Chapter 10
Soil and Site Potential

Lawrence A. Morris and Robert G. Campbell

Abstract

Southern pine plantation management centers on the soil resource. This chapter introduces the reader to the major soil groups and soil-vegetation associations of the South. Specific mechanisms through which soil conditions can affect seedling establishment and plantation growth are described and general relationships between soil properties and site quality reviewed. Applications of soils information in projecting plantation yield, selecting species and genotype for planting, choosing equipment, assessing insect and disease hazards, and developing fertilizer and pesticide recommendations are illustrated. Finally, means for manipulating soil conditions to increase production are suggested.

10.1 Introduction

Plantation forestry is fundamentally different from the forestry familiar to us from silvicultural textbooks, which Stone [102] termed "regulated" forestry. In regulated forests, the fundamental resource we manage is the trees. The productive potential of a site is considered fixed, and soils information is used primarily for inventory purposes.

In contrast, in plantation forestry, the fundamental resource is the land, and especially the soil. Tree species and families that make the best use of this resource are selected. The productive potential is not considered fixed, but can be degraded or improved by management activities. Thus, detailed soils information is as important to plantation forestry as it is to farming — maybe more so. Farmers at least have the opportunity to correct their mistakes each year. Foresters must live with theirs.

In this chapter, we introduce the reader to the major soil groups and soil-vegetation associations of the South, and discuss general relationships between soil properties and site quality. We show how this information may be applied for making initial decisions concerning the profitability of plantation management, as well as for determining harvest scheduling and equipment selection, identifying site-preparation requirements, allocating species and genotypes to sites, and developing herbicide, insecticide, and fertilizer recommendations.

10.2 Physiographic Provinces and Soils of the South

Five factors contribute to soil development: parent material, climate, organisms, topography, and time [52]. At a regional scale, all of these are combined in physiographic provinces. Physiographic provinces in which southern pine are commercially important (Fig. 10.1) include the Coastal Plain (Lower, Middle, and Upper), Piedmont, Ozark Plateaus and Ouachita Mountains, Valley and Ridge, and Appalachian and Interior Low Plateaus. Only in the Blue Ridge Mountains and Mississippi River Valley are southern pine not commercially important. Within each of these provinces, differences in topographic position and parent material (and, to a lesser extent, climate, organisms, and time) have resulted in local differences in predominant soil conditions. These differences in soils and their relationship to tree growth and regeneration are large enough for these provinces to be useful for organizing soils information (for example, see [2].

No single soil is typical of the southern pine region. Of the 10 major soil orders recognized by the Soil Conservation Service (SCS), eight occur in the South and seven of these are at least locally important in plantation forestry (Fig. 10.2, Table 10.1). Although not inclusive, this list does identify dominant soils managed for southern pine production. Major differences in species and family selection, harvest and equipment scheduling, site-preparation and planting prescriptions, and thinning and fertilization recommendations occur among, as well as within, these regions.

10.2.1 Coastal Plain

Most pine plantation management is conducted within the Coastal Plain province. It is an area where sediments have deposited along former ocean-front beaches, rivers, and sounds. About 160 km wide in Virginia, the Coastal Plain extends south and then westward into Texas, where it reaches 650 km in width. Beginning at sea level, the Coastal Plain rises in a series of terraces to a maximum elevation of between 100 and 200 m where it contacts the Piedmont. North of a line extending at about 29° north

M.L. Duryea & P.M. Dougherty (eds), Forest Regeneration Manual, pp. 183–206.

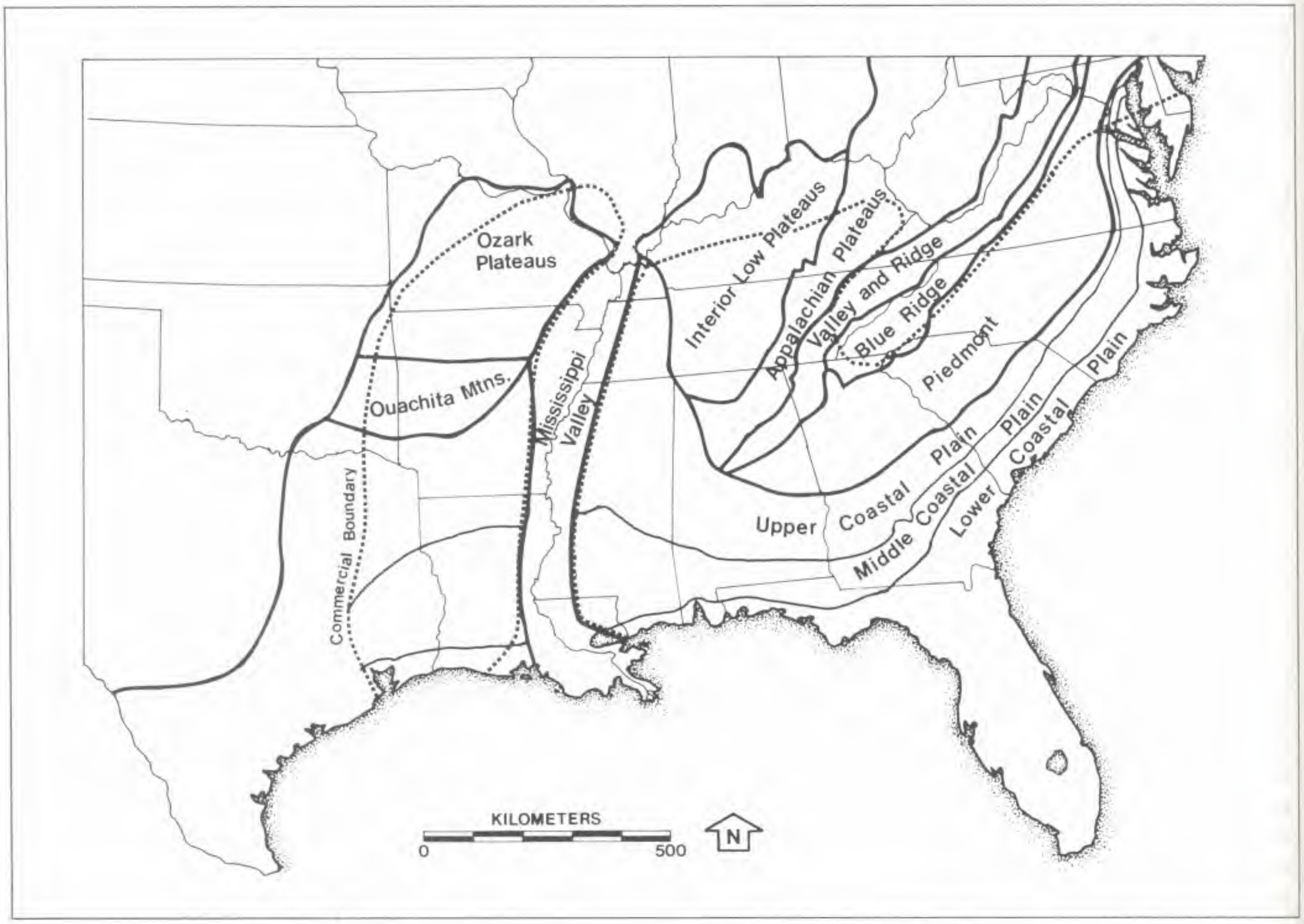

Figure 10.1. Physiographic provinces of the South (redrawn from [51]).

latitude (between Gainesville and Starke, Florida), soils are characterized as thermic (mean annual temperature between 15 and 22°C at 50-cm depth, mean difference between summer-winter temperatures > 5°C); south of this latitude, soils are characterized as hyperthermic (mean annual temperature > 22°C, mean summer-winter difference < 5 °C). Topography ranges from hilly near the boundary with the Piedmont to nearly level at low elevations near the ocean.

10.2.1.1 Lower Coastal Plain

The Lower Coastal Plain includes that area of the Coastal Plain formed on the most recently deposited sediments. Relief is low, and elevations do not exceed 30 m. Large areas of poorly to very poorly drained soils (particularly Haplaquepts and Humaquepts) exist in interfluvial areas between rivers and streams. Many Lower Coastal Plain areas have been above water only since the beginning of the recent interglacial period, and profiles are shallow with poorly developed argillic horizons. Both 1:1 (nonexpanding) and 2:1 (expanding) layered clay minerals are common. Organic soils occur where drainage is restricted on broad interstream divides, bays, and low-elevation flats. Phosphorus (P) deficiencies are common in the Lower Coastal Plain, and most of the 250,000 ha of forestland annually fertilized with P during plantation establishment are located here.

Included within the Lower Coastal Plain are a number of habitat types recognized by both foresters and soil scientists because of their unique plant-soil associations.

Flatwoods, as described by McCulley [61], are landscapes in northern Florida and southern Georgia dominated by an overstory of mixed slash *(Pinus elliottii* Engelm.) and longleaf *(P. palustris* L.) pine with an understory of wiregrass *(Aristida* spp.), gallberry *(Ilex glabra* L. Gray), and saw palmetto *(Seronoa repens* B. Small). These areas are typified by poorly to somewhat poorly drained soils developed on coarse-textured sediments low in weatherable minerals which have a subsoil (B) horizon of accumulated organic matter (Haplaquods). Paleudults and Hapludults are common on moderately well- or better drained areas and Paleaquults in very poorly drained cypress *(Taxodium distichon* var. *nutans* Ait.) ponds.

Wet mineral flats, also known as savannahs, pitcher plant flats, and prairies [82], are found along both the Gulf and Atlantic Coasts. These areas are characterized by poorly and very poorly drained soils developed in slack-water

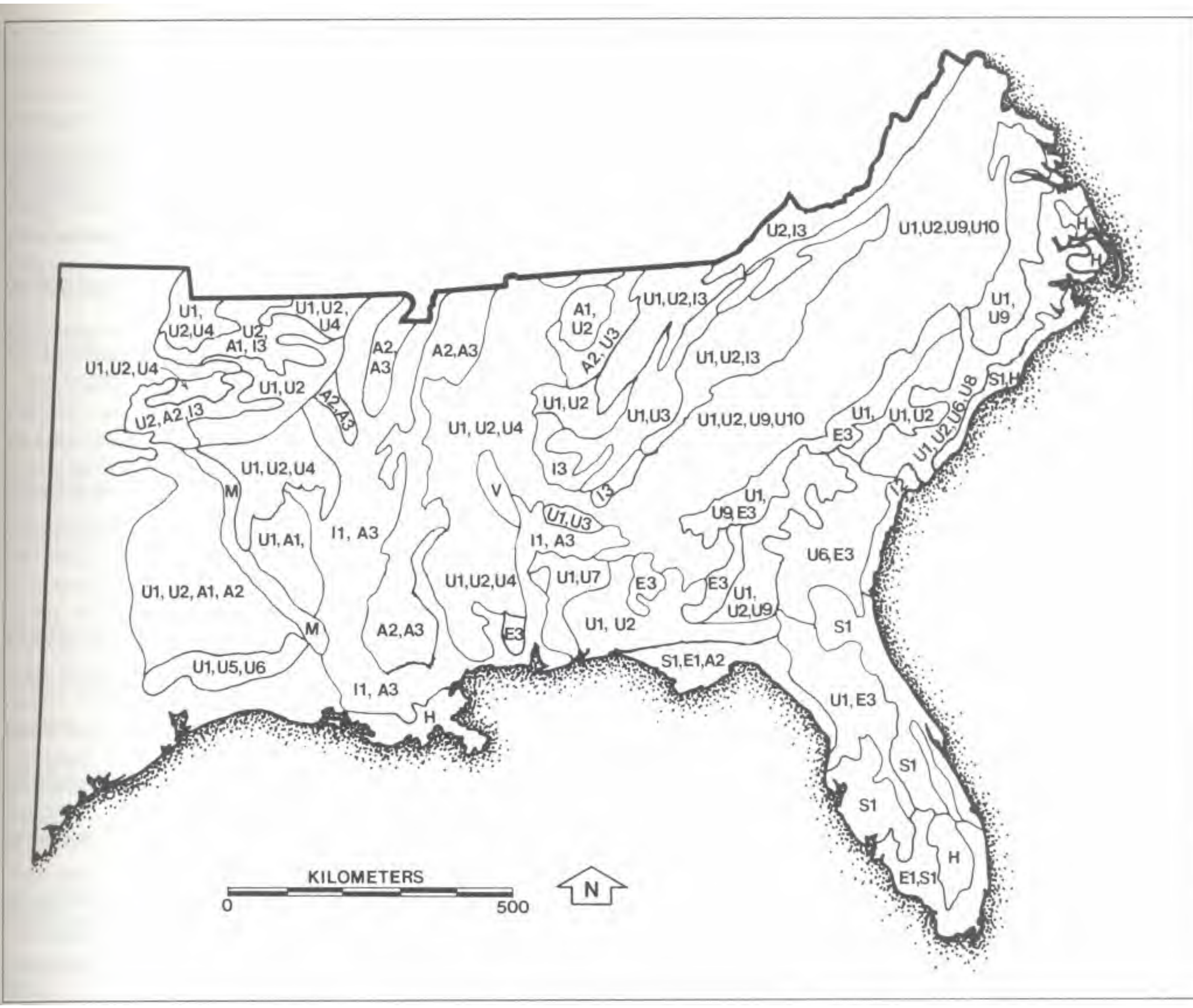

Figure 10.2. Soils of the South (adapted from [75]). Symbols are explained in Table 10.1.

deposits and, consequently, soils are fine textured. Very poorly drained and poorly drained Paleaquults, Haplaquults, and Humaquepts characterize this area. With the exception of P, which can be severely deficient, fertility in this habitat type is often high; site indexes on drained and P-fertilized areas in excess of 25 m (base age 25 years) are common.

