement counts were obtained. Counts made in the soil are divided by the standard count to get a count ratio. By using a standard count made on each measurement day, the effects of isotope decay and daily machine variation are reduced to a minimum.

In the initial stages of the project in 1967 and again in the present study after replacement of the detector, the probe had to be calibrated prior to use. The same procedure was used in both instances. First, several uniformly moist layers of soil were located in the soils under study. The selected layers were at least 2-ft thick and located at least 1 ft below the soil surface. Temporary access tubes were installed and five 1-min counts were taken at the middle of each layer. Then three soil samples were taken from the desired depth within 6 inches of the access tube. Moisture contents were determined in the laboratory on an oven-dry weight basis and these were averaged. The ratios of the five 1-min counts to the standard count were also averaged. The average ratios were plotted against their respective average laboratory moisture contents. The computed formula for the linear

relationship was Y = -2.1198 + 15.5199 X, where Y is the moisture content in percent and X is the ratio of measurement counts to the standard count.

Analysis of the data for the regression equation showed an r value of .9149. This formula used for the original calibration applies to the five-year data on moisture utilization. Data for the second calibration (after detector replacement) were handled similarly. Readings and moisture contents were plotted and the resulting graph is shown in Figure 2. Analysis of these data showed an r value of .9599. The computed formula for the new linear relationship was Y = -1.7057 + 13.9155 X and was used for all measurements after 1972.

Soil Bulk Density Measurement by the Nuclear Method

One procedure used in the determination of soil properties that limit rooting depth was the measurement of bulk density of each horizon in the soil profile *in situ* with a Troxler Model 504 Depth Density Probe. The Model 504 probe fits the same standard class-150 aluminum irrigation tubing (1.9" I.D., 2.0" O.D.) as the Model 104 moisture probe. They both are used with the Model 200-B Scaler, although at different operating voltages.

Mechanically, the density probe is similar to the moisture probe. It consists of a radiation source and a detector which is connected to the scaler by a cable. In theory, it works somewhat differently. The radioactive

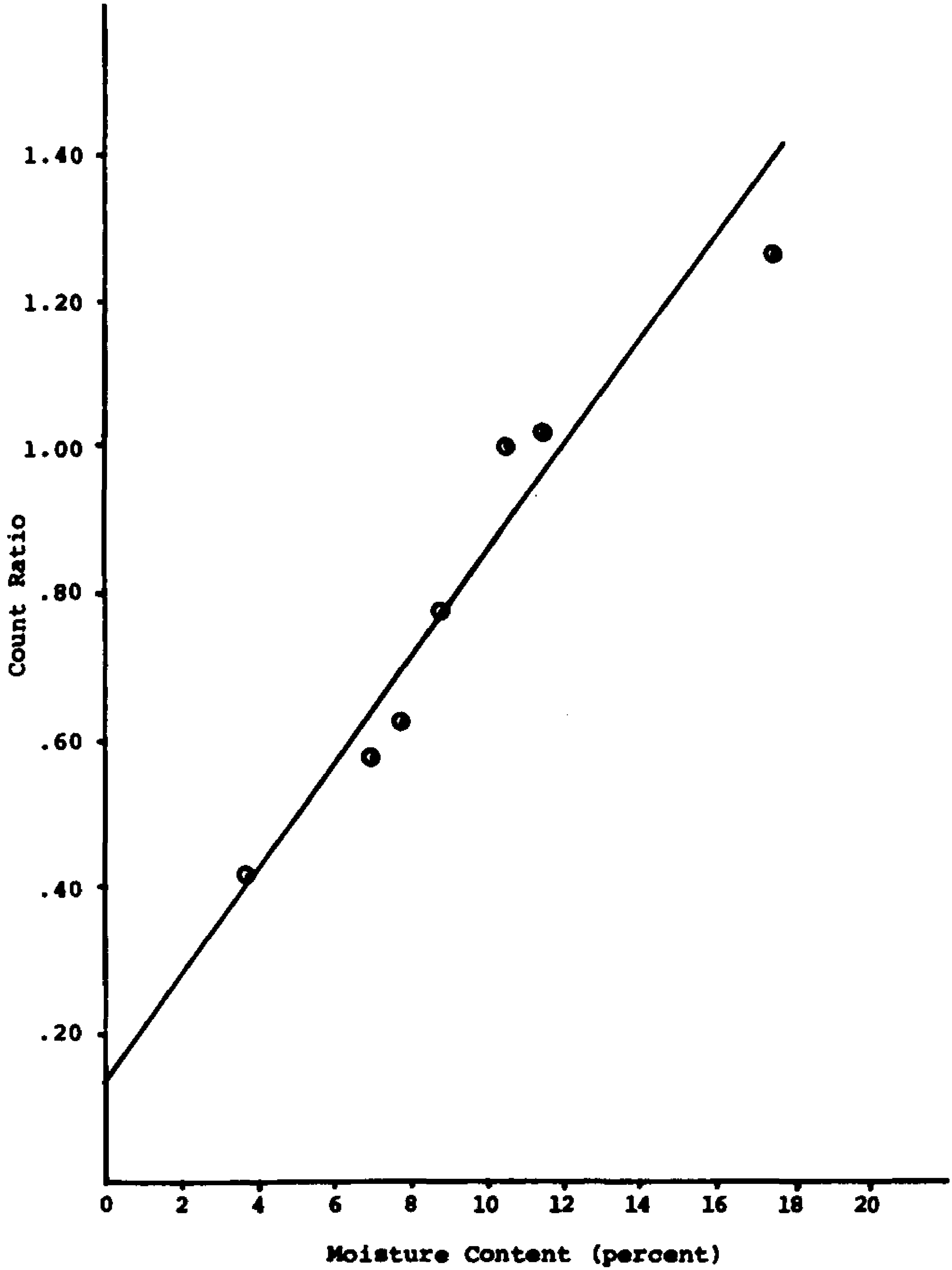

Figure 2. Calibration curve for soil moisture probe.

source, in this case 3 mc of Radium-226, in the density probe emits gamma radiation at a constant rate. The subsurface wet density of soils is measured by using back-scatter and absorption of the radiation. According to Troxler Laboratories' Operation and Maintenance Manual, the emitted gamma rays interact with the surrounding medium, soil, and the number of scattering events in a given time is a function of the density of the medium.

A calibration curve for wet density measurements as supplied by the manufacturer was utilized.

Before any measurements were taken, an attempt was made to determine the center of measurement of the probe. In the operating instructions supplied with the probe it was stated that the probe effectively measures the density of a spherically shaped volume approximately 5 inches in radius. From the schematic diagram for "Center of Density Determination" in the instruction manual, it was determined that lowering the probe 10 1/2 inches centered the test area of the probe at the bottom of the standard or soil surface if the standard is touching the soil. This figure corresponded closely to the 11-inch measurement point used by the Louisiana Highway Department Research Unit for similar equipment (personal communication with Mr. James Melancon of the research department). Once the center of the test area was located with reference to a known point, then the measured cable could be used to lower the probe to any desired depth.

Before the density measurements were taken with the nuclear equipment in the summer of 1973, the access tubes were thoroughly dried out with absorbent patches affixed to a plunger. New rubber stoppers were inserted to the bottom of each hole, dessicator bags containing calcium chloride were hung in each tube, and the tops were sealed with another stopper. This step was included to ensure an absence of condensed moisture in the tubes. Additionally, roofing compound was poured around the soil surface-access tube junction to prevent any entry of surface water around the access tube.

As a first step for _in situ_ density measurements, duplicate 30-sec readings were taken on all selected plots at all 1-ft depth intervals, followed by appropriate standard counts. This was then followed by duplicate 30-sec readings of moisture content. Five 30-sec standard readings were taken with the moisture probe on the measurement days. Next, all pairs of density and moisture readings were averaged and each mean was divided by the appropriate mean standard count to obtain count ratios for both types of measurements.

A program was then written for computer calculation of wet bulk density, percent moisture on an oven-dry weight basis, and dry bulk density. The wet bulk density computation formula was supplied by Troxler Laboratories, Inc. The calculation formula for our equipment follows:

$$\text{wet bulk density} = \frac{\ln\left[\dfrac{\dfrac{A}{\text{standard count}}}{\text{Count ratio}}\right]}{B}$$

A = 128386.0 (provided by Troxler Electronics)
B = 0.908260 (provided by Troxler Electronics)
standard count for our density probe = 24782.0

The calculation of percent moisture on an oven-dry weight basis was accomplished with the following regression equation:

$$Y = -1.70567 + 13.91551\ X$$

where X = count ratio
Y = moisture content, oven-dry weight basis

Dry bulk density was computed by the use of the relationship shown below (Vomocil 1954):

$$\text{dry bulk density} = \frac{\text{wet bulk density} \times 100}{100 + \%\ \text{moisture dry-weight basis}}$$

By examining the dry bulk densities obtained at each 1-ft level in all soils, the depths where distinct changes in dry bulk density occurred were then evident. Further sampling involved taking paired readings of density and moisture with the nuclear gauges at each 3-inch increment between all the 1-ft levels showing distinct density changes in an effort to more accurately locate the changes in dry bulk density in the soil profiles.

Determination of the Effective Depth of Rooting

Prior to the onset of soil and root sampling in the field, an attempt was made to determine the effective depth of rooting through the use of the soil moisture utilization

data of prior years. Soil moisture content should not be reduced very much during the growing season at levels in the soil where few tree roots occur. The weekly soil moisture measurements made on these selected plots during the growing season of 1970 were plotted graphically by measurement date and soil depth. Plotting of these data showed the depth at which the decrease in soil moisture content was minimal. This level of little or no decrease in soil moisture was assumed to contain few roots. The effective depth of rooting then was judged to be the depth of the soil profile down to where soil moisture was not utilized to any extent.

Collection of Field Samples

Actual sampling began in the fall of 1973 and continued through the fall of 1974. The long sampling period was due to the complexity of the sampling procedures and the necessity of conducting some of the tests on fresh undisturbed samples in the laboratory soon after they were obtained in the field. The same procedures were utilized on all plots. The length of time required for sample collection depended on the depth of sampling for individual plots.

The following is a brief description of the sampling procedure used on each plot. First, moisture measurements were made at preselected soil depths. Second, soil samples were taken with a coring machine at two locations. On a few plots, sampling from the second location was delayed

due to the deep sampling required. Third, a series of core samples for determination of root distribution were removed from the area. Fourth, a soil pit was then dug by hand. Duplicate core samples and loose undisturbed samples were obtained during the pit-digging process. The depth of the soil pit was determined by the depth to the water table at the time of sampling. The method of placement of sampling locations around an access tube is shown in Figure 3. A more complete description of the sampling procedure is given in the following sections.

Soil moisture at time of sampling. -- Prior to the actual collection of soil samples on any plot, duplicate moisture measurements were made at all pre-selected sampling depths with the nuclear depth moisture gauge along with a series of standard readings. This was accomplished early in the day immediately before the extraction of the first soil samples on each plot. This step was included in order that we might utilize nuclear moisture data along with standard laboratory moisture determinations on samples obtained by digging.

Soil core sampling by machine. -- Two sets of soil cores were taken at each access tube with a Giddings Model SGRP-ST Hydraulic Soil Coring and Sampling Machine. The machine was trailer-mounted and was pulled to the sampling site by an International 140 tractor (Plate 2). The unit with tractor was very maneuverable. Core samples were

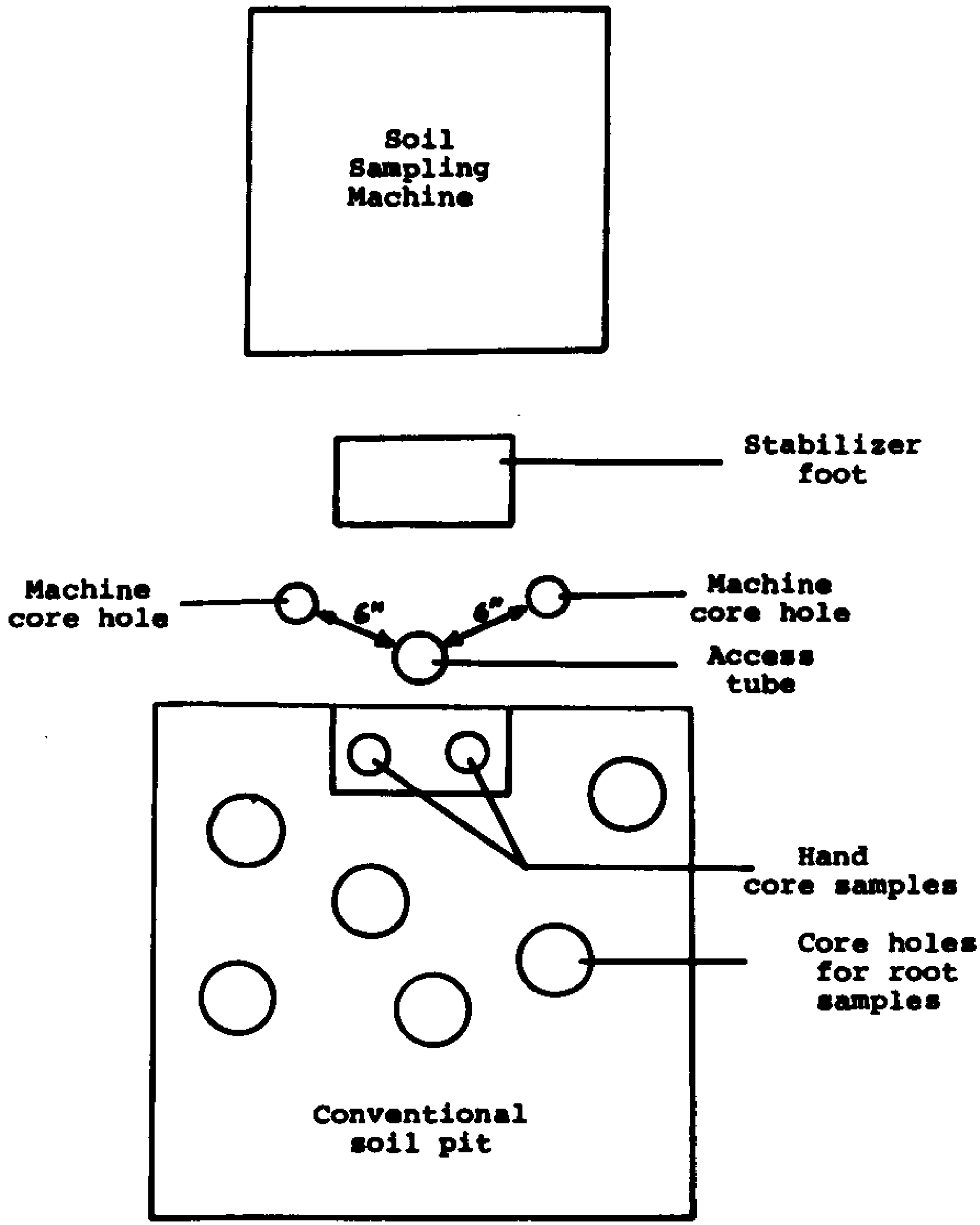

Figure 3. Schematic diagram showing location of sampling points around an access tube.

Plate 2. The Giddings trailer-mounted soil coring machine was backed into position for sampling on plot 7.

obtained with slotted soil tubes 2 1/4 inches by 48 inches fitted with a quick relief bit.

The unit was positioned so that the two core samples could be taken within 6 inches of the access tube on each plot. These two coring holes, on one side of the access tube, were within the zone measured by nuclear gauges.

The procedure involved sampling at each core hole to the depth of the particular access tube or to the maximum depth possible. The depths actually sampled varied tremendously depending upon soil moisture conditions existing at the time of sampling and other soil conditions encountered. On plots where the cores could be extracted only from relatively shallow depths, samples from both soil core holes around each access tube were obtained on the same day of sampling. On other plots, only the first core-hole was completed in one day.

As each coring tube was pulled from the soil, the core was measured and sectioned into 3-inch segments. Those samples from the desired sampling depths were placed in wide-mouth pint-size canning jars and sealed prior to the laboratory tests. With the slotted coring tubes, the soil core could be sectioned with knives or chisels while still in the tube. In most instances, removal of sections from the tube was easy because the inside diameter of the coring tube is larger than that of the cutting bit and the sample sections were simply extracted from the end opposite the

cutting bit. Cores from extremely wet, sandy or heavy clay soil layers had a tendency to become jammed in the coring tube.

Core sample segments taken included those at each foot of depth in the profile and those between foot depths which had distinct changes in soil bulk density as previously determined by the nuclear depth density gauge.

Soil sampling by hand. -- The area on the opposite side of each access tube from the core holes was used for a conventional soil pit. Before the pit was dug, a series of random core samples were taken for loblolly pine root distribution studies from the area which was to be unearthed in the digging process.

The pits were dug to obtain duplicate cores of undisturbed soil samples. The cores of soil were approximately 2 inches in diameter by 3 inches long, filling a brass core having a volume of 200 cm^3. These soil core samples were taken within 6 inches of the access tube with a soil core sampler similar to that developed by Jamison, Weaver, and Reed (1950). The location of core sampling by hand is shown in Figure 3.

Several soil clods in as naturally undisturbed condition as possible were also taken within 6 inches of the access tube along with each pair of core samples. The reason for obtaining two types of samples was that three different tests to determine soil bulk density were to be

carried out in the laboratory, one on enclosed soil cores and two on soil clods.

The soil cores were covered and sealed with masking tape and the loose soil clods were sealed in jars prior to laboratory tests.

Collection of root samples. -- Soil core samples for studies of root distribution were taken with the same Giddings unit used for collecting soil samples. The soil coring tubes used for root samples were 4 1/2 inches in diameter by 48 inches long with a 4 1/2-inch cutting bit.

Five core samples were taken from the area where the soil pit was to be dug. These were located randomly within 5 ft of each access tube. Later, after all soil sampling was completed, 15 additional core samples were taken from the undisturbed area within 5 ft of each access tube. These were located on the ground by distance and compass direction from each access tube with a table of random numbers. Some locations were changed in the field because it was physically impossible to obtain two core samples within a few inches of each other or to locate a sample on a spot of ground where one of the machine's two anchors was previously placed. The core-sample locations were also stratified so that one-half of the core samples occurred on the side of the access tube opposite the soil pit area. It was originally planned to utilize the large diameter coring tubes to extract soil cores to the previously determined

maximum effective depth of rooting. This was not possible in some cases. Even after extensions for the anchors were constructed, thus changing the anchoring depth to 6 ft, the machine did not have the hydraulic-pressure capability necessary to sample deeper than 4 ft with the large diameter tubes. Therefore the 4 1/2-inch tubes were used to sample to a depth of 4 ft. Root samples were taken at greater depths with the 2 1/4-inch tubes but these data were not analyzed.

After each soil core was extracted, it was sectioned into 6-inch segments from the soil surface to the depth desired. These were then placed in plastic bags, tied up, and labeled by plot, core number, and depth.

The tree roots were separated from the soil by washing on a series of two screens, the top screen being the larger, made of 1/8-inch hardware cloth, and the smaller bottom screen made from window screen wire. The root samples were then placed in plastic bags, labeled, and reserved for laboratory analysis. The roots were later divided into eight size classes: < 1 mm, 1 mm - 2.5 mm, 2.5 mm - 0.5 cm, 0.5 cm - 1.0 cm, 1.0 cm - 2.0 cm, 2.0 cm - 4.0 cm, 4.0 cm - 8.0 cm, and > 8.0 cm. They were then dried in an oven for at least 24 hours at 105°C and the oven-dry weights obtained for each size class.

Laboratory Procedures for Soil Samples

Percolation rate determination on soil cores. -- The undisturbed core samples, in the brass cores, were first tested for percolation rate, or the rate at which water moved through the soil.

Rates thus obtained in the lab are not absolute values for soil *in situ* but are useful in comparing different soils and layers within a soil. The method used was that described by Shaw (1952). Since 73.1 ml is equal to 1 inch in the brass cores utilized, percolation amounts in ml were converted to inches to give percolation rates per hour.

Porosity and bulk density determinations on soil cores. -- The previously saturated soil cores were then weighed and transferred to a moisture tension table for determination of porosity. The tension table used was similar to one developed by Leamer and Shaw (1941). The apparatus was also later described by Hoover, Olson, and Metz (1954). The core samples remained on the tension table for at least 6 hours at 0 cm tension before the first removal and weighing. They were returned to the table and allowed to drain at 60 cm tension for 6 more hours. Following this, they were weighed again and dried in an oven at a temperature of 105°C for 24 hours. An oven-dry weight was calculated for the soil in each core sample.

The total porosity of each core sample was obtained by the following equation:

$$\text{Total porosity (\%)} = \frac{\text{Saturated wt. - oven-dry wt.}}{\text{volume of core}} \times 100$$

The noncapillary porosity was considered to be equal to the volume of water lost by the soil cores following the application of 60 cm. of moisture tension. The equation is shown below:

$$\text{Noncapillary porosity (\%)} = \frac{\text{Saturated wt. - 60 cm. tension wt.}}{\text{volume of core}} \times 100$$

The capillary porosity (i.e., the water that is drained from the soil at tensions greater than 60 cm.) was calculated as the difference between total and noncapillary porosity.

The bulk density of each soil core was computed by the following equation:

$$\text{Bulk density (g/cm}^3\text{)} = \frac{\text{Oven-dry weight of soil}}{\text{volume of core}}$$

Textural analysis was not performed on these core samples. Instead, the loose samples taken at the same profile positions were utilized for soil texture determination as will be discussed later.

Soil color determinations. -- Soil colors were determined on the loose soil samples, while still in a field-moist condition, with a standard Munsell soil color book. The main or matrix color was determined as well as the colors of mottles observed. Soil color was also determined on all samples from one machine-extracted core for each

plot because some of the soil cores were obtained at depths below those of the loose samples.

The determination of mottle colors also provided a direct measurement of depth to mottling.

Soil textural analysis. -- All loose samples from the soil pit and samples from one core hole were used for textural analysis. The analysis was done by the Bouyoucos method as modified by Patrick (1958). Patrick's modification requires that only two determinations, for the 60-micron and 2-micron size limits, be made for a simplified calculation of the proportion of sand, silt, and clay present in a soil sample. Samples were prepared for analysis by the method described by Day (1956). Duplicate tests were run on each sample. From the calculated percentages of sand, silt, and clay, the texture of each soil sample was read from the standard soil-textural triangle.

Early in the laboratory determination of soil texture a problem developed when many samples with high sand contents had uncorrected hydrometer readings considerably lower than the minimum 20 g/l listed in Patrick's table for the 50-micron separation. The table was extended to provide sedimentation times for the samples with high sand contents. The time of sedimentation was calculated from Stokes' equation as shown by Patrick (1958). Values for the effective depth of the hydrometer were obtained from the American Society of Testing Materials (1955). Values of viscosity

of water were obtained from standard tables (Weast 1971). The extended values for the sedimentation times for the 50-micron separation are shown in Table 3.

Field capacity and wilting point determinations. -- Moisture contents for all loose soil samples from the soil pit and core samples from one core hole were determined at 1/3 and 15 atm of pressure, representing soil field capacity and wilting points, respectively.

Field capacity values were obtained with a pressure plate extractor manufactured by Soil Moisture Equipment Co., Santa Barbara, California. The method involves measuring the moisture retained by saturated soil samples which have been subjected to a tension of 1/3 atm on a porous ceramic plate (Richards 1948).

Wilting point values were obtained with a pressure membrane extractor. The method involves subjecting the soil samples to a tension comparable to that exerted by plants at the wilting point, 15 atm tension, and measuring the moisture retained against this tension (Richards 1949).

Duplicate subsamples were run for both field capacity and wilting point and then mean values were obtained for each sample.

Bulk density by wax-coated clod technique. -- One of the major objectives of the study was to correlate measured soil bulk density with density measurements taken with the

Table 3. Extended values of sedimentation time for the 50-micron separation

R[a]	Sedimentation temperature					
	20°C	22°C	24°C	26°C	28°C	30°C
	Seconds					
18	59	56	54	51	49	47
16	61	58	55	53	51	48
14	62	59	57	54	52	50
12	64	61	58	55	53	51
10	65	62	59	57	54	52
8	67	64	61	58	55	53

[a]Uncorrected hydrometer reading in grams per liter.

nuclear depth density gauge. Soil core samples taken by hand with the hammer-driven sampler could not be obtained at all levels where distinct density changes occurred nor could they be obtained at depths below the water table, but samples were obtained at desired depths below the water table with the soil coring machine. The wax-coated clod technique was used to determine bulk density on the loose soil samples from the soil pit and on samples from one of the machine core holes.

The method used was basically that described by Blake (1965), but certain modifications were used. Tisdall (1951) reported that the clod method usually gives higher bulk density values than other methods. One reason for this is that the soil volume is the air-dry volume, which is likely to be slightly less than the volume of a field-moist sample used in other methods.

The first deviation from the method as presented by Blake was to utilize soil clods or peds in a field-moist condition since these were available. Another deviation was to use an 8-inch length of ordinary sewing thread with a loop at both ends to suspend the sample for weighing and dipping in the melted paraffin. A 500 g weight with a metal arm was placed in the balance pan of a top-loading Mettler balance (800 g capacity). The samples, undisturbed clods or peds of 10 to 30 g in weight, were suspended from the arm to obtain the desired weight measurements: weight

of unwaxed soil clod in air, weight of waxed clod in air, and weight of wax-enclosed soil clod in water.

Density values were obtained on four subsamples from each loose and core sample. Moisture content was determined on samples from each jar. The calculation of bulk density involved two equations, the first for calculation of the oven-dry weight of the soil clod sample as follows:

$$W_{ods} = \frac{W_{sa}}{100 + P(100)}$$

Bulk density (Db) was then calculated by the formula:

$$D_b = \frac{(dw)\ (W_{ods})}{[W_{sa} - W_{spw} + W_{pa} - (W_{pa}\ dw/dp)]}$$

where P = percent water on oven-dry weight basis,

W_{sa} = net weight of soil clod in air,

W_{ods} = oven-dry weight of soil clod or ped,

dw = density of water at temperature of determination,

W_{spw} = net weight of waxed soil clod in water,

W_{pa} = weight of paraffin coating in air by subtraction, and

dp = density of paraffin (approximately 0.9).

A computer program was utilized to make these calculations. Mean values of each set of four subsamples were used in the statistical analyses.

Certain aspects of the method need to be emphasized. The paraffin should be kept at a constant temperature of 60°C, because paraffin is most suitable for use when it begins to solidify around the sides of its container. The

weight of 8 inches of sewing thread is negligible and no allowance is needed for this weight. The method is not suitable for soils that are coarse textured and friable because the clods must be coherent enough to allow them to be suspended in a loop of thread.

Bulk density of saran-coated soil fragments. -- Core samples from one core-hole on each plot were used in determination of bulk density by coating soil fragments with a liquid saran resin. Two fragments from each sample were used and, in addition, two fragments from each sample were tested by the paraffin technique. The paired sub-samples were included for a comparison test of the two methods.

The methodology employed was basically that briefly described by Brasher et al. (1966). This method was also utilized by Goddard, Runge, and Walker (1971) to determine bulk density of soil cores. The method used was from an unpublished paper by Brasher, Davidson, and Valassis (obtained from Dr. George A. Caldwell, Agronomy Department, Louisiana State University).

The method requires a Dow Saran Resin F-220. An inquiry with The Dow Chemical Company's regional sales office in December 1973 revealed that Dow no longer manufactured the F-220 resin but did have F-300 and F-320 resins. This may require alterations in the future use of

this method. A supply of F-220 resin was obtained from Dr. George A. Caldwell at LSU.

The resin powder was first dissolved in methyl ethyl ketone. Since most of the soils studied were coarse textured and quite porous, a viscous 1:4 solution was made. This should have alleviated the problem of the solution penetrating large pores as the soil fragments were coated. A solution containing 250 g of resin and 1 kg of solvent was prepared by pouring the weighed quantity of resin into a 1 kg container of solvent. The solvent can be obtained in 1 kg quantities in a bottle large enough to contain the entire mixture. Occasional vigorous shaking of the mixture will insure dissolution of all the resin.

A quantity of solution sufficiently deep to allow the complete submergence of soil clods was transferred to a covered metal can. The can was kept covered when samples were not being dipped not only because the solvent was volatile but the fumes were rather unpleasant.

Soil fragments or clods weighing between 10 and 30 g were removed from the soil cores stored in the sample jars. A 24-inch-long piece of strong, small diameter thread was doubled and looped around the fragment. Small paper label tags of a uniform size were affixed to each sample. An average weight (W1) was determined for a thread and tag. The samples were then suspended from the balance as in the paraffin technique and weighed in air (W2). They were

immediately and rapidly dipped in the solution and suspended from a wire line. They were re-dipped after 5 min and thereafter at 12-min intervals until five coatings were applied to all fragments. Thirty minutes after the last dipping, the samples were weighed in air (W3) and in water (W4). They were then placed on an oven rack covered with aluminum foil and dried for 24 hours at 105°C. Upon removal and initial cooling (only cool enough to handle), they were weighed again in air (W5) and in water (W6). Weights in water (W4) and (W6) were for volume determinations.

When air bubbles appeared during the last weighing (W6), the entire procedure was repeated. This did not occur except when the oven-drying period was over 24 hours. As stated in the paper by Brasher et al. (1966), a number of fragments should be dipped 1 or 2 min apart for maximum efficiency. This method did not work with extremely coarse-textured soils. This was also the case with the paraffin coating technique.

A number of calculations were required, but a computer program was written to facilitate this work. The equations were as follows:

<u>Bulk density (uncorrected)</u>

$$\text{Db (moist)} = \frac{W5 - W1}{W3 - W4} \qquad \text{Db (oven-dry)} = \frac{W5 - W1}{W5 - W6}$$

Correction equations:

<u>Weight and volume of coating</u>

(1) Air-dry weight (w1) = W3 - W2

(2) Oven-dry weight (w2) = wl - (wl x 0.10) where 0.10 is the percent of weight loss due to oven-drying.

(3) Volume air dry or oven dry (vl) = $\frac{wl}{1.3\ g/cm^3}$ where 1.3 g/cm^3 is the density of the coating.