Pocosins, found extensively in the Lower Coastal Plain of Virginia and the Carolinas, are characterized by broadleaf evergreen vegetation with scattered pond pine (*Pinus serotina* Michx.) and occur on broad interstream divides or other areas where runoff is restricted by either old beach ridges or more recent dune formations [24]. Under the resulting wet conditions, organic matter accumulates, obscuring the original landscape features and forming a dome with the deepest organic deposits at the center. Except near the outer edges, where Humaquepts with a relatively thick surface accumulation of organic matter occur, most pocosin soils are Histisols. Poor moisture relationships are the major factor affecting regeneration in these soils. Undisturbed, they have a very low hydraulic conductivity and are difficult to drain [93], yet beds formed for local drainage may not retain moisture. Consequently, most site preparation is designed to enable planting in mineral soil and is restricted to soils with surface organic layers < 90 cm deep.

10.2.1.2 Middle Coastal Plain

The Middle Coastal Plain is moderately dissected with relief between valleys and plateaulike uplands ranging to 30 m. Interstream divides are narrower than in the Lower Coastal Plain, and very poorly and poorly drained soils are less common. Paleudults and Hapludults are the dominant great groups on uplands, with Fluvaquepts and Fluvaquents occurring along valley bottoms. Kaolinite, a 1:1 clay mineral, is dominant in the clay fraction. Subsoils with fine loamy to loamy textures are most common.

Upland areas of the Middle Coastal Plain in the Carolinas contain oval northwest-southeast oriented depressions called Carolina Bays [83]. Although the origin

Table 10.1. Features of the eight soil orders and important great groups occurring in the South [76].

SOIL ORDER Great group	Map symbol (see Fig. 10.2)	Distinguishing features
ALFISOLS		Soils that have a B (subsoil) horizon of clay accumulation and contain a relatively high percentage of the base cations potassium (K), calcium (Ca), and magnesium (Mg) on the cation exchange complex (CEC).
Paleudalfs	A1	Alfisols that are moist, lack a seasonally high water table, and have a thick B horizon of clay accumulation.
Hapludalfs	A2	Alfisols that are moist, lack a seasonally high water table, and have a thin B horizon of clay accumulation.
Fragiudalfs	A3	Alfisols containing a fragipan (brittle horizon restricting water movement, root growth) that are moist, lack a seasonally high water table, and experience dry periods during summer.
Fragiaqualfs[1]		Alfisols containing a fragipan that are wet and have a seasonally high water table.
ENTISOLS		Soils lacking pedogenic horizons
Psammaquents	E1	Coarse-textured Entisols that are either permanently or seasonally wet with water tables near the soil surface.
Haplaquents		Entisols that are either permanently or seasonally wet with water tables near the soil surface and that have a thin, fine-textured B horizon.
Quartzipsamments	E3	Coarse-textured Entisols (loamy fine sand or coarser), dominated by minerals resistant to weathering (e.g., quartz).
HISTOSOLS	H	Soils composed largely of partially decomposed organic matter.
INCEPTISOLS		Soils with minimal horizon development. Materials in the horizon may have been altered or moved, but major accumulations of clay or organic matter are absent.
Haplaquepts	I1	Inceptisols that have seasonally high water tables and a thin surface accumulation of organic matter.
Humaquepts	I2	Inceptisols that have a seasonally high water table and a thick, dark mineral or organic surface horizon.
Dystrochepts	I3	Inceptisols that have a light-colored surface and a low percentage of base cations K, Ca, and Mg on the CEC.
MOLLISOLS	M	Soils that have a thick, dark-colored surface horizon and a high percentage of base cations. Mollisols do not occur widely in the South.
SPODOSOLS		Soils with a subsurface B horizon containing accumulations of organic matter, iron (Fe), and aluminum (Al). Usually formed in coarse-textured deposits and have a low percentage of base cations K, Ca, and Mg on the CEC.
Haplaquods	S1	Spodosols that have a seasonally high water table and moderately developed B horizon containing dispersed organic matter, Al, and Fe.
Haplohumods		Spodosols that are moist with B horizons containing dispersed organic matter and Al but little Fe.
ULTISOLS		Acid, deeply leached soils that have a B horizon of clay accumulation and that are usually moist except during brief summer periods.
Paleudults	U1	Ultisols that are usually moist, seldom experience an extended dry period, and have a thick B horizon of medium to high CEC clay accumulation.
Hapludults	U2	Ultisols that are usually moist, seldom experience an extended dry period, and have a thin B horizon of medium to high CEC clay accumulation.
Rhodudults	U3	Ultisols that are usually moist, seldom experience an extended dry period, and have dark-red subsurface horizons of medium to high CEC clay accumulation.
Fragiudults	U4	Ultisols that are usually moist, seldom experience an extended dry period, and have a fragipan.
Paleaquults	U5	Ultisols that have seasonally high water tables.
Fragiaquults	U6	Ultisols that have seasonally high water tables and a dense-brittle fragipan.
Ochraquults	U7	Ultisols that have seasonally high water tables and a light-colored or thin, dark surface horizon.
Umbraquults	U8	Ultisols that have seasonally high water tables, seldom experience an extended dry period, and have a thick, dark-colored surface horizon.
Kandiudults	U9	Ultisols that are usually moist, seldom experience an extended dry period, and have a thick B horizon of low CEC clay accumulation.
Kanhapludults	U10	Ultisols that are usually moist, seldom experience an extended dry period, and have a thin B horizon of low CEC clay accumulation.
VERTISOLS	V	Soils containing a high percentage of clays that shrink and swell greatly upon wetting and drying. Only limited areas of Vertisols occur in the South.

[1] Great groups not followed by a map symbol are not extensive in any area.

of these bays is unknown, they apparently were formed by wind or water erosion in fine loamy or coarser textured sediments [24]. On the northwest side, the poorly drained Paleaquults or Histisols of the bay center grade into the uplands. On the southeast side, and much of the northeast and southwest sides, they end in a rim of well- to excessively well-drained Quartzipsamments and Hapludults with thick surfaces of loam or coarser textured materials. Drainage of the bay, which is often necessary for pine regeneration, may be hampered by the presence of this rim.

10.2.1.3 Upper Coastal Plain

The Upper Coastal Plain, also termed the hilly Coastal Plain, is a transition area. Near its contact with the Piedmont the topography is hilly, sediments are thin, and areas of residual Piedmont soils and Coastal Plain are intermixed. Sediments become thicker, and there is less relief toward the coast. Soils in the Upper Coastal Plain are well drained and deep; Paleudults and Kandiudults are the dominant great groups. Relatively deep, loam or coarser textured surface soils often overlay the finer textured subsoils. Kaolinite is the dominant clay mineral.

The extensive areas of sandhills found in the Upper Coastal Plain of the Carolinas and Georgia are characterized by an overstory of drought-tolerant longleaf pine and turkey oak *(Quercus laevis* Walt.) and somewhat excessively drained to excessively drained, coarse-textured Entisols (Quartzipsamments) intermixed with Kandiudults. Available water holding capacity (see 10.3.2 for details on water storage and availability) is extremely low on many sandhill sites. Topography is hilly to rolling.

Extending in a 40 km wide band from northeastern Mississippi and into Alabama in a broad crescent, the Black Belt is a famous cotton-producing area of the Old South. Its name derives from the dark-colored soils developed from weathering of Cretaceous chalk. The topography is gently rolling to nearly level. Large areas in this region have neutral to alkaline pH (soil reaction), and 2:1 clays with high shrink-swell potential are common. Eutrocrepts, Hapludalfs, and Paleudalfs are common soil great groups. Loblolly pine *(Pinus taeda* L.) occurs where acid surfaces exceed 25 cm. On soils with < 25 cm of acid surface, eastern redcedar *(Juniperus virginiana* L.) is common. Pine regeneration can be hampered by high soil pH and resulting nutrient imbalance, as well as by poor aeration and the limited periods during which soil physical conditions permit planting and operation of equipment in these "sticky" clay soils.

10.2.2 Piedmont

The Piedmont is the nonmountainous area of the Appalachian Highland Region extending from the Blue Ridge Mountains east and south toward the Coastal Plain (see Fig. 10.1). Elevations range from near 550 m at its contact with the mountains of North Georgia to just over 90 m at its contact with the Coastal Plain in Virginia. The Piedmont is heavily dissected, with few broad interstream areas. Upland soils, typified by Hapludults, Kandiudults, Kanhapludults, Paleudults, and Rhodudults, are well drained. Piedmont soils have formed in place from weathering of parent rock, and bedrock characteristics are important in soil formation. Texture, which is useful for differentiating soil series in the Coastal Plain, is less so for differentiating Piedmont soils because most have clay-textured B horizons. Instead, soil color, which is related to mineralogy, is used to classify Piedmont soils. Darker colored soils are developed from basic rocks (those containing < 50% silica dioxide), lighter colored soils from granitic materials. Soil thickness is also an important criterion for differentiating Piedmont soils.

Virtually all of the Piedmont was once farmed for cotton, and Piedmont soils reflect the severe erosion that occurred during that period. Subsoil horizons are found at or near the surface on many of these sites. Mechanical resistance to root penetration is high in such horizons, and slow root extension is a major factor affecting regeneration success. Soil characteristics that reflect the degree of erosion and past land use, such as SCS erosion class or surface horizon depth, are important for grouping Piedmont soils.

10.2.3 Ozark Plateaus and Ouachita Mountains

This region of rugged hills, narrow valleys, and a few large plateaus occupies northern Arkansas, southern Missouri, and eastern Oklahoma (see Fig. 10.1). In the Ouachita Mountains, soils are developed from interbedded and folded shales, sandstones, quartzites, and cherts; in the Ozark Plateaus from bedded limestone, chert, and dolomite. Soils formed from these parent materials are rocky, and skeletal family modifiers (indicating the presence of rock fragments in the soil) are the norm. Fragipans restricting root development and water movement are common; in the Ozarks, they are often associated with a windblown mantle [79], particularly on broad ridges. Dystrocrepts, Hapludults, Hapludalfs, and Fragiudalfs are common soil great groups frequently occurring together in complex patterns. Shortleaf *(Pinus echinata* Mill.) and loblolly pine are the dominant pines throughout much of this area, growing in mixture with oak in natural stands. Both low available water holding capacity and high mechanical resistance of soils must be overcome for successful pine establishment on many sites in these provinces.

10.2.4 Valley and Ridge

This province, extending southwest from New York to its terminus in central Alabama (see Fig. 10.1), is a belt of folded mountains consisting of limestone valley lowlands separated by low interbedded shale and sandstone ridges. Soils on the highest ridges and steep slopes tend to be formed from acid sandstones, those on the lower slopes from acid shales. Profiles are immature. Dystrocrepts and Fragiocrepts in loamy-skeletal textural classes are common. Available water holding capacity in many of these soils is low. This, and the difficulty of operating on steeper sites, both influence regeneration success. Hapludults and Fragiudults also occur, particularly on gentle slopes. Soils formed in the limestone valleys are thicker and have clay and fine loamy-textured B horizons. Few valleys are forested.

10.2.5 Appalachian and Interior Low Plateaus

West of the Ridge and Valley lies a large plateau underlain by strong, nearly level sandstone, limestone, and shale beds characterized by high narrow ridges, steep slopes, and narrow valleys (see Fig. 10.1). Soils of this area are low in fertility and are characterized by well-drained Hapludults and Dystocrepts in fine loamy-skeletal textural families. Two divisions are recognized, the Appalachian Plateau and the Interior Low Plateaus. Smalley [94-99] has described the geology, soils, and vegetation of these areas in detail.

Parent material in the Appalachian Plateau is interbedded sandstone, conglomerate, siltstone, and shale. Soils on the ridges and steep slopes are relatively shallow, ranging from 0.5 to 1.5 m deep, predominantly Hapludults and Dystrocrepts in loamy-skeletal families. Generally, soils in midslope positions contain more rock fragments than soils in upper or lower slope positions. Most soils formed on lower slopes were developed in colluvium and are deep (from 2 to 5 m). Eutyrocrepts are common in this slope position. Except for soils on southwest aspects, which have thermic temperature regimes, most soils have mesic temperature regimes (mean annual temperature between 8 and 15°C, mean summer-winter difference > 5°C).

The Interior Low Plateaus are underlain by a limestone of varying coarseness and purity. In the eastern section, limestones are relatively pure; in the western section, shale and cherty limestones predominate. Both thermic and mesic temperature regimes occur; mesic regimes prevail in Kentucky, thermic regimes in Tennessee and Alabama. Thin silty deposits overlie much of the area. On broad rounded hills, soils are developed in residuum from limestone and in thin silty deposits. Deep well-drained and moderately fertile Hapludults and Hapludalfs occur within these areas and in lower slope positions. Subsoil texture ranges from loam to clay and is often cherty. Excessively well-drained and well-drained Dystrocrepts and Hapludults are common on narrow ridges and upper slopes in more dissected areas. Fragiudalfs are found on gently sloping lands of the western rim of the Plateau.

10.3 Mechanisms Affecting Plantation Establishment and Tree Growth

Soils supply trees with water, 13 essential plant nutrients and physical anchorage. For water and nutrients to be taken up by the tree, three conditions must exist: (1) water and nutrients must be in available forms in the soil profile, (2) roots must be able to grow into the soil where water and nutrients are found, and (3) water and nutrients must be able to move to the root in response to gradients established at the root surface. For seedlings, soil conditions affecting root growth are of great importance. Even on water- and nutrient-poor sites, the total supply of resources exceeds seedling requirements. Because only the water and nutrient supply within the established rooting volume is available for uptake, the ability of the seedlings to develop a root system capable of accessing these supplies, and not the supply itself, most often limits survival and growth. Later, after establishment, limitations in total availability become more important.

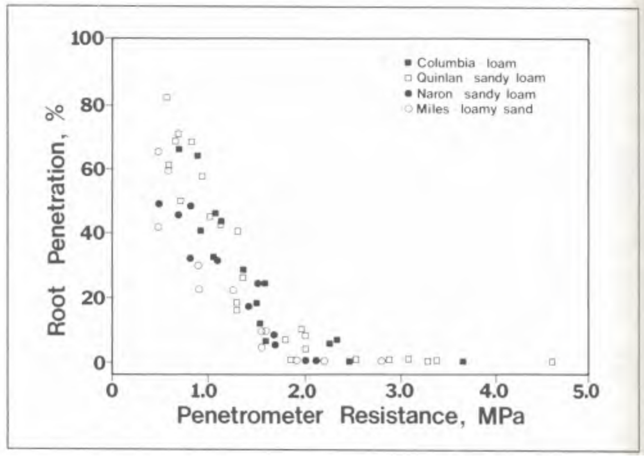

Figure 10.3. Relationship between penetrometer resistance, an index of soil strength, and cotton, *Gossypium hirsutum* L., taproot penetration for four soils of different texture (different symbols) over a range of bulk densities (1.25 to 1.85 glcm^3) and moisture (-0.02 to —0.1 MPa bar matric potential) (adapted from [105].

10.3.1 Mechanical Impedance

Roots can grow (elongate) through the soil matrix in one of two ways: (1) by growing through soil pores larger than their own diameter, or (2) by enlarging pores smaller than their own diameter through pressure generated by turgor. The root tip of southern pines ranges from 1.0 to 2.0 mm in diameter. In most instances, because few continuous pores > 2 mm in diameter exist in the soil, roots enlarge smaller pores while elongating; important exceptions are found where roots grow along major cleavage planes and in old root channels. Root growth along such pores is particularly important in firm subsoils of many Piedmont sites and in shallow soils above fractured parent material. Where root growth is largely due to expansion of smaller pores, root elongation rate is controlled by soil strength (the resistance of soil to the movement of its particles under force). As soil strength, as measured by resistance to penetration, increases, root elongation decreases up to a critical strength of about 2.5 MPa; above this value, root growth essentially ceases (Fig. 10.3).

The resistance of a given soil to root penetration depends on moisture content. At low moisture contents, the tension of water films holds soil particles and aggregates together,

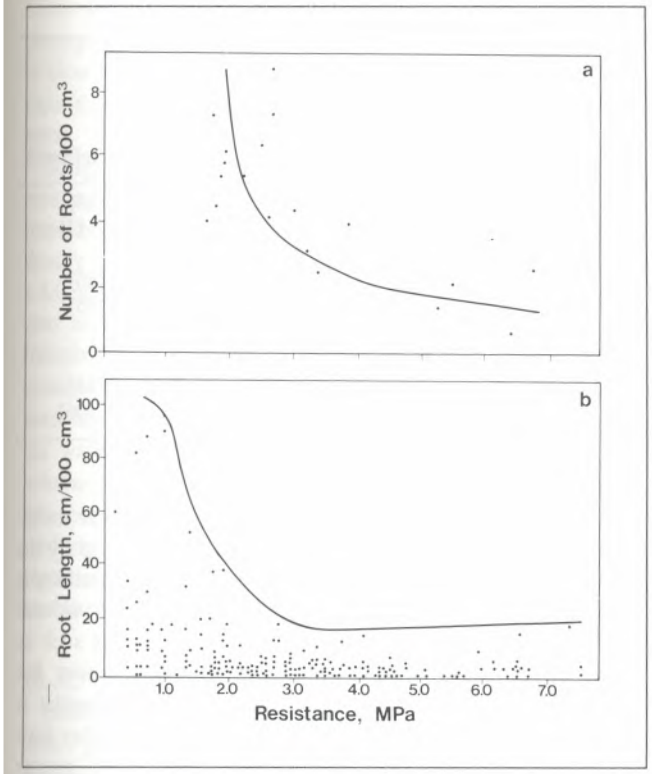

Figure 10.4. Relationship between root frequency and soil strength as measured by resistance to penetration for (a) radiata pine [43] and (b) slash pine [unpubl. data, 113] on sandy soils.

and more force is required to separate particles than at higher moisture contents. As moisture contents increase, binding forces decrease, and roots can more easily penetrate the soil.

Direct relationships between mechanical impedance and survival and growth of southern pine species have not been established. For radiata pine (*Pinus radiata* D. Don) grown on sandy soil where aeration was good, Greacen and Gerard (as cited in [43]) found rooting density to be reduced as penetration resistance increased above 2.0 MPa (Fig. 10.4a); in slash pine (Pinus elliottii Engelm) grown on a Haplaquod, rooting density was found to decrease as penetration resistance increased above 1.0 MPa (Fig 10.4b). Above 3.0 MPa resistance, root growth was restricted to old root channels and other large pores and density was low. The practical effect of high impedance is to concentrate roots in the surface few centimeters of soil by redirecting lateral root growth along the bottom and sides of the original planting hole upward toward the surface [39]. This reduces the volume of exploited soil and increases seedling moisture stress during dry periods.

10.3.2 Water Storage and Availability

10.3.2.1 Available water holding capacity

Within a given volume of soil, the total quantity of water potentially available for root uptake and the rate at which that water can be supplied to roots depend on the total volume, size, and shape of soil pores. These in turn depend on soil texture, soil structure, organic matter content, degree of compaction, and, to a lesser extent, soil mineralogy and chemistry. It is entirely possible for clay and sand soils to have the same total pore volume. They will, however, have different pore-size distributions and markedly different water-storage and supply characteristics.

Under well-drained conditions, available water holding capacity is considered to be the volume of water held in the soil between field capacity (upper limit of available water) and the permanent wilting point (lower limit). Field capacity is defined as the volume of water retained after drainage due to gravity from a thoroughly saturated soil. For fine-textured soils, field capacity is generally reached at a matric potential of —0.03 MPa (0.3 bar); for coarse-textured soils at —0.01 MPa (0.1 bar). Permanent wilting point is the soil moisture content at which plants that have wilted during the day will not regain turgor at night in a saturated atmosphere. The permanent wilting point is generally reached at matric potentials near —1.5 MPa (-15 bar). Neither field capacity nor permanent wilting point are, in fact, fixed. Water continues to move from the soil at field capacity, and wilting points differ for different species, families, and trees of varying vigor. Moreover, not all water within this upper and lower limit is equally available; for instance, at higher matric potentials (lower soil-water tension), water is more easily extracted from the soil and flow rates are greater. Despite these limitations, available water holding capacity is a useful concept for field applications.

Available water holding capacity is greatest in silt loam-textured soils. The large pores of sand fail to hold water against gravity, and the small pores of clay loam and clays hold much of their undrained water too tightly to be absorbed by plant roots (Fig. 10.5). In rocky (skeletal) soils, water holding capacity is reduced in proportion to the

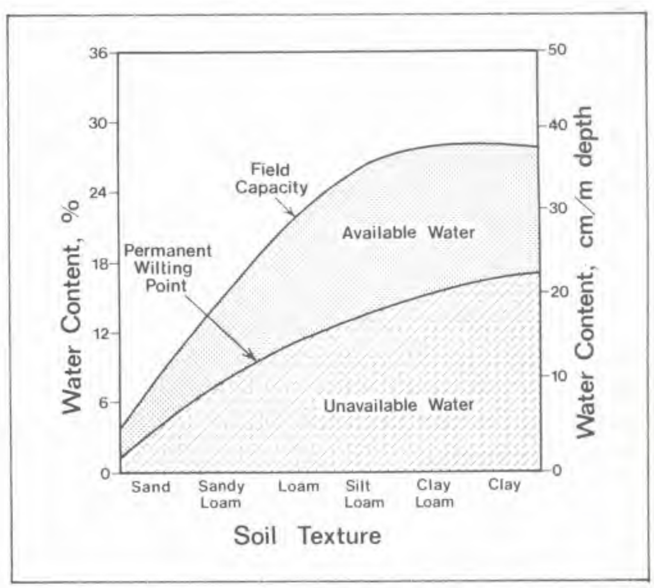

Figure 10.5. Water storage in soils of varying textures (adapted from [6]).

Pine Species	Surface-soil texture	Stand age, yr	Period of year	Ferti-lization	Water table: Treatments	Water table: Depth for best tree growth, cm.	Reference
Slash, loblolly	Muck loam	11	Feb.	None	Drainage gradient	64	[84]
Slash, loblolly	Sand	5	All year	P/none	Naturally fluctuating, controlled 46 and 91 cm	46	[117]
Slash	Sandy loam	6	Jan.-Feb.	None	Naturally fluctuating	46	[66]
Loblolly	Sandy loam	2	All year	P/none	Controlled at 0, seasonal (0 winter, 61 summer), continuous at 61 cm	Seasonal	[65]
Loblolly	Sandy loam	12–31	All year	None	Naturally fluctuating	74	[44]
Loblolly	Loam-	5–7	Jan.	P	Naturally fluctuating	61+	[106]

volume of coarse fragments. A sandy loam profile of 1-m depth will contain about 5 cm of available soil water. Large amounts of coarse fragments, such as occur in skeletal soils of the Ozarks, can reduce this by as much as 60%, and if a fragipan is present at the 50-cm depth, available water holding capacity may be as little as 1.5 cm. In contrast, silt loam soils with 1 m of free rooting will contain approximately 15 cm of available water at field capacity.

10.3.2.2 Availability Above a Water Table

Capillary attraction, resulting from the combination of adhesion, cohesion, and surface tension of water in contact with soil, causes water to move upward in the soil pores above the water table. The water in this capillary zone is available for root uptake in soils with a water table near the soil surface. This greatly increases available water, particularly in coarse-textured soils. For instance, in a sandy loam soil with a water table at 100 cm, total storage in the surface 1 m is increased by 10 cm, the amount of additional water held in the pores within the 35-cm capillary zone that would normally drain.

In poorly and very poorly drained soils of the Coastal Plain, a relationship exists between depth to the water table and growth of young stands (Table 10.2). The depths for best tree growth represent a compromise between damage to the root systems resulting from poor aeration when water tables are high for long periods and benefits from water stored in the saturated zone.

10.3.2.3 Movement to roots

At any one time, only a small portion of the available soil water lies within the immediate vicinity of adsorptive surfaces of tree roots. Uptake of water depends on the extension of roots into moist soil and the movement of water to root surfaces in response to potential gradients. When soil strength is low and oxygen diffusion adequate, growth is maximized at water potentials near field capacity. Root extension decreases as moisture potential increases or decreases around this maximum.