<u>Weight of fragment (corrected for coating, tag and thread</u>

(1) Moist (w3) = (W3 - wl) - Wl

(2) Oven-dry (w4) = (W5 - w2) - Wl

<u>Volume of fragment (corrected for volume of coating and density (D) of displaced water)</u>

(1) Moist (v2) = $\frac{W3 - W4}{D\ displaced\ H_2O}$ - vl

(2) Oven-dry (v3) = $\frac{W5 - W6}{D\ displaced\ H_2O}$ - vl

<u>Bulk density corrected</u>

(1) Db (moist) = $\frac{w4}{v2}$ (2) Db (oven-dry) = $\frac{w4}{v3}$

The previous calculation equations are the same as those presented by Brasher et al. in their unpublished paper except that they applied one coating of saran resin in the field and therefore had to make a different correction for the air-dry weight of the coating.

Statistical Analyses

A number of types of statistical analyses were employed in this study. Analyses of variance techniques for a randomized block design were utilized to compare measurements of bulk density obtained by soil cores taken by hand with bulk densities obtained by the nuclear depth density

gauge, wax-coated clod method, and resin-coated clod method. Likewise, gravimetric soil moisture measurements were compared with those moisture measurements made with the nuclear depth moisture gauge.

Multiple correlation analyses were run to determine the degree of association between all soil physical properties which were examined in the study.

Finally, a multiple regression technique involving the maximum R-square improvement procedure was employed to determine the soil physical properties which accounted for the greatest variation in the individual size classes of loblolly pine roots and to determine which soil factors might be limiting to the deeper penetration of roots.

RESULTS AND DISCUSSION

The results of this research will be discussed in four general categories. The first deals with comparisons of laboratory and field determinations of bulk density and soil moisture. The second portion concerns correlation analyses of all soil properties studied. The third section covers the changes in soil moisture during the study period. Lastly, the effects of the physical properties of the soil on loblolly pine root distribution are discussed.

Comparisons of Laboratory and Field Tests on Bulk Density and Soil Moisture Determinations

Nuclear bulk density with undisturbed soil core values. -- Bulk density values obtained with the nuclear depth density gauge were compared with those determined from undisturbed soil core samples. A preliminary analysis of variance was employed on all soil layers, with values determined by both methods, in a randomized-block design to test for significant differences in the two methods. Differences between mean bulk density values for the two methods were highly significant ($P < .01$). Phillips et al. (1960) indicated the need to adjust radiation density values to make them comparable to core values obtained by standard core sampling methods.

Following the preliminary analysis of variance, bulk density values were compared again. Vomocil (1954) stated

that the one-probe system measures the average density of an 8- to 10-inch layer of soil. Therefore I decided to use measurements taken farther apart. For the next test only measured densities at least 1 ft apart were analyzed, again by randomized block design. The analysis of variance is shown below:

Source	DF	Mean Square	F	Probability Level
Method	1	0.2759	49.59**	0.0001
Residual	65	0.0055		

The new analysis of variance showed highly significant differences between undisturbed soil-core bulk density values and nuclear bulk density values at the same depth levels in the soil.

Following this analysis, effects of soil texture and its interaction with the methods used were tested. A least-squares analysis technique was employed and the partial sums of squares were divided into method, texture, and their interaction. Textural classes consisted of three groupings according to the percentage of sand in the samples as follows: all samples with more than 75% sand (> 75), samples having 50 to 75% sand (50-75), and those samples containing less than 50% sand (< 50). The analysis of variance by the method of least squares is shown below for the comparison of nuclear density and soil-core bulk density.

Source	DF	Mean Square	F	Probability Level
Methods	1	0.0512	3.50	0.0634
Texture group	2	0.0437	2.99	0.0521
Interaction	2	0.0071	0.48	0.6238
Error	126	0.0146		

All of the F values were non-significant, so apparently there was no interaction of percent sand in the soils sampled and the methods tested here for bulk density determinations. There was a non-significant F value (3.50) for differences between methods when methods were adjusted for effects of texture group and interaction.

The adjusted mean value of 66 nuclear density determinations was 1.58 g/cm^3 compared to the corresponding mean of 1.66 for soil-core bulk density values. Phillips et al. (1960) found mean values of bulk density determined by core and radiation methods to be in general agreement. They used a surface density gauge in testing only plow-layer densities. They stated that one necessary assumption has to be the homogeneity of soil relative to density and moisture. The soil must be homogeneous to the point where gamma rays penetrate and return to the detector.

The mean bulk density values by percent sand were as follows:

Method	Number of samples	Percent sand	$\bar{X}$ bulk density g/cm^3
Nuclear	38	> 75	1.64
Core	38	> 75	1.71
Nuclear	26	50-75	1.60
Core	26	50-75	1.71
Nuclear	2	< 50	1.51
Core	2	< 50	1.55

Thus, the nuclear method gave lower (by 0.07 to 0.11 g/cm^3) bulk density values than density values for soil cores if the sand percent was greater than 50%. Both methods resulted in similar values for soils with less than 50% sand, but the number of samples was too small to really indicate a reliable trend.

Resin-coated clod values with those from undisturbed soil cores. -- Many times undisturbed soil cores cannot be obtained in excessively sandy, rocky or gravelly, heavy clay, or very wet soils. Determining the density of an undisturbed clod, fragment, or ped of soil may be the only solution for some of the soil conditions just described. In this research I wanted to determine the bulk density of soil fragments obtained with hydraulic soil-coring equipment from horizons below the water table. A resin-coating technique was one of the two methods tried. A preliminary analysis of variance compared the values obtained by resin-coated clods with values from undisturbed soil cores to determine any differences in the methods. The analysis of variance is shown below:

Source	DF	Mean Square	F	Probability Level
Method	1	0.02120	6.13*	0.0158
Residual	51	0.00346		

I found that differences between values obtained by the two methods were significant ($P < .05$). The mean bulk density of 52 paired samples as determined from soil cores was 1.704 compared to that from resin-coated clods of 1.733 g/cm^3. Goddard et al. (1971) also compared bulk density values obtained from clods with values obtained from undisturbed soil cores. They reported $\bar{X}$ values of 1.420, 1.480, and 1.487 g/cm^3 for resin-coated clods at three different depths; densities obtained with the undisturbed soil-core method were 1.275, 1.315, and 1.373 g/cm^3, respectively, at the same sampling depths. The differences in the two methods were even greater than those I obtained for all samples, irrespective of depth.

Following this test, a least squares analysis of variance was completed to determine soil textural effects and any interaction with the density determination methods. Textural groupings were similar to those used in comparisons of nuclear density values with those from soil cores. The analysis of variance is shown below:

Source	DF	Mean Square	F	Probability Level
Methods	1	0.0204	2.43	0.1221
Texture group	2	0.0273	3.25*	0.0417
Interaction	2	0.0031	0.37	0.6955
Error	98	0.0084		

There was no interaction between sampling methods and the percent sand when determining soil bulk density on resin-coated clods and undisturbed soil cores. However, the effect of soil texture, in this case the percent sand, did show significance ($P < .05$). The significance of texture group showed that the percent sand in samples had an effect on bulk density regardless of the method used.

Mean bulk density values for both methods were divided by percent sand as shown below:

Method	Number of samples	Percent sand	$\bar{X}$ bulk density g/cm^3
Resin	24	> 75	1.74
Core	24	> 75	1.71
Resin	26	50-75	1.73
Core	26	50-75	1.71
Resin	2	< 50	1.66
Core	2	< 50	1.55

When the percentage of sand was greater than 50, both methods gave very similar bulk density values, though the soil core densities were slightly lower than the resin densities, but only by 0.02 to 0.03 g/cm^3. The average values by both methods were much less for the samples containing less than 50% sand. The core density values were 0.10 g/cm^3 lower than resin densities but the number of samples with less than 50% sand was very limited. The resin technique is particularly good for immediate coating of samples in the field to keep them in a field-moist condition. Brasher et al. (1966) reported that the saran

resin requires no heating for field use, is flexible on the clod after application, and can be used to determine moisture-volume changes with time.

Wax-coated clod values with those from undisturbed soil cores. -- Soil bulk density values also were determined on wax-coated soil clods or fragments obtained as loose soil samples from areas immediately between the duplicate undisturbed soil cores. These were taken at 6-inch levels in all soils sampled. A preliminary analysis of variance was used to compare the mean values of four wax-coated sub-samples for each soil sample with the mean values of the corresponding duplicate soil core samples. The analysis of variance was as follows:

Source	DF	Mean Square	F	Probability Level
Method	1	0.1506	60.24**	0.0001
Residual	83	0.0025		

Differences in soil bulk density values were highly significant ($P < .01$). The results are somewhat different than those for the previously described resin-coating technique. The mean bulk density values for 84 paired samples were 1.66 for soil cores and 1.62 g/cm^3 for wax-coated clod samples. Tisdall (1951) found bulk density values on wax-coated undried clods to be significantly higher than values obtained on undisturbed soil cores. He studied soils that had a medium- to heavy-clay B horizon. He stated that the

wax-coated clod method should require the coating application on undried clods whereas some other workers have applied the coating after the clods have been oven-dried. Perry (1942) oven-dried clods prior to dipping in wax. Moist clods were utilized by Shaw (1917), an early advocate of the method. Tisdall (1951) reported the undried wax-coated clod method to be the best approach to an absolute method.

The effect of texture and its interaction with the method was then examined in another analysis of variance with the least squares method. The same texture groups were employed in this case. The analysis of variance follows:

Source	DF	Mean Square	F	Probability Level
Method	1	0.0146	2.15	0.1452
Texture group	2	0.0388	5.71**	0.0044
Interaction	2	0.0018	.26	0.7653
Error	162	0.0068		

This analysis provides the best indication of lack of interaction between method and texture, even though the effect of percentage of sand was highly significant in this analysis. This significance is probably indicative of the real problems when the wax-coated method is used on soils with high sand contents and, consequently, larger pore sizes. Basically, excess wax (paraffin) enters the larger pores and distorts the volume-weight of soil fragments or clods. Perry (1942) emphasized the importance of a thin coating of wax to reduce such errors.

A division of bulk density means by method and percent sand is shown below:

Method	Number of samples	Percent sand	$\bar{X}$ bulk density g/cm^3
Wax-coated	53	> 75	1.66
Core	53	> 75	1.72
Wax-coated	29	50-75	1.66
Core	29	50-75	1.72
Wax-coated	2	< 50	1.55
Core	2	< 50	1.55

Certain features of these methods are evident in this comparison. The mean values from wax-coated clods were 0.06 g/cm^3 lower for all samples having more than 50% sand. However, the two methods gave exactly the same bulk density values when there was less than 50% sand in the sample. This is again indicative of the problem incurred with the wax-filled pores associated with soils of higher sand content. Shaw (1917) stated that the wax-coated clod method offers a means of making very accurate determinations on all but the more sandy soils. In contrast, Arbol and Palta (1968) reported that the uncertainty regarding the thickness of the wax film and corrections needed to account for this makes the method unfit for any precise measurements.

<u>Paired wax-coated samples and paired resin-coated samples from the same soil sample</u>. -- Soil samples taken with the hydraulic coring machine from a second hole on each plot were used for a comparison test with these two

methods. Duplicate samples were tested by each technique from all 1-ft depth levels in each soil profile. Results from an initial analysis of variance are given below:

Source	DF	Mean Square	F	Probability Level
Method	1	0.4279	62.77**	0.0001
Residual	69	0.0068		

As one would expect from the previously discussed analyses there were highly significant ($P < .01$) differences between the values obtained by these two methods. Earlier it was shown that resin-coated density values were higher than soil core values, whereas wax-coated density values were lower than values obtained from undisturbed soil cores.

Wax-coated density values for 68 samples were averaged and the mean was 1.61 compared to the average for the 68 resin coated samples of 1.72 g/cm^3. This was a difference of 0.11 g/cm^3.

A least-squares analysis was used to determine any texture and interaction effects as in earlier comparisons. The analysis of variance follows:

Source	DF	Mean Square	F	Probability Level
Methods	1	0.2336	23.83**	0.0001
Texture group	2	0.0379	3.87*	0.0229
Interaction	2	0.0044	0.45	0.6444
Error	130	0.0098		

In this comparison, there was, for the first time, a highly significant difference between the two methods after the

means were adjusted for the effects of texture group (percent sand). Again there was no indication of an interaction of texture groups with the methods but differences due to the percent sand in samples were significant ($P < .05$). When density means for the two methods were subdivided by percent sand, all values of paired wax-coated samples in the three classes were consistently lower than those for resin-coated clods. The smallest differences occurred in mean values for samples having from 50 to 75% sand.

Wax-coated clod method on two different soil samples from the same level in the soil profile. -- The two types of soil samples utilized in this test were taken from opposite sides of each access tube but usually within a horizontal distance of about 1 ft of each other. One type was dug as a loose sample from soil pits and the other was extracted with the coring machine. Very close results should be expected unless soil bulk density varied greatly in a small zone. The preliminary analysis of variance is shown below:

Source	DF	Mean Square	F	Probability Level
Sample type	1	0.0057	0.92	0.6571
Residual	74	0.0062		

There was no difference in values obtained by this method from the two samples taken from the same soil horizons. The mean bulk density of clods from soil coring samples was 1.626 compared to a mean of 1.638 g/cm^3 for the loose

samples from the soil pit. Goddard et al. (1971) obtained comparative values on cored clods and natural clods from a conventional soil pit. Values were 1.420, 1.480, and 1.487 for cored clods from three depths. These compared favorably with values on loose clods of 1.422, 1.482, and 1.510 for the three depths, respectively. There was little difference in the methods by which clods were obtained; however, they coated clods with saran resin, not with wax as I did in this test.

The least-squares method of analysis revealed an especially interesting facet of this test. The analysis of variance is as follows:

Source	DF	Mean Square	F	Probability Level
Method	1	0.0062	0.61	0.4348
Texture group	2	0.1334	13.21**	0.0001
Interaction	2	0.0190	1.88	0.1528
Error	144	0.0101		

Differences between the methods and the interaction effects were not significant but the effects of texture were highly significant ($P < .01$). As already discussed, texture effects were most important in comparisons where the wax-coated technique was used.

<u>Nuclear method with resin-coated technique</u>. -- An initial analysis of variance similar to other comparisons was conducted as follows:

Source	DF	Mean Square	F	Probability Level
Method	1	0.2505	35.79**	0.0001
Residual	65	0.0070		

There were highly significant differences between the nuclear method of determining density and the resin-coated clod method.

The least-squares analysis of variance was run to determine texture effects and to find out if interaction was significant. The analysis of variance is shown below:

Source	DF	Mean Square	F	Probability Level
Method	1	0.1283	12.22**	0.0007
Texture group	2	0.0353	3.56*	0.0373
Interaction	2	0.0148	1.41	0.2473
Error	126			

Here again differences between methods were highly significant ($P < .01$) but the effect of texture groups was only significant ($P < .05$). Interaction effects were not significant.

Nuclear values compared to those by wax-coated clod technique. -- As in previous comparisons, a preliminary analysis of variance was utilized but demonstrated no significant difference in values obtained from the nuclear method and wax-coated clods.

With the least-squares method in a later analysis, other significant differences became apparent in the comparison of these methods. The analysis follows:

Source	DF	Mean Square	F	Probability Level
Method	1	0.0588	4.99*	0.0268
Texture group	2	0.0959	7.99**	0.0008
Interaction	2	0.0974	8.11**	0.0007
Error	164			

Here obtaining a new F value from a partial sum of squares showed that differences due only to methods were significant ($P < .05$). The effect of texture grouping was highly significant, as it was in the comparison of wax-coated density values with soil core values. It is interesting to note that this comparison is the only one in which a significant interaction ($P < .01$) was found.

The following comparison of the mean values for each method according to percent sand brings out some striking differences:

Method	Number of samples	Percent sand	$\bar{X}$ bulk density g/cm^3
Nuclear	47	> 75	1.65
Wax-coated	47	> 75	1.65
Nuclear	30	50-75	1.61
Wax-coated	30	50-75	1.67
Nuclear	8	< 50	1.63
Wax-coated	8	< 50	1.43

Mean bulk density was the same by both methods for samples with more than 75% sand. Soil samples with 50 to 75% sand had mean density values lower by 0.06 g/cm^3 when measured by the nuclear method. Samples with less than 50% sand, however, had density values higher by 0.20 g/cm^3 when measured by the nuclear method. In all tests, soil

samples with less than 50% sand had lower bulk densities regardless of the method used to determine density.

Overall comparison of bulk density methods. -- The soil-core method is widely used and can be considered as a standard in bulk density determinations. The mean bulk density for all samples by the nuclear method was 0.08 g/cm^3 lower than the value for soil cores. The mean of all resin-coated clods was only 0.03 g/cm^3 higher than the value for all soil cores. On the other hand, the value obtained for wax-coated clods was 0.04 g/cm^3 lower than the mean from soil cores. For relative measurements, any of the four methods can be used to determine bulk density. Field collection of soil clods is easier but laboratory procedures for coated-clods are more involved.

Nuclear soil moisture values with those by gravimetric method. -- An initial analysis of variance was performed to determine differences in the methods and is shown below:

Source	DF	Mean Square	F	Probability Level
Method	1	137.7920	11.63**	0.0013
Residual	93	11.8512		

I found differences between methods to be highly significant ($P < .01$). Stone et al. (1960) compared gravimetric sampling with neutron measurements at the same locations and reported rather poor agreement within locations.

The least-squares method was then utilized as described previously for other comparisons. The analysis of variance follows:

Source	DF	Mean Square	F	Probability Level
Method	1	418.8929	24.29**	0.0001
Texture group	2	336.1902	19.50**	0.0001
Interaction	2	161.6986	9.38**	0.0003
Error	182	17.2392		

The differences due to the method were shown to be highly significant and moisture contents differed among texture groups. These differences depended in degree upon the method used and were highly significant ($P < .01$) and interaction between methods and percent sand was also highly significant.

A comparison of mean values by both methods grouped only by percent sand points out the greater moisture holding properties of soils with less sand and more silt plus clay. The comparison is shown below:

Number total samples	Percent sand	$\bar{X}$ moisture content %
110	> 75	13.98
60	50-75	13.78
18	< 50	20.33

The grouping of moisture means by method and percent sand clearly shows differences in the methods. This comparison is as follows:

Method	Number of samples	Percent sand	$\bar{X}$ moisture content %
Nuclear	55	> 75	13.70
Gravimetric	55	> 75	14.27
Nuclear	30	50-75	13.07
Gravimetric	30	50-75	14.49
Nuclear	9	< 50	15.49
Gravimetric	9	< 50	25.18

Soil samples with more than 50% sand are fairly close in mean moisture values. Values determined by the nuclear method are only about 1% lower than moisture means determined gravimetrically. The real problem arises with soils having less than 50% sand. The nuclear moisture content average for only nine samples was almost 10% lower than mean moisture content determined gravimetrically. This is a large difference. Van Bavel et al. (1956) reported that one disadvantage of the nuclear method is the loss of sensitivity at high moisture contents. Sartz (1972) found that variance in water content determined by the neutron method increased with depth at high water contents but was more uniform with lower water contents.

I might mention that in the construction of a moisture calibration curve no samples with less than 50% sand were utilized. In the sandy loam soils studied, soil layers of low sand content, less than 50%, were found only in certain subsoils or in the top 18 inches of the profile. In the case of the subsoils, there were high clay percentages at depths ranging from 6.5 to 14.5 ft on plot 10. Topsoils

were high in silt content in the upper 6- to 18-inch levels. Neither of these levels of soil were used in calibrating the nuclear depth moisture gauge.

Mean values of moisture by the nuclear method are lower than gravimetric means for all texture groupings. Lawless et al. (1963) reported that neutron probes tend to underestimate soil moisture content at wet-dry interfaces or in stratified profiles. This was probably the major reason for the lack of agreement for these two methods.

Correlations among Soil Physical Properties

As a preparatory step in determining the soil physical properties that might have the greatest influence on root distribution of loblolly pine, I determined the correlation coefficients among the soil properties. The soil properties for all plots are shown in Tables 21 through 30 in Appendix B. Table 4 contains all of the correlation coefficients. The number of samples involved in different correlations varied from 116 to 271. Data on the number of samples and probability levels of significance are not shown. The correlations concerned with bulk density and soil moisture determinations will be discussed as will soil properties found to be very highly correlated.

Correlations for soil bulk density. -- Correlation coefficients for bulk density tests are shown below:

Table 4. Correlation coefficients among physical properties of the Coastal Plain soils under study.

	Percolation rate	Noncapillary porosity	Capillary porosity	Total porosity	Density (soil cores)	Sand percent	Clay percent	Silt percent	Gravimetric water	Density (wax-coating)	Field capacity	Wilting point	Density (nuclear)	Density (resin-coating)	Nuclear water	Silt + clay percent	Available water
Depth	-.166	-.370	-.021	-.546	.447	.083	.304	-.364	.295	.173	.190	.327	.489	.265	.578	-.083	.059
Percolation rate		.431	-.334	.166	-.295	.191	-.210	-.081	-.230	-.207	-.099	-.217	-.148	-.051	-.003	-.191	.036
Noncapillary porosity			-.729	-.447	-.595	.157	-.582	.132	-.401	-.312	-.469	-.651	-.480	-.105	-.650	-.157	-.104
Capillary porosity				.287	.011	-.519	.367	.315	.663	-.143	.582	.419	.247	-.388	.474	.519	.424
Total porosity					-.818	-.458	-.335	.596	.342	-.600	.104	-.364	-.413	-.612	-.310	.458	.409
Density (soil cores)						.375	.325	-.512	-.118	.674	-.080	.357	.635	.592	.455	-.375	-.373
Sand percent							-.720	-.827	-.560	.543	-.791	-.676	.039	.428	-.191	-1.000	-.750
Clay percent								.205	.624	-.427	.866	.947	.196	-.202	.416	.720	.669
Silt percent									.285	-.407	.414	.186	-.234	-.423	-.078	.827	.515
Gravimetric water										-.463	.648	.631	.352	-.341	.597	.561	.564
Density (wax-coating)											-.561	-.415	.350	.566	.113	-.543	-.576
Field capacity												.873	.091	-.341	.348	.791	.934
Wilting point													.202	-.208	.429	.676	.642
Density (nuclear)														.265	.597	-.039	-.005
Density (resin-coating)															-.012	-.428	-.396
Nuclear water																.191	.238
Silt + clay percent																	.749
Available water																	

Methods	Resin-coated clod		Nuclear		Soil core	
	r value	No. samples	r value	No. samples	r value	No. samples
Wax-coated clod	.566**	176	.350**	198	.674**	168
Resin-coated clod			.265**	165	.592**	116
Nuclear					.635**	122

All r values were highly significant ($P < .01$). As a point of differentiation, I believe that any correlation coefficients (r) that are less than 0.5 should not be considered as representing a close degree of association even though they may be significant. For the bulk density data, values obtained by soil-core methods are most closely correlated with those from wax-coated clods. Values from soil cores also show a high degree of association with those of resin-coated clods and nuclear measurements. The only other bulk density values that are closely correlated are those of wax-coated and resin-coated clods. Bulk density values obtained by the nuclear method are not closely related to those obtained by either clod method.

Another aspect worthy of consideration is the degree of association between bulk density values determined by each of the methods and the percentages of sand, silt, and clay in the soils, as shown below:

Bulk density values by method	Soil separates		
	Sand	Silt	Clay
	r values		
Soil core	.375**	-.512**	.325**
Wax-coated clod	.543**	-.407**	-.427**
Resin-coated clod	.428**	-.423**	-.202**
Nuclear	.039	-.234**	.196**

The density values of wax-coated clods had the highest correlation with percent sand, indicating increasing density values with increases in sand content. Soil clods with higher sand contents relative to percentages of the other separates have a higher proportion of noncapillary-sized pores. Many may be filled with melted wax during the coating process thereby affecting the density of the clods.

With both coating methods for density determinations there were negative correlations with the percentage of clay in the samples. Here, density values decrease with increasing proportions of clay. Neither of the coatings usually penetrate the smaller-sized pores found in samples with high clay contents.

Correlation coefficients obtained for density values by the soil core and nuclear methods are positive with clay content rather than negative as was the case with the clod density values. Correlation coefficients obtained by Broadfoot and Burke (1958) for bulk density relationships were .18** with sand, -.31 with silt**, and .10** with clay. Their r values were lower than I obtained but their data were similar in that both clay and sand were positive values and silt was negative. Silt also had the highest

correlation with bulk density when determined by the core method, both in my data and those of Broadfoot and Burke. The negative r value for silt content can probably be best explained by the decrease in the silt fraction with depth in these soils and by the general increase in bulk density values with increasing depth in the soil profiles.

Bulk density as determined by soil cores was closely associated with values obtained for total porosity. The correlation between bulk density and total porosity was highly significant with a calculated r value of -.818. The negative relationship indicates that decreases in total porosity will be associated with increases in bulk density. Free et al. (1940) also found a high negative correlation, -.99, between bulk density and total porosity.

Correlations for soil moisture measurements. -- The relationship between soil moisture as determined with the neutron moisture gauge and with gravimetric samples in the laboratory was computed. I obtained an r value of .597 that was highly significant ($P < .01$). I would have expected a higher r value, i.e., a closer relationship, especially since the calibration curve for the neutron gauge was constructed by using gravimetric samples from the same soils as used in this study. The lower correlation from using all samples is probably due to measurements on soil-moisture discontinuities made where two differing horizons join. In the construction of the calibration curves only 2- to

3-ft thick soil layers having uniform soil moisture contents were used and the measurements were then taken at the middle of the layer. The nuclear method has a high enough correlation with the gravimetric method to be used as a replacement for the gravimetric method in most work.

Correlations of soil moisture constants. -- The soil moisture constants determined in this research were highly correlated with the soil textural fractions. The correlation coefficients are as follows:

Soil moisture constants	Soil separates			
	Sand	Silt	Clay	Silt + Clay
	------------- r values	------------		
Field capacity	-.791**	.414**	.866**	.791**
Wilting point	-.676**	.186**	.947**	.676**
Available moisture	-.750**	.515**	.669**	.750**

The highest correlation observed is between wilting point and the clay fraction. Soil samples that contain higher clay contents will have higher wilting points, and clay content is more closely associated with the wilting point than with field capacity. The amount of moisture removed at 1/3 atm tension is that moisture held in larger pores, not moisture more strongly held by cohesion and adhesion in smaller pores around the clay particles. Patrick et al. (1964) reported correlation coefficients for clay with field capacity and wilting point of .867 and .976, respectively. These agree well with those

obtained in this research although data were obtained on alluvial soils from a sugar cane-growing region.

I found all soil moisture constants to have a high negative correlation with sand content and to be positively correlated with silt content, although the r values are lower for silt. Salter et al. (1966) indicated that available-water capacity of a soil was negatively correlated with percentage of coarse sand and positively correlated with the percentages of silt-size soil particles. Petersen et al. (1968) also reported that available moisture was negatively correlated with sand and positively correlated with silt content.

Petersen et al. (1968) also found a negative correlation between available moisture and clay content. However, I found a positive correlation, r value of .669, that was highly significant. Lund (1959) reported that no correlation between clay content and available moisture was found in alluvial soils in Louisiana. He concluded that silt particles were of primary importance in controlling available moisture in soils. Silt content is important as well as the proportion of all three major fractions in determining how closely related available moisture is to clay content.

I determined correlation coefficients between available moisture and both field capacity and wilting point and found them to be .934 and .642, respectively. The high

correlation with field capacity is similar to results obtained by Petersen et al. (1968). They reported that available moisture was highly correlated with field capacity whereas wilting point showed either no correlation or a negative correlation. I found a positive correlation between wilting point and available moisture. It is possible to obtain these differing results for the same reasons as discussed for the clay-available moisture relationship since clay and wilting point had a very high correlation coefficient, .947.

Fluctuations in Soil Moisture

Changes in soil moisture were examined for the 5-year period from 1968 through 1972. Monthly means of total soil moisture in inches per ft were obtained for three different soil depths. Total moisture was determined for the 0- to 1-ft, 0- to 4-ft and 0- to 7-ft profiles. The 0- to 1-ft profile was selected because the greatest percentage of small roots were within that depth. The 0- to 4-ft profile corresponded to the depth of root sampling. A profile from the surface to a depth of 7 ft was chosen because it included all weekly soil moisture measurements that exhibited any changes during the years studied. Below 7 ft moisture remained generally constant throughout the year.

Moisture fluctuations in three plots will be discussed to illustrate all plots in the study. A comparison of changing moisture levels between a well-drained and poorly-

drained soil is shown in Figure 4. Fluctuations in soil moisture amounts for three different slope positions on the same plot are illustrated in Figure 5. In general, soil moisture loss or use followed the same depletion trends on all plots examined regardless of slightly differing density levels (basal area) or number of trees per plot. Bay and Boelter (1963) studied three widely-differing levels of stocking in red pine, ranging from 60 to 140 ft^2 of basal area per acre, and found similar general trends. Sartz (1972) reported that soil moisture was gradually depleted over the growing season in Wisconsin except where heavy rainfall recharged the profile. Recharge by rainfall during the growing season, shown by increases in total soil moisture, was evident in a number of years that were monitored in southeast Louisiana.