Once the soil has been penetrated by a root, water uptake at the root surface reduces water potential, creating a gradient for further water flow. The rate of water movement to the root is controlled by the gradient and by the hydraulic conductivity of the soil. Hydraulic conductivity is greatest in saturated conditions and decreases as soil moisture content decreases. Coarse-textured soils such as sand have high hydraulic conductivity when wet, but conductivity decreases quickly as soil water potential is decreased. In contrast, fine-textured soils such as clay have lower hydraulic conductivities when wet, but greater conductivities when dry (Fig. 10.6). The low hydraulic conductivities of coarse-textured soils at moisture potentials much below field capacity contribute to moisture

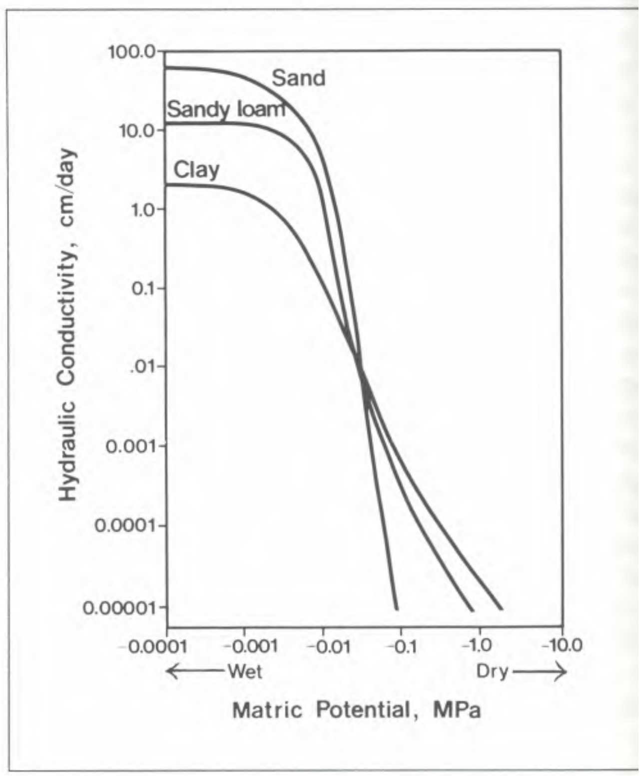

Figure 10.6. Relationship between soil-water matic potential and hydraulic conductivity for soils of three different textures (adapted from [35]).

stress when transpirational demand is high. For instance, in pines growing in a coarse-textured soil, stomata will begin to close early in the day even though soils are near field capacity and predawn xylem water potential indicates little stress.

Dougherty and Gresham [26] estimate that a planted pine seedling with a groundline diameter of 0.35 cm will transpire a maximum of 27 g of water/day. At a planting density of 2,000 stems/ha, this is equivalent to 54 kg/ha or $<6.0 \times 10^{-4}$ cm water/day. If surface evaporation were zero and no competing plant species were present and transpiring water, at field capacity even a sandy soil would contain enough water in the surface 20 cm to meet seedling needs for 185 days. For an established stand transpiring 0.2 cm water/day and occupying the same 20 cm rooting volume, availability decreases to 7 days supply. Although this example is extreme, it does underscore a point: seedling survival and growth depend largely on soil conditions that affect root development and transport. For established stands, total water storage also is important.

10.3.3 Aeration

Excess soil water does not directly injure pine roots: pine roots grow vigorously in well-oxygenated solutions. Adverse effects of poor aeration are the result of insufficient air-filled pore space for transfer of oxygen to respiring roots. This condition generally occurs when (1) the volume of large pores that do not retain water against gravity and are air-filled at field capacity is low because of natural conditions or soil compaction, or (2) water tables are high. On sites without a water table in the rooting zone, slow diffusion of oxygen limits growth as the air-filled soil volume at field capacity approaches a critical level of 10% [116]. Root restriction in soils with seasonally high water tables is worse in soils with low percentages of large pores but can occur regardless of pore-size distribution. Seedlings are less severely influenced by a rise in water table during winter, when respiration rates are lower, than during summer. Fluctuation in the water table tends to increase damage as roots that develop in the zone above the water table are subjected to environments that alternate between suboptimum moisture and inadequate oxygen.

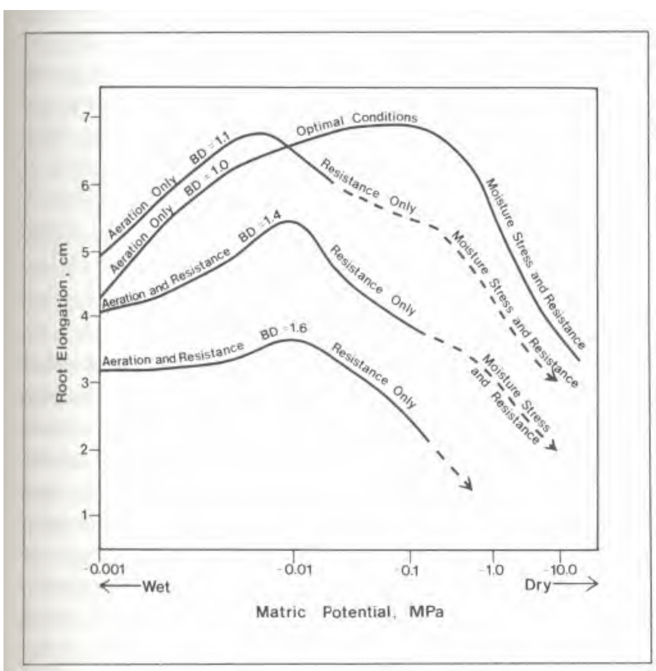

Figure 10.7. Contribution of mechanical resistance, aeration, and moisture to root elongation during a 48-hour growth period in a sandy soil compacted to four bulk densities (BDs) and held at different soil water matric potentials (adapted from [291).

Because soil strength, water and nutrient availability, and oxygen diffusion all affect root growth, determining the influence of a specific soil factor on root growth is difficult in the field. Eavis [29] attempted to partition the effects of soil strength and aeration on root development of three agronomic crops and found that curves could be developed for the relationship between root growth and moisture conditions but that the shape and controlling factor depended on soil bulk density (mass of dry soil per unit volume) (Fig. 10.7). Although such relationships have not been developed for southern pines, similar patterns are likely. On the same site, root growth can be limited by poor aeration during wet periods and mechanical impedance and low water availability during dry periods. Generally, the former would be more important on poorly drained sites, the latter on well-drained upland sites.

10.3.4 Temperature

Root growth of southern pine is optimized at soil temperatures between 20 and 25°C. Temperatures above or below this optimal range decrease root growth and, presumably, increase mortality and decrease aboveground growth. For loblolly pine, root growth is near maximum at 25°C [5]. Above this temperature, root respiration increases and growth decreases up to temperatures of about 45°C, at which point trees may die [112]. A near linear decrease in root respiration occurs below the 25°C optimum down to 5 °C, at which point root elongation essentially stops.

Although all southern pines can grow in soils with thermic temperature regimes, differences among species exist. Both Virginia (*Pinus virginiana* Mill.) and shortleaf pine are native where average annual soil temperature falls below 10°C (mesic temperature regime); loblolly, sand [*Firms clausa* (Chapm. ex Engelm.) Vasey ex Sarg.], longleaf, and slash pine extend into central Florida where annual soil temperatures exceed 22°C (hyperthermic regime). Nevertheless, except at the extreme and upper elevations of Interior Low and Appalachian Plateaus and Valley and Ridge provinces, soil temperature is not a major constraint in species selection.

Direct root or stem injury to seedlings resulting from either too high or too low a temperature is rare. Winter frost heaving of planted seedings has been reported for southern pine, particularly for smaller seedlings with shallow, less developed root systems. Such frost heaving is most common on fine-textured poorly drained soils where upward capillary movement of water from deeper soil layers is greatest. Because of low heat capacity, organic soil horizons formed into raised beds can freeze to > 20 cm depth. Mortality of recently planted seedlings on organic soils in the Coastal Plain of North Carolina can be attributed to water stress resulting from relatively high transpirational demand during periods when soils were frozen.

Slow root growth associated with low soil temperatures may be largely responsible for high moisture stress in seedlings outplanted during winter when soils are wet and transpirational demands relatively low. In Australia, radiata pine seedlings transplanted in late September when soil temperatures average 11°C are more severely stressed than seedlings planted in November when temperatures rise to between 12 and 16°C, even though rainfall is lower [73]; this appears due to slow root growth below a critical temperature of about 11°C. For loblolly pine, Carlson [13] has shown root-growth potential to be low below 10°C for all families tested. Above 10°C, root-growth potential increased approximately linearly until at least 20°C.

The maximum temperature reached at the soil surface depends upon heat capacity and thermal conductivity, both of which depend strongly on water content. The potential for direct heat injury is greatest for seedlings planted in dry soils with dark surfaces and low thermal conductivity.

10.3.5 Soil Reaction (pH)

Southern pine are tolerant of acid soil conditions. Although pH is optimal at about 5.6, pines grow well in soils with pH values ranging from 4.5 to 6.5 [82]. Within this range, differences in growth are largely due to differences in nutrient availability and the mobility of toxic elements. Instances where soil reaction is a major consideration in regeneration are limited to mine reclamation or to afforestation of Coastal Plain sites where calcareous materials are close to the surface. Such soils are common in the Black Belt of Alabama and Mississippi and, locally, elsewhere in the Coastal Plain.

10.3.6 Nutrient Availability

Of the 16 nutrients essential for growth, 13 are supplied by the soil: the macronutrients nitrogen (N), P, potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S) which, because of their role as a constituent part of plant proteins, cell walls, or chlorophyll, are required in relatively large quantities; and the micronutrients boron (B), iron (Fe), manganese (Mn), copper (Cu), zinc (Zn), molybdenum (Mo), and chlorine (C1), which are an integral part of enzymes and are required in only small amounts. All can limit growth. Worldwide, growth limitations have been documented for all but the micronutrients Mo and Cl. Forest-fertilization research in the South indicates that micronutrient deficiencies may limit growth on poorly drained Coastal Plain soils [21], but limitations of the macronutrients N, P, and K are the most common.

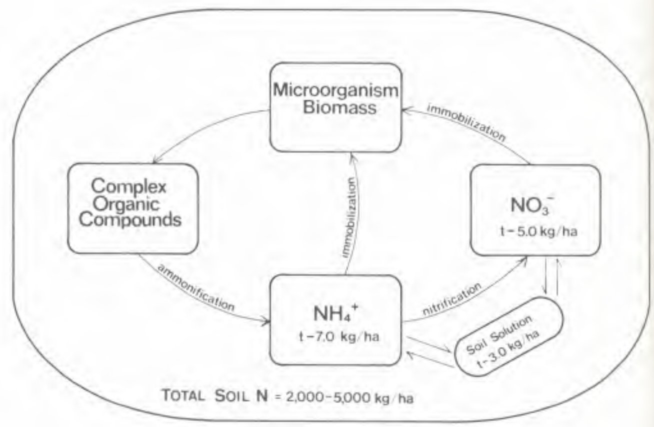

Figure 10.8. Nitrogen (N) transformations and estimated ranges in the size of N pools for a slash pine stand on an Ultic Haplaquod (t = trace quantity).

The direct role of soil fertility in seedling establishment is not clear. Generally, nutrient demands of seedlings are low compared to the potential supply in the soil profile. Thus, nutrient deficiencies in seedlings occur only when low availability is coupled with restricted root growth, conditions that limit quantities of nutrients in soil solution and their transfer to the root surface and/or depletion by competing vegetation. It is not possible to separate seedling and root response to nutrient conditions from water supply and the overall rooting environment. Where overall fertility is low, roots of woody species proliferate in areas with the most favorable nutrient supply [81, 101], and for most nutrients, an increase in supply in one portion of the root system does not appear to alter nutrient-constrained growth in other portions [27]. Thus, initial root development and seedling growth are reduced by any soil horizon in which availability of any essential nutrient, except K, which is physiologically mobile, is low. When low available K limits growth, increases in one portion of the root system appear to stimulate growth of the entire root system [81].

10.3.6.1 Nitrogen

Although some data indicate that N can be absorbed directly in organic compounds, virtually all N is absorbed by tree roots as inorganic ammonium N (NH_4^+) or nitrate N (NO_3), the products of microbial decomposition of organic matter. As depicted in Figure 10.8, availability of these compounds depends upon mineralization, the breakdown of complex organic compounds by different groups of microorganisms. Two steps are recognized: ammonification, which is the conversion of organically bound nitrogen to ammonium, and nitrification, which is the oxidation of reduced ammonium to nitrate. As long as there is abundant reduced carbon (C) for energy, much of this mineralized N is recycled within the microorganism populations. It is not until the C/N ratio is reduced to about 11/1 that large amounts of inorganic NH_4^+ or NO_3^- enter

Table 10.3. Factors influencing organic matter decomposition and nitrogen (N) mineralization rates in forest soils.

Factor	Relationship	Common forest-management impacts
Temperature	N mineralization is doubled for every 10°C increase in soil temperature between 5° and 30°C.	Overstory removal can increase surface soil temperature by 5–10°C during summer. Forest-floor removal can increase temperature by an additional 5°C.
Moisture	Mineralization is maximum at moisture contents near field capacity and can be stimulated by wetting and drying cycles.	Drainage or bedding increases mineralization through more favorable surface-soil moisture regimes.
Substrate quality	Net mineralization is low until C/N ratios are reduced from > 100/1 in fresh slash to 20–25/1. Prior to this, mineralized N is used by decomposers.	Types of slash left on site can affect mineralization. Fine branches and needles decompose and release N more quickly than branches and stem.
pH	Ammonification occurs over a wide range of pH values, but nitrification is suppressed below a pH of 4.5–5.0.	Burning increases pH and amount of inorganic N in mobile (easily leached) NO_3 forms.
Tillage	Mineralization rates can be doubled by soil tillage because of improved aeration and mixing or organic materials with mineral soil.	Both disking and bedding increase N mineralization partially as a result of soil tillage.

into soil solution. The presence of microsites with low C/N ratios are responsible for net N mineralization in surface soils beneath southern pine with C/N ratios between 25/1 and 35/1.

Under most conditions, < 1% of the total N in mineral and organic soil layers is in inorganic forms available to seedlings, and only under unusual conditions is more than a week's supply in soil solution. Tree growth depends upon continual replenishment of this supply. As such, factors that affect the activity of microorganisms - soil temperature, moisture, and pH; the amount and chemical characteristics of substrate required by microorganisms as an energy source; and the abundance of favorable microsites, particularly as affected by tillage - have a major influence on N availability (Table 10.3).

Nitrogen is seldom deficient in young stands. Under well-aerated conditions, additions of fresh slash (logging debris), warmer soil temperatures, increased soil moisture, and mixing of organic and mineral soil horizons which accompany establishment all contribute to accelerated N mineralization and increased availability. Only under wet conditions do exceptions occur. For instance, Maki [59] observed N deficiencies in seedlings planted on very poorly drained soils where site preparation had included disking large amounts of coarse debris into the mineral soil surface; apparently, mineral N was immobilized by microbes decomposing the coarse debris, which has a high C/N ratio.

Generally, herbaceous and grass competitors of young pine can use large amounts of available N. Therefore, N additions at planting without appropriate weed control often reduce seedling growth by stimulating growth of competing species.

10.3.6.2 Phosphorus

The primary form of available P in acid forest soils is H2PO4-. Although small quantities of inorganic P may be absorbed on the anion exchange sites and made available by exchange reactions, P availability is largely controlled by solution chemistry and is maximized between pH values of 6.0 and 7.0. Under more acidic conditions, P combines with soluble hydroxides of Fe and aluminum (Al) to form insoluble compounds. At pH values > 7.0, Ca precipitates form, and solution concentrations of P are reduced.

As much as 50% of the P in forest soils can occur in organic forms and, like N, and may be released by decomposition. As such, factors affecting microbial activity can be expected to affect P availability. However, the relative importance of changes in these factors to P supply are not well understood, and our concept of P availability is largely based on inorganic reactions.

Even in soils where relatively large amounts of inorganic P are available, deficiencies can occur because of restricted root development. As previously mentioned, nutrients must move from mineral and organic surfaces to the root in water before uptake is possible. Two processes contribute to this: convection (movement in the mass flow of water) and diffusion (movement in response to a concentration gradient). Phosphorus solubility is so low that only small amounts occur in soil solution as a function of equilibrium chemistry, and mass flow to the roots could not supply the P required by developing plantations. Almost all phosphorus arrives at the root surface in response to diffusion gradients established by uptake at the surface of actively growing roots. The distances that P can move by diffusion vary by soil type and moisture content, but in all cases are small (typically < 1 mm). Thus, P uptake is particularly dependent not only on available supply, but also on a dense root system able to fully utilize that supply. Soil factors that restrict root development, such as poor aeration or high soil strength, disproportionately reduce uptake of P in relation to that of other nutrients.

10.3.6.3 Potassium

Cations such as K^+, Ca^{++}, Mg^{++}, and NH_4^+ are held in the soil through electrostatic attraction to negatively charged soil particles and organic matter, the positive charge of the cations balancing the negative charge of the soil. These surface cations are in quasi-equilibrium with cations in the soil solution. However, the concentration of any individual cation in solution is governed by the total cation exchange capacity (CEC) of the soil (total negative charge available to hold cations) and the type and relative proportion of other elements in solution and on the exchange surface. This exchange surface is the major source of plant-available K, Ca, and Mg. Soils with high clay or organic matter contents have large surface areas with excess negative charge and, therefore, high CECs. These soils are least likely to be deficient in K, Ca, or Mg. Where K deficiencies have occurred in the South, soils have been coarse textured with low CECs.

In general, increasing the concentrations of any cation increases the absolute concentration of K in solution and its plant availability in the short term, but decreases the amount of K on the exchange site. If K in solution is leached, long-term availability is reduced; such a long-term loss is one potential adverse effect of acid deposition, which replaces K and other cations on the exchange complex with H^+.

As with phosphorus, potassium is supplied to the root by both convection and diffusion. However, it diffuses farther than P, and its uptake is less affected by root density. Seedling growth on somewhat poorly to very poorly Coastal Plain soils has been increased by K additions when N and P are available in ample supply; however, K fertilization is not yet recommended as a standard regeneration practice [21] because results are highly variable and no soil or tissue has been successful in predicting tree response to K fertilization.

10.4 Evaluating Plantation Sites Using Soils Information

Accurate and precise soil maps are the key to using soils information in decisionmaking processes. Soil maps, developed for most of the region in which southern pine grow, range from statewide delineations of major soil groups based on geologic parent materials to specialized surveys for individual tree farms. Broad-scale state or county maps (1:250,000 or greater) are useful for evaluating forest cover types, planning major land acquisitions, and evaluating disease and insect outbreaks. Finer resolution is required for silvicultural decisionmaking. Second-order SCS soil surveys, with scales of between 1:15,000 and 1:30,000 and delineation of map units as small as 1 ha, are available for more than half the counties in the South and are widely used for harvest, regeneration, and intermediate silvicultural prescriptions. In addition, many forest-products companies have implemented soil survey programs. Although each uses somewhat different standards for map development, many use SCS soil series as the basic classification unit, further grouping or subdividing on the basis of local conditions and management needs.

Ideally, the completed soil survey provides necessary information at fine enough resolution to assist forest managers in evaluating each of the following:

(1) productive potential
(2) limitations to equipment use
(3) insect and disease hazard
(4) species and genotype selection
(5) fertilizer requirements at establishment
(6) pesticide use.

Few surveys contain all of the information potentially needed for making management decisions; therefore, an on-site visit and additional sampling are often required.

10.4.1 Productive Potential

A land manager's first need is to establish the level of management intensity appropriate for each stand. Sites with a productive potential below some minimum cannot be profitably managed for timber and fiber production. Above this minimum, the more productive the land, the greater the funds that can be profitably invested in regeneration and silvicultural treatments. Correlations between soil conditions and site index of natural or plantation stands provide initial information necessary in plantation forestry.

10.4.1.1 Correlation of soil characteristics to productive potential

The yield of biomass or specific products from a plantation depends upon three general considerations: (1) the potential of the land to support and grow a designated forest crop under ambient climatic conditions, (2) the degree to which this productive potential of a site is used by crop species to accumulate biomass in merchantable components of the tree, and (3) the extent to which crop trees can be protected from damaging agents. Soil conditions are directly related to the first consideration and indirectly related to the latter two.

Most of the relationships between soil conditions and the productive potential of a site have been established by the many (over 40) correlative soil-site studies conducted in the South between 1950 and 1975 [15]. Most of these utilized site index, the height of dominant and codominant trees of a given species at a base age of 25 or 50 years, as an index of productive potential.

In virtually all soil-site studies conducted in the South, some measure of the depth of surface horizons with favorable rooting conditions is the characteristic most closely correlated with site index. In the Coastal Plain, profile features that reflect the presence of water tables which restrict root development, such as drainage class [60, 85, 121] or depth to mottling [17, 85, 86, 110], have been found to be the most useful indexes of this depth. In abandoned farmland of the Piedmont, surface-soil depth (A or A plus E horizon) is the single most useful factor for

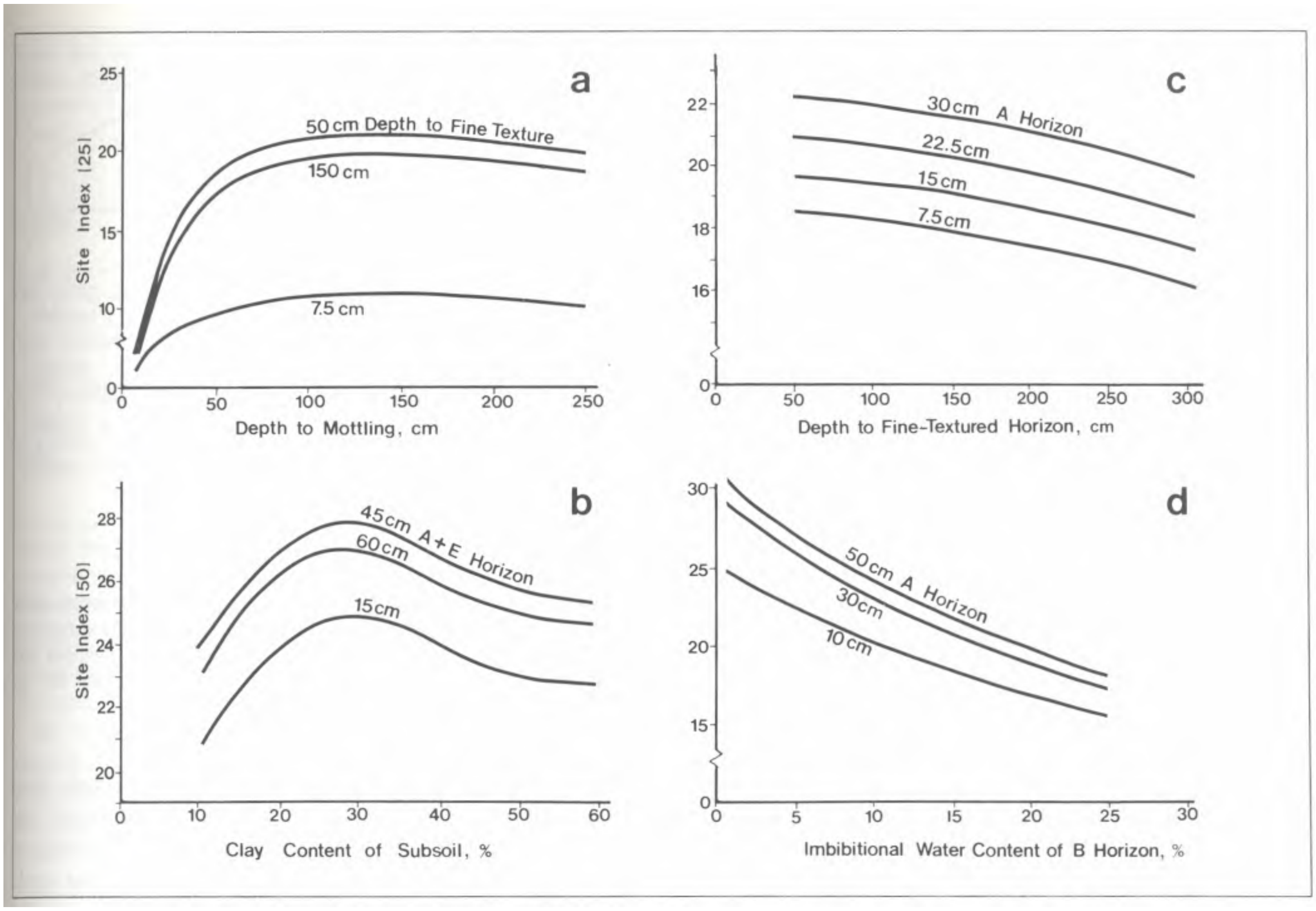

Figure 10.9. Relationships between soil properties and site index (height, in, at base age 25 or 50) for the (a) Lower Coastal Plain, (b) Upper Coastal Plain, (c) Sandhills, and (d) Piedmont (adapted from [86, 122, 88, 19], respectively).

discriminating among sites of differing productivity [16, 19, 54]; in the coarser textured soils of the Ozarks and Ouachitas, soil volume is most often described by depth to a fragipan [42]. Because large amounts of coarse fragments, which reduce soil volume, are common in this region, coarse-fragment content is an important modifier of surface depth [42, 74].

Measures of subsoil quality, particularly as they affect moisture availability, are the next most important characteristics associated with productive potential. These subsoil characteristics have often been combined with surface-soil depth to produce broad relationships between soils and tree growth within a physiographic region or habitat type (Fig. 10.9). In many cases, relationships between subsoil characteristics and tree growth are modified by surface-soil depth. As with surface-soil conditions, the subsoil variables that best reflect differences in subsoil conditions differ among regions. In the Lower Coastal Plain, soil texture is a useful modifier for basic relationships among winter water table, rooting depth, and productivity because of its relation to water storage and movement [30, 86, 121]. In the Upper Coastal Plain of Arkansas, clay content was found to be the subsoil characteristic that best reflected rooting and water supply characteristics of the subsoil [122]. In the Piedmont, where most subsoils are clay textured, site index for shortleaf and loblolly pine was related to surface-soil depth and subsoil consistency; site index increased with depth and decreased imbibitional water content (a measure of the shrink-swell capacity of clay determined from the difference in water and xylene absorption) [17].

Organic matter content, because of its relationship to water and nutrient supply characteristics, has occasionally been associated with site quality of southern pine, particularly on coarse-textured soils where it is associated with available water holding, capacity [42]. Other soil factors can be locally important. On Coastal Plain soils underlain by calcareous marls, soil pH has been associated with productivity, with growth better under more acid conditions [30, 57]. Extractable nutrient concentrations have rarely been useful in developing such general site-productivity relationships; however, Ellerbe and Smith [30] and McKee [62] have shown that chemical properties can improve correlations between soil characteristics and productive potential in the Lower Coastal Plain once soils are narrowed to a series level.