One important point which should be discussed is the similarity of the moisture curves on all plots for the 0- to 4-ft and 0- to 7-ft profiles. The 0- to 7-ft curves contain the same data found in the 0- to 4-ft curves; in other words, the amounts of total soil moisture are cumulative for all three profiles, from the surface to 7 ft. Depletion of soil moisture appears to be most pronounced in the 0- to 4-ft data. Taylor and Haddock (1956) indicated that soil moisture was removed most rapidly where the root density was highest. Strand (1968) found higher levels of soil moisture in lower soil depths under Douglas-fir stands at the time of maximum soil depletion. He stated

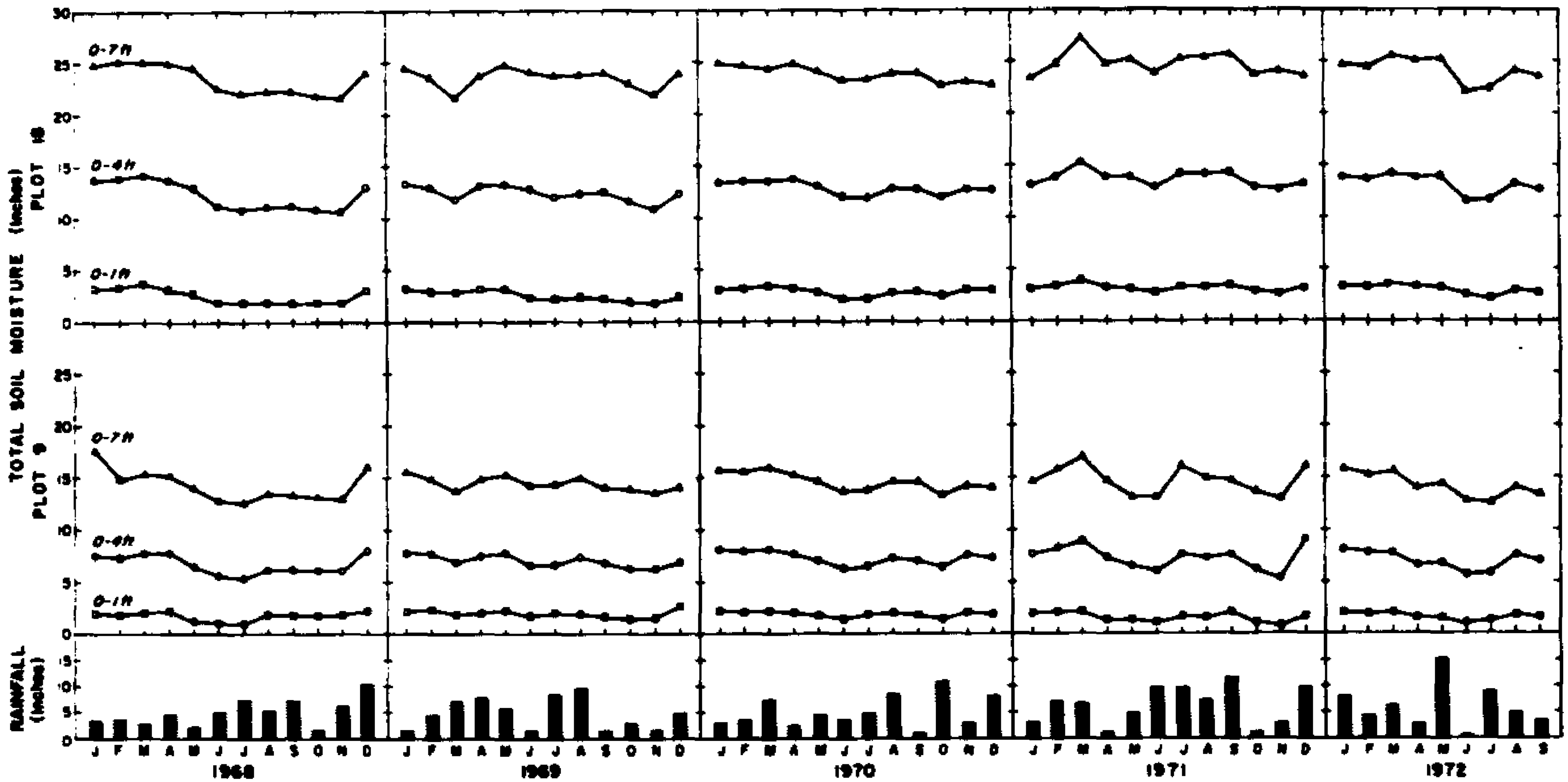

Figure 4. Comparison of total soil moisture in a well-drained soil (Plot 9), Ruston sandy loam, with a poorly drained soil (Plot 18), Myatt-Mashulaville complex.

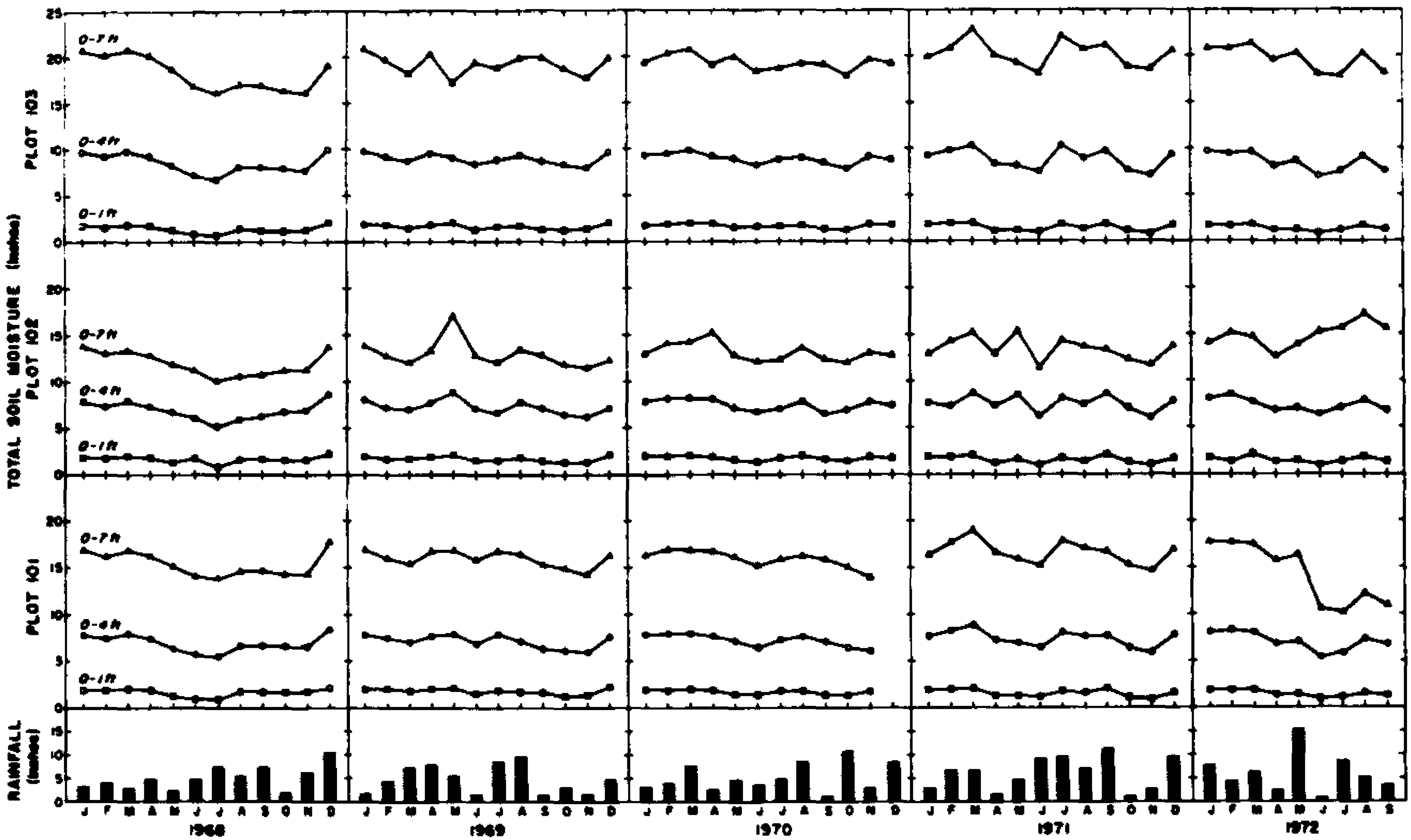

Figure 5. Comparison of total soil moisture at upper (10-1), middle (10-2), and lower (10-3) slope positions in a Ruston sandy loam.

that this was probably due to lower concentrations of roots at that depth and capillary rise of water in soil.

Subsequent sampling for root distribution showed many roots in the upper 2 ft but relatively fewer roots at the 3- and 4-ft levels. A few roots were observed, however, at even greater depths while excavating the soil pits. The decreases in total soil moisture shown in the 0- to 7-ft data are more pronounced in the surface 4 ft and therefore the 7-ft curves should and do closely parallel the 4-ft curves. Bay and Boelter (1963) reported that some soil moisture withdrawal took place down to 7 ft. They also found some red pine roots extending that deep although most roots were concentrated in the 0- to 3-ft horizon. They stated that of the total water lost in the 7-ft profile, approximately 60% occurred in the upper 3 ft. Stransky and Wilson (1966) as well as Harlan and White (1968) reported that soil moisture depletion decreased with increase in depth of the soil profile. In southeast Louisiana, with loblolly pine, there was relatively little increase in moisture loss when the moisture contents in the three additional feet of soil profile were added to the 0- to 4-ft profile curves. The 0- to 7-ft curves follow the same trends with the only difference being the total moisture contained in the 4- to 7-ft soil depth. The use of data for the entire 7 ft of depth is primarily to show the total soil moisture content down through the depth where no moisture utilization was apparent.

Comparison of soil moisture levels on well-drained and poorly-drained soils. -- One of the most obvious points is that the poorly-drained soil on Plot 18 contains more total moisture in all three profiles than the corresponding profiles on Plot 9, the well-drained soil in Figure 4. This certainly is to be expected. In the 0- to 7-ft profile on Plot 18 the total moisture is never below 20 inches while in the same profile depth on Plot 9, total moisture is never above 20 inches.

Monthly rainfall data are shown for the entire measurement period. The month with the highest rainfall was May 1972, but because this rainfall occurred in the growing season, there was no noticeable increase in soil moisture for horizons close to the soil surface and only a slight increase in total moisture in the 7-ft profile. The moisture on both plots continued to decrease greatly because the wettest month, May, was followed by the driest month, June, in the study period.

The pattern of soil moisture changes during the growing season of 1971 was quite different. From a peak of soil moisture storage in March on both plots there was a sharp drop in total soil moisture with the onset of the growing season which in this case coincided with a very dry April. Increasing rainfall in May and June was not sufficient to offset increased extraction of soil moisture by the actively growing loblolly pines. Continuing adequate

rainfall in July, August and September was sufficient to cause increases in total soil moisture. Marston (1962) found that soil drying during the growing season was frequently interrupted by summer rainstorms, and on a number of his plots this rainfall exceeded the depletion, wetting the soil to field capacity. In my study, another dry period in October and November of 1971 was associated with further decreases in soil moisture. This is an indication that pine stands are continually extracting soil moisture and growing through the fall months.

Soil moisture can also decrease in the winter months in southeast Louisiana. Soil moisture decreased on both plots from a peak in December 1968 through March 1969. This decrease occurred in what is usually considered to be the dormant season. January 1969 was quite dry (as was true in all years monitored except 1972) but rainfall increased in February and March 1969 while total soil moisture decreased. An opposite trend was evident in the winter months of November-December 1970 and January-February-March 1971. Rainfall in late 1970 was not as great as in 1968 but total soil moisture increased in early 1971 with increasing rainfall.

During most years of the study period, total soil moisture was at a minimum in June. Bay (1963) measured a large decrease in available soil moisture and found that this coincided with the greatest monthly radial growth of

red pine. In my study there was a period of low total soil moisture in the early fall months of October and November in most years studied. This is the point at which diameter growth usually slows in southeast Louisiana.

Comparison of soil moisture levels at three slope positions on a well-drained Ruston soil. -- Close examination of the data in Figure 5 shows an unusual variation in total soil moisture levels in the 0- to 7-ft profiles on the three different slope positions. Total soil moisture for these profile depths was generally less at the middle-slope monitoring position, plot 10-2, than at the upper-slope position, plot 10-1, and the lower slope position, plot 10-3. This was observed consistently for the entire study period. There are valid reasons for this result. First, the upper-slope position had very few trees nearby (none, on one side of this access tube) and consequently there were fewer roots to remove soil moisture. Second, the distribution of roots was greater at lower depths on plot 10-2, the middle-slope position, than at any other sampling location studied. Third, there was probably lateral movement of water within the profile down this steep slope as indicated by the high moisture content in the 0- to 7-ft depth on plot 10-3.

The middle-slope position curve shows greater changes in total soil moisture in the 0- to 7-ft profile than the 0- to 4-ft profile with increases or decreases in monthly

rainfall. These greater increases and decreases are evident in all years except 1968, for which the curves are very similar. The increasing spring rainfall in 1969 added a greater amount of total soil moisture in the 0- to 7-ft profile than in the 0- to 4-ft profile. The decrease in June with lower rainfall and increased moisture utilization by the trees was proportionately greater also. For the most part, the moisture utilization portrayed in the 0- to 7-ft profiles reflects the usage of soil moisture by loblolly pine roots in the effective rooting zone, the upper 4 ft. On all plots, changes in the surface foot are not large even though a large percentage of smaller roots are found in this zone. Basically, in the surface foot there is less water stored and therefore less water is available to be utilized by tree roots.

Soil moisture depletion curves. -- The average monthly moisture contents (inches per ft) at 1-ft levels down to a depth of 7 ft were plotted for 1970 and 1971. Data for three selected months -- April, June and August -- during the growing season were used, along with the 15-atm moisture content (wilting point) for each soil level.

Three dry-site plots (10-1, 9, and 15) exhibited similar depletion patterns as shown in Figures 6, 7 and 8. There was a decrease in moisture at the 1-ft level from April to June in 1970 with an increase almost back to the April content by August. Sander (1970) found soil water

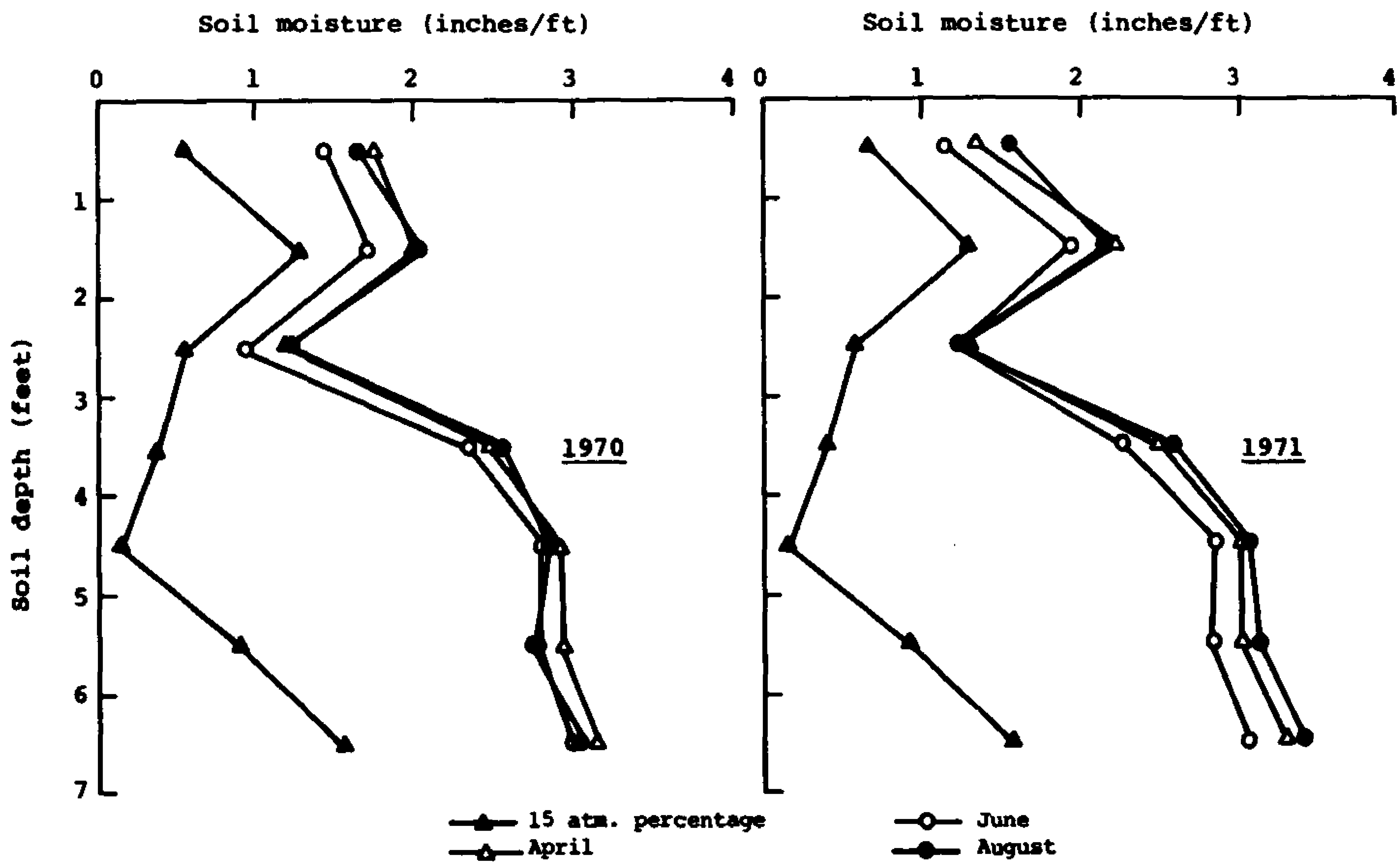

Figure 6. Soil moisture depletion curves for plot 10-1.

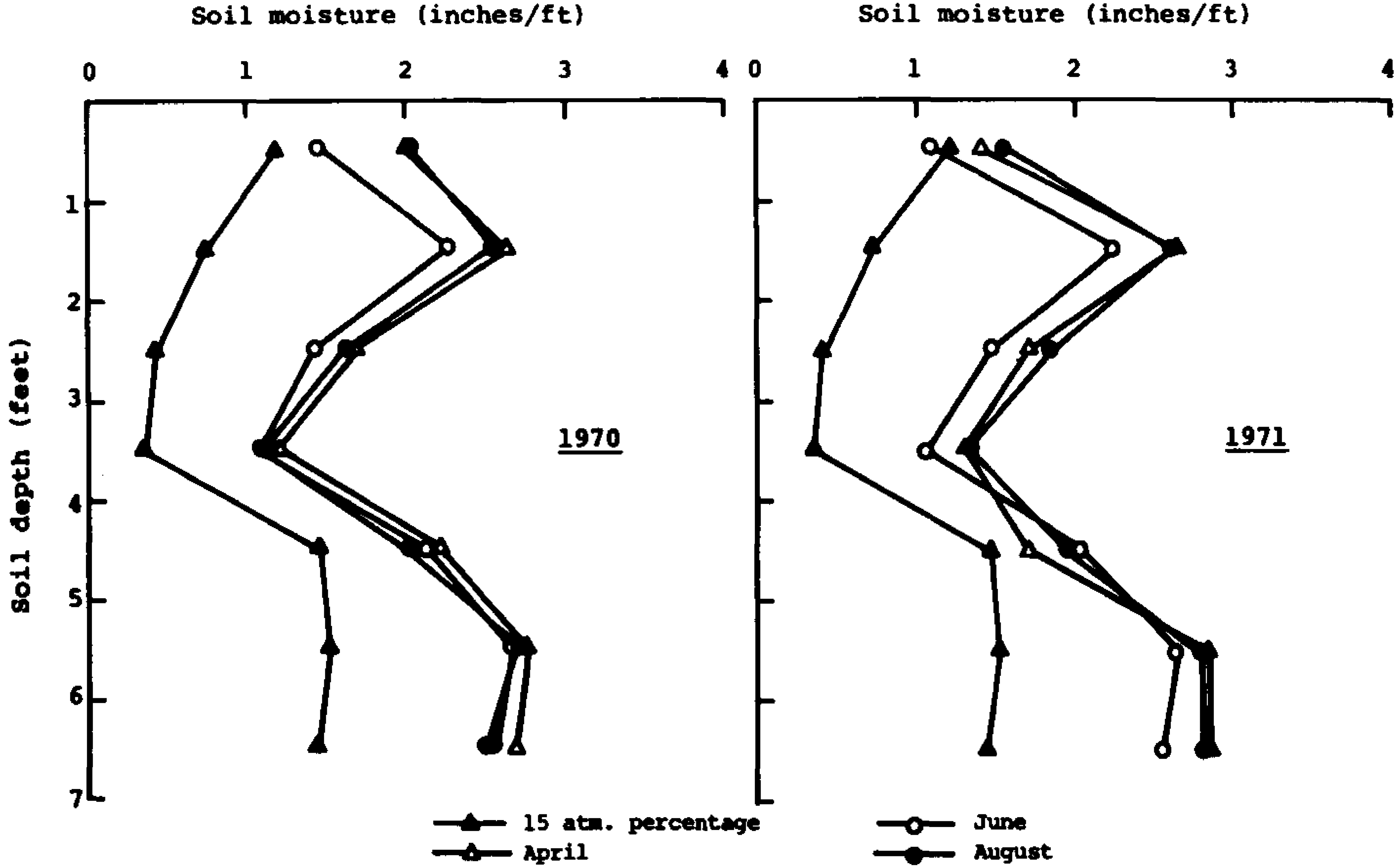

Figure 7. Soil moisture depletion curves for plot 9.

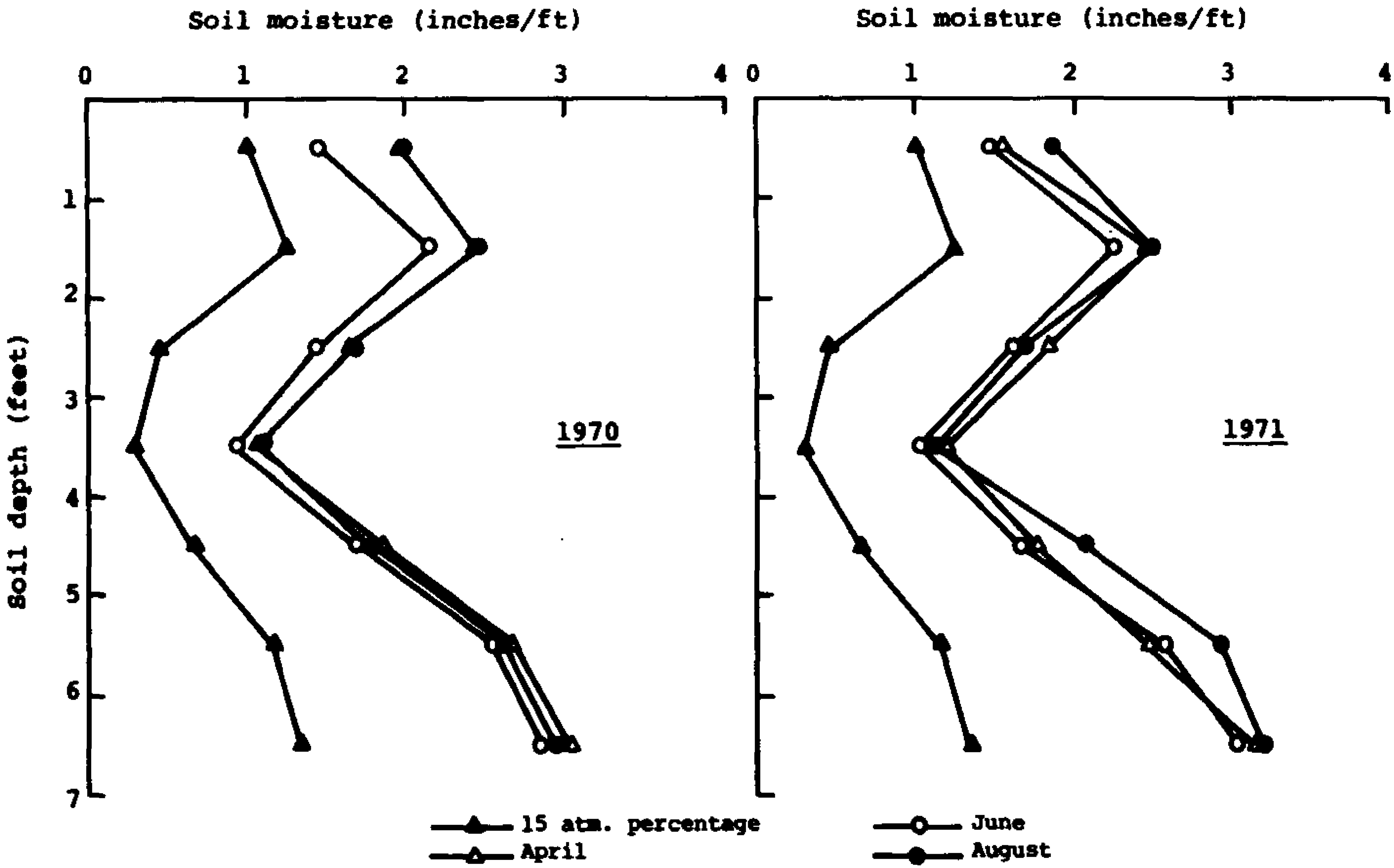

Figure 8. Soil moisture depletion curves for plot 15.

use to be characterized by depletion primarily from the surface soil early in the growing season. In 1971, August moisture at the 1-ft level was slightly higher than in April. Moisture in all three months was higher at the 2-ft level following a trend similar to the 15-atm moisture curve. At the 3- and 4-ft levels, soil moisture decreased similarly to the wilting-point curve. The percentages of silt and clay decreased at 3 and 4 ft and less water could be held in the soil (Tables 25, 26 and 29 in Appendix B). Moisture in the three months shown was much higher at the 5-ft level and remained so down to 7 ft. The only time that soil moisture content was below the 15-atm percentage on these three plots was during June 1971 at the 1-ft level.

Moyle and Zahner (1954) measured soil moisture depletion where soil moisture dropped from saturation in late May to near the wilting point in late June. They found that soil moisture was not depleted below 3 ft, presumably because few roots were located below this depth. Fehrenbacher et al. (1969) indicated that the amount of available soil water that plants can use depends on the extent of their root systems and how deep the roots penetrate into the soil. Griffin (1967) stated that denser layers may restrict root growth in places, resulting in less moisture depletion and higher moisture contents in layers below root penetration. Most roots on these plots were in the upper few feet but on plot 9 I did find one vertical root 18 ft deep.

Plots 1, 4, 5 and 18 have very similar moisture depletion curves that are illustrated in Figures 9, 10, 11 and 12. The greatest usage of soil moisture occurred during June in both years at the 1-ft level, and moisture content was higher at the 2-ft level. Lorio and Hodges (1971) reported an early tendency toward uniform depletion on flat sites with water extraction limited to depths of about 75 cm. They later found loblolly pine roots to be restricted to these depths. Zahner (1955) reported that where effective root depth was severely restricted by poor aeration, most water was supplied by surface layers. Herring (1968) also found that most of the soil moisture used by a lodgepole pine stand came from the upper 2 ft of the soil because most of the roots were limited to this depth. Zahner and Stage (1966) indicated that the surface horizons are recharged frequently by rain and therefore the most prolific root concentration occurs there. The concentration of roots, they stated, results in rapid water depletion from the surface layers. On plots 4 and 18 (Figures 10 and 12) moisture content remained almost constant from 3 ft down through the 7-ft level shown. On plots 1 and 5 (Figures 9 and 11) soil moisture content remained constant throughout the growing season beginning at the 5-ft level. The only decrease in soil moisture content on the wet-site plots occurred from 4 to 5 ft on plot 5 (Figure 11). The 4-ft level on plot 5 had the highest moisture content in

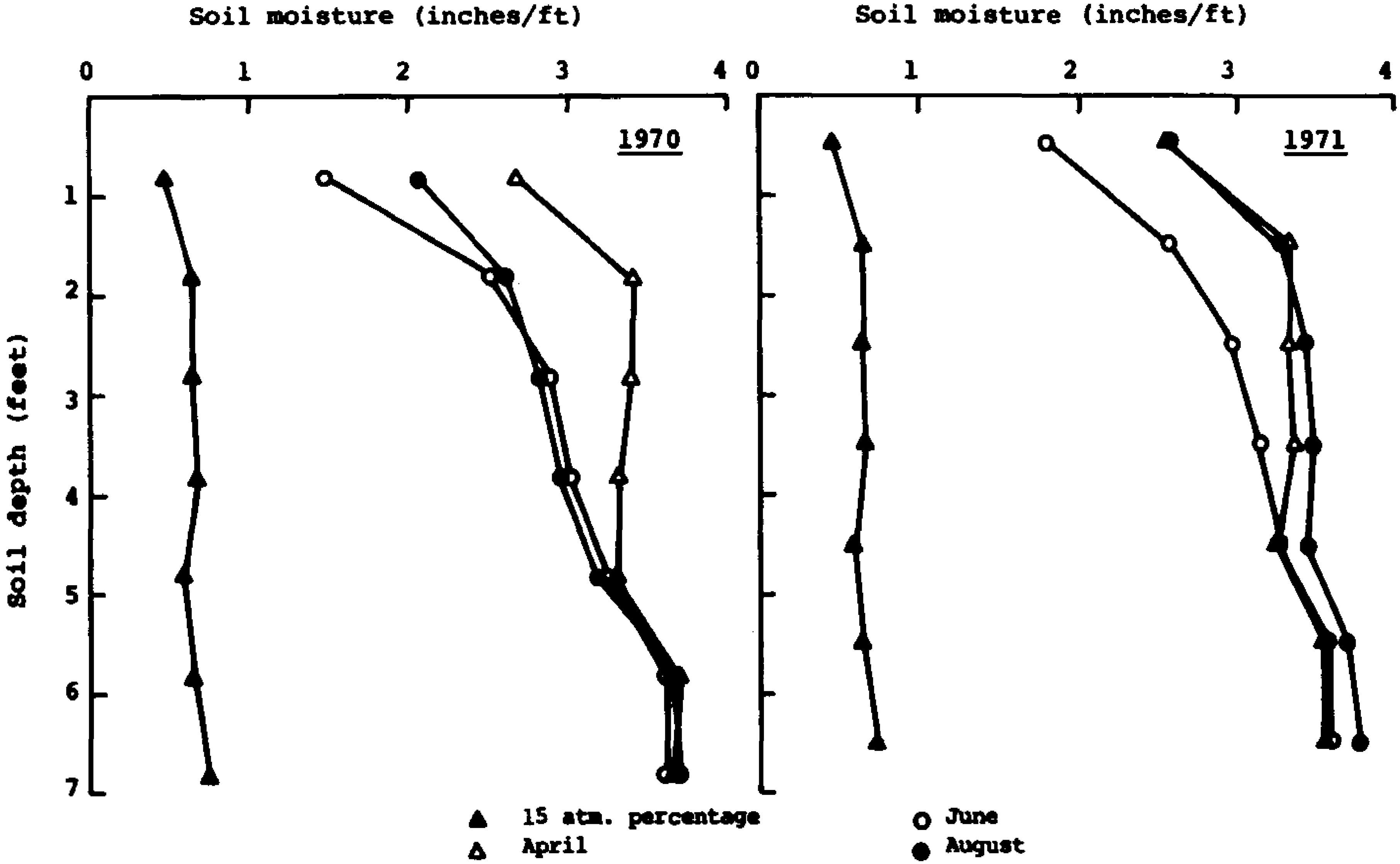

Figure 9. Soil moisture depletion curves for plot 1.

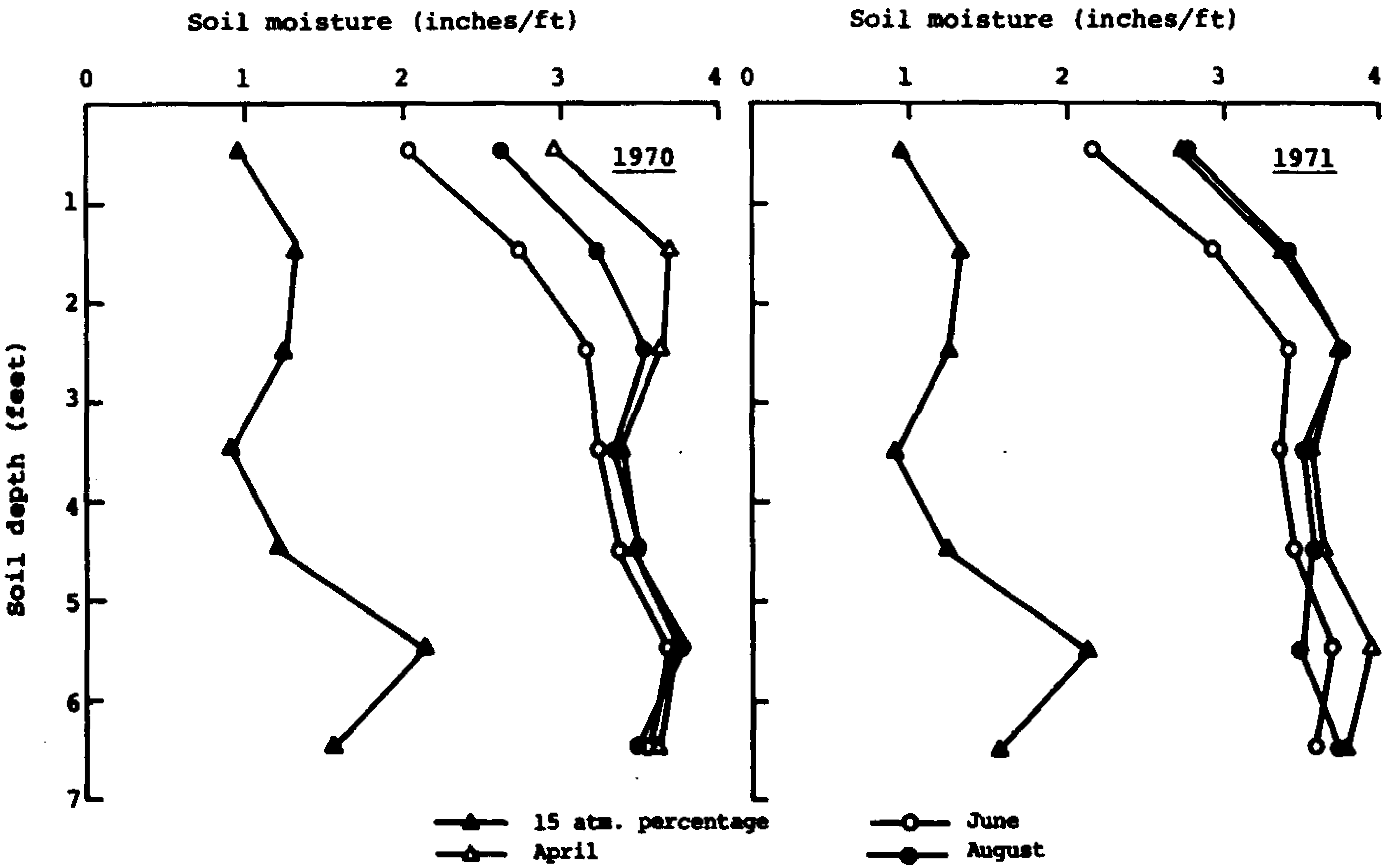

Figure 10. Soil moisture depletion curves for plot 4.

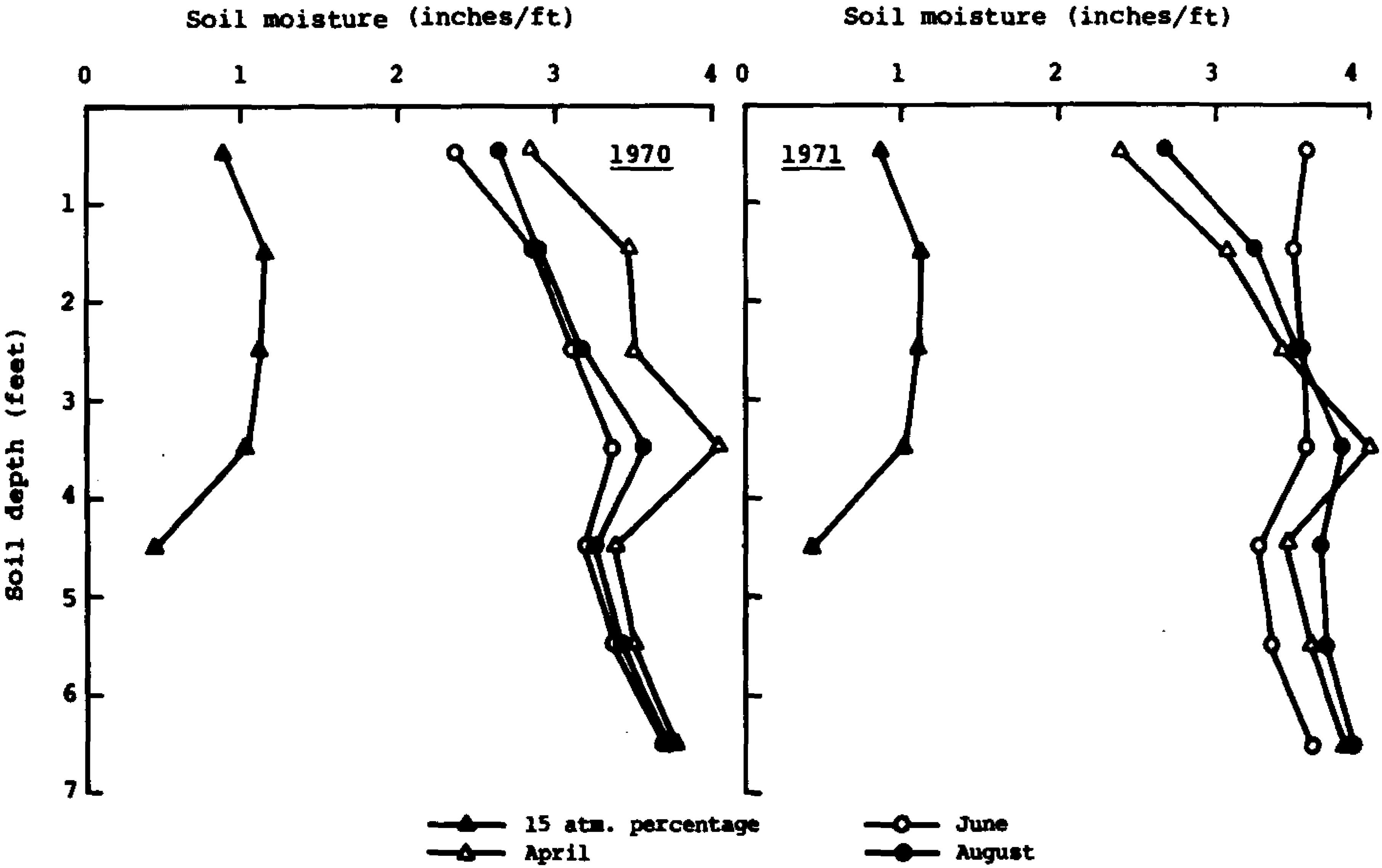

Figure 11. Soil moisture depletion curves for plot 5.

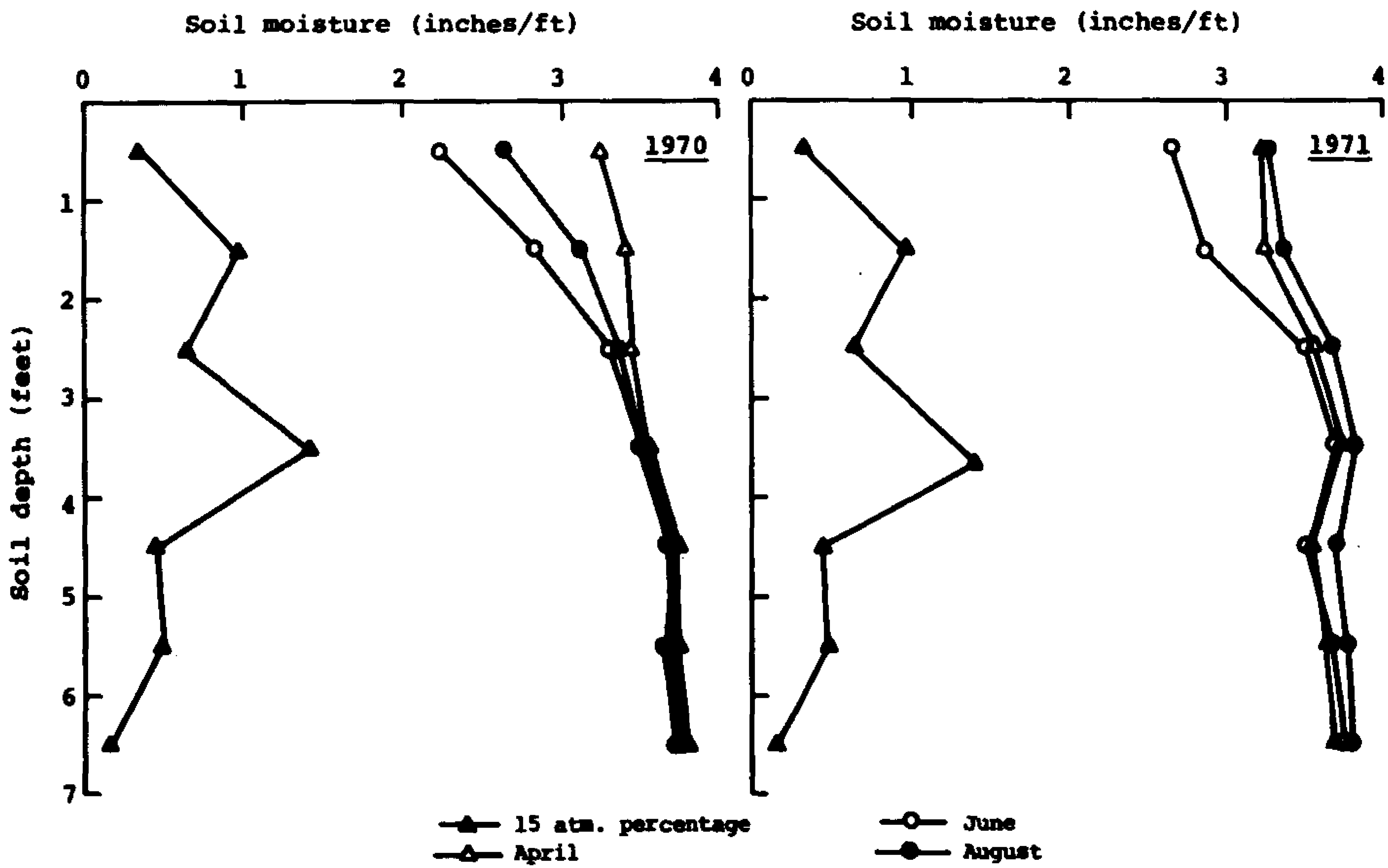

Figure 12. Soil moisture depletion curves for plot 18.

any level of any plot, except plot 10-3 at 7 ft. Samples could only be obtained to a depth of 5 ft on plot 5 even with the coring machine because of a wet, extremely sandy layer and therefore soil layers below this level were not examined (Table 23, Appendix B).

Plots 10-3 and 7, shown in Figures 13 and 14, had depletion curves that were similar in that soil moisture content generally increased continually with depth. They differ in that plot 10-3 did not increase from 2 to 3 ft at the same rate as shown for plot 7. Also, plot 7 showed a decrease in moisture from 3 to 4 ft. This decrease followed the curve of the 15-atm percentage and coincided with a decrease in clay content from 3 to 4.5 ft (Table 24, Appendix B.

Plot 10-2, shown in Figure 15, is the only plot where soil moisture was depleted below the wilting point. In April 1970, soil moisture content was high enough to be available at 4, 5 and 6 ft. This was not the case in 1971 nor during June and August of 1970. This plot had the greatest depletion of moisture at lower depths, 4 to 5 ft, than any other plot studied.

Patric et al. (1965) reported that measured water loss from lower depths resulted from both local absorption and upward movement through the soil. Kramer and Coile (1940) believed that capillary movement of water toward roots was so slow under average field conditions that it was of negligible importance. Plot 10-2 was the only plot that

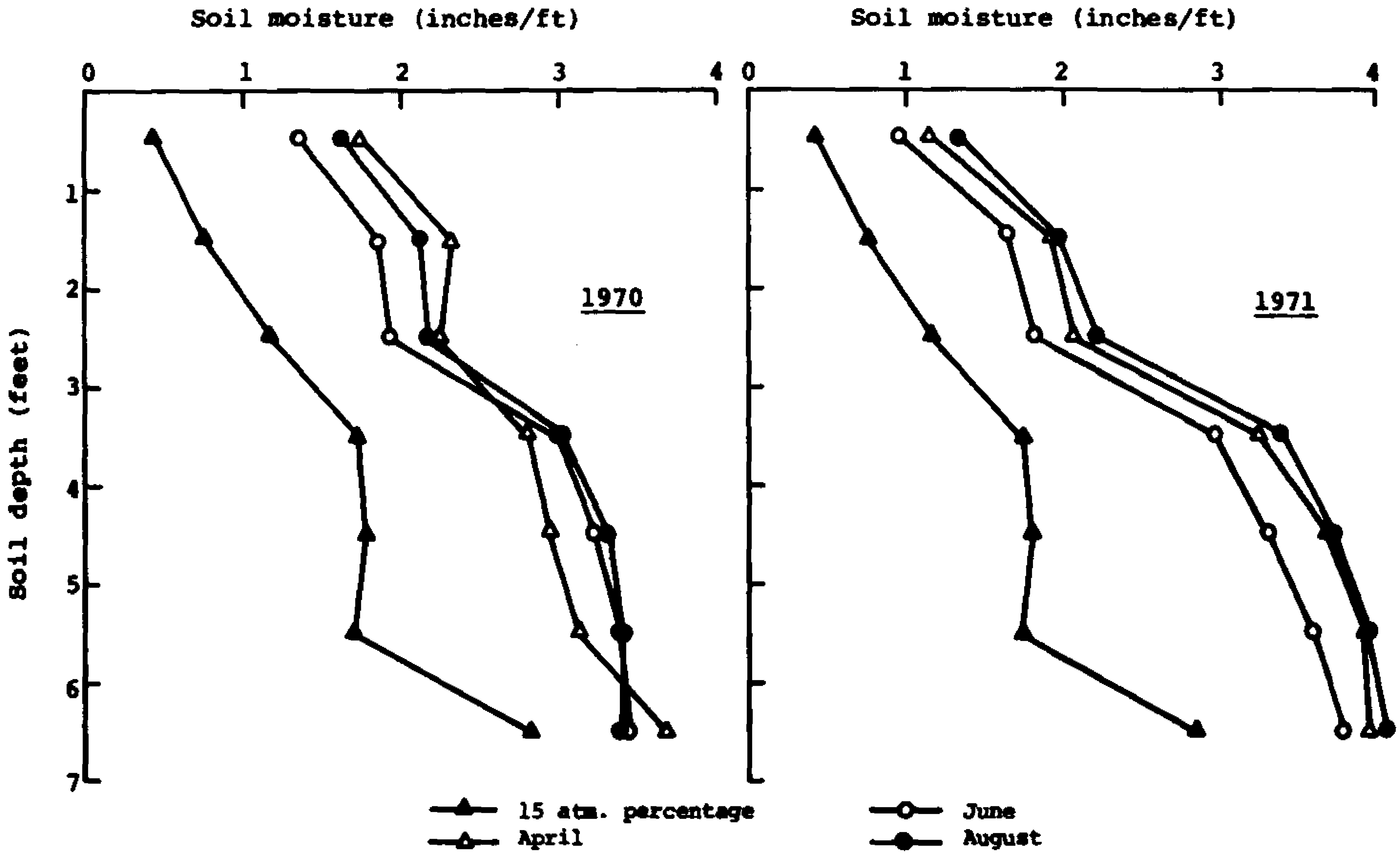

Figure 13. Soil moisture depletion curves for plot 10-3.

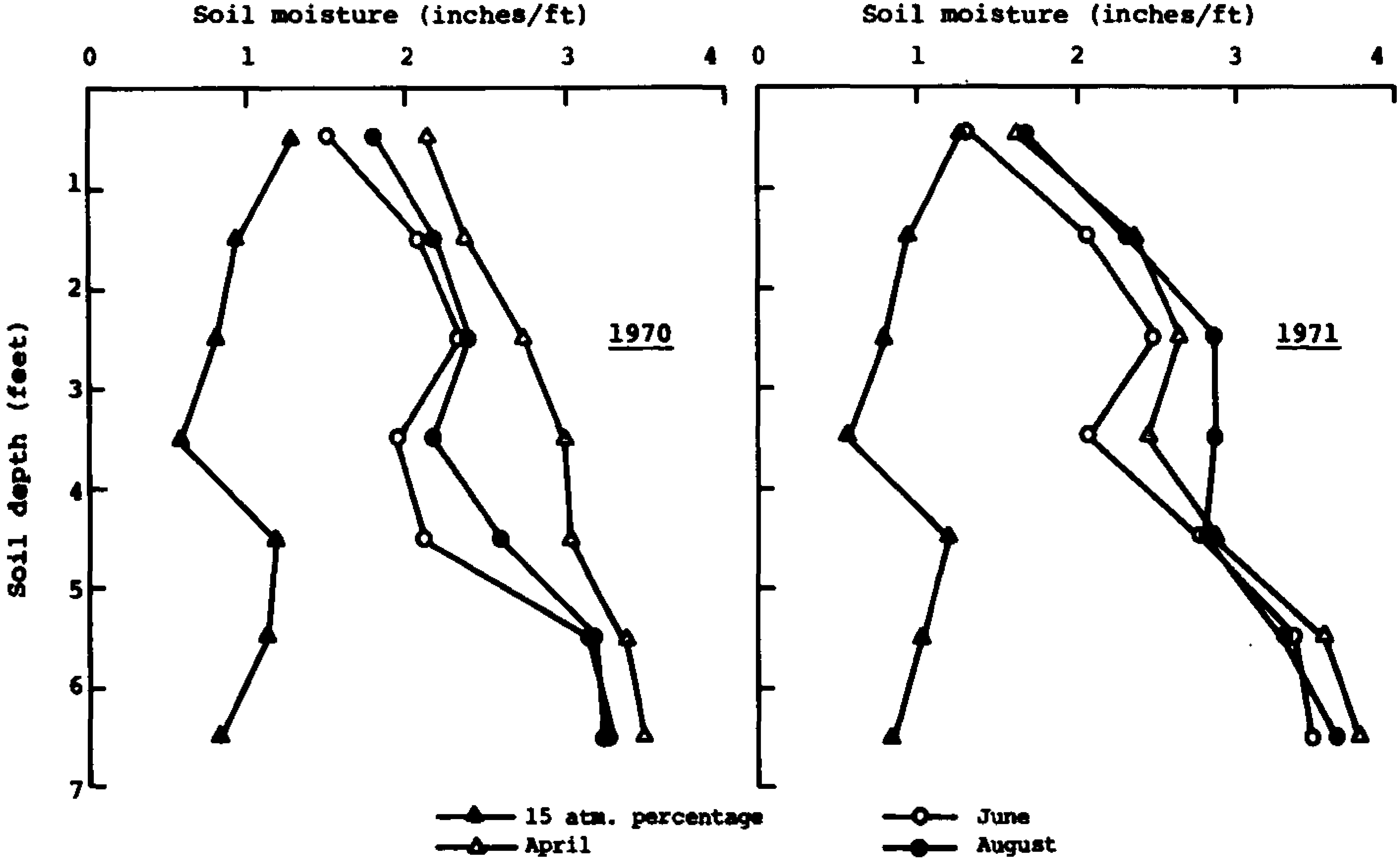

Figure 14. Soil moisture depletion curves for plot 7.

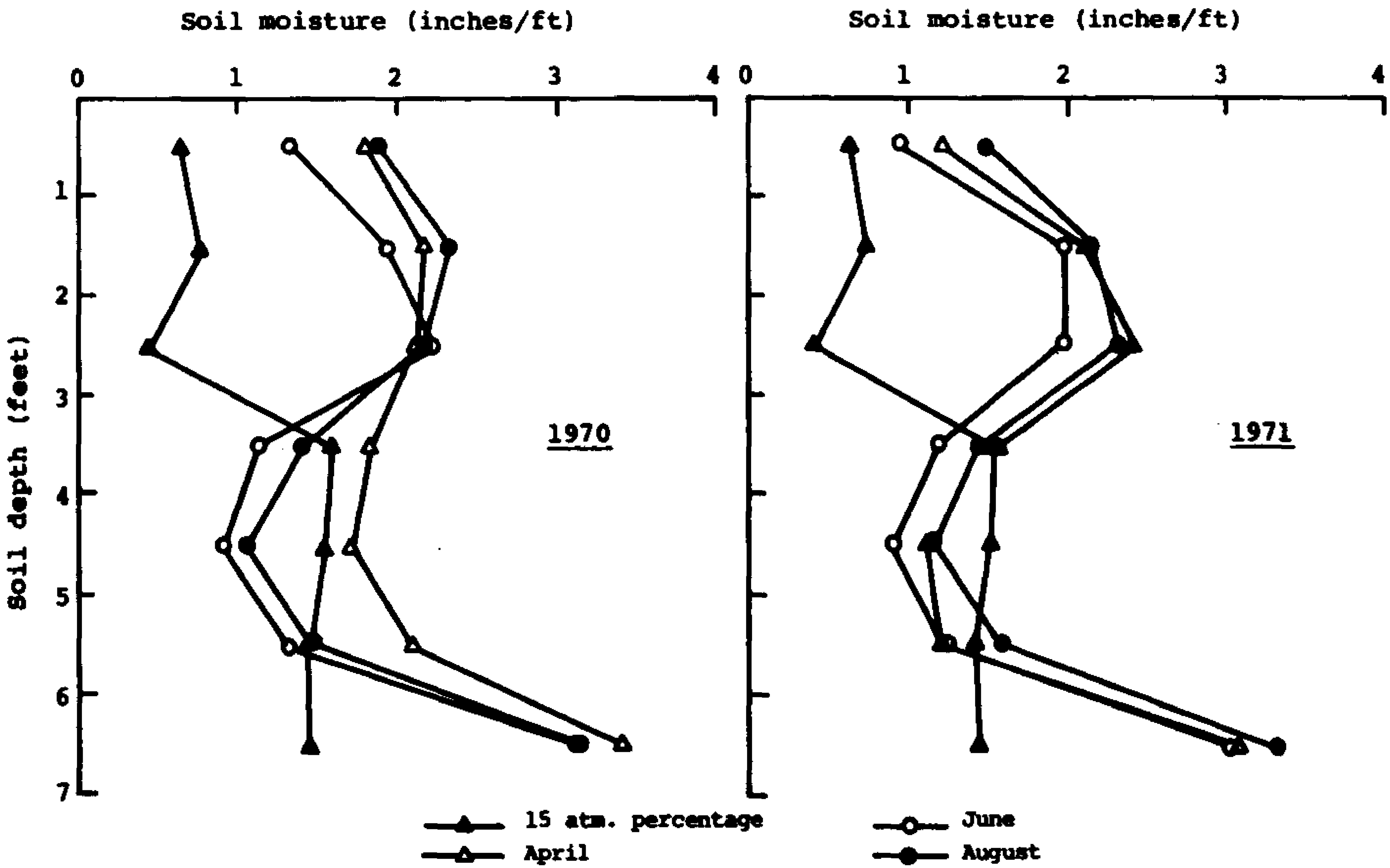

Figure 15. Soil moisture depletion curves for plot 10-2.

had tree roots well distributed down to 3 ft; almost 50% of the roots sampled were found below 2 ft. Roots were distributed deeply and moisture was consequently depleted at greater depths on this plot. This was not the case on other plots where 75 to 90% of the roots sampled were in the surface foot of soil. Bay and Boelter (1963) studied soil moisture trends in red pine stands and never found moisture contents depleted to the theoretical wilting point during their study.

Distribution of Loblolly Pine Roots

Root data were summarized and will be discussed in the following sections. The percentage of oven-dry mass of roots in each size class and in all size classes combined are presented by depth intervals.

By size class. -- In general, roots of the larger size classes were not encountered as frequently when depth of sampling increased. This trend was definitely more pronounced with the larger-sized roots than with smaller root size classes. As a consequence, there was a great deal of variation in distribution of large roots, i.e. those greater than 1 cm in diameter. Coile (1940) did not try to determine significant differences in weight of roots in size classes above 0.3 inch because of the large variation. He stated that considerable data would have been necessary to make valid comparisons of larger-sized roots.

An increase in mass of roots in two size-classes, 1.0 to 2.0 cm and 2.0 to 4.0 cm, was observed on plots 10-1, 10-2 and 15 from the surface down to about 2 ft as shown in Tables 5, 6 and 7. On these plots, percentage of mass of larger-sized roots varied but did tend to increase from the surface downward. Schultz (1972) also observed an increase of larger roots at depths of 15 to 45 cm.

Within the smaller root size-classes, i.e., those less than 1 cm, the majority of the root mass was found in the surface 6 inches of soil and the percentage mass decreased with increasing depth. This trend was consistent on all plots. Schultz (1972), working with slash pine, found that 50% of the total root-surface area was in the top 30 cm of the soil. He found the remaining roots to be evenly distributed between 30 and 120 cm and further stated that rooting below 120 cm was very sporadic except under the stem of each tree. Schultz (1972) and Moir and Bachelard (1969) also found that fine roots decreased with increasing depth in the soil.

On wet sites. -- The wet-site plots were located on the minor stream terraces and characteristically have a high water table, especially in the winter months. Soil mottling was evident at depths of 12 to 24 inches. Soil color determinations are presented in Tables 21 through 30 in Appendix B.

Table 5. Percentage distribution of oven-dry root mass by size class and depth for Plot 10-1.

Depth	Size classes								Average for all classes combined
	< 1.0 mm	1.0 mm-2.5 mm	2.5 mm-0.5 cm	0.5 cm-1.0 cm	1.0 cm-2.0 cm	2.0 cm-4.0 cm	4.0 cm-8.0 cm	> 8.0 cm	
Feet	Percent								
0.5	48.45	38.42	45.68	39.62	16.08	53.30	-	-	42.00
1.0	17.41	13.35	16.84	32.47	35.57	46.70	-	-	34.77
1.5	12.59	8.45	9.09	17.44	14.43	-	-	-	8.50
2.0	10.69	12.81	11.32	6.52	33.92	-	-	-	9.77
2.5	4.83	20.84	9.36	3.95	-	-	-	-	3.36
3.0	2.76	3.81	4.68	-	-	-	-	-	0.94
3.5	1.72	2.32	3.03	-	-	-	-	-	0.60
4.0	1.55	-	-	-	-	-	-	-	0.06
Total	100.00	100.00	100.00	100.00	100.00	100.00	-	-	100.00

Table 6. Percentage distribution of oven-dry root mass by size class and depth for Plot 10-2.

Depth	Size classes								Average for all classes combined
	< 1.0 mm	1.0 mm- 2.5 mm	2.5 mm- 0.5 cm	0.5 cm- 1.0 cm	1.0 cm- 2.0 cm	2.0 cm- 4.0 cm	4.0 cm- 8.0 cm	> 8.0 cm	
Feet	Percent								
0.5	41.64	35.96	37.27	19.06	-	24.76	-	-	18.29
1.0	13.60	10.71	14.93	16.74	17.06	31.72	-	-	21.37
1.5	11.31	9.89	17.36	21.80	22.08	-	-	-	13.29
2.0	9.51	15.51	10.52	3.11	56.19	-	-	-	18.61
2.5	7.22	4.43	6.80	16.69	4.67	43.52	-	-	20.73
3.0	2.89	5.35	1.58	9.61	-	-	-	-	2.64
3.5	13.00	16.59	11.09	7.67	-	-	-	-	3.73
4.0	0.83	1.56	0.45	5.32	-	-	-	-	1.34
Total	100.00	100.00	100.00	100.00	100.00	100.00	-	-	100.00

Table 7. Percentage distribution of oven-dry root mass by size class and depth for Plot 15.