10.4.1.2 Mapping

Differing management objectives and philosophies influence how soil mapping units are identified. In the SCS approach, mapping units are developed on the basis of recognizable characteristics such as drainage, texture, color, and horizon thickness without *specifically considering factors affecting forest productivity*. In contrast, soil mapping units used by Weyerhaeuser and other forest products-companies have been specifically developed to incorporate soil properties known to be correlated with forest growth.

In the most recent SCS soil surveys, site index for locally important commercial species is estimated in the woodland management and productivity portion of the interpretation section. In older surveys, commercially important species were placed within a site-index class. Where these productivity estimates are for soils of limited extent and are developed within the survey area, they can be accurate. However, site-index estimates reported in SCS surveys may be developed in stands with different regeneration histories and often include data from geographically distant but similar soils. The wide range of productive potentials included in SCS soil series and mapping units has been criticized [14, 18]. Productivity estimates for soil series which have wide geographic ranges or highly variable subsoil conditions influencing tree growth can be improved by use of additional site characteristics, climatic conditions, chemical analyses, and physiographic features [62, 118]. For instance, McKee [62] found that site index at age 50 ranged from 26.5 to 32.9 m for the Craven series in South Carolina. A multiple regression using surface soil N, clay content, and pH accounted for 60% of the variation within the series.

In the South, Weyerhaeuser [11] utilizes carefully selected stands of plantation loblolly pine to measure tree growth regionally and establish "baseline" productivity (site index). Site index is determined for a minimally manipulated even-aged stand on a particular soil and landform that developed under a given set of climatic conditions. Typically, this would be a flat-planted stand of trees of native genetic origin. Under the same management regime, another location with the same soil and landform conditions and similar climate should produce a stand with a comparable site index. Under a different regime, site index could be reduced, remain unaltered, or increase. Site indexes determined from these baseline conditions are correlated with edaphic, climatic, and physiographic variables previously shown to be associated with tree growth. From these relationships, soil series are described that differ in inherent productivity and response to management treatments.

Comparison of an SCS soil survey with an industrial soil survey for the same area indicates differences in features used to delineate map units and in the level of detail. Industrial surveys are normally more detailed than SCS surveys, at least in part because SCS survey standards for forested land are lower than those for adjacent agricultural or developed areas. On the site indicated in Figure 10.10, the area west of the spur road (shaded) was mapped Pantego loam with some Croatan muck and Rains fine sandy loam in the SCS survey. A typical site-preparation

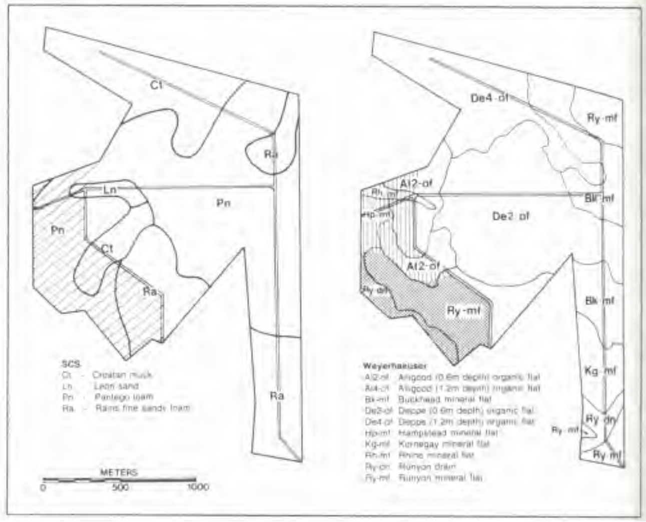

Figure 10.10. A Soil Conservation Service (SCS) second-order soil survey and a Weyerhaeuser soil survey for the same tract of forested land. The difference in boundary location and mapping detail resulted in different prescriptions for the shaded area [48, 100].

prescription for these soil types would be V-blade shear and roller drum chopping followed by a broadcast burn before bedding. If site preparation had been prescribed on the basis of the SCS survey, the entire shaded area would have received this treatment. However, in the Weyerhaeuser soil survey, the same area includes five mapping designations. Experience has shown that both Alligood units (Al2-of and A14-of) require shearing with a KG-blade and windrowing before acceptable beds can be formed. Thus, two site-preparation regimes would be prescribed for this area. The dot-shaded portion dominated by the Runyon units would be sheared, chopped, and burned, along with most of the rest of the site, whereas the line-shaded portion dominated by the Alligood units would be sheared and windrowed.

Many forest-products companies and large agencies have sufficient experience with different forestry operations to have developed an understanding of how specific operations affect baseline productivity (site index). An example of such a localized system for adjusting productivity estimates is presented in Table 10.4. Where available, these adjustments provide a basis by which the economics of individual forestry operations can be evaluated.

10.4.2 Limitations to Equipment Use

Forestry practices have major effects on both physical and chemical soil conditions. Soil compaction, a reduction in the volume of pores (particularly large pores, which do not retain water against gravity), is common on harvested areas throughout the South [36-38, 103]. Because compaction increases as the number of machine passes increases, it is greatest on primary skid trails. However, areas that do not receive concentrated traffic may also be compacted

Table 10.4. Baseline productivity adjustments, as measured by change in site index (height at base age 25), for soils of varying texture, drainage characteristics, or depth in the Lower Coastal Plain (adapted from [11]).

	Site index change, m							
	Sand-loamy and		Sandy-loam-silt loam		Silty clay loam-clay		Organic	
Activity	Poorly drained[1]	Well drained	Poorly drained	Well drained	Poorly drained	Well drained	< 25 cm deep	> 25 cm deep
Prelogging drainage	+1.5	0	+4.5	0	+3.0	0	+3.0	+10.0
Wet-condition logging	–1.5	0	–3.0	–1.5	–3.0	–3.0	–1.5	0
Dry-condition logging	0	0	–1.5	0	–1.5	0	0	0

[1] "Poorly drained" includes very poorly to somewhat poorly drained soils; "well drained" includes moderately well to well-drained soils.

during harvest and regeneration. Compacted soils are characterized by reduced rates of water infiltration, lower hydraulic conductivity when saturated, decreased gas diffusion, reduced oxygen availability, and increased soil strength — all of which are detrimental to tree growth (see 10.3, this chapter).

For a given load, compaction is greatest at moisture contents near field capacity. Water tension holding individual soil particles together is low, and large pores do not contain water that would prevent particles from being forced into them. The water content that defines this point varies by texture; it is lowest for sand and highest for clay. Loam soils have a near uniform distribution of particles and can be compacted to the greatest degree.

The degree of compaction is most easily (and most often) measured by bulk density. For any particular soil, there exists a bulk density beyond which root growth is severely restricted even at optimum moisture contents. On the basis of published studies, Daddow and Warrington [23] developed a growth-limiting bulk density triangle (Fig. 10.11). Growth reductions can be expected for a soil of given texture when bulk density exceeds the critical value indicated by the bold lines. Note that growth reductions can be expected at lower bulk densities in finer than coarser textured soils. Although this triangle should be used only for conditions where aeration is not a problem and for soils with > 3% organic matter and < 10% coarse fragment content, it does provide a useful guideline for evaluating compaction on upland forest areas.

Puddling, which is the destruction of soil structure, occurs when heavy equipment is operated on wet soils with high silt or clay contents. Under these conditions, water in the pore space keeps particles and aggregates from being compressed. Instead, they slip against one another, breaking aggregates apart and reorienting fine particles along similar planes. This greatly reduces permeability to air and water. Rutting is the most obvious manifestation that a soil is puddled.

At moisture contents approaching and greater than field capacity, puddling is of greater concern than compaction. Unlike compaction, puddling is most severe in clays where

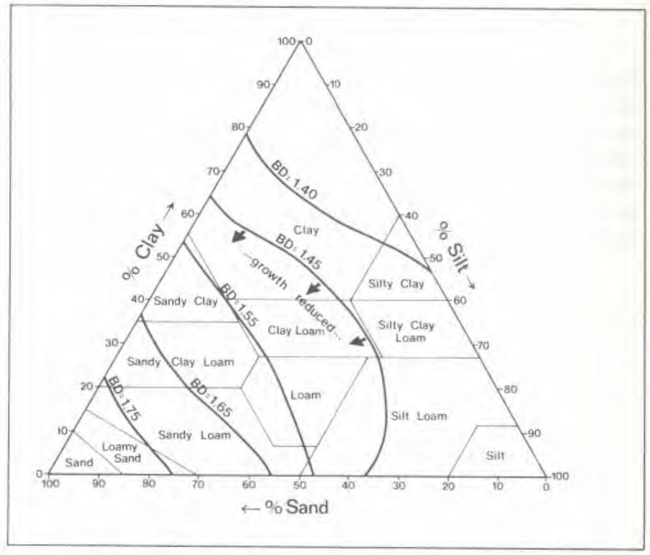

Figure 10.11. Growth-limiting bulk density (BD) triangle for various soil textures (adapted from [23]).

individual clay particles are platelike and are easily oriented along the same plane. McKee et al. [64] developed guidelines for use of equipment on sites with seasonally high water tables where puddling hazards are greatest (Fig. 10.12). Operations should be planned to avoid susceptible areas during wet periods and should be suspended when conditions indicate rutting is likely.

Topsoil removal and nutrient loss associated with mechanical windrowing or piling operations or logging could have a major impact upon the long-term nutrient supply in intensively managed plantations [72]. Although information is generally lacking on the magnitude of such losses, analyses based on nutrient budgets and fertilizer response curves suggest that yields will be reduced most on coarse-textured Haplaquods (flatwoods) of the Lower Coastal Plain with low N reserves. Soils high in organic matter content, such as Humaquepts, appear least likely to be affected by piling [77].

10.4.3 Insect and Disease Hazard

Opportunities for reducing pest damage and disease in

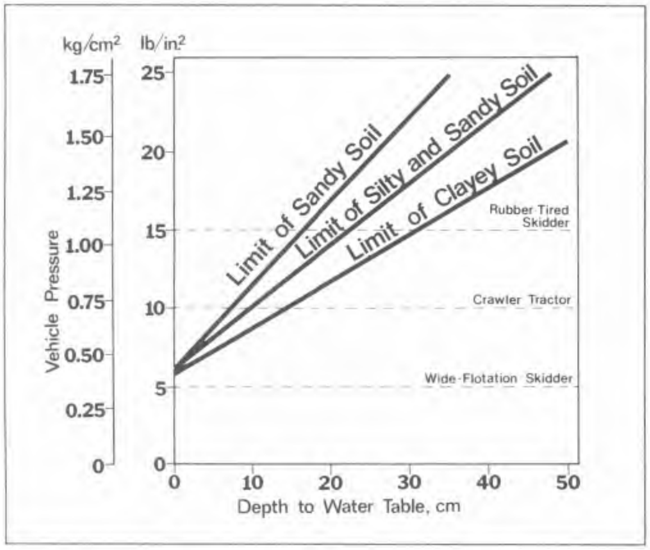

Figure 10.12. Puddling (rutting) hazard for mechanical operations on soils with water tables near the soil surface. Hazard is minimized when the ground pressure exerted by the vehicle is less than the limit identified for a selected soil texture and water-table depth. Expected maximum ground pressures for three vehicle types are indicated by the dashed lines (adapted from [64]).

plantations are greatest during regeneration. Appropriate species selection and site preparation can affect the extent of the pest problem throughout the rotation (see chapter 20, this volume). Damage from insect pests and disease (Table 10.5) has been related to a number of soil factors which can be determined from soil maps or evaluated in the field.

Littleleaf disease, the major disease problem in shortleaf pine stands of the Piedmont, results from a combination of factors including poor nutrition, poor aeration, and repeated attack by root pathogens. Damage is greatest on eroded soils of low fertility and poor internal drainage where root damage caused by *Phytophthora cinnamomi* Rands. is greatest. Under intermittently waterlogged conditions characteristic of these areas, fungus spore dispersal and infection are near optimal. Campbell and Copeland [12] developed a disease hazard rating using erosion class and characteristics affecting internal soil drainage. More recently, Oak [78] demonstrated the utility of this rating system by developing a soil hazard map using information available from second-order SCS soil surveys.

Damage from fusiform rust *(Cronartium fusiforme)* is also related to soil factors. Increased incidence of fusiform rust is generally associated with high soil fertility [50, 68] and well-drained soil conditions [50]. Hollis and others [50] suggest that rust tends to be more prevalent on well-drained soils at least partially because of increased presence of oak, the alternate host, and higher inoculum potential.

Although not widespread, root rot caused by *Heterobasidion annosum* can severely damage stands in localized areas. Morris and Frazier [69] developed a system for hazard rating based on soil texture, drainage, and previous land use; hazards were highest on well-drained old fields.