Depth	Size classes								Average for all classes combined
	< 1.0 mm	1.0 mm-2.5 mm	2.5 mm-0.5 cm	0.5 cm-1.0 cm	1.0 cm-2.0 cm	2.0 cm-4.0 cm	4.0 cm-8.0 cm	> 8.0 cm	
Feet	Percent								
0.5	51.60	37.10	28.56	24.46	8.40	63.25	-	-	29.44
1.0	13.51	22.74	24.37	24.87	56.39	-	-	-	27.15
1.5	15.20	20.33	38.44	38.90	35.21	-	-	-	30.36
2.0	13.32	13.21	6.73	10.33	-	-	-	-	6.29
2.5	4.50	3.30	1.90	1.44	-	36.75	-	-	6.47
3.0	1.68	0.64	-	-	-	-	-	-	0.11
3.5	-	2.29	-	-	-	-	-	-	0.15
4.0	0.19	0.39	-	-	-	-	-	-	0.03
Total	100.00	100.00	100.00	100.00	100.00	100.00	-	-	100.00

The greatest percentage of roots (all size-classes combined) were found in the surface layer on Plots 18, 4, 5 and 1 -- 81.85, 73.15, 58.96, and 53.84%, respectively. Data for these plots are presented in Tables 8, 9, 10 and 11. Lorio et al. (1972) found a higher concentration of loblolly pine roots of all size classes in the 0- to 20-cm depth on flat sites.

Turner (1936) reported the percentages of total cross-sectional area of shortleaf pine roots in the upper 18 inches of the profile to be 96.7, 92.5, and 87.1 for Caddo, Hanceville, and Susquehanna soils, respectively. Turner attributed the higher root concentration in the Caddo series to poor soil aeration because the soil was flat and poorly drained. Coile (1937) reported on the vertical distribution of the various size-classes of loblolly pine roots from a 35-year-old stand growing in Alamance loam. There was a preponderance of the smallest size-class of roots, less than 0.1 inch in diameter, near the surface. The location of this size-class was important to Coile because it indicated the location of the greatest water-absorbing surfaces.

Many other researchers have reported similar findings for root distribution, especially in relation to the top 6 inches of soil profiles. Billings (1938) studied roots of shortleaf pine and found 56 to 64% of all roots in the top 6 inches. He found 17 to 25% in the next 6 inches. Eighty percent of all roots found were from 0.01 to 0.1 inch in

Table 8. Percentage distribution of oven-dry root mass by size class and depth for Plot 18.

Depth	Size classes								Average for all classes combined
	< 1.0 mm	1.0 mm-2.5 mm	2.5 mm-0.5 cm	0.5 cm-1.0 cm	1.0 cm-2.0 cm	2.0 cm-4.0 cm	4.0 cm-8.0 cm	> 8.0 cm	
Feet	Percent								
0.5	70.78	80.04	73.24	80.14	85.38	-	-	-	81.85
1.0	22.47	17.65	17.67	6.93	9.52	100.00	-	-	10.53
1.5	2.97	0.15	0.78	2.43	-	-	-	-	0.97
2.0	2.38	1.08	3.38	10.50	5.10	-	-	-	5.61
2.5	0.40	-	-	-	-	-	-	-	0.02
3.0	0.20	-	-	-	-	-	-	-	0.01
3.5	-	0.15	-	-	-	-	-	-	0.01
4.0	0.80	0.93	4.93	-	-	-	-	-	1.00
Total	100.00	100.00	100.00	100.00	100.00	100.00	-	-	100.00

Table 9. Percentage distribution of oven-dry root mass by size class and depth for Plot 4.

Depth	Size classes								Average for all classes combined
	< 1.0 mm	1.0 mm- 2.5 mm	2.5 mm- 0.5 cm	0.5 cm- 1.0 cm	1.0 cm- 2.0 cm	2.0 cm- 4.0 cm	4.0 cm- 8.0 cm	> 8.0 cm	
Feet	Percent								
0.5	52.46	55.78	61.79	83.32	79.48	77.82	41.03	-	73.15
1.0	10.40	12.40	6.83	5.48	6.96	16.88	58.97	-	12.75
1.5	11.14	12.99	13.19	4.68	13.07	5.30	-	-	8.61
2.0	9.96	6.48	3.56	2.29	-	-	-	-	1.53
2.5	10.25	6.37	7.01	-	0.49	-	-	-	1.79
3.0	3.71	4.25	5.84	4.23	-	-	-	-	1.75
3.5	1.78	1.73	1.78	-	-	-	-	-	0.41
4.0	0.30	-	-	-	-	-	-	-	0.01
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	-	100.00

Table 10. Percentage distribution of oven-dry root mass by size class and depth for Plot 5.

Depth	Size classes								Average for all classes combined
	< 1.0 mm	1.0 mm-2.5 mm	2.5 mm-0.5 cm	0.5 cm-1.0 cm	1.0 cm-2.0 cm	2.0 cm-4.0 cm	4.0 cm-8.0 cm	> 8.0 cm	
Feet	Percent								
0.5	30.73	44.77	47.35	36.05	76.80	78.26	-	-	58.96
1.0	18.31	9.37	13.48	21.06	15.37	21.74	-	-	17.87
1.5	11.62	9.37	4.57	22.72	6.53	-	-	-	8.49
2.0	8.76	7.71	10.75	7.73	-	-	-	-	4.51
2.5	13.85	8.68	6.35	7.59	0.60	-	-	-	4.02
3.0	12.11	9.37	12.07	4.85	-	-	-	-	4.30
3.5	4.14	10.73	5.43	-	0.70	-	-	-	1.83
4.0	0.48	-	-	-	-	-	-	-	0.02
Total	100.00	100.00	100.00	100.00	100.00	100.00	-	-	100.00

Table 11. Percentage distribution of oven-dry root mass by size class and depth for Plot 1.

Depth	Size classes								Average for all classes combined
	< 1.0 mm	1.0 mm-2.5 mm	2.5 mm-0.5 cm	0.5 cm-1.0 cm	1.0 cm-2.0 cm	2.0 cm-4.0 cm	4.0 cm-8.0 cm	> 8.0 cm	
Feet	Percent								
0.5	36.69	41.46	55.63	64.93	67.84	56.72	58.45	-	53.84
1.0	38.40	37.07	25.60	13.43	19.89	22.13	-	-	17.35
1.5	13.99	10.70	9.54	10.71	11.47	7.43	-	100.00	17.33
2.0	6.31	6.97	6.72	4.04	-	-	41.55	-	4.70
2.5	0.51	0.66	-	2.83	0.80	-	-	-	0.50
3.0	-	1.41	1.53	-	-	13.72	-	-	5.69
3.5	2.05	0.83	0.98	4.06	-	-	-	-	0.54
4.0	2.05	0.90	-	-	-	-	-	-	0.05
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

diameter. Reed (1939) also worked with shortleaf and loblolly pine root systems. He reported 88.5% of all roots observed to be in the top 6.5 inches or down through the A_2 horizon. Cheyney (1932) found that most of the jack pine roots were in the upper foot of soil, with the greatest percent of these occurring in the top 6 inches.

Root distribution for plot 18 (Table 8) was quite striking; over 90% of the root mass sampled was in the surface foot (Plate 3). The plot had a high water table. A soil pit could only be dug to a depth of 2 ft in October 1973 due to the water table. Almost no roots were found below this depth by core sampling. Schultz (1973) studied slash pine seedlings planted in furrows and beds and found many trees planted in furrows had dead taproots at the water table. The effect of shallow rooting on this plot can not have been very detrimental since this plot represents one of the better sites studied (based on the site index determined from the existing stand of loblolly pine).

On dry sites. -- Plots 9, 7, 10-1 and 10-3, considered to be dry sites, were found to have 52.08, 45.28, 45.05, and 42.00%, respectively, of all roots in the surface 6 inches. These data are shown in Tables 12, 13, 5 and 14. Two plots, 15 and 10-2, summarized in Tables 6 and 7, had a more even distribution of all roots in their profiles with only 29.44 and 18.29%, respectively, in the top 6 inches. Both were located on Ruston soils and were on slopes. Plot

Plate 3. Shallow rooting of loblolly pine on plot 18 where mottles were evident at a depth of 1 ft.

Table 12. Percentage distribution of oven-dry root mass by size class and depth for Plot 9.

Depth	Size classes								Average for all classes combined
	< 1.0 mm	1.0 mm-2.5 mm	2.5 mm-0.5 cm	0.5 cm-1.0 cm	1.0 cm-2.0 cm	2.0 cm-4.0 cm	4.0 cm-8.0 cm	> 8.0 cm	
Feet	Percent								
0.5	32.74	32.81	27.21	55.74	62.95	-	-	-	52.08
1.0	19.28	12.81	25.19	7.71	3.02	-	-	-	9.35
1.5	23.99	34.24	20.96	28.08	22.40	-	-	-	24.07
2.0	16.82	9.06	16.86	4.90	11.63	-	-	-	11.05
2.5	3.59	4.89	0.56	1.72	-	-	-	-	0.84
3.0	2.02	1.01	2.78	-	-	-	-	-	0.64
3.5	0.66	1.87	5.42	-	-	-	-	-	1.15
4.0	0.90	3.31	1.02	1.85	-	-	-	-	0.82
Total	100.00	100.00	100.00	100.00	100.00	-	-	-	100.00

Table 13. Percentage distribution of oven-dry root mass by size class and depth for Plot 7.

Depth	Size classes								Average for all classes combined
	< 1.0 mm	1.0 mm-2.5 mm	2.5 mm-0.5 cm	0.5 cm-1.0 cm	1.0 cm-2.0 cm	2.0 cm-4.0 cm	4.0 cm-8.0 cm	> 8.0 cm	
Feet	Percent								
0.5	37.79	43.94	46.26	51.03	64.29	-	-	-	45.28
1.0	12.94	3.98	12.23	19.86	35.71	100.00	-	-	26.83
1.5	8.56	10.60	20.79	5.88	-	-	-	-	8.29
2.0	8.14	5.68	7.81	13.22	-	-	-	-	7.78
2.5	9.60	19.32	12.57	5.20	-	-	-	-	6.98
3.0	12.32	6.63	0.14	4.81	-	-	-	-	3.26
3.5	8.35	9.47	-	-	-	-	-	-	1.35
4.0	2.30	0.38	0.20	-	-	-	-	-	0.23
Total	100.00	100.00	100.00	100.00	100.00	100.00	-	-	100.00

Table 14. Percentage distribution of oven-dry root mass by size class and depth for Plot 10-3.

Depth	Size classes								Average for all classes combined
	< 1.0 mm	1.0 mm-2.5 mm	2.5 mm-0.5 cm	0.5 cm-1.0 cm	1.0 cm-2.0 cm	2.0 cm-4.0 cm	4.0 cm-8.0 cm	> 8.0 cm	
Feet	Percent								
0.5	52.72	42.23	37.68	33.80	46.68	100.00	-	-	45.05
1.0	14.66	2.70	4.43	16.76	8.57	-	-	-	9.83
1.5	6.10	7.09	9.63	4.43	-	-	-	-	3.84
2.0	7.41	12.05	14.88	11.16	14.86	-	-	-	11.90
2.5	7.74	14.08	28.06	20.27	-	-	-	-	12.51
3.0	7.74	6.31	0.29	4.23	-	-	-	-	2.37
3.5	0.66	8.33	4.78	3.98	9.78	-	-	-	5.76
4.0	2.97	7.21	0.25	5.37	20.11	-	-	-	8.74
Total	100.00	100.00	100.00	100.00	100.00	100.00	-	-	100.00

10-2 was on a steep, short slope and 15 was on a longer, more gradual slope. One reason for the even distribution is that more roots of the larger size classes were found at greater depths on these plots. Lorio et al. (1972) similarly reported that large roots were distributed to greater depths on mound sites than on flats. Sampling variation also may have accounted for this distribution, however. Moir and Bachelard (1969), working in Monterrey pine plantations, found that soil cores immediately adjacent to one another contained large discrepancies in root content.

In general. -- The majority of loblolly pine roots occurred in the surface 2 ft on all plots although roots were found at greater depths. Box (1967) found 83% of the total root biomass of 6-year-old loblolly pines in the upper 18 inches of soil in southeastern Louisiana. Troendle (1970) found 75 to 90% of roots in the upper 2 ft of soil in West Virginia. Stoeckler and Curtis (1960) reported that the upper 2 ft corresponded to the zone of most abundant rooting in Wisconsin. Research cited in the previous discussion also confirms this general result.

Influence of Soil Physical Properties on Root Distribution

Two types of statistical analyses were used to investigate the relationships of the various soil properties studied to the distribution of loblolly pine roots. The soil properties are presented in Tables 21 through 30 in

Appendix B. First, analyses of variance were used to compare differences in soil physical properties between three soil layers. Soil properties at the bottom of the effective rooting-zone were compared to those at the soil depth where no moisture depletion occurred and at the depth 1 ft above the level of no moisture depletion. The effective-rooting-zone depth used was that part of the soil profile containing 75% or more of the total root mass that was sampled on each plot. The three depths selected for each plot are shown in Table 15. In these analyses, values for each soil physical property were combined for all plots.

Similar analyses of variance were run on data separated on the basis of wet-site and dry-site plots. Plots 1, 4, 5 and 18 were considered as wet sites while 9, 10-1, 10-2 and 15 were dry sites (Plate 4). In this analysis, plots 7 and 10-3 were omitted because they were somewhat atypical and I wanted to determine any interaction effects on wet- and dry-site plots. Second, multiple regression analysis by the maximum R^2 improvement procedure was utilized to determine the soil properties that would explain the greatest percent of the total variation encountered in distribution of root mass. A number of multiple regression analyses were run.

Differences in soil properties by depth. -- Many physical properties in the soil layer at the bottom of the effective rooting-zone (Layer 1) were significantly

Table 15. Depths of soil layers at bottom of effective rooting-zone, at zone of no moisture depletion and at zone 1 ft above no moisture depletion.

Plot number	Depth in profile		
	Layer 1[a]	Layer 2[b]	Layer 3[c]
	---------- feet ----------		
1	1.5	3.0	4.0
4	1.0	3.0	4.0
5	1.0	4.0	5.0
7	1.5	6.0	7.0
9	1.5	5.0	6.0
10-1	1.0	4.0	5.0
10-2	2.5	4.0	5.0
10-3	2.5	4.0	5.0
15	1.5	6.0	7.0
18	0.5	3.0	4.0

[a] Horizon at bottom of zone containing 75% or more of root mass

[b] Horizon 1 ft above zone of no-moisture depletion

[c] Horizon with no moisture depletion

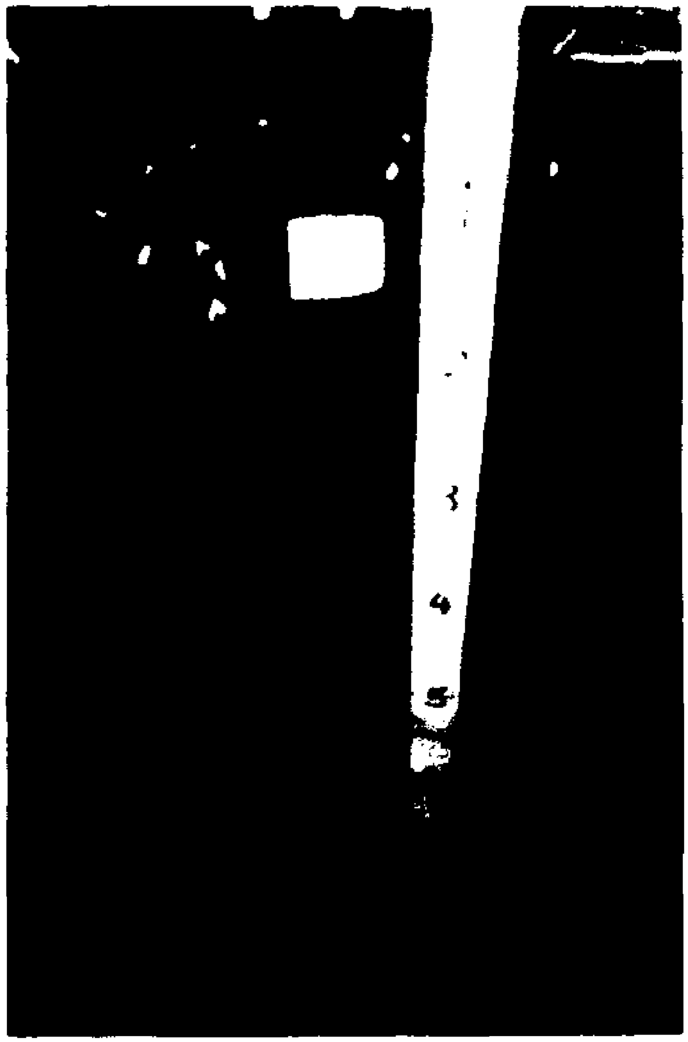

Plate 4. A typical soil pit on a dry site, plot 9.

different from those in the level of no moisture depletion (Layer 3) and those in the level located 1 ft above no depletion of soil moisture (Layer 2). The results of the analyses of variance for comparisons of soil properties by depth comprise Table 16.

Differences in bulk density between the base of the rooting zone and levels where few roots exist, as evidenced by no moisture usage, were highly significant. The increases in bulk density were accompanied by reductions in total pore space. Similar results were reported by Lull (1959) and Broadfoot and Bonner (1966). Capillary porosity decreased significantly (0.05 level) from Layer 1 to Layer 2 while reductions in noncapillary porosity were not significant. However, the differences in total porosity were highly significant. McQueen (1968) reported that the absorbing root weight for 65-year-old stands of Scotch pine was positively related to soil porosity. Since noncapillary porosity did not differ significantly even though it did decrease with depth, the changes in total porosity appear to be influenced primarily by the decreases in capillary porosity.

All of the changes in porosity are related to texture of the soil. The differences in silt content produced the highest F values of any soil property. Decreases in silt content from Layer 1 to Layers 2 and 3 coincided with increases in the sand percentage while clay content remained almost constant. The amount of silt and the clay

Table 16. Results of analysis of variance for comparisons of mean values of soil properties at three depths (75% root-mass basis).

	Mean values for depths			F values	
Soil property	Layer 1[a]	Layer 2[b]	Layer 3[c]	$\bar{X}_1$ vs. $\bar{X}_2$	$\bar{X}_1$ vs. $\bar{X}_3$
Bulk density (g/cm^3)	1.58	1.76	1.75	26.21**	23.86**
Noncap. porosity (%)	9.28	8.30	7.67	1.89	0.74
Cap. porosity (%)	29.05	24.95	26.19	5.57*	2.54
Total porosity (%)	36.86	33.35	33.60	11.09**	9.02**
Sand (%)	55.09	76.13	78.41	11.67**	14.34**
Clay (%)	12.91	12.09	12.59	0.11	0.02
Silt (%)	25.68	11.79	9.00	45.87**	66.09**
Silt + clay (%)	38.35	23.88	21.59	18.54**	24.85**
15 atms. moisture (%)	4.71	5.21	5.09	0.45	0.27
Available moisture (%)	8.49	5.76	4.56	5.13*	10.66*
Percolation rate (inches/hr)	1.07	1.43	2.19	0.16	1.50
Mean soil oxygen content, Apr. - Oct. (%)	19.93	16.45	12.98	8.89**	28.10**
No. weeks with free water table in rooting zone	1.20	5.00	6.35	7.34*	11.98**

a/Horizon at bottom of zone containing 75% or more of root mass

b/Horizon 1 ft above zone of no moisture depletion

c/Horizon with no moisture depletion

fraction have the greatest influence on capillary porosity and the amount of water available to tree roots (Coile and Schumacher 1953, Curlin 1960, and Salter and Williams 1965).

Soil oxygen content is an important factor controlling the development of tree root systems. The analysis of variance technique showed highly significant differences in soil oxygen content in the growing season between Layer 1 and Layers 2 and 3 where roots were considerably less numerous. Oxygen data were those of Hu (1971) and Ward (1972). Patrick et al. (1973) found that increases in oxygen content were associated with increases in subsoil root development of cotton in Louisiana. Patrick et al. (1969) also reported marked differences in sugar cane root content related to oxygen content. Soil oxygen content appeared to be adequate over the growing season at all levels compared, even though the decreases with depth were significant in my study.

Soil Layer 1 contained the highest silt content. There were large decreases in silt content and increases in sand content in Layers 2 and 3. These changes affected capillary porosity and, in turn, the available moisture supply.

The increases in bulk density probably have influenced the depth of rooting also. The mean differences were from only 1.58 to 1.75 g/cm^3 but Gessel and Cole (1958) reported limiting densities for root penetration to be 1.6 to 1.8

g/cm^3 for western conifers. Foil and Ralston (1967) reported that root weight of loblolly pine seedlings was negatively correlated with bulk density over a range in density from 0.8 to 1.4 g/cm^3.

Differences in soil properties between wet and dry sites. -- Analyses of variance were carried out to determine significant differences between soil properties on wet and dry sites. Average values for each depth level on dry sites were compared with corresponding values on wet sites. Table 17 includes the results of these analyses. Differences in the mean values for all properties were tested for the effects of increasing depth in the profile and for possible interaction effects of depth with plots having different moisture regimes.

Differences in percentage of the clay fraction and total porosity for wet and dry plots were significant ($P < .05$). Average values for clay content in three comparisons are as follows:

	Comparison	No. of samples	$\bar{X}$ percent clay
1.	Layers 1, 2 and 3 on wet plots	12	9.05
	Layers 1, 2 and 3 on dry plots	12	14.64
2.	Layer 1 all plots	8	12.85
	Layer 2 all plots	8	11.01
	Layer 3 all plots	8	11.67
3.	Wet plot layer 1	4	8.56
	Wet plot layer 2	4	8.99
	Wet plot layer 3	4	9.59
	Dry plot layer 1	4	17.12
	Dry plot layer 2	4	13.04
	Dry plot layer 3	4	13.75

Table 17. Results of analyses of variance for comparison of soil properties at selected depths on wet and dry sites.

Soil property	Source and F values		
	Wet vs. dry plots	Depth	Interaction
Bulk density (g/cm^3)	0.29	17.62**	0.46
Silt + clay %	0.001	10.50*	0.06
Sand %	1.97	6.66*	1.06
Clay %	7.37*	0.19	0.36
Silt %	2.24	26.16**	0.09
Available water %	0.29	2.32	0.11
Total porosity %	7.93*	5.20	0.44
Capillary porosity %	4.02	2.46	0.14
Wilting point %	1.54	0.06	0.08
Percolation rate (inches/hr)	0.15	0.78	0.70
Soil oxygen content % $\bar{X}$ over two growing seasons	96.60**	68.72**	36.94**

The mean clay percent in the rooting zone of wet plots was about half that on dry plots. The wet plots had lower clay contents in all three layers shown compared to dry plots. Mean clay content increased slightly with depth on the wet plots. Mean clay content decreased from 17.12% in Layer 1 on dry plots to about 13% in Layers 2 and 3. There was no significant interaction with depth as shown in Table 17.

Soil oxygen content varied greatly between wet and dry plots. This is to be expected. The differences were highly significant and the interaction of wet and dry plots with depth was also highly significant ($P < .01$). Average values for soil oxygen content in three comparisons are as follows:

	Comparison	No. of samples	$\bar{X}$ percent soil oxygen
1.	Layers 1, 2 and 3 on wet plots	11	14.47
	Layers 1, 2 and 3 on dry plots	10	19.81
2.	Layer 1 all plots	8	19.89
	Layer 2 all plots	8	16.76
	Layer 3 all plots	5	14.71
3.	Wet plot layer 1	4	19.92
	Wet plot layer 2	4	13.97
	Wet plot layer 3	3	10.18
	Dry plot layer 1	4	20.57
	Dry plot layer 2	4	19.56
	Dry plot layer 3	2	19.27

From the mean values shown (averaged over two growing seasons) one can observe a large decrease in soil oxygen content in the wet-plot soils below the rooting zone. The decrease does not occur on the dry plots even during the growing season.

In Layer 1, soil oxygen content differed very little between wet and dry plots. The mean oxygen content of Layers 2 and 3 on the dry plots was about the same as that in Layer 1 on the wet plots. Since few roots were found in Layers 2 and 3 on the dry plots, reduced oxygen content in Layers 2 and 3 on the wet plots does not appear to be a limiting factor to the growth of loblolly pine roots at these depths. Instead, the major factor limiting the deeper distribution of loblolly pine roots on the wet-site plots appears to be the high water table (Zahner 1955, Burton 1971, and McMinn and McNab 1971).

Relationship of Selected Soil Physical Properties to Root Distribution by Multiple Regression Analyses

Step-wise multiple regression analyses were run to determine the soil physical properties that influenced the distribution of various size-classes of roots in the soil profile. A maximum R^2 improvement procedure was utilized to determine which soil property accounted for or explained the greatest proportion of the total variation. Here, total variation refers to the amount of variation explained by all soil properties used in any single analysis.

Many regression analyses were run. In a few analyses, root mass data were totaled for cores from the 20 samples for each plot. Others utilized root masses by each size class and depth segment from individual cores on each plot.

In some analyses, root-mass data were grouped by size-class combinations. Depth position in the profile was included as a variable in part of the analyses, whereas other regressions investigated the effects of the soil properties on different size classes at the various sample depths.

In the discussions that follow, the soil properties for a best equation were selected for each analysis. The best equation is defined as the one that explains the greatest percent of the total variation. The equation selected as best is usually the one in which the soil properties show the greatest significance. It is also the one where the addition of another variable does not significantly increase the percentage of variation explained or change the significance level of the previous variables.

Step-wise regressions using six variables with depth not included as a variable. -- Multiple regression analyses were run with the following selected soil properties: silt plus clay percent, bulk density, clay percent, non-capillary porosity, capillary porosity, and field capacity. Both individual and combination size-classes were utilized. The results of these analyses are presented in Table 18. The soil properties and their significance levels for the different size classes are grouped by 1/2-ft depth segments and the soil properties are abbreviated.

In general all six of the variables together accounted for only a small percentage of the variation occurring in

Table 18. Determination of best equations to explain variation in root mass with six variables but depth not included as a variable.

Root size class	Depth in feet	Soil properties	Percent of variation explained	Percent variation with all variables
< 1.0 mm	0.5	S+C[b]**, Db[a]*	5.9	6.8
	1.0	S+C**, FC[c]**	9.0	14.0
	1.5	FC*, CP[d]	3.2	3.5
	2.0	CP*, FC	2.5	2.8
	2.5	Clay*	3.4	4.5
	3.0	S+C*	4.8	6.3
	3.5	Db*, CP	4.1	6.8
	4.0	S+C**, FC**, Db**, CP**, Clay**	34.7	35.1
1.0-2.5 mm	0.5	S+C**, Db**	12.2	16.3
	1.0	S+C**, FC**	18.7	27.2
	1.5	FC*, S+C	2.6	4.2
	2.0	CP*, FC	5.0	5.8
	2.5	N-C.P[e]*, CP*, S+C	3.8	5.5
	3.0	CP*	3.8	4.0
	3.5	Db*, S+C	4.3	7.2
	4.0	N-C.P, CP	6.1	7.5
< 0.5 cm	0.5	S+C**, Db**	7.7	10.8
	1.0	S+C**, FC**	10.4	18.7
	1.5	Db**, N-C.P**	4.6	6.4
	2.0	CP**	3.6	4.3
	2.5	N-C.P**, FC	3.7	4.7
	3.0	FC*	3.3	3.8
	3.5	N-C.P**, CP	7.7	10.7
	4.0	N-C.P, CP	4.9	7.5
0.5-1.0 cm	0.5	S+C*, Db	2.6	2.9
	1.0	CP*	2.4	3.7
	1.5	Db**	2.0	4.1
	2.0	CP	0.2	2.0
	2.5	N-C.P**, FC	3.7	4.7
	3.0	Db	0.4	0.8
	3.5	Db**, S+C**	7.9	8.3
	4.0	FC	1.4	3.1
1.0-2.0 cm	0.5	Clay**	4.3	5.3
	1.0	N-C.P	1.0	2.5
	1.5	Db	1.6	2.7
	2.0	CP*, Db	3.6	4.8
	2.5	N-C.P*	2.7	4.1
	3.0	-	-	-
	3.5	S+C, CP	3.5	3.9
	4.0	FC	3.1	4.1

Table 18. --Continued.

Root size class	Depth in feet	Soil properties	Percent of variation explained	Percent variation with all variables
2.0-4.0 cm	0.5	Clay, S+C	0.6	1.2
	1.0	N-C.P**	3.6	5.1
	1.5	Db*, N-C.P*, Clay*, S+C	3.6	3.7
	2.0	-	-	-
	2.5	N-C.P*	3.0	4.0
	3.0	S+C**, N-C.P*, Clay*, S+C	8.2	8.8
	3.5	-	-	-
	4.0	-	-	-
> 4.0 cm	0.5	N-C.P**, Db**, CP	13.9	15.1
	1.0	CP	0.2	1.1
	1.5	FC, Clay, S+C	3.0	4.2
	2.0	FC	2.0	3.0
	2.5	-	-	-
	3.0	-	-	-
	3.5	-	-	-
	4.0	-	-	-

[a] Db = bulk density

[b] S+C = silt plus clay percent

[c] FC = field capacity

[d] CP = capillary porosity

[e] N-C.P = noncapillary porosity

— = no samples obtained

root distribution regardless of size class or depth. The highest percentage of variation explained, 35.1%, was in roots less than 1.0 mm in diameter at a depth of 4.0 feet. Here, no variables were significant until five variables were included in the equation; then all five were highly significant, accounting for 34.7 out of the total of 35.1% with all six variables.

The size-class grouping of all roots less than 0.5 cm is very important as this grouping includes the fine roots primarily involved in absorption of moisture and nutrients. Researchers have used different limits for fine root classification as follows: Armson (1972) less than 1 mm, Safford and Bell (1973) less than 3 mm, and Lorio et al. (1972) less than 5 mm. I have chosen the limit of less than 5 mm (0.5 cm) for fine roots. To the 0.5-ft soil level, silt plus clay and bulk density were highly significant ($P < .01$), while in the next 6 inches, down to 1.0 ft, silt plus clay and field capacity were highly significant. At 1.5 ft, bulk density was highly significant. At 2 ft, noncapillary porosity became significant. From this depth down through 4 ft in the profile, either noncapillary or capillary porosity were important factors affecting the distribution of fine roots.

An examination of all individual root size-classes in the surface 6 inches showed that silt plus clay and bulk density affected smaller size roots and clay was an

important property to larger roots. Similarly, in the next 6-inch zone, silt plus clay and field capacity accounted for the most variation with smaller roots and either capillary or noncapillary porosity explained more variation with larger root sizes.

There did not seem to be any other consistent trends for soil property influences on a particular root size-class at any selected depth with these particular soil variables. Other analyses were more useful.

Four-variable regressions with depth not included as a variable. -- An effort was made to clarify the important soil influences on root distribution by using different variables and also by picking certain variables which are less related than silt plus clay and clay, for instance, as in the analyses previously discussed. The selected variables were sand, clay, bulk density and total porosity. The results of these analyses are included in Table 19. Even with fewer variables, it is extremely difficult to select soil properties that explain most of the variation within size-class groups at individual depths. For instance, there is no trend evident in the significance of soil properties at the various depths within the smallest root size class. At different depths the properties that are significant also differ. Additionally, very little of the total variation is explained by only four variables.

Table 19. Determination of best equations to explain variation in root mass with four variables but depth not included as a variable.

Root size class	Depth in feet	Soil properties	Percent of variation explained	Percent variation (with all variables)
< 1.0 mm	0.5	Sand**, Db[a]	5.6	6.5
	1.0	TP[b]	1.6	2.1
	1.5	Sand	1.1	1.6
	2.0	TP, Db	1.7	1.8
	2.5	Clay*	3.4	3.9
	3.0	Sand*	4.3	5.3
	3.5	TPI, Clay	5.0	5.4
	4.0	Sand**, Db**	13.4	16.5
1.0-2.5 mm	0.5	Sand**, Db**, TP*	7.1	7.1
	1.0	Clay**, Sand*	4.6	5.8
	1.5	Sand, TP	1.2	1.7
	2.0	Db**, TP	4.3	5.2
	2.5	Db*, Clay	2.7	3.5
	3.0	Clay	2.1	3.9
	3.5	TP**	4.3	6.1
	4.0	Clay	2.1	4.9
< 0.5 cm	0.5	Sand**, Clay*	9.7	9.7
	1.0	Sand**, Clay**, Db**	14.3	17.8
	1.5	Sand*, Db**, TP*	17.1	18.0
	2.0	TP	2.4	3.2
	2.5	Sand**	7.1	7.4
	3.0	Db**	10.2	14.1
	3.5	TP**	14.2	15.7
	4.0	Db**, Clay**, TP**, Sand**	35.1	35.1
0.5-1.0 cm	0.5	Sand*, Db, TP	2.1	2.2
	1.0	Db*, TP	3.0	3.5
	1.5	Db*	2.0	4.0
	2.0	Sand	0.1	0.1
	2.5	Sand	2.1	2.7
	3.0	Db	0.4	0.4
	3.5	Db**, Sand**	7.9	8.2
	4.0	Clay	0.9	2.8
1.0-4.0 cm	0.5	Clay**	3.3	3.6
	1.0	Db	0.9	1.5
	1.5	Db	1.4	1.9
	2.0	Db, Sand	2.5	4.0
	2.5	Sand	1.8	2.6
	3.0	Sand**, Db, TP	6.3	6.3
	3.5	Clay	0.8	1.6
	4.0	Clay	1.9	3.3

Table 19. --Continued.

Root size class	Depth in feet	Soil properties	Percent of variation explained	Percent variation (with all variables)
> 4.0 cm	0.5	Sand**	2.8	3.6
	1.0	TP	0.1	0.2
	1.5	Clay	1.0	1.5
	2.0	Clay, Db	1.4	2.2
	-	-	-	-
All roots	0.5	Clay**, Db*, TP	5.4	6.1
	1.0	TP*, Db	4.5	7.4
	1.5	Clay*, TP	3.1	4.7
	2.0	Sand	2.1	2.6
	2.5	TP	1.4	2.6
	3.0	TP**	11.1	16.9
	3.5	TP**, Sand**	13.5	15.6
	4.0	TP*, Sand*, Clay*, Db	16.4	16.4

[a]Db = bulk density

[b]TP = total porosity

— = no samples obtained

One soil physical property, sand, does appear to have a significant influence on roots of all size classes except one (1.0 - 4.0 cm) in the surface 6 inches.

One additional grouping of roots was used for analyses by the maximum R^2 improvement technique. All root-mass data were combined and analyzed by depth intervals. Here, clay, total porosity, and bulk density all appeared to significantly influence root mass in the surface horizons. Total porosity became more significant, as did percent sand, in the deeper soil layers sampled.

Analyses run with these four variables did not explain very much of the total variation encountered in the distribution of loblolly pine roots. It is possible that a greatly increased intensity of sampling could have reduced the total variation because there was a large amount of variation among root-core samples on the various plots.

Multiple regression analyses using seven variables with soil depth included as a variable. -- Another set of stepwise regression equations was utilized in an attempt to explain more of the variation in root distribution and to determine which soil properties had the most significant influence on the distribution of various sizes of roots. The results obtained are presented in Table 20. The most significant soil properties are shown for individual size classes, pairings of root size classes, and all sizes of roots combined. For these analyses the root-mass data

Table 20. Determination of best equations to explain variation in root mass with seven variables including depth as a variable.

Root size classes	Soil properties	Percent of variation explained	Percent variation with all variables
< 1.0 mm	depth**, silt+clay*	57.9	61.3
1.0-2.5 mm	depth**, silt+clay*	32.3	37.0
2.5 mm-0.5 cm	depth**, bulk density*, clay	51.2	55.6
0.5-1.0 cm	depth**, silt+clay	43.4	46.6
1.0-2.0 cm	depth**, percolation rate*	29.5	34.0
2.0-4.0 cm	depth**, noncapillary porosity*	21.3	25.2
4.0-8.0 cm	depth**, field capacity	6.8	9.3
> 8.0 cm	depth, field capacity	1.6	4.2
< 2.5 mm	depth**, silt+clay*	42.7	46.5
2.5 mm-1.0 cm	depth**, bulk density	48.9	53.2
1.0-4.0 cm	depth**, field capacity*	28.3	31.7
> 4.0 cm	depth*, field capacity	6.3	10.9
all roots	depth**, field capacity*	36.7	39.3

from 20 cores on each plot were combined by respective size-classes and depths to comprise a composite sample for each plot. This step eliminated some of the variation in root distribution. Often, in individual root-core samples from a single plot, roots of each size-class were not found at all depths. Combining data from 20 cores produced a single composite sample with data occurring in more size-classes at all depths.

The effects of the inclusion of depth as a variable to account for the variation in root distribution is readily apparent in an examination of Table 20. Soil depth was highly significant ($P < .01$) in all size classes and combinations of size classes except two. The exceptions occurred with the larger sizes of roots. The variation in large root sizes was expected and this variation was pointed out by Coile (1940) in a previous study. The variation in larger root sizes could only be reduced by a greatly increased intensity of sampling.

Another important aspect was the greater percent of total variation explained by the use of all variables, when depth was also considered as a variable. More than 50% of the total variation was accounted for in the smaller-sized root classes. Obviously, soil depth was the major component of the best equations to explain variation in root mass. The second soil property in the equation was not even significant ($P < .05$) in some size classes when depth was the primary variable.

Combining samples to get a composite sample for each plot and the inclusion of depth as a variable made it possible to determine the soil property (other than depth) that had the most influence on roots of a particular size. In the case of the roots of the two smaller classes, less than 2.5 mm, the silt-plus-clay content accounted for a significant percent of the variation encountered.

Bulk density was a significant ($P < .05$) factor in the distribution of roots ranging in diameter from 2.5 mm to 0.5 cm. Its effect was no longer significant when roots of the next larger size were combined as seen in the center portion of Table 20, but bulk density did influence the distribution of roots ranging in size from 2.5 mm to 1.0 cm, regardless of depth in the soil.

The distribution of the larger, noncapillary-sized pores appeared to account for a significant amount of the variation in the 1.0- to 2.0-cm and 2.0- to 4.0-cm root sizes. Both percolation rate and noncapillary porosity are dependent on the quantity of large pores in the soil. Both properties significantly affected the distribution of these sizes of roots in the soils sampled.

Field capacity of the soil had the greatest effect on the distribution of larger-sized roots, though it was not significant until two of the size classes were combined.

When root-mass data were combined for all size classes, the total variation accounted for was reduced. This was

probably due to the greater variation occurring in the larger-sized root classes. With all roots combined, field capacity explained a significant amount of the total variation. Field capacity is affected by the percentage of silt and clay and by the proportion of different-sized pores in the soil.

Soil depth as a variable accounted for most of the variation in root distribution. This was primarily due to the fact that loblolly pines on these soils were quite shallow rooted and the amount of variation in root distribution increased with depth and within larger-sized root classes. Many other researchers have found most of the tree roots to be in the surface horizons (Toumey and Kienholz 1931, Yeager 1935, Hopkins and Donahue 1939, Kalela 1949, Dingle and Burns 1954, Curtis 1964, and others).

SUMMARY AND CONCLUSIONS

Root systems are important to trees for water and nutrient absorption and for storage of food reserves. They function also for physical support and anchorage of the tree. Therefore, extent of root growth in the soil affects the ultimate growth of the whole tree. The development of a tree's root system is largely, but not exclusively, dependent on soil characteristics.

Most studies of the effects of soil physical properties on the development of tree root systems have been done on tree seedlings or young trees. This has been due primarily to the expense involved in studying mature tree root systems.

The major purpose of this study was to determine which soil physical properties, either singly or in combination, affect the distribution of mature loblolly pine root systems and limit or restrict the penetration of pine roots in the soil profile. Secondary objectives were to characterize representative Coastal Plain soils with respect to their capacity to retain soil moisture, and to study the seasonal use of soil moisture by mature loblolly pine stands. Additionally, values of soil moisture and bulk density were determined by nuclear methods and were compared to data obtained by other methods.

Eight quarter-acre circular plots were chosen for this study in mature, 40- to 50-year-old loblolly pine stands on the Lee Memorial Forest in Washington Parish near Bogalusa, Louisiana. The selected plots were located on six different soil series found on varying topographic situations typical of the lower Coastal Plain. Hardwood competition was controlled by injection and mist-blowing of herbicides from 1968 through 1972. Weekly or biweekly measurements of changes in soil moisture at 1-ft intervals were made with a neutron probe during the five-year study period. Biweekly determinations of soil oxygen content were also available on these plots for the 1970 and 1972 growing seasons.

Bulk density readings were taken in situ with a nuclear depth density probe to characterize density changes in the soil profiles. Dry bulk density values were determined by adjustment with appropriate soil moisture contents obtained with the neutron probe.

Collection of soil and root samples was begun in 1973. Soil samples were taken within 6 inches of each access tube from either horizons in the profiles where changes in density occurred or at 1/2-ft intervals. They were obtained by hand from a conventional soil pit and/or from cores extracted with a hydraulic soil sampling machine. Laboratory tests performed on soil samples included determinations of percolation rate; noncapillary, capillary, and total

porosity; bulk density by three methods; field capacity; wilting point; available moisture; moisture content at time of sampling; soil color and mottling; and textural class.

Root sampling consisted of obtaining 20 4 1/2-inch-diameter cores, with the hydraulic coring machine, to a depth of 4 ft around each of the access tubes. After the cores were sectioned into 6-inch segments, the roots were separated from the soil by wet-sieving, divided into eight size classes, and dried.

Analyses of variance techniques for a randomized block design were used to compare bulk density and soil moisture values obtained by different methods. Multiple correlation analyses were used to determine the degree of association among all soil physical properties studied.

Multiple regression analyses, with the maximum R^2 improvement procedure, were employed to determine the soil properties that explained the greatest variation in root distribution for root size classes and by depth in the profile.

Differences between mean bulk density values obtained by the nuclear method and those from standard soil cores were highly significant ($P < .01$). The average value of 66 nuclear density determinations was 1.58 g/cm^3 compared to 1.66 for soil core bulk density.

The mean bulk density of 52 soil cores was 1.70 g/cm^3 compared to 1.73 for resin-coated clods. This difference

was only significant ($P < .05$). Another coating method produced a mean bulk density value lower than that of soil cores. The mean for wax-coated clods was 1.62 g/cm^3 compared to 1.66 for soil cores, and this difference was highly significant ($P < .01$).

The soil core method is widely used for bulk density determinations and is generally considered as a standard method. Any of the four methods can be used for measurements of density where a high degree of precision is unnecessary, as long as the method is specified. The mean bulk density differences from the standard soil-core density are as follows:

(1) density by nuclear back-scattering = 0.08 g/cm^3 lower than soil-core density

(2) density by resin-coated clods = 0.03 g/cm^3 higher than the soil-core density

(3) density by wax-coated clods = 0.04 g/cm^3 lower than soil-core density.

Nuclear density measurements would be especially suitable in studies where access tubes are already installed. Measurements of soil bulk density by the nuclear method are better than other methods because less soil disturbance occurs. The installation of access tubes can be accomplished more quickly than excavations for "undisturbed" soil cores. Results are obtained more quickly because no laboratory work is involved.

Resin-coatings for clods are preferable to wax coatings for three reasons. First, values by the resin-coating method are closer to those of standard cores. Second, the wax-coating method is more tedious in use because the wax must be kept at a constant temperature of 58 to 60°C to function properly. Third, the resin-coating technique is particularly good for coating samples immediately in the field to keep them in a field-moist condition.

The resin-coating method is useful for bulk density determinations in soil layers that are too stony or gravelly to allow the use of the standard core method. It can also be used to advantage with soil clods or fragments taken from below the water table where the standard soil core method can not be utilized at all.

Differences in nuclear and gravimetric soil moisture measurements were highly significant ($P < .01$). However, soil moisture measurements in soils with more than 50% sand were quite close. Since many soils in the Coastal Plain contain more than 50% sand, the nuclear measurement of moisture is an acceptable replacement for more time-consuming gravimetric determinations. The nuclear method is especially well-suited for continual measurement of changes in moisture content in undisturbed soils and its accuracy is more than adequate where relative measurements are required.

Correlation analysis showed soil-core density values to be more highly correlated with wax-coated clod densities

(r = .674) than with densities by other methods. Correlation coefficients for both nuclear and resin-coated density with soil-core density were .635 and .592, respectively.

Positive correlations were found between bulk density values by all four methods and percent sand in the soil, while the relationships with silt were all negative. Negative r values for percent silt were due to decreases in the silt fraction with depth in the profiles and by increases in bulk density values with increasing depth. Nuclear and soil core density were positively related to percent clay with r values of .196 and .325, respectively. Both coating methods of density determinations were negatively related with clay, indicating decreases in density with increasing proportions of clay.

Bulk density of soil cores had a negative correlation, an r value of -.818, with total porosity. Decreases in total porosity are associated with increases in bulk density.

The highest correlation coefficient obtained, .947, was that between the wilting point, 15 atm moisture content, and percent clay in the soil. An r value of .866 was determined for field capacity and percent clay. Soils with high clay contents had high wilting points and clay content was more closely associated with wilting point than field capacity. The moisture removed at 1/3 atmospheres tension is moisture held in larger pores, not

moisture more strongly held by cohesion and adhesion in smaller pores around the clay particles.

All soil moisture constants were negatively correlated with percent sand and positively correlated with percent silt, but the relationships with silt were not as strong as with sand.

Correlation coefficients between available moisture and both field capacity and wilting point were determined to be .934 and .642, respectively. The weaker relationship with wilting point was due to the greater variations in soil moisture content at 15 atm moisture tension.

Depletion of soil moisture was most pronounced in the upper 4 ft of all soil profiles. However, soil moisture did fluctuate below 4 ft on some plots. Soil moisture changes were not detected below 7 ft.

Total moisture stored in the soil was determined monthly for the upper 7 ft of each soil profile during the 5-year study period. In the 0- to 7-ft profile of a poorly-drained soil, moisture always totaled more than 20 inches. On a well-drained soil total moisture was always less than 20 inches.

June was generally the month when soil moisture was at a minimum, primarily due to the depletion of moisture by actively growing pines. Rainfall during the summer months was usually not sufficient to offset the continued evapotranspiration in the pine stands studied, but moisture

did increase slightly from the low point in June. Another period of low soil moisture occurred in October and November in most years. Soil moisture levels did not begin to increase significantly until winter rainfall began in December and January.

Soil moisture actually began to decrease from December 1968 through March 1969 even though rainfall increased in February through March after a relatively dry January. This season was an exception, because in most years soil moisture was at a peak in March and April at the onset of the growing season.

Soil moisture was depleted below the wilting point on only one plot which was located on a fairly steep slope. This plot had tree roots evenly distributed to a depth of 2.5 ft. Some lateral moisture movement may also have occurred downslope at profile depths of 4 to 5 ft.

Generally large roots were not found as frequently as smaller roots at deeper sampling depths. As a consequence there was a great deal of variation in distribution of large roots, i.e. those greater than 1 cm in diameter.

On eight of ten plots, 75% of the total root mass sampled was found to be in the surface 18 inches of the profile. On two plots on a steep slope, 75% of roots sampled were located in the top 30 inches of the profile. On three of four stream-terrace plots 75% of the roots were in the surface 12 inches.

Analysis of variance was used to compare soil properties at the lower level of the zone of rooting to those at levels where moisture was not utilized. The analyses showed the following properties to differ significantly ($P < .01$). Mean bulk density increased from 1.58 to 1.75 g/cm^3, while mean total porosity decreased from 36 to 33%. Average sand content increased from 55 to about 78%, while silt content decreased from 25 to about 9% in the levels where moisture was not utilized and where few roots were found. Mean soil oxygen content during the growing season decreased from 19 to 13%.

Decreases in soil oxygen as a consequence of loss of total pore space and high water tables influenced the depth of rooting on wet sites. Decreases in silt and increases in sand content with depth caused a significant ($P < .05$) decrease in moisture available to tree roots. Increased bulk density from 1.58 to 1.76 g/cm^3 with depth was also a significant factor limiting the deeper distribution of loblolly pine roots.

Soil oxygen content was not a limiting factor to root penetration on dry-site plots. Soil oxygen content below the rooting zone on dry sites was about 19%, essentially the same as the 19% in the rooting zone on wet sites. Below the rooting zone, oxygen content decreased to an average of 10% on wet sites.

Step-wise multiple regression analyses with six variables showed that silt plus clay and bulk density were significant ($P < .01$) influences on fine roots, i.e. those less than 5.0 mm in diameter, in the surface 6 inches of the profile. Fine roots were more abundant where lower bulk densities and higher silt contents occurred. Down to 1 ft, silt plus clay and field capacity were highly significant. At 1.5 ft bulk density was highly significant, while at 2 ft, noncapillary porosity became significant. Root mass of fine roots decreased with depth as bulk density increased and noncapillary porosity decreased. From 2 to 4 ft noncapillary and capillary porosity were important factors affecting the distribution of fine roots. Larger roots in the surface 6 inches were influenced most by clay content. Throughout the rest of the 4 ft profile, capillary and noncapillary porosity explained more of the variation in distribution of larger roots than did other soil properties tested.

Similar regression analyses run with four different variables showed that percent sand had a significant influence on roots in the surface 6 inches. Analyses with four variables, i.e. sand content, bulk density, total porosity, and clay content, did not explain much of the total variation encountered. Considerable variation in root mass coupled with the small number of samples in each depth class resulted in the low percentages of variation explained.

A third set of multiple regression analyses were run with seven variables with depth included as a variable. The root mass data from 20 cores on each plot were combined by size-classes and depths to comprise a composite sample for each plot. Soil depth as a variable accounted for most of the variation in the distribution of root mass. This was primarily due to the fact that loblolly pines on most of these soils were quite shallow rooted and the amount of variation in root distribution increased with depth.

The use of depth as a variable and the use of a composite sample in these analyses indicated the soil properties that accounted for most of the variation in particular root size-classes. Roots smaller than 2.5 mm were influenced most by silt-plus-clay content, while bulk density influenced roots more from 2.5 mm to 1.0 cm. Field capacity had the greatest influence on roots larger than 1.0 cm in diameter. It is evident then that no single soil property has limited the depth of rooting of these mature loblolly pines. The distribution of roots was due to the influences of several properties which affected roots of different sizes. The combined effects of soil oxygen, moisture, and the above soil properties have influenced root distribution, especially on wet sites.

Lower soil bulk densities and higher total porosities in the zones of rooting were conducive to adequate aeration and were beneficial to root development, especially for the

growth of smaller roots important for absorption of water and nutrients. Tree growth was benefited by the higher silt contents in the rooting zones because of the high moisture holding properties of the silt-sized fraction. Soil layers with higher bulk density and lower porosity below zones of rooting influenced the deeper distribution of roots but had a beneficial effect on tree growth by reducing moisture movement down through the soil. Decreases in aeration due to fluctuating water tables influenced root distribution on wet sites.

All sites studied were excellent for loblolly pine growth, although root distribution varied among plots. Roots were more deeply distributed on drier sites, while most roots were found at shallow depths on wetter sites. Shallow rooting on wet sites was not detrimental to loblolly pine growth because the greater amount of soil moisture available for tree growth contributed to higher site index values on wet-site plots than on dry-site plots.

Perhaps future studies on the effects of soil physical properties on the development of tree root systems might be done in stands of seedling- and sapling-size trees. Also in similar studies on soil moisture utilization, dendrometer bands or similar measurement devices could be used to study changes in tree growth.

Two other aspects of root distribution relative to the present study may be worthy of further investigation.

Excavations of root systems of selected trees on wet and dry sites could be useful to check on depth of rooting as determined in this study. Also, an evaluation of the distance of trees in relation to the area where root samples were collected could be of value.

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APPENDIX A

Description of the Soils

The following descriptions of the Bibb, Kalmia, Lexington, Mashulaville, Myatt, Ruston and Stough soils on the study plots are excerpts taken from the descriptive legend for the soil survey of the J. G. Lee, Sr. Memorial Forest as prepared by the Soil Conservation Service, U. S. Department of Agriculture, October 1970.

BIBB SERIES

The soils of the Bibb series are in the coarse-loamy, siliceous, acid, thermic family of Typic Fluvaquents. They are gray, poorly drained and moderately permeable soils located on the floodplains of the local streams. They have formed in loamy alluvium from the Coastal Plains. They are associated with the Bruno, Myatt, Stough and Mashulaville soils. They are more poorly drained than the Bruno and Stough soils, coarser textured than Myatt, Stough and Mashulaville soils, and lack the fragipan found in the Mashulaville and Stough soils.

Bibb soils have dark gray surface layers about 11 inches thick. Texture is silt loam to fine sandy loam. The subsoils are gray fine sandy loam. Permeability is moderate and runoff is slow. Available water capacity is moderate. The reaction is medium acid to strongly acid in the surface and is strongly acid in the underlying layers. Wetness and frequent flooding are problems on these soils.

A representative profile of Bibb fine sandy loam, frequently flooded, was described on the Forest by soil scientists of the Soil Conservation Service, U. S. Department of Agriculture, as follows:

A_1 -- 0-7". Dark gray (10YR 4/1) fine sandy loam; weak coarse subangular blocky structure which breaks into weak fine granular; friable; common pores; few small thin patches of bleached silt grains; medium acid; clear smooth boundary.

A_{12} -- 7-11". Dark gray (10YR 4/1) silt loam with common medium faint dark brown (10YR 4/3) mottles; massive, friable; strongly acid; clear wavy boundary.

B_2 -- 11-24". Gray (10YR 5/1) very fine sandy loam with many coarse distinct strong brown (7.5YR 5/6) mottles; weak very coarse subangular blocky structure; firm; slightly brittle; common pores; thin clay films in some root channels; strong brown is mostly confined to root channels and structural faces; about 15-17 percent clay; strongly acid; clear smooth boundary.

B_3 -- 24-35". Gray (10YR 6/1) fine sandy loam with few fine distinct yellowish brown (10YR 5/6) mottles; massive; firm; few pores; strongly acid; clear smooth boundary.

IIC_1 -- 35-50". Gray (10YR 5/1) fine sandy loam with thin strata light gray (10YR 7/1) loamy fine sand; massive; very friable; few pores in root channels; strongly acid; grandual wavy boundary.

$IIIC_2$ -- 50-60". Dark grayish brown (10YR 4/2) loamy sand with pockets of light gray and gray loamy sand; single grain structure; very friable; strongly acid.

Range in Characteristics: The A_1 horizon ranges from very dark gray (10YR 3/1) to grayish brown (10YR 5/2). Texture is fine sandy loam to silt loam. Thickness ranges from 4 to 12 inches, but very dark gray layers are less than 8 inches thick. The B and C horizons are gray fine sandy loam or very fine sandy loam. Reaction is medium acid to strongly acid in the A horizon and strongly acid in the B and C horizons.

KALMIA SERIES

The Kalmia series is a member of the fine-loamy over sandy or sandy-skeletal, siliceous, thermic family of Typic Hapludults. The soils of the Kalmia series, silty subsoil variant, have very dark grayish brown surface layers and yellowish brown subsoils. These soils are similar to those of the Kalmia series, but are outside the range due to a silt content of 30 to 40 percent in the 20 to 40 inch section.

Kalmia soils occur at relatively low elevations between the uplands and the local stream floodplains. They are similar to the Ruston and Benndale soils but are not as strongly weathered. Kalmia soils are not as red as the Ruston soils.

Permeability is moderate and the surface runoff is medium. The available water capacity is moderate. It is strongly acid in the surface and strongly acid to very strongly acid in the subsoils.

A representative profile of Kalmia fine sandy loam, silty subsoil variant, 0 to 1 percent slopes, was described on the Lee Memorial Forest by the Soil Conservation Service, U. S. Department of Agriculture, as follows:

Ap	--	0-6".	Very dark grayish brown (10YR 3/2) moist, grayish brown (10YR 5/2) dry fine sandy loam; weak very fine granular structure; loose when dry, very friable when moist and non-plastic when wet; many roots and root channels present; strongly acid; abrupt smooth boundary.
B_1	--	6-9".	Yellowish brown (10YR 5/4) fine sandy loam; weak medium subangular blocky structure; friable; many roots, pin holes present; strongly acid; abrupt smooth boundary.
B_{2t}	--	9-26".	Strong brown (7.5YR 5/8) light sandy clay loam; weak medium to coarse sub-angular blocky structure; friable; few patchy clay films on ped surfaces; few pin holes present; very strongly acid; diffuse wavy boundary.
B_{3t}	--	26-40".	Yellowish brown (10YR 5/8) light sandy clay loam; weak medium subangular blocky structure; very friable; few clay bridges between sand grains; few pin holes present; very strongly acid; diffuse wavy boundary.

C -- 40-58". Brownish yellow (10YR 6/6) loamy fine sand with streaks of light brown (10YR 7/3) loamy fine sand; single grain; very friable; very strongly acid.

Range in Characteristics: The A horizon ranges from very dark grayish brown (10YR 3/2) to yellowish brown (10YR 5/4) and from 3 to 7 inches thick. Texture is fine sandy loam or very fine sandy loam. The Bt horizons range from yellowish brown (10YR 5/4) to strong brown (7.5YR 5/8), including brownish yellow (10YR 6/6). Texture is fine sandy loam, sandy clay loam or loam. Reaction is strongly acid or very strongly acid.

LEXINGTON SERIES

The Lexington series is a member of the fine-silty, mixed, thermic family of Typic Paleudalfs. These soils have brown silt loam A horizons, and reddish brown silty clay loam Bt horizons underlain by sandy loam. There is evidence of clay eluviation and secondary clay accumulations below the zone of maximum accumulation.

Lexington soils are nearly level to sloping topography, with slope gradients of 2 to 15 percent most common. These soils are formed in a silty mantle (commonly loess) about 2 to 3 feet thick overlying sandy Coastal Plain material. Lexington soils are well drained and moderately permeable. They are associated with the memphis, Ruston, and Providence soils. Memphis soils have a solum thickness of 48 inches or more with less than 5 percent sand throughout. Ruston soils have more than 15 percent sand, and Providence soils have fragipans.

A typifying pedon of Lexington silt loam (cultivated) is described in the National Cooperative Soil Survey as follows:

Ap	--	0-7".	Brown (10YR 4/3) silt loam, weak fine granular structure; very friable; many fine roots; strongly acid; abrupt smooth boundary. (5 to 9 inches thick).
B_{21t}	--	7-12".	Reddish brown (5YR 5/4) silty clay loam; crushed color strong brown (7.5YR 5/6); moderate medium subangular blocky structure; friable; patchy clay films; strongly acid; clear smooth boundary. (8 to 16 inches thick).
B_{22t}	--	22-34".	Reddish brown (5YR 5/4) silt loam, crushed color strong brown (7.5YR 5/6); moderate medium and coarse subangular blocky structure; friable; patchy clay films; strongly acid; clear smooth boundary. (8 to 16 inches thick).
B_{23t}	--	34-38".	Dark brown (7.5YR 4/4) silt loam with noticeable amount of sand (approximately 15 to 25 percent); weak medium and coarse subangular blocky structure; very friable; thin patchy clay films; strongly acid; clear smooth boundary. (4 to 12 inches thick, this layer begins

from about 27 to 40 inches below the surface).

IIB_{24t} & IIB_3 -- 38-50". Dark brown (7.5YR 4/4) sandy loam; approximately 15 percent clay; weak medium and subangular blocky structure; very friable; few thin patchy clay films; strongly acid; clear smooth boundary. (6 to 30 inches thick).

IIA'_2 & IIB'_{2t} -- 50-85". Alternating layers of yellow (10YR 7/6) loamy sand 1 to 3 inches thick and reddish brown (5YR 4/4)sandy loam 1/4 to 1 inch thick. The yellow loamy sand is loose, single grain, and sand grains are uncoated. The bands of reddish brown sandy loam are very friable or loose and have very weak blocky structure that with slight pressure breaks to weak fine granular structure; some sand grains are coated; there are very few patchy clay films; this brown sandy loam layer has pockets (about 10 percent) of yellow loamy sand or sand. This 35-inch thick horizon consists of about 75 percent yellow loamy sand layers (IIA'2) and the remainder is reddish brown sandy loam (IIB'2t).

From 85 to 112 inches, the yellow loamy sand layers and the dark brown sandy loam layers are about the same thickness, about 2 inches each.

<u>Range</u> <u>in</u> <u>Characteristics</u>: Reaction for the whole profile ranges from medium to strongly acid. Texture of the A horizon is silt loam. Texture of the Bt horizon is silt loam or silty clay loam. Sand content increases with depth. The IIA horizons are loamy sand and sand. The IIB horizons are sandy loam and loam.