Lorio and Sommers [58] developed a hazard rating for southern pine beetle *(Dendroctonus frontons* Zimm.) damage on shortleaf and loblolly pine in the Gulf Coastal Plain using landform and soil characteristics. Conditions which extended the period of rapid early-season growth and decreased the trees' production of protective chemicals increased susceptibility. On these sites, susceptibility was greatest on wet soils with silty textures. Soils with impeded internal permeability were particularly susceptible to attack.

10.4.4 Species and Genotype Selection

Several factors are involved with determining species suitability for various soils (see also chapter 11, this volume). Potential growth is central but is modified by the desired products, disease and insect hazards, site-preparation prescription, fertilization level or other cultural treatments, and rotation length. For instance, slash pine is the preferred species on poorly drained Haplaqults, Paleaqults, and Haplaquepts in the Coastal Plain with low levels of extractable P; however, loblolly pine will perform better on these sites when P is added at planting [46]. Species comparisons done at an early age may be misleading. Indeed, the widespread planting of slash pine on droughty sandhill sites during the early 1960s was largely based on such early comparisons, which showed it superior to sand or longleaf pine. However, the early growth advantage of slash pine was not maintained on these sites, and both sand and longleaf pine ultimately had higher yields [53]. Caution must also be exercised in interpreting comparisons for a species like loblolly pine, which ranges widely. For this species and, to a more limited extent, others, results from comparisons depend on the seed source or families used [123].

Slash and loblolly pine are the preferred species, having greatest projected volume growth during typical 25- to 30-year rotations throughout the Coastal Plain. Generally, of the two species, loblolly pine appears to yield greater volumes over the rotation except on spodosols without an underlying clay layer (Typic Haplaquods). For instance, Cole [20] summarized results from slash and loblolly pine species comparisons in the Coastal Plain of South Carolina, Georgia, and Florida. Six seed sources were used for each species tested. At 9 years of age, loblolly pine was significantly more productive as measured by total volume (64 to 69% greater) or weight (54 to 46% greater) than slash pine on all soils except Haplaquods. Similar results point to superior volume growth of loblolly on clay- to loam-textured soils throughout the Coastal Plain [8, 10, 45, 108]. In contrast, comparing four southern pine species (slash, longleaf, loblolly, and sand) in the Coastal Plain of Louisiana and Arkansas, Shoulders [92], found that slash pine heights were greatest on somewhat poorly drained or wetter sites at age 15 and that slash pine height growth was as good as that of other species on moderately well and well-drained sites. Unlike in the many other studies that found greater yields with loblolly than slash, these sites had a low incidence of fusiform rust which did not affect relative species performance.

Table 10.5. Soil conditions associated with major diseases of southern pine.

Disease	Physiographic province	Pine species	Soil conditions	Reference
Littleleaf (*Phytophthora cinnamomi* and other factors)	Piedmont	Loblolly, shortleaf	Incidence and severity increased on shallow soils with poor internal drainage.	[12, 78]
		Shortleaf	Increased by additions of inorganic N.	[87]
Fusiform rust (*Cronartium fusiforme*)	Coastal Plain (Flatwoods)	Slash	Increased incidence associated with increased drainage and increased extractable soil P; these soil conditions associated with increased oak, the alternate host.	[49, 50]
		Slash, loblolly	Greater incidence on moderately well and well-rained sandy loam than on poorly drained sands.	[89]
Heterobasidion annosum	Coastal Plain	Loblolly	Increased incidence with decrease in capillary pore space.	[1]
		Loblolly	Increased incidence with increased soil pH and Mn concentration and decreased K and Mg concentrations.	[120]
		Slash, loblolly	Low hazard, on poorly drained Haplaquods.	[55]
	(Gulf States)	Loblolly, slash	Increased incidence at higher soil pH and lower surface-soil organic matter and silt content.	[33]
	Piedmont	Loblolly	Low hazard when depth to clay-textured subsoil < 0.3 m.	[34]
Spot die-out	Piedmont	Slash	Problem on fine-textured soils with low oxidation reduction potential (poor aeration).	[22]
Pitch canker (*Fusarium moniliforme*) var. *subglutinans*	Valley and Ridge	Virginia pine	Increased incidence on poorly drained sites.	[4]

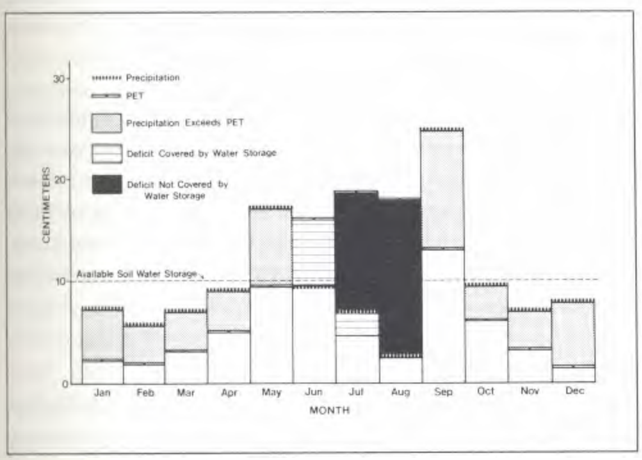

Figure 10.13. Determining soil-moisture deficit using available water holding capacity, monthly estimates of potential evapotranspiration (PET), and precipitation. In this example, precipitation exceeded PET for all months except June, July, and August. Enough available water was stored in the soil profile to compensate for the June precipitation deficit; however, a soil-moisture deficit of 28 cm existed for July and August (adapted from [56]).

In the Coastal Plain, loblolly pine is less suitable on coarse-textured, excessively drained Quartzipsamments than longleaf or sand pine [9, 41], and less suitable on Haplaquods than slash pine [20, 46, 119]. Loblolly pine is recommended throughout the Piedmont [7] except in the upper Piedmont of North Carolina and Virginia (elevations > 500 m) where ice damage is common; there, shortleaf pine is often recommended. In the Ozarks and Ouachita Mountains, planted loblolly pine has been found to grow faster than shortleaf pine across a range of sites including those previously dominated by shortleaf. The potential for higher mortality of loblolly pine during severe drought is greater, and shortleaf pine may be preferred on soils with low water-holding capacities due to the presence of a fragipan and on southwest aspects. Alternatively, drought-tolerant local sources of loblolly pine may be planted on these sites. In a study of loblolly pine provenances, Lambeth et al. [56] found that loblolly from coastal North Carolina sources grew faster than that from local sources, but risk associated with drought-induced mortality was greater. They proposed a system for allocating sources based on summer soil-moisture deficit. In their system,

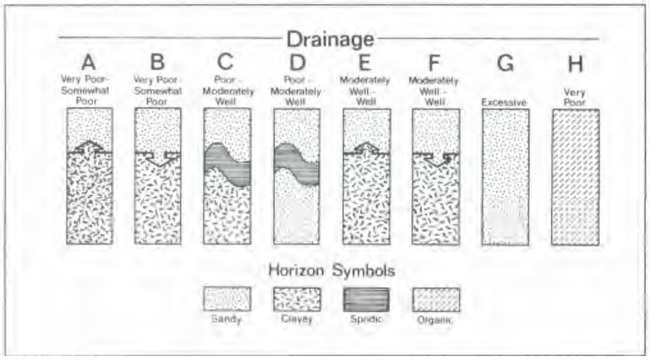

Figure 10.14. Soil groups developed by the Cooperative Research in Forest Fertilization Program, University of Florida, for fertilizer application in the Coastal Plain (adapted from [21]).

total available moisture in the rooting zone is estimated from the textures of each horizon (such as in Fig. 10.5) and horizon depth. This estimate is reduced by the rock volume and the adjusted soil-moisture storage compared with precipitation deficits calculated from the difference between potential evapotranspiration (PET) [109] and expected precipitation for a drought year (Fig. 10.13). Only drought-tolerant sources of loblolly pine were planted on sites with expected soil-moisture deficits > 32 cm during dry years.

Smalley [94, 95, 97-99] lists loblolly, shortleaf, and Virginia pine as desirable species in the Appalachian and Interior Low Plateaus. Because of the greater progress in loblolly pine tree-improvement programs, it should be favored. At elevations below 500 m, loblolly pine should be planted on better soils throughout this region.

10.4.5 Fertilizer Requirements at Establishment

Soil groupings developed by the Cooperative Research in Forest Fertilization (CRIFF) program at the University of Florida have proven particularly useful for selecting and estimating the response of Coastal Plain sites to fertilization. CRIFF separates Coastal Plain soils into eight broad groups on the basis of drainage, subsoil characteristics, and depth to subsoil horizons (Fig. 10.14). In general, soils within each of these groups are similar with respect to properties that bear on fertilizer needs. Phosphorus deficiencies are common in soils within the A and B groups, which normally require P fertilization at establishment [21]. Seedlings planted on soils in the C, D, E, and F groups seldom respond to additions of P at establishment (additions of N will often increase growth in mid rotation stands [31]).

10.4.6 Pesticide Use

A number of pesticides used for insect, disease, and weed control in newly established plantations (e.g., carbofuran, hexazinone, and picloram) are formulated as pellets, granules or liquids for application to the soil

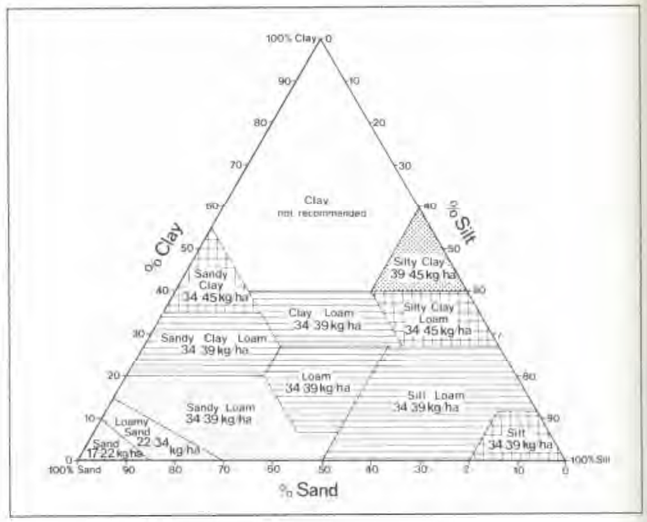

Figure 10.15. Recommended rates, in kilograms per hectare, for site preparation with Pronone for soils of different surface textures (adapted from [63]).

surface. Soil moisture, texture, and organic matter content affect the activity and application rates of these chemicals. Generally, soil-active pesticides should be applied to moist soils when rainfall necessary to move active ingredients into the soil can be expected. Chemical movement will be greater in coarse- than fine-textured soils, and rates will often be lower in the former. Many pesticides combine with organic matter, to form stable, inactive compounds and recommended rates often increase as organic matter content increases. An example of the relationship between soil texture and recommended application rate for Pronone® (containing 10% hexazinone as its active ingredient) is presented in Figure 10.15.

10.5 Manipulating Soil Conditions to Increase Production

Site preparation is often prescribed to reduce amounts of slash and control competing vegetation. However, site preparation also provides an opportunity to improve soil conditions affecting seedling establishment and growth by removing physical barriers restricting root development, improving water storage and availability, reducing temperature stress, or increasing nutrient supply.

10.5.1 Root Development

As illustrated by the results of the many soil-site studies conducted in the South, even under natural conditions the productivity of many sites is limited by conditions that restrict root development. In intensively managed forests, poor rooting conditions can be exacerbated during harvest. Recent field studies have found that significant compaction occurs during harvest of southern pine plantations [25, 36-38], creating soil conditions that restrict root growth in skid trails and elsewhere. Natural processes slowly correct

Table 10.6. Characteristic site conditions where ameliorative soil treatments are applied and soil properties corrected (adapted from [1071).

Site condition	Treatment	Soil factors modified
High water table	Drainage	Improves aeration; aides trafficability.
	Bedding	Improves aeration, soil structure.
Excess surface runoff; low infiltration rate	Terracing[1]	Impedes surface runoff.
	Ripping/subsoiling[2]	Impedes surface runoff; increases infiltration, permebility.
Surface soil with high soil strength, massive structure, compaction/puddling	Disking, bedding, subsoiling	Improves aeration; reduces soil strength; improves infiltration, permeability.
Subsoil with high soil strength, massive structure, shallow low pan	Subsoiling	Reduces soil strength; improves infiltrations, permeability.
Stony, shaly, etc., surface soil	Subsoiling	Changes rock orientation; improves planting quality and ease of planting.

[1] Small berms might be formed with a modified ripper.
[2] Terms sometimes are used synonymously; may be shallow or deep.

these conditions [80]. Some management practices can quickly improve them.

On moderately well to well-drained upland soils, where mechanical resistance to root penetration is a major concern, disk harrowing and subsoiling provide the greatest potential to improve rooting. For both operations, the major influence is on root development in the disturbed soil zone. Outside of this zone, rooting density is unaffected. Because of this disk harrowing, which improves soil conditions in the surface 15 to 20 cm of soil, is most effective where root restrictions result from surface soil compaction such as occurs in non-skid trail areas of harvested sites [36-38]. Where roots are restricted by inherently poor subsoil conditions, such as on eroded Piedmont sites, in skeletal soils of the Ouachita Mountains, or in deeply compacted skid trails, subsoiling or ripping is likely to be more effective.

Bedding, the construction of a raised berm, has the greatest potential to increase rooting volume and density on poorly drained soils with unfavorably high water tables; there, it provides a zone of well-aerated soil favorable to root growth. Root density in young pine stands is greater in beds than in nonbedded (or interbedded) areas of soils ranging from clay [47] to sand [90]. Improved seedling performance from bedding of upland sites largely results from improvements in other soil and site conditions, including decreased competition, greater nutrient availability, and, perhaps, increased precipitation infiltration and storage of available water.

Options for altering existing soil conditions or ameliorating those caused by current or past management practices are summarized in Table 10.6.

10.5.2 Water Storage and Availability

Available soil water is largely a function of rooting volume, and operations that improve rooting also increase water available to trees. However, the proportion of this potentially available water actually used by pine stands is determined by the amount and type of competing vegetation. So weeding provides an obvious way of increasing available water for crop trees.

Moisture supply also can be increased through soil manipulation. Removing slash and litter may increase the amount of water reaching the soil surface. Swank et al. [104] have estimated forest-floor interception to be between 5 and 7.5 cm/year in loblolly pine plantations. The recovery of even half of this annual loss would be significant. The actual benefit of decreased interception, however, depends on rainfall patterns and soil texture. For instance, Ginter et al. [40] found that removing litter beneath longleaf pine on a coarse-textured soil increased soil water content following rainfall, but resulted in lower soil water and increased pine moisture stress during dry periods. Presumably, this was the result of increased surface evaporation in the absence of an intact forest floor. On upland sites, subsoiling or bedding on the contour can reduce runoff and increase infiltration through dry surface layers into the subsoil during rainfall [67], as well as improve rooting volume (as previously mentioned).

On poorly drained soils, soil management aims to maximize the depth to the water table during winter when roots are damaged by poor aeration while increasing the amount of water retained on site during dry periods. This can be accomplished with bedding, which lifts seedlings above the water table, or through use of controlled drainage. In winter, sites are allowed to drain freely; in spring, boards, (flash-boards) are placed in specially constructed culverts to allow maximum retention of water. Optimal depths to the water table listed in Table 10.2 provide reasonable targets for water-table control.

10.5.3 Thermal Stress

Although changes in soil physical conditions and soil moisture affect temperature, the major influence exerted during site preparation is on forest-floor condition. Because of its low thermal conductivity, an intact forest floor insulates mineral soil from both high and low temperature extremes. In Florida, soil temperature at the 10-cm depth was 5°C lower on harvested sites prepared for planting with procedures that maintained an intact forest floor than on sites where the forest floor was removed during windrowing [71]. Maximum temperature recorded at the surface of the mineral soil was reduced from 65°C to 40°C beneath the intact forest floor.

Soil temperatures of < 10°C are common in the rooting zone in the northern portion of the thermic regime and in mesic regimes. Because wet soils have a high heat capacity and are slow to warm in spring, site-preparation activities which improve drainage and increase soil temperature enhance seedling survival. Either removing the insulating forest floor or physically manipulating the microtopography is helpful. One of the advantages of bedding poorly drained sites may be the warmer spring soil temperatures and resulting increase in root growth.

The potential for heat injury is greatest for seedlings planted on dry, coarse-textured soils where both thermal conductivity and water availability are low. Seedlings planted on excessively drained sandhill soils (Quartzipsamments) may benefit from the presence of a forest floor which, by decreasing soil temperature, reduces the possibility of direct heat injury. Shade cards, which are used to improve microenvironments in the West, may have a place on dry-site plantings in the East.

10.5.4 Nutrient Supply

Fertilization is a direct way to increase nutrient supply (for more detail, see chapter 14, this volume). In addition to fertilization, nutrient supply can also be improved by various indirect means which promote decomposition and mineralization.

10.5.4.1 Nitrogen

As discussed in 10.3.6.1, mineralization of organic N is maximized at soil moisture contents near field capacity and increases with soil temperature. Site-preparation operations that remove or break up the forest floor and decrease thermal insulation of the mineral soil surface lead to an increase in soil temperature [32, 91]. Such treatments also increase soil moisture because of decreased vegetation cover and lower transpiration. Improved temperature and moisture conditions plus the attendant mixing of organic materials with mineral soil increase N availability.

These increases can be large. In a study of N mineralization following regeneration of a 22-year-old loblolly pine stand in the North Carolina Piedmont, Vitousek and Matson [114] found N mineralization during 2 years following planting to be 20 kg/ha greater in shear, pile, and disked areas, where the forest floor was either removed or incorporated into mineral soil, than in chopped areas, where the forest floor was largely left intact. The advantages of these short-term increases in N may, however, be small in comparison to the disadvantages. In a survey of 1- to 5-year-old plantations in the Upper Coastal Plain and Piedmont, Vitousek and Matson [115] found that site-preparation treatments that removed forest floor and slash from the planting surface by piling reduced the nitrogen mineralized from surface soils in controlled incubations. Thus, it seems likely that once differences in temperature and moisture among site-preparation treatments become small, shear and piled sites will have lower available N.

Bedding concentrates organic matter and surface soil into localized areas which are more easily warmed and, on wet sites, improves aeration, which stimulates N mineralization. During the first year following site preparation, Morris [70] found that total inorganic N concentrations averaged 3.6 ppm in the soil solution beneath beds and only 2.31 ppm in interbedded areas. When bedding is not associated with piling, such short-term increases in mineralization do not appear to significantly decrease long-term N availability.

In established stands, N mineralization can be increased by burning, which reduces C/N ratios of organic materials, increases soil temperatures, reduces quantities of allelochemicals that inhibit nitrification, and decreases uptake by competing vegetation (see also chapter 12, this volume).

10.5.4.2 Phosphorus

The capacity to increase the supply of soil available P is small unless fertilization is used. Few studies have reported differences in either soil extractable P concentrations or soil solution P concentrations among site-preparation treatments. Where such increases have been reported [3, 111], they appear to be associated with differences in the sampling zone resulting from soil addition or removal. Improvements in P nutrition that result from bedding or drainage are due to either (1) a change in oxidation states that releases P from Fe compounds, or (2) improved rooting volume and greater utilization of available supply.

10.5.4.3 Potassium

The supply of K can be increased by site preparation because K is not structurally bound in plants cells and, consequently, is easily leached from fresh litter. Both exchangeable K and K in soil solution are increased by the addition of logging slash. Thus, K availability is increased by site-preparation operations that leave slash on site. Because K does not volatilize at temperatures reached in site-preparation burns, it will be more plentiful following burning.

10.6 Conclusions and Recommendations

Technologically sound plantation management requires

(1) understanding the influence that soil conditions have on stand health and tree growth, (2) appreciating the potential for improving or degrading these soil conditions, and (3) surveying soils in sufficient detail to reliably delineate land of similar productive potential and comparable response to silvicultural treatment. Although deficiencies exist in each of these areas, available soils information has proven useful and been widely applied in southern pine plantation management.

Soils information is most valuable when used throughout the decision-making process. For a specific forest area, the first step is to determine what soils information is available (if any) and its level of detail. Assuming the area has been mapped by the SCS, the following procedure is recommended:

Before harvest:

(1) Identify wetland areas within the forest for which management activities may be restricted (see Chapter 9, this volume). All organic soils (Histisols) and poorly and very poorly drained mineral soils (great groups such as Haplaquents with aquic moisture regimes, see Table 10.1) should initially be included within this area.

(2) For large areas that will be harvested over several years, use soils to delineate harvesting blocks so that the new stands will be of similar site potential and will require similar silvicultural treatments.

(3) Identify and place bounds on the productive potential of each identified block using site index and available information on variance of individual soil series or mapping units (see 10.4.1). Determine blocks for which productive potential is high enough to warrant plantation establishment.

(4) Schedule harvesting and select equipment based on soil drainage and soil texture so that compaction and rutting will be minimized (see 10.4.2).

(5) Identify any special insect and disease problems on the site that may be related to soil conditions (see 10.4.3).

(6) Select species and genotype for planting using soil properties as a guide so that the genetic potential is fully expressed and the risk minimized (see 10.4.4).

(7) Determine expected response to fertilization (see 10.4.5) and evaluate investment opportunities.

(8) As necessary, use information on soil texture and organic matter content in formulating pesticide recommendations (see 10.4.6).

(9) Identify growth-limiting soil factors and estimate the growth response to various site-preparation alternatives (see 10.5). Evaluate investment opportunities of site preparation alternatives (see chapter 2, this volume).

After harvest:

(10) Assess compaction damage and modify site preparation to include appropriate soil ameliorative treatments (see 10.5.1).

(11) Estimate seedling survival and prescribe the number of seedlings to be planted on the basis of desirable stocking, expected moisture stress (see Fig. 10.13), and amount of plant competition expected for the soils and selected site-preparation treatments (see chapter 19, this volume).

References

1. Alexander, S. A., and J. M. Skelly. 1973. Disease incidence and disease severity in loblolly pine planted on two soil hazard types. Pages 184-191 *In* Proc. IV International Conference on *Fomes annosus* (E. G. Kuhlmen, ed.). U.S.D.A. Forest Serv., Southeast. Forest Exp. Sta., Asheville, N.C.
2. American Pulpwood Association. 1985. Southwide pine regeneration survey. Washington, D.C. 37 p.
3. Banker, R. E., J. H. Miller, and D. E. Davis. 1983. First-year effects of rootraking on available nutrients in Piedmont Plateau soils. Pages 23-25 *In* Proc. 2nd Biennial Southern Silvicultural Research Conference (E. P. Jones, Jr., ed.). U.S.D.A. Forest Serv., Southeast. Forest Exp. Sta., Asheville, N.C. Gen. Tech. Rep. SE-24.
4. Barnett, P. E., and E. Thor. 1979. Effects of site and inheritance on *Fusarium* incidence in Virginia pine. Pages 159-161 *In* Proc. Symposium for the Management of Pines in the Interior South. Nov. 7-8, 1988, Knoxville, Tenn. U.S.D.A. Forest Serv., Southeast Area, State and Private Forestry, Atlanta, Ga. Techn. Publ. SA-TP2.
5. Barney, C. W. 1951. Effects of soil temperature and light intensity on root growth of loblolly pine seedlings. Plant Physiol. 26:146-163.
6. Brady, N. C. 1974. The Nature and Properties of Soils. 8th ed. Macmillan Publishing Co., Inc., New York. 639 p.
7. Branan, J. R., and E. J. Porterfield. 1971. A comparison of six species of southern pines planted in the Piedmont of South Carolina. U.S.D.A. Forest Serv., Southeast. Forest Exp. Sta., Asheville, N.C. Res. Note SE-171. 3 p.
8. Brightwell, C. S. 1971. Comparative performance of slash and loblolly pine. Union Camp Corp., Savannah, Ga. Wood Res. Note 25.3 p.
9. Burns, R. M. 1973. Comparative growth of planted pines in the sandhills of Florida, Georgia and South Carolina. Pages 124-134 *In* Proc. Sand Pine Symposium. U.S.D.A. Forest Serv., Southeast. Forest Exp. Sta., Asheville, N.C. Gen. Tech. Rep. SE-2.
10. Cain, M. D. 1978. Planted loblolly and slash pine response to bedding and flat disking on a poorly drained site - an update. U.S.D.A. Forest Serv., South. Forest Exp. Sta., New Orleans, La. Res. Note SO-237. 6 p.
11. Campbell, R. G. 1978. The Weyerhaeuser land classification system. Pages 74-82 *In* Proc. Soil Moisture-Site Productivity Symposium (W. E. Balmer, ed.). Nov. 1-3, 1977, Myrtle Beach, S.C. U.S.D.A. Forest Serv., Southeast. Area, State and Private Forestry, Atlanta, Ga.
12. Campbell, W. A., and 0. L. Copeland. 1954. Littleleaf disease of shortleaf and loblolly pines. U.S.D.A. Forest Serv., Washington, D.C. Circ. 940.41 p.
13. Carlson, W. C. 1986. Root system considerations in the quality of loblolly pine seedlings. South. J. Appl. Forestry 10:87-92.
14. Carmean, W. H. 1961. Soil survey refinements needed for accurate classification of black oak site quality in southeastern Ohio. Soil Sci. Soc. Am. Proc. 25:394- 397.
15. Carmean, W.H. 1975. Forest site quality evaluation in the United States. Adv. Agron. 27:209-269.

16. Coile, T. S. 1948. Relation of soil characteristics to site index of loblolly and shortleaf pines in the lower Piedmont region of North Carolina. School of Forestry, Duke Univ., Durham, N.C. Bull. 13.78 p.
17. Coile, T. S. 1952. Soil and the growth of forests. Adv. Agron. 4:329-398.
18. Coile, T. S. 1960. Summary of soil-site evaluation. Pages 77-85 *In* Southern Forest Soils, 8th Forestry Symposium Proc. (Paul V. Bunns, ed