MASHULAVILLE SERIES

The Mashulaville series is a member of the coarse-loamy, siliceous, thermic family of Typic Fragiaquults. The soils of the Mashulaville series are gray, poorly drained, slowly permeable, and have fragipans.

Mashulaville soils are on the smooth local stream terraces. They are adjacent to the Myatt, Stough, Kalmia and Bibb soils. They are more poorly drained than the Kalmia and Stough soils and finer textured and more developed than the Bibb soils. Bibb, Myatt and Kalmia lack fragipans.

A representative profile of Mashulaville very fine sandy loam in an area of Myatt-Mashulaville complex was described on the Lee Memorial Forest by the Soil Conservation Service, U. S. Department of Agriculture, as follows:

A_1 -- 0-2". Dark gray (10YR 4/1) very fine sandy loam; weak fine granular structure; slightly hard when dry, friable when moist, abundant roots and partly decomposed litter; worm casts; medium acid; boundary abrupt, smooth.

A_{21} -- 2-6". Gray (10YR 6/1) very fine sandy loam with few, fine distinct yellowish brown (10 YR 5/6) mottles; massive; very firm; abundant worm casts and roots; medium acid; boundary abrupt, smooth.

A_{22x} -- 6-16". Gray (10YR 6/1) very fine sandy loam with few fine distinct yellowish brown (10YR 5/6) mottles; massive, firm; abundant worm casts and root channels; strongly acid; boundary clear, wavy.

A_{23x} -- 16-23". Gray (10YR 6/1) fine sandy loam with few, fine distinct yellowish brown (10YR 5/6) mottles; very firm; massive; few worm casts and pin holes; strongly acid; boundary clear, wavy.

A_{24x} -- 23-28". Gray (10YR 6/1) very fine sandy loam with common, medium distinct yellowish brown (10YR 5/6) mottles; very firm; massive; few pin holes; strongly acid; boundary clear, wavy.

B_x -- 24-48". Gray (10YR 6/1) sandy clay loam with many, medium, distinct yellowish brown (10YR 5/8) mottles; massive; very firm;

few patchy clay film in pores; few pin holes; strongly acid; boundary clear, wavy.

Range in Characteristics: The A1 horizon is dark gray to grayish brown very fine sandy loam or silt loam 1 to 5 inches thick. The A2 horizon ranges from very fine sandy loam or loam. Thickness ranges from 10 to 26 inches. All or part of the horizon may be brittle and compact. The Bx horizon ranges from gray (10YR 5/1) to light brownish gray (2.5YR 6/2). Texture is dominantly sandy clay loam to clay loam, but ranges to heavy fine sandy loam in layers less than 6 inches thick. The reaction ranges from medium acid to strongly acid in the surface layer and is strongly acid in the underlying layers.

MYATT SERIES

The soils of the Myatt series are in the fine-loamy, siliceous, thermic family of Typic Ochraquults. They are gray, poorly drained and slowly permeable soils situated on the smooth local stream terraces. They have formed from old acid alluvium washed from the Coastal Plains. They are associated with the Mashulaville, Stough, Kalmia and Bibb soils. Kalmia and Stough soils are better drained than Myatt, the Bibb soils are coarser textured and less developed than Myatt, and the Stough and Mashulaville have fragipans.

Permeability of Myatt soils is low and surface runoff is slow. The available water capacity is moderate. Reaction is medium to strongly acid in the surface ranging to very strongly acid in the subsoil. Wetness is a problem.

A representative profile of Myatt very fine sandy loam was described on the Lee Memorial Forest by the Soil Conservation Service, U. S. Department of Agriculture, as follows:

A_1 -- 0-6". Dark gray (10YR 4/1) moist, light gray (10YR 7/1) dry, very fine sandy loam; weak, very fine granular structure; slightly hard; many roots; strongly acid; abrupt smooth boundary.

A_{21g} -- 6-12". Gray (10YR 5/1) very fine sandy loam with few fine distinct yellowish brown (10YR 5/6) mottles; weak, medium subangular blocky structure; friable; many roots; strongly acid abrupt smooth boundary.

A_{22g} -- 12-18". Gray (10YR 6/1) very fine sandy loam with many medium distinct yellowish brown (10YR 5/6) mottles; weak medium subangular blocky structure; firm; few thin patchy clay films in pores; roots and root channels are common; few pin holes; very strongly acid, diffuse wavy boundary.

B_{tg} -- 18-48". Gray (10YR 6/1) sandy clay loam with many medium distinct yellowish brown (10YR 5/6) mottles; moderate medium subangular blocky structure; thin patchy clay films; slightly plastic; few roots and pin holes present; very strongly acid.

<u>Range in Characteristics</u>: The A horizon is gray fine sandy loam or very fine sandy loam 12 to 22 inches thick. The B

horizon is gray (10YR 5/1, 6/1) or light brownish gray (10YR 6/2). Texture of the B horizon varies from very fine sandy loam to loam, clay loam, or sandy clay loam. Thickness ranges from 25 to 40 inches. Mottles are dominantly yellowish brown. The reaction is strongly acid to very strongly acid.

RUSTON SERIES

The Ruston series is in the fine-loamy, siliceous, thermic family of Typic Paleudults. Ruston soils are well drained and moderately permeable. Available water capacity is moderate. They have a brown surface and a yellowish red subsoil. Ruston soils occur on moderate to steep slopes and ridgetops. They have developed in loamy Coastal Plains sediments.

A representative profile of Ruston fine sandy loam, 3 to 8 percent slope, was described on the Lee Memorial Forest by the Soil Conservation Service, U. S. Department of Agriculture, as follows:

A_1	--	0-8".	Dark grayish brown (10YR 4/2) fine sandy loam with common medium faint yellowish brown (10YR 5/6) mottles; massive; friable; medium acid; clear wavy boundary.
B & A	--	8-10".	60% yellowish red (5YR 4/6) sandy clay loam and 40% yellowish brown (10YR 5/4) fine sandy loam; weak coarse subangular blocky structure; friable; few clay films in pores; strongly acid; clear smooth boundary.
B_{21t}	--	10-18".	Yellowish red (5YR 4/6) clay loam with few faint yellowish brown mottles; moderate medium subangular blocky structure; friable; many thin clay films; very strongly acid; gradual smooth boundary.
B_{22t}	--	18-28".	Yellowish red (5YR 4/6) sandy clay loam; weak medium subangular blocky structure; friable; few patchy clay films; very strongly acid; clear smooth boundary.
A'_2	--	28'36".	Strong brown (7.5YR 5/6) fine sandy loam with common medium distinct yellowish red (5YR 5/6) mottles; weak coarse subangular blocky structure; friable; slightly brittle; thin pale brown ped coats; very strongly acid; clear wavy boundary.
B'_{21t}	--	36'56".	Red (2.5YR 4/6) sandy clay loam with few fine distinct yellowish brown (10YR 5/6) mottles; weak medium subangular blocky structure; friable; many thin

discontinuous clay films; very strongly acid; gradual smooth boundary.

B'_{22t} -- 56-72". Yellowish red (5YR 5/8) fine sandy loam; weak medium subangular blocky structure; friable; few clay films; very strongly acid.

Range in Characteristics: The A_1 horizon ranges from very dark grayish brown (10YR 3/2) to brown (10YR 5/3). The A_2 horizon ranges from brown (10YR 5/3) to light yellowish brown (10YR 6/4). The B horizons range from yellowish red (5YR 5/6) to red (2.5YR 4/8). Texture is sandy clay loam, clay loam or loam. Reaction is medium acid to strongly acid in the surface layers and very strongly acid in the subsoil.

STOUGH SERIES

The Stough series is in the coarse-loamy, siliceous, thermic family of Fragiaquic Paleudults. The soils of the Stough series are brown with gray mottles and have compact lower subsoils layers. They are somewhat poorly drained and moderately permeable. Surface runoff is slow and available water capacity is moderate. The soil is strongly acid throughout. Wetness and low fertility are the main problems.

Stough soils are on the flat to gently sloping local stream terraces. They have developed in alluvium from Coastal Plain uplands. They are associated with the Myatt, Mashulaville and Kalmia soils. Stough soils are better drained than the Myatt and Mashulaville soils and more poorly drained than the Kalmia soils. In addition, Myatt and Kalmia lack fragipans.

A representative profile of Stough very fine sandy loam, 0 to 1 percent slope, was described on the Lee Memorial Forest by the Soil Conservation Service, U. S. Department of Agriculture, as follows:

A_1 -- 0-4". Dark grayish brown (10YR 4/2) moist, light brownish gray (10YR 6/2) dry, very fine sandy loam; weak, very fine granular structure; slightly hard when dry; many roots; strongly acid; abrupt smooth boundary.

A_2 -- 4-10". Brown (10YR 5/3) very fine sandy loam with common medium distinct yellowish brown (10YR 5/6) mottles and red (2.5YR 4/8) stains on cleavages and in root channels; weak, very fine granular to medium subangular blocky structure; friable; many roots; strongly acid; abrupt wavy boundary.

B_{2t} -- 10-14". Brownish yellow (10YR 6/6) light sandy clay loam with common, medium distinct pale brown (10YR 6/3) mottles; weak medium subangular blocky structure; friable; few soft brown concretions and pin holes present; few patchy clay films; few roots; very strongly acid; gradual wavy boundary.

B_{x1} -- 14-18". Yellowish brown (10YR 5/6) very fine sandy loam with common, medium, distinct gray (10YR 6/1) mottles; weak, medium platy structure; firm; few soft brown concretions and pin holes present; very strongly acid; abrupt, smooth boundary.

B_{x2} -- 18-30". Gray (10YR 6/1) fine sandy loam with common, medium distinct yellowish brown (10YR 5/6) mottles; weak medium to coarse platy structure; firm; slightly brittle; few pin holes present; very strongly acid; abrupt, smooth boundary.

B_{x3} -- 30-58". Yellowish brown (10YR 5/6) fine sandy loam with common, medium, distinct gray (10YR 6/1) mottles; weak medium subangular blocky structure; firm; slightly brittle; patchy clay films on ped faces; very strongly acid.

Range in Characteristics: The A horizon is dark grayish brown to brown very fine sandy loam, fine sandy loam or silt loam 6 to 10 inches thick. The B_{2t} horizons range from yellowish brown (10YR 5/4) to brownish yellow (10YR 6/6). Mottles of gray or light brownish gray are dominant. The B_x horizons are yellowish brown and gray fine sandy loam to light sandy clay loam. Depth to compact and brittle layers ranges from 14 to 27 inches.

APPENDIX B

Soil Profile Descriptions

All ten study plots are described in detail. Sampling data are presented for the following soil physical properties: percolation rate, porosity, texture, bulk density, color, presence of mottling, moisture content at time of sampling, field capacity and wilting point. Moisture content values are shown on an oven-dry weight basis.

Table 21. Soil profile description for plot 1, Stough very fine sandy loam

Depth in profile (Feet)	Percolation rate (Inches/hour)	Porosity (%)			Mechanical analysis (%)			Texture class	Bulk density (g/cm^3)	Soil color		Moisture content at sampling time	Field capacity moisture (%)	Wilting point moisture (%)
		Noncap	Cap	Total	Sand	Silt	Clay			Matrix	Mottles			
0.5	0.272	13.4	27.3	40.7	59.4	33.1	7.5	SL	1.50	10 YR 5/1	*	14.3	6.9	1.6
1.0	0.195	11.5	28.5	40.0	53.8	38.1	8.1	SL	1.51	7.5YR 6/0	7.5YR 5/6	14.9	12.8	2.9
1.25	-	-	-	-	55.6	36.3	8.1	SL	1.57	7.5YR 5/0	7.5YR 6/6	13.8	4.7	2.6
1.5	0.184	11.5	25.9	37.4	65.0	29.4	5.6	SL	1.65	7.5YR 6/0	5 YR 4/6	13.0	13.9	3.9
2.0	0.137	9.4	24.5	33.9	77.5	16.9	5.6	LS	1.78	7.5YR 6/0	5 YR 4/6	12.5	5.1	2.8
2.5	0.289	10.8	23.4	34.2	75.0	17.5	7.5	SL	1.79	7.5YR 7/0	7.5YR 4/6	12.8	11.5	4.1
3.0	0.096	8.0	24.3	32.3	82.5	11.3	6.2	LS	1.82	7.5YR 7/0	7.5YR 3/2	12.4	9.0	3.6
3.5	0.217	9.0	24.8	33.8	78.7	16.3	5.0	LS	1.78	7.5YR 6/0	7.5YR 5/6	13.1	10.1	2.5
4.0	0.094	9.6	24.9	34.5	79.4	10.6	10.0	SL	1.76	5 YR 4/6	7.5YR 7/0	14.5	8.5	3.1
4.5	0.248	8.5	24.9	33.4	75.6	18.8	5.6	LS-SL	1.82	5 YR 5/4	7.5YR 4/0	13.6	6.8	2.0
5.0	0.346	9.3	25.0	34.3	77.5	10.6	11.9	SL	1.77	10 YR 6/1	7.5YR 5/6	22.2	7.4	3.1
5.5	-	-	-	-	85.0	6.3	8.7	LS	1.70	7.5YR 6/0	*	18.1	5.0	3.1
6.0	-	-	-	-	80.0	11.2	8.8	LS	1.70	7.5YR 6/0	*	19.1	9.1	3.1
6.5	-	-	-	-	80.0	11.3	8.7	LS	1.62	7.5YR 5/8	*	1.3	9.3	4.0
7.0	-	-	-	-	86.2	3.8	10.0	LS	1.67	7.5YR 7/0	7.5YR 4/0	19.1	5.1	3.6
8.0	-	-	-	-	80.0	7.5	12.5	SL	1.76	7.5YR 7/0	-	17.8	4.9	3.9
9.0	-	-	-	-	73.7	14.4	11.9	SL	1.72	10 YR 7/2	7.5YR 6/6	15.8	11.3	5.4
9.5	-	-	-	-	83.8	6.2	10.0	LS	1.57	7.5YR 5/6	5 YR 4/6	22.4	6.0	3.0
10.0	-	-	-	-	80.6	10.0	9.4	LS	**	-	-	24.7	5.7	4.2
10.5	-	-	-	-	71.2	12.5	16.3	SL	1.76	7.5YR 7/0	7.5YR 6/6	15.0	8.9	5.8
11.0	-	-	-	-	75.6	10.0	14.4	SL	1.74	7.5YR 7/0	7.5YR 5/6	17.9	7.8	5.3
11.5	-	-	-	-	83.7	6.9	9.4	LS	1.64	7.5YR 7/0	10 YR 6/6	16.5	9.3	4.0
12.0	-	-	-	-	78.7	9.4	11.9	SL	1.76	7.5YR 7/0	7.5YR 5/6	15.1	6.4	4.4
12.5	-	-	-	-	71.2	16.3	12.5	SL	1.72	10 YR 6/4	10 YR 7/1	16.9	12.7	5.8

Table 21. --Continued

Depth in profile (Feet)	Percolation rate (Inches/hour)	Porosity (%)			Mechanical analysis (%)			Texture class	Bulk density (g/cm³)	Soil color		Moisture content at sampling time (%)	Field capacity moisture (%)	Wilting point moisture (%)
		Noncap	Cap	Total	Sand	Silt	Clay			Matrix	Mottles			
13.0	-	-	-	-	73.8	15.6	10.6	SL	1.77	10 YR 7/6	7.5YR 7/0	17.1	12.7	5.7
14.0	-	-	-	-	75.6	7.5	16.9	SL	1.69	7.5YR 7/0	10 YR 6/6	15.6	11.8	5.5
14.5	-	-	-	-	70.6	11.9	17.5	SL	1.70	7.5YR 7/0	*	16.3	15.4	7.8

* Zero value or none observed
**Too sandy to determine bulk density
\- Test not made for this sample

Table 22. Soil profile description for plot 4, Kalmia very fine sandy loam

Depth in profile (Feet)	Percolation rate (Inches/hour)	Porosity (%)			Mechanical analysis (%)			Texture class	Bulk density (g/cm^3)	Soil color		Moisture content at sampling time (%)	Field capacity moisture (%)	Wilting point moisture (%)
		Noncap	Cap	Total	Sand	Silt	Clay			Matrix	Mottles			
0.5	0.109	6.8	31.2	38.0	63.7	27.5	8.8	SL	1.53	10 YR 3/1	*	20.7	19.6	4.5
1.0	0.080	7.1	29.0	36.1	63.1	27.5	9.4	SL	1.62	10 YR 5/3	*	16.2	11.3	4.4
1.5	0.269	5.3	30.5	35.8	62.5	24.4	13.1	SL	1.65	10 YR 5/4	10 YR 6/2	18.2	19.8	5.8
2.0	0.201	5.1	30.1	35.2	62.4	23.8	13.8	SL	1.66	10 YR 6/4	10 YR 6/1	18.7	19.3	6.3
2.5	0.205	5.0	30.8	35.8	63.1	25.0	11.9	SL	1.65	10 YR 5/4	5 YR 4/4	17.0	19.2	5.7
2.75	-	-	-	-	64.4	23.1	12.5	SL	1.70	10 YR 7/1	5 YR 5/6	18.2	21.8	6.5
3.0	0.029	4.2	30.3	34.5	66.9	22.5	10.6	SL	1.79	7.5YR 7/0	10 YR 6/4	15.9	18.5	5.5
3.25	-	-	-	-	70.0	20.6	9.4	SL	1.82	10 YR 6/4	10 YR 7/1	14.0	8.5	5.5
3.5	0.016	5.0	26.4	31.4	75.6	15.6	8.8	SL	1.79	10 YR 5/3	10 YR 7/1	13.7	12.6	4.2
4.0	-	-	-	-	75.0	13.1	11.9	SL	1.77	10 YR 7/1	7.5YR 4/4	14.5	9.6	5.1
4.25	-	-	-	-	82.5	7.5	10.0	LS	1.73	10 YR 6/4	10 YR 7/1	14.8	7.4	4.3
5.0	-	-	-	-	81.2	8.8	10.0	LS	1.70	5 YR 4/4	*	17.8	15.4	5.9
5.5	-	-	-	-	73.7	12.5	13.8	SL	1.59	7.5YR 5/6	7.5YR 7/0	20.2	22.4	8.3
6.0	-	-	-	-	47.5	34.4	18.1	L	1.62	10 YR 6/3	10 YR 7/1	21.0	19.9	10.0
6.5	-	-	-	-	58.7	24.4	16.9	SL	1.53	10 YR 5/6	10 YR 7/1	20.3	7.6	18.0
7.0	-	-	-	-	46.2	34.4	19.4	L	1.58	10 YR 6/3	5 YR 4/8	22.5	8.8	21.3

*Zero value or none observed
-Test not made for this sample

Table 23. Soil profile description for plot 5, Bibb silt loam

Depth in profile (Feet)	Percolation rate (Inches/hour)	Porosity (%)			Mechanical analysis (%)			Texture class	Bulk density (g/cm^3)	Soil color		Moisture content at sampling time (%)	Field capacity moisture (%)	Wilting point moisture (%)
		Noncap	Cap	Total	Sand	Silt	Clay			Matrix	Mottles			
0.5	0.075	11.5	33.5	45.0	43.7	46.9	9.4	L	1.40	2.5YR 6/0	*	19.0	12.6	3.1
1.0	0.004	8.1	26.7	37.8	44.4	45.0	10.6	L	1.69	10 YR 6/3	*	14.6	19.9	4.2
1.5	0.000	6.7	28.2	34.9	53.1	33.1	13.8	SL	1.80	-	-	14.2	14.5	5.6
2.0	0.001	5.5	28.1	33.6	56.3	30.0	13.7	SL	1.82	10 YR 6/4	2.5YR 7/0	14.8	12.0	5.7
2.5	0.000	5.2	26.8	32.0	58.7	31.9	9.4	SL	1.88	7.5YR 6/0	5 YR 5/6	15.3	17.8	4.2
2.75	-	-	-	-	59.4	30.6	10.0	SL	1.77	7.5YR 7/0	10 YR 6/6	17.4	7.4	4.6
3.0	0.000	4.2	27.8	32.0	58.7	29.4	11.9	SL	1.86	7.5YR 6/0	7.5YR 5/8	17.0	18.2	5.0
3.5	0.000	5.0	29.1	34.1	60.6	26.9	12.5	SL	1.84	7.5YR 6/0	7.5YR 5/8	17.8	9.2	5.6
3.75	-	-	-	-	61.3	23.7	15.0	SL	1.67	10 YR 6/1	7.5YR 5/8	21.0	19.2	6.4
4.0	0.014	4.5	27.2	31.7	71.2	17.5	11.3	SL	1.87	10 YR 5/6	10 YR 7/1	21.1	10.3	5.0
4.5	-	-	-	-	88.8	6.2	5.0	S	**	-	-	26.2	2.8	1.2
4.75	-	-	-	-	92.5	4.4	3.1	S	**	-	-	23.1	2.3	0.8
5.0	-	-	-	-	81.9	13.7	4.4	LS	**	-	-	24.1	5.6	2.3

* Zero value or none observed
**Too sandy to determine bulk density
- Test not made for this sample

Table 24. Soil profile description for plot 7, Lexington silt loam

Depth in profile (Feet)	Percolation rate (Inches/hour)	Porosity (%)			Mechanical analysis (%)			Texture class	Bulk density (g/cm^3)	Soil color		Moisture content at sampling time (%)	Field capacity moisture (%)	Wilting point moisture (%)
		Noncap	Cap	Total	Sand	Silt	Clay			Matrix	Mottles			
0.5	.493	15.2	30.0	45.2	45.6	44.4	10.0	L	1.31	10 YR 5/6	*	19.2	17.7	4.5
1.0	.312	11.4	29.1	40.5	44.4	35.6	20.0	L	1.43	7.5YR 5/4	7.5YR 5/6	18.4	19.8	8.3
1.25	-	-	-	-	52.5	32.5	15.0	SL	1.55	7.5YR 5/6	*	16.6	15.8	6.7
1.5	.476	9.0	31.3	40.3	46.2	35.0	18.8	L	1.53	7.5YR 5/6	7.5YR 5/8	18.3	18.5	7.1
1.75	-	-	-	-	50.0	33.7	16.3	L	1.46	7.5YR 5/6	7.5YR 4/4	17.8	12.2	6.5
2.0	.279	9.9	32.2	42.1	66.9	25.0	8.1	SL	1.51	-		13.3	10.3	3.8
2.5	.061	6.8	30.8	37.6	53.1	31.9	15.0	SL	1.60	10 YR 5/6	5 YR 2/2	16.5	15.3	5.8
3.0	.008	5.7	29.0	34.7	69.4	23.1	7.5	SL	1.71	-		12.2	6.5	2.8
3.5	.020	7.9	26.0	33.9	76.2	18.8	5.0	SL	1.75	7.5YR 5/6	5 YR 5/6	12.0	8.1	2.8
3.75	-	-	-	-	72.4	21.3	6.3	SL	1.70	10 YR 5/5	*	11.3	5.1	2.1
4.0	.292	9.3	21.7	31.0	77.5	17.5	5.0	LS	1.76	10 YR 6/6	10 YR 6/4	10.8	6.5	2.4
4.25	-	-	-	-	76.9	19.4	3.7	LS	1.81	10 YR 6/6	10 YR 7/4	10.5	3.8	1.9
4.5	3.524	5.7	24.7	30.4	81.2	13.8	5.0	LS	1.69	7.5YR 5/6	5 YR 5/8	11.6	6.7	1.7
4.75	-	-	-	-	80.6	6.3	13.1	SL	1.69	10 YR 5/6	10 YR 6/4	15.5	9.1	6.1
5.0	.140	4.7	27.1	31.8	75.0	10.6	14.4	SL	1.76	10 YR 7/4	*	14.1	7.5	5.2
5.5	.002	5.9	28.6	34.5	77.4	6.3	16.3	SL	1.71	7.5YR 5/8	*	16.8	9.9	7.2
6.0	*	5.6	27.3	32.9	76.9	13.1	10.0	SL	1.70	10 YR 6/4	*	10.7	7.7	4.4
6.25	-	-	-	-	83.7	3.8	12.5	LS	1.70	10 YR 5/6	*	14.1	6.1	4.8
6.5	.001	5.1	27.2	32.3	76.9	5.6	17.5	LS	1.69	10 YR 6/6	2.5YR 4/6	15.3	10.9	5.6
7.0	.010	7.3	26.4	33.7	81.8	4.4	13.8	SL	1.77	10 YR 6/6	2.5YR 4/6	14.5	7.9	3.9
7.5	.001	5.8	25.5	31.3	82.5	2.5	15.0	SL	1.75	10 YR 6/6	2.5 YR 4/5	14.6	8.9	5.9
8.0	*	6.9	25.0	31.9	83.7	2.5	13.8	LS	1.75	10 YR 7/4	10 YR 5/6	13.8	6.9	5.6

* Zero value or none observed
- Test not made for this sample

Table 25. Soil profile description for plot 9, Ruston sandy loam

Depth in profile (Feet)	Percolation rate (Inches/hour)	Porosity (%)			Mechanical analysis (%)			Texture class	Bulk density (g/cm^3)	Soil color		Moisture content at sampling time (%)	Field capacity moisture (%)	Wilting point moisture (%)
		Noncap	Cap	Total	Sand	Silt	Clay			Matrix	Mottles			
0.5	0.037	10.0	25.4	35.4	57.4	36.3	6.3	SL	1.65	10 YR 5/3	*	14.1	14.6	2.6
1.0	0.108	7.8	28.0	35.8	53.1	32.5	14.4	SL	1.59	5 YR 4/4	*	16.2	11.7	6.0
1.25	-	-	-	-	48.7	28.8	22.5	L	1.56	5 YR 4/6	*	18.2	19.9	8.8
1.5	0.110	5.7	30.0	35.7	51.2	29.4	19.4	L	1.61	5 YR 4/6	*	17.7	17.8	6.8
1.75	-	-	-	-	58.7	25.0	16.3	SL	1.73	5 YR 4/4	*	14.7	15.2	6.1
2.0	0.205	11.5	22.6	34.1	73.7	17.5	8.8	SL	1.71	5 YR 4/4	*	12.1	8.4	3.9
2.25	-	-	-	-	72.5	20.0	7.5	SL	1.66	5 YR 5/4	*	10.9	10.7	3.3
2.5	0.516	14.6	18.8	33.4	80.0	13.7	6.3	LS	1.71	5 YR 5/4	*	9.4	10.2	2.7
2.75	-	-	-	-	80.0	11.3	8.8	LS	1.45	5 YR 4/4	*	8.8	6.9	2.6
3.0	1.508	16.2	19.3	35.5	81.2	13.8	5.0	LS	1.68	7.5YR 5/4	*	8.2	4.7	2.4
3.25	-	-	-	-	85.0	10.0	5.0	LS	1.44	7.5YR 5/4	*	8.3	11.1	1.9
3.5	1.984	18.0	17.4	35.4	83.1	11.9	5.0	LS	1.60	7.5YR 6/6	*	7.5	3.4	1.6
3.75	-	-	-	-	85.0	10.0	5.0	LS	1.55	10 YR 5/4	*	7.5	6.7	1.5
4.0	1.380	19.2	15.6	34.8	75.6	18.8	5.6	LS-SL	1.63	10 YR 6/4	*	7.8	4.8	2.0
4.25	-	-	-	-	73.1	13.8	13.1	SL	1.72	5 YR 4/6	*	11.5	7.6	4.5
4.5	0.672	15.2	16.5	31.7	82.5	15.0	2.5	LS	1.73	10 YR 6/3	*	12.6	8.2	5.5
4.75	-	-	-	-	71.9	12.5	15.6	SL	1.73	2.5YR 4/6	*	13.5	9.6	7.0
5.0	0.138	9.8	21.4	31.2	71.3	10.6	18.1	SL	1.75	5 YR 5/8	*	13.2	10.3	6.9
5.5	0.003	4.9	25.8	30.7	70.0	7.5	22.5	SCL	1.76	5 YR 5/6	*	13.4	13.8	7.5
6.0	0.003	5.8	25.9	31.7	73.8	10.0	16.2	SL	1.76	2.5YR 5/6	*	12.5	10.2	6.6
6.5	0.280	8.1	25.0	33.1	71.9	10.0	18.1	SL	1.74	2.5YR 4/6	*	12.5	8.8	5.8
7.0	0.068	7.7	24.6	32.3	75.0	9.4	15.6	SL	1.72	2.5YR 4/6	*	11.9	11.2	6.7
7.5	0.043	8.0	24.5	32.5	79.4	5.6	15.0	SL	1.73	2.5YR 4/6	*	11.6	11.6	6.4
8.0	0.722	12.6	23.2	35.8	78.7	4.4	16.9	SL	1.67	2.5YR 4/6	*	12.7	9.2	7.6
8.5	0.623	12.1	22.8	34.9	81.2	2.5	16.3	SL	1.70	2.5YR 4/6	*	12.8	13.9	6.8

Table 25. --Continued

Depth in profile (Feet)	Percolation rate (Inches/hour)	Porosity (%)			Mechanical analysis (%)			Texture class	Bulk density (g/cm^3)	Soil color		Moisture content at sampling time (%)	Field capacity moisture (%)	Wilting point moisture (%)
		Noncap	Cap	Total	Sand	Silt	Clay			Matrix	Mottles			
9.0	0.176	10.1	23.3	33.4	78.1	5.6	16.3	SL	1.74	2.5YR 4/6	*	12.1	9.2	6.3
9.5	0.191	9.6	23.7	33.3	79.4	5.6	15.0	SL	1.72	2.5YR 5/8	*	11.8	14.6	6.4
10.0	0.137	8.6	23.5	32.1	80.0	5.6	14.4	SL	1.75	5 YR 4/8	*	11.8	7.3	5.8
10.5	3.676	8.9	23.2	32.1	80.0	3.1	16.9	SL	1.77	2.5YR 5/8	*	12.2	14.4	7.6
11.0	0.334	8.1	22.9	31.0	78.1	3.1	18.8	SL	1.80	2.5YR 4/6	*	12.6	9.5	7.6
11.5	0.046	3.5	27.0	30.5	80.6	3.8	15.6	SL	1.73	2.5YR 4/8	*	10.2	13.9	7.5
12.0	0.311	4.1	27.5	31.6	79.4	4.4	16.2	SL	1.73	2.5YR 5/6	*	12.2	10.5	7.8
12.5	0.081	4.4	27.9	32.3	80.6	3.8	15.6	SL	1.74	5 YR 5/8	*	12.7	14.7	7.9
13.0	0.961	3.8	28.1	31.9	79.4	7.5	13.1	SL	1.69	5 YR 6/8	*	12.1	13.3	7.1
13.5	0.002	3.7	27.3	31.0	83.8	5.6	10.6	LS	1.77	5 YR 6/8	*	11.8	12.0	6.6
14.0	0.110	3.3	27.0	30.3	81.9	5.6	12.5	SL	1.78	5 YR 5/8	*	12.5	9.6	6.6
14.5	0.209	6.5	27.3	33.8	81.2	6.9	11.9	SL	1.74	5 YR 7/8	*	12.2	11.6	6.8
15.0	0.012	5.5	27.0	32.5	78.8	8.1	13.1	SL	1.70	5 YR 7/8	*	17.5	14.9	6.8
16.0	0.038	6.8	25.4	32.2	83.7	3.8	12.5	LS	1.72	5 YR 6/8	*	12.9	12.1	6.1
17.0	0.174	6.1	23.9	30.0	84.4	4.4	11.2	LS	1.78	5 YR 5/6	*	11.4	11.0	5.3
18.0	0.133	6.3	27.3	33.6	83.7	4.4	11.9	LS	1.67	5 YR 5/6	*	12.0	11.1	5.6

*Zero value or none observed
-Test not made for this sample

Table 26. Soil profile description for plot 10-1, Ruston sandy loam

Depth in profile (Feet)	Percolation rate (Inches/hour)	Porosity (%)			Mechanical analysis (%)			Texture class	Bulk density (g/cm^3)	Soil color		Moisture content at sampling time (%)	Field capacity moisture (%)	Wilting point moisture (%)
		Noncap	Cap	Total	Sand	Silt	Clay			Matrix	Mottles			
0.5	3.605	15.6	25.4	41.0	68.8	26.2	5.0	SL	1.50	10 YR 5/4	*	22.5	5.5	2.1
1.0	0.628	11.6	25.7	37.3	66.9	24.4	8.7	SL	1.50	7.5YR 6/6	*	12.1	7.0	3.4
1.25	-	-	-	-	60.7	26.2	13.1	SL	1.49	7.5YR 5/6	*	14.3	18.6	5.2
1.5	0.571	12.3	27.8	40.1	56.2	26.3	17.5	SL	1.46	5 YR 5/6	*	15.3	14.4	6.6
1.75	-	-	-	-	54.4	28.1	17.5	SL	1.57	5 YR 5/8	*	16.9	19.8	7.8
2.0	2.035	10.3	28.4	38.7	58.7	23.8	17.5	SL	1.53	5 YR 5/6	*	15.9	17.8	6.6
2.5	1.139	12.6	25.8	38.4	73.8	16.2	10.0	SL	1.54	5 YR 5/6	*	12.0	15.7	4.3
3.0	2.541	15.3	23.9	39.2	83.7	11.3	5.0	LS	1.47	7.5YR 6/6	*	8.0	9.9	2.4
3.5	2.094	17.6	16.9	34.5	88.8	7.5	3.7	LS	1.59	10 YR 7/4	*	6.8	7.4	1.7
3.75	-	-	-	-	93.1	5.0	1.9	S	1.49	10 YR 7/4	*	6.1	5.7	1.4
4.0	2.085	19.3	13.6	32.9	93.1	6.3	0.6	S	1.59	10 YR 7/4	*	6.0	6.6	1.2
4.5	2.005	20.4	12.5	32.9	94.4	3.7	1.9	S	1.63	10 YR 7/4	*	5.8	2.1	1.3
4.75	-	-	-	-	91.2	5.0	3.8	S	**	10 YR 6/4	*	5.1	3.9	0.5
5.0	4.427	17.8	13.2	31.0	95.0	2.5	2.5	S	1.63	10 YR 6/4	*	4.6	4.2	0.9
5.5	9.989	23.8	10.6	34.4	80.6	8.1	11.3	SL	1.55	5 YR 5/8	*	8.8	12.6	4.1
5.75	-	-	-	-	79.4	5.0	15.6	SL	1.62	7.5YR 6/6	*	11.9	13.8	6.8
6.0	7.437	17.3	14.8	32.1	78.8	3.1	18.1	SL	1.63	7.5YR 6/6	*	12.6	13.9	7.4
6.25	-	-	-	-	78.1	3.8	18.1	SL	1.80	7.5YR 6/6	5 YR 5/8	13.0	20.3	7.2
6.5	0.013	9.2	24.0	33.2	86.2	3.8	10.0	LS	1.75	7.5YR 6/6	2.5YR 5/6	10.4	12.7	5.1
6.75	-	-	-	-	78.8	3.7	17.5	SL	1.75	5 YR 6/8	2.5YR 6/8	13.7	19.7	8.1
7.0	0.005	6.5	25.4	31.9	80.6	4.4	15.0	SL	1.78	7.5YR 6/6	5 YR 4/8	14.1	14.5	8.3
7.5	0.013	6.3	25.6	31.9	81.3	2.5	16.2	SL	1.79	5 YR 5/6	*	12.3	14.5	7.1
8.0	0.002	4.5	24.2	28.7	75.6	5.0	19.4	SL	1.87	7.5YR 6/6	5 YR 5/4	12.1	15.5	7.9
8.5	0.001	4.8	25.7	30.5	81.9	3.7	14.4	SL	1.86	7.5YR 6/6	10 YR 4/6	11.8	10.5	6.3

Table 26. --Continued

Depth in profile (Feet)	Percolation rate (Inches/hour)	Porosity (%)			Mechanical analysis (%)			Texture class	Bulk density (g/cm^3)	Soil color		Moisture content at sampling time (%)	Field capacity moisture (%)	Wilting point moisture (%)
		Noncap	Cap	Total	Sand	Silt	Clay			Matrix	Mottles			
9.0	0.003	5.1	24.2	29.3	76.9	3.1	20.0	SCL-SL	1.83	7.5YR 5/8	10 YR 7/6	13.6	15.5	8.4
9.5	0.003	5.3	27.6	32.9	78.1	3.8	18.1	SL	1.82	7.5YR 5/8	*	13.6	11.3	8.2
10.0	0.026	7.7	24.2	31.9	80.0	4.7	16.3	SL	1.77	7.5YR 6/6	*	14.8	14.8	7.0
10.5	0.013	10.2	25.8	36.0	82.5	6.2	11.3	LS	1.69	10 YR 7/4	*	13.2	15.3	5.8
11.0	0.014	6.5	27.0	33.5	76.3	5.0	18.7	SL	1.72	10 YR 7/1	*	15.4	17.0	8.3
11.5	0.003	5.3	26.4	31.7	81.3	5.6	13.1	SL	1.77	10 YR 8/1	*	14.5	13.3	6.3
12.0	0.005	8.1	25.5	33.6	80.0	5.0	15.0	SL	1.72	10 YR 6/6	*	14.7	14.0	7.3
12.5	0.173	6.6	27.9	34.5	84.4	3.7	11.9	LS	1.78	10 YR 7/6	*	15.5	16.9	6.6
13.0	0.013	7.4	28.0	35.4	84.4	4.4	11.2	LS	1.72	10 YR 6/6	*	24.2	14.0	5.8

* Zero value or none observed

**Too sandy to determine bulk density

- Test not made for this sample

Table 27. Soil profile description for plot 10-2, Ruston sandy loam

Depth in profile (Feet)	Percolation rate (Inches/hour)	Porosity (%)			Mechanical analysis (%)			Texture class	Bulk density (g/cm^3)	Soil color		Moisture content at sampling time (%)	Field capacity moisture (%)	Wilting point moisture (%)
		Noncap	Cap	Total	Sand	Silt	Clay			Matrix	Mottles			
0.5	*	17.9	23.4	41.3	76.2	21.3	2.5	LS	1.42	10 YR 4/3	*	21.0	16.4	3.2
1.0	1.732	12.6	20.1	32.7	76.9	18.1	5.0	LS	1.61	7.5YR 5/4	*	10.5	15.3	3.5
1.25	-	-	-	-	70.6	16.3	13.1	SL	1.60	5 YR 4/8	*	3.1	10.2	4.1
1.5	.050	11.1	26.9	38.0	70.0	11.9	18.1	SL	1.57	5 YR 4/6	*	15.5	14.8	5.9
1.75	-	-	-	-	75.6	11.3	13.1	SL	1.48	5 YR 4/4	*	13.6	9.7	6.9
2.0	5.581	16.5	20.4	36.9	77.5	10.0	12.5	SL	1.55	5 YR 5/6	*	10.9	13.3	3.8
2.25	-	-	-	-	79.4	12.5	8.1	LS	1.45	5 YR 5/6	*	8.8	9.6	3.0
2.5	1.655	22.5	15.0	37.5	86.9	8.1	5.0	LS	1.64	7.5YR 5/6	*	6.8	9.1	2.6
2.75	-	-	-	-	88.7	5.0	6.3	LS	1.50	7.5YR 5/6	*	5.8	6.0	2.3
3.0	1.187	18.6	15.8	34.4	83.1	8.1	8.8	LS	1.69	7.5YR 5/6	*	7.7	7.9	2.6
3.25	-	-	-	-	76.9	5.6	17.5	SL	1.62	5 YR 5/6	*	11.5	12.8	6.0
3.5	1.391	7.1	22.8	29.9	71.8	6.3	21.9	SCL	1.85	5 YR 5/6	*	13.3	12.4	8.8
3.75	-	-	-	-	73.7	5.0	21.3	SCL	1.57	5 YR 5/6	*	13.6	16.2	9.0
4.0	4.008	8.1	24.8	32.9	71.2	8.8	20.0	SL-SCL	1.78	5 YR 5/8	*	14.0	14.1	9.2
4.5	5.400	5.0	27.1	32.1	74.3	4.4	21.3	SCL	1.84	5 YR 5/6	*	13.0	18.2	7.9
5.0	16.686	6.8	26.5	33.3	78.7	6.3	15.0	SL	1.74	2.5YR 5/6	*	4.3	14.3	6.4
5.5	.693	5.4	27.1	32.5	76.9	8.1	15.0	SL	1.76	2.5YR 5/6	*	10.6	16.0	7.4
6.0	2.020	7.9	25.3	33.2	80.0	7.5	12.5	SL	1.73	2.5YR 4/8	5 YR 5/8	10.4	11.1	4.8
6.5	.091	6.5	24.3	30.8	78.1	4.4	17.5	SL	1.76	2.5YR 5/6	10 YR 7/3	11.1	13.6	6.5
7.0	.090	6.6	22.6	29.2	78.1	7.5	14.4	SL	1.76	10 YR 6/4	5 YR 5/6	10.0	14.1	5.0
7.5	.093	10.1	20.1	30.2	83.7	3.8	12.5	SL	1.71	10 YR 6/4	2.5YR 4/6	11.4	12.8	7.5
8.0	*	6.4	25.0	31.4	71.9	2.5	25.6	SCL	1.76	10 YR 7/1	2.5YR 4/6	15.6	14.2	10.6
8.5	.004	5.6	27.0	32.6	78.1	4.4	17.5	SL	1.78	10 YR 6/6	2.5YR 4/6	13.9	14.1	8.9
9.0	.153	5.4	27.0	32.4	75.0	7.5	17.5	SL	1.77	2.5YR 4/6	10 YR 7/1	13.7	17.0	7.1
9.5	.065	8.2	26.4	34.6	80.6	4.4	15.0	SL	1.74	2.5YR 4/6	*	14.1	14.7	5.7

Table 27. --Continued

Depth in profile (Feet)	Percolation rate (Inches/hour)	Porosity (%) Noncap	Porosity (%) Cap	Porosity (%) Total	Mechanical analysis (%) Sand	Mechanical analysis (%) Silt	Mechanical analysis (%) Clay	Texture class	Bulk density (g/cm^3)	Soil color Matrix	Soil color Mottles	Moisture content at sampling time (%)	Field capacity moisture (%)	Wilting point moisture (%)
10.0	.172	6.6	26.5	33.1	80.0	6.2	13.8	SL	1.77	10 YR 7/4	2.5YR 4/6	17.4	17.3	5.5
10.25	-	-	-	-	-	-	-	-	1.58	-	-	17.6	-	-
10.5	.018	6.9	28.5	35.4	84.3	3.8	11.9	LS	1.76	7.5YR 6/6	10 YR 6/1	18.4	13.4	5.3
11.0	-	-	-	-	86.2	5.0	8.8	LS	1.65	10 YR 7/4	*	16.4	10.6	0.3
11.5	-	-	-	-	86.8	6.9	6.3	LS	1.63	10 YR 7/4	*	15.6	8.1	3.5
12.0	-	-	-	-	57.5	29.4	13.1	SL	1.65	10 YR 7/4	10 YR 7/1	17.8	23.3	6.4
12.5	-	-	-	-	36.6	38.4	25.0	L	1.57	10 YR 7/4	10 YR 7/1	21.4	28.9	10.7
13.0	-	-	-	-	44.4	28.1	27.5	CL	1.42	10 YR 8/1	10 YR 7/4	23.7	30.9	12.4
13.5	-	-	-	-	25.0	44.4	30.6	CL	1.48	10 YR 3/6	10 YR 7/4	25.8	35.0	1.7
14.0	-	-	-	-	13.7	46.3	40.0	SC-SCL	1.42	10 YR 4/3	10 YR 7/1	27.0	39.7	16.5
14.5	-	-	-	-	22.4	41.3	36.3	CL	1.56	10 YR 4/3	10 YR 7/1	15.2	36.5	14.8

* Zero values or none observed

- Test not made for this sample

Table 28. Soil profile description for plot 10-3, Ruston sandy loam

Depth in profile (Feet)	Percolation rate (Inches/hour)	Porosity (%) Noncap	Cap	Total	Mechanical analysis (%) Sand	Silt	Clay	Texture class	Bulk density (g/cm^3)	Soil color Matrix	Mottles	Moisture content at sampling time (%)	Field capacity moisture (%)	Wilting point moisture (%)
0.5	1.948	4.3	35.6	39.9	76.3	18.7	5.0	LS	1.75	10 YR 4/2	*	10.1	15.6	2.1
1.0	0.452	5.9	30.8	36.7	74.4	21.9	3.7	LS	1.65	10 YR 5/6	*	9.6	9.1	2.5
1.25	-	-	-	-	72.1	24.1	3.8	SL	1.71	10 YR 5/6	*	9.5	9.1	2.5
1.5	0.038	2.4	28.4	30.8	70.0	24.4	5.6	SL	1.75	10 YR 5/4	*	10.1	15.2	2.9
1.75	-	-	-	-	66.3	25.0	8.7	SL	1.77	10 YR 5/6	*	7.6	10.5	3.4
2.0	0.018	3.2	27.3	30.5	69.4	21.9	8.7	SL	1.78	10 YR 5/6	*	9.1	16.7	3.8
2.5	0.040	5.0	28.0	33.0	75.0	16.2	8.8	SL	1.77	5 YR 4/8	*	9.7	16.8	4.0
3.0	0.032	4.5	28.7	33.2	75.0	10.0	15.0	SL	1.73	5 YR 5/8	*	11.7	18.3	6.5
3.5	*	1.7	30.0	31.7	76.2	4.4	19.4	SL	1.75	5 YR 5/8	*	14.7	18.9	7.8
4.0	0.068	2.0	31.1	33.1	80.0	2.5	17.5	SL	1.73	5 YR 5/8	*	15.6	19.0	7.8
4.5	0.073	2.2	31.7	33.9	79.4	5.6	15.0	SL	1.76	5 YR 5/8	*	16.4	18.4	7.2
5.0	0.002	2.2	32.7	34.9	78.8	3.7	17.5	SL	1.77	5 YR 5/8	*	16.1	11.3	8.2
5.25	-	-	-	-	78.8	3.7	17.5	SL	1.74	7.5YR 5/6	*	16.8	20.9	8.2
5.5	0.030	2.6	32.6	35.2	78.5	6.5	15.0	SL	1.68	10 YR 6/6	5 YR 4/8	17.3	16.1	7.5
5.75	-	-	-	-	78.8	5.6	15.6	SL	1.58	5 YR 4/8	*	18.7	11.8	7.7
6.0	-	-	-	-	77.5	6.3	16.2	SL	1.64	5 YR 5/8	*	17.5	21.7	8.4
6.5	-	-	-	-	75.0	11.9	13.1	SL	1.71	5 YR 5/8	*	15.8	19.6	7.6
7.0	-	-	-	-	21.1	51.3	27.6	SL	1.51	2.5YR 7/6	2.5YR 4/4	24.1	34.3	13.6
7.25	-	-	-	-	15.0	51.3	33.7	SCL	1.59	10 R 4/4	*	22.3	27.5	16.5
7.5	-	-	-	-	31.3	26.2	42.5	C	1.45	2.5Y N7/	*	29.0	40.9	19.2
7.75	-	-	-	-	26.2	26.9	46.9	C	1.32	10 YR 7/1	*	32.0	47.8	14.8
8.0	-	-	-	-	27.5	27.5	45.0	C	1.27	7.5YR N7/	*	33.7	41.2	21.7
8.25	-	-	-	-	31.3	30.6	38.1	CL	1.39	7.5YR 7/0	10 R 5/6	30.9	47.7	15.7
8.5	-	-	-	-	30.6	23.5	45.9	C	1.37	10 YR 7/1	*	32.9	49.1	22.1

Table 28. --Continued

Depth in profile (Feet)	Percolation rate (Inches/hour)	Porosity (%)			Mechanical analysis (%)			Texture class	Bulk density (g/cm^3)	Soil color		Moisture content at sampling time (%)	Field capacity moisture (%)	Wilting point moisture (%)
		Noncap	Cap	Total	Sand	Silt	Clay			Matrix	Mottles			
8.75	-	-	-	-	16.2	22.5	61.3	C	1.22	10 YR 7/1	*	42.1	62.0	29.5
9.0	-	-	-	-	18.8	21.2	60.0	C	1.22	5 Y 7/2	10 R 6/2	41.6	62.9	29.2
9.5	-	-	-	-	13.1	25.6	61.3	C	1.23	10 YR 7/2	*	38.8	36.6	25.2

* Zero value or none observed
\- Test not made for this sample

Table 29. Soil profile description for plot 15, Ruston sandy loam

Depth in profile (Feet)	Percolation rate (Inches/hour)	Porosity (%)			Mechanical analysis (%)			Texture class	Bulk density (g/cm^3)	Soil color		Moisture content at sampling time (%)	Field capacity moisture (%)	Wilting point moisture (%)
		Noncap	Cap	Total	Sand	Silt	Clay			Matrix	Mottles			
0.5	.048	12.0	25.7	37.7	61.2	31.3	7.5	SL	1.51	7.5YR 5/6	*	10.0	11.8	3.1
1.0	.010	8.2	27.7	35.9	53.7	31.9	14.4	SL	1.56	5 YR 4/8	*	12.6	15.5	5.7
1.5	.009	7.2	30.3	37.5	50.0	30.0	20.0	L	1.56	5 YR 4/8	*	14.0	15.5	7.5
2.0	.010	5.2	26.3	31.5	56.8	26.9	16.3	SL	1.73	5 YR 4/8	*	13.1	9.7	6.4
2.25	-	-	-	-	64.3	24.4	11.3	SL	1.64	2.5YR 4/5	*	10.6	11.5	4.1
2.5	.064	10.1	22.0	32.1	72.5	18.8	8.8	SL	1.74	5 YR 5/8	*	9.2	10.9	3.3
2.75	-	-	-	-	76.2	16.9	6.9	SL	1.65	5 YR 5/8	*	8.3	4.0	3.1
3.0	.431	15.1	19.9	35.0	75.0	18.1	6.9	SL	1.70	5 YR 5/8	*	7.3	4.5	2.5
3.5	.782	17.0	18.4	35.4	80.0	15.0	5.0	LS	1.73	5 YR 5/6	*	6.0	2.4	1.7
4.0	1.354	18.1	16.8	34.9	80.6	14.4	5.0	LS	1.64	5 YR 6/4	*	5.7	3.3	1.4
4.25	-	-	-	-	80.6	14.4	5.0	LS	1.73	5 YR 5/6	5 YR 7/1	6.8	4.1	2.8
4.5	1.202	17.6	18.1	35.7	80.6	14.4	5.0	LS	1.67	7.5YR 5/6	7.5YR N8/	7.1	4.8	3.5
4.75	-	-	-	-	73.7	17.5	8.8	SL	1.81	5 YR 7/2	5 YR 6/8	7.4	4.0	3.0
5.0	1.754	17.5	17.2	34.7	74.4	13.1	12.5	SL	1.66	5 YR 4/6	*	9.7	10.9	5.3
5.5	.424	9.8	21.0	30.8	73.1	11.9	15.0	SL	1.74	5 YR 4/8	*	11.8	11.1	5.2
6.0	.032	7.6	21.7	29.3	68.8	13.1	18.1	SL	1.81	5 YR 4/6	*	11.6	7.9	6.3
6.25	-	-	-	-	73.7	11.9	14.4	SL	1.74	2.5YR 4/8	*	11.4	6.6	5.7
6.5	.013	5.1	24.8	29.9	74.4	10.0	15.6	SL	1.79	5 YR 4/8	*	11.2	6.4	5.5
6.75	-	-	-	-	75.0	12.5	12.5	SL	1.70	5 YR 5/6	*	10.4	9.6	4.9
7.0	.026	4.5	24.8	29.3	74.4	10.6	15.0	SL	1.81	5 YR 5/8	*	10.7	6.4	5.2
7.5	.047	4.8	26.0	30.8	73.1	11.9	15.0	SL	1.82	5 YR 4/8	*	12.6	12.2	6.2
8.0	.122	4.5	26.5	31.0	73.1	10.6	16.3	SL	1.81	7.5YR 6/6	5 YR 5/6	13.0	10.5	5.5
8.5	.173	5.1	26.7	31.8	72.5	10.0	17.5	SL	1.79	5 YR 5/8	2.5YR 4/6	13.9	7.8	6.3
9.0	.101	5.3	26.4	31.7	78.1	6.9	15.0	SL	1.80	2.5YR 4/6	*	14.1	7.1	6.2
9.5	*	5.3	26.1	31.4	77.4	6.3	16.3	SL	1.76	5 YR 4/8	*	14.0	11.3	5.3

Table 29. --Continued

Depth in profile (Feet)	Percolation rate (Inches/hour)	Porosity (%)			Mechanical analysis (%)			Texture class	Bulk density (g/cm^3)	Soil color		Moisture content at sampling time (%)	Field capacity moisture (%)	Wilting point moisture (%)
		Noncap	Cap	Total	Sand	Silt	Clay			Matrix	Mottles			
10.0	.027	5.5	27.2	32.7	76.3	8.1	15.6	SL	1.77	2.5YR 4/8	*	15.2	11.2	6.5
10.5	.027	4.8	28.6	33.4	78.7	6.9	14.4	SL	1.84	5 YR 5/6	*	13.6	8.1	6.8
11.0	.221	4.5	27.5	32.0	76.2	6.9	16.9	SL	1.80	5 YR 6/8	*	13.4	11.8	7.0
11.5	.101	5.9	26.5	32.4	75.6	6.9	17.5	SL	1.76	7.5YR 7/6	*	12.9	11.8	7.1
12.0	.008	5.0	25.1	30.1	75.0	7.5	17.5	SL	1.76	7.5YR 6/8	*	13.9	12.4	6.6
12.5	.026	5.0	24.7	29.7	74.3	9.4	16.3	SL	1.78	7.5YR 6/6	*	14.8	9.0	7.6
13.0	.029	5.4	24.7	30.1	76.9	8.1	15.0	SL	1.77	10 YR 8/4	*	14.9	9.4	7.6
13.5	.044	4.9	25.4	30.3	78.1	7.5	14.4	SL	1.77	2.5YR 5/6	*	12.5	12.8	6.5
14.0	.320	4.9	25.5	30.4	76.2	8.8	15.0	SL	1.77	5 YR 5/8	*	12.9	11.7	6.9
14.5	.097	5.1	25.9	31.0	75.0	10.0	15.0	SL	1.78	5 YR 6/8	*	13.6	15.4	7.7
15.0	.005	4.5	26.2	30.7	73.7	11.3	15.0	SL	1.77	7.5YR 7/6	*	13.5	12.6	8.0
15.5	.016	5.1	26.8	31.9	75.0	10.6	14.4	SL	1.76	7.5YR 7/6	*	13.6	15.5	7.3
16.0	.001	5.0	25.8	30.8	75.0	10.0	15.0	SL	1.79	5 YR 6/6	*	13.6	14.5	7.0
16.5	.013	6.2	25.8	32.0	76.2	12.5	11.3	SL	1.74	7.5YR 7/6	*	12.3	15.1	6.9
17.0	.063	5.2	25.1	30.2	77.5	10.0	12.5	SL	1.77	5 YR 7/3	*	12.4	13.6	6.2
17.5	.026	5.0	26.9	31.9	75.0	12.5	12.5	SL	1.76	7.5YR 8/2	*	13.3	13.9	6.7
18.0	.005	6.6	29.0	35.6	71.3	13.1	15.6	SL	1.71	7.5YR 7/2	*	14.7	16.0	7.2

* Zero value or none observed
- Test not made for this sample

Table 30. Soil profile description for plot 18, Myatt-Mashulaville complex

Depth in profile (Feet)	Percolation rate (Inches/hour)	Porosity (%)			Mechanical analysis (%)			Texture class	Bulk density (g/cm^3)	Soil color		Moisture content at sampling time (%)	Field capacity moisture (%)	Wilting point moisture (%)
		Noncap	Cap	Total	Sand	Silt	Clay			Matrix	Mottles			
0.5	1.072	13.6	31.7	45.3	74.4	20.0	5.6	LS-SL	1.42	2.5YR 3/0	*	20.1	7.2	1.8
1.0	0.048	6.9	26.6	33.5	77.5	17.5	5.0	LS	1.71	10 YR 6/2	*	16.1	7.5	1.7
1.5	0.935	9.7	30.0	39.7	83.1	8.1	8.8	LS	1.63	7.5YR 5/6	*	19.6	8.8	4.5
2.0	0.081	7.9	31.5	39.4	85.0	5.0	10.0	LS	1.63	10 YR 7/1	5 YR 5/8	20.4	8.2	4.6
2.5	-	-	-	-	-	-	-	-	1.61	5 YR 4/6	7.5YR 7/0	-	-	-
2.75	-	-	-	-	85.6	5.6	8.8	LS	1.66	10 YR 7/1	5 YR 4/6	20.5	6.6	3.6
3.0	-	-	-	-	85.0	7.5	7.5	LS	1.69	7.5YR 7/0	7.5YR 5/8	18.8	6.3	3.1
3.5	-	-	-	-	66.9	23.1	10.0	SL	1.72	7.5YR 7/0	5 YR 4/8	17.9	14.9	5.7
4.0	-	-	-	-	72.5	13.1	14.4	SL	1.68	5 YR 5/8	-	20.8	14.4	6.7
4.5	-	-	-	-	61.3	25.6	13.1	SL	1.69	7.5YR 5/6	7.5YR 6/0	18.7	18.2	7.3
5.0	-	-	-	-	93.7	1.9	4.4	S	1.52	-	-	23.9	4.5	2.2
6.0	-	-	-	-	91.3	3.7	5.0	S	**	-	-	25.0	4.9	2.2
6.5	-	-	-	-	92.5	3.1	4.4	S	**	-	-	23.5	6.8	2.1
7.0	-	-	-	-	95.6	1.9	2.5	S	1.51	5 YR 4/6	*	23.9	2.2	0.9
7.75	-	-	-	-	86.3	8.1	5.6	LS	**	-	-	20.3	7.1	2.4
8.0	-	-	-	-	86.2	10.0	3.8	LS	1.73	7.5YR 4/0	10 YR 7/1	16.6	7.4	2.2
8.5	-	-	-	-	76.2	19.4	4.4	LS	1.47	10 YR 3/1	10 YR 6/1	22.3	7.0	2.5

* Zero value or none observed
**Too sandy to determine bulk density
- Test not made for this sample

VITA

Conrad Wheless Brewer was born in Wadesboro, North Carolina, on December 23, 1940 and is the only son of Mr. and Mrs. Ray C. Brewer.

He attended elementary schools in Charlotte, North Carolina, and Decatur, Georgia. After graduating from Decatur High School in May of 1959, he entered Emory University in Atlanta, Georgia. He transferred to the University of Georgia in 1961 to study forestry and was awarded the Bachelor of Science degree in Forestry in May of 1964.

Brewer began work toward his Master of Science degree as a graduate assistant in the School of Forestry at the University of Georgia in 1964. After the completion of his course work and research, he began work as a research forester with West Virginia Pulp and Paper Company in Summerville, South Carolina, while he completed his thesis. He was awarded the Master of Science degree in 1966.

He began work toward the Doctor of Philosophy degree in September of 1969 as a graduate research assistant in Louisiana State University's School of Forestry and Wildlife Management. He continued his course work and research at LSU while serving on the faculty as an Instructor in Forestry from September of 1970 through May of 1975.

Brewer has continued writing his dissertation while employed as an Assistant Professor of Forestry working in Extension activities in the College of Forest and Recreation Resources at Clemson University.

Upon the successful completion of the requirements of the Doctor of Philosophy degree, he plans to continue his career in forestry education and research.

Brewer was married to the former Elizabeth Stevens Williams of Dawson, Georgia, on March 19, 1964. They have four children, Conrad W., Jr., Ray C., II, Susan Patricia, and Mary Elizabeth.

EXAMINATION AND THESIS REPORT

Candidate: Conrad Wheless Brewer

Major Field: Forestry

Title of Thesis: Rooting Depth of Mature Loblolly Pine (Pinus taeda L.) as Influenced by Physical Properties of the Soil in Southeastern Louisiana.

Approved:

Major Professor and Chairman

Dean of the Graduate School

EXAMINING COMMITTEE:

Date of Examination:

November 3, 1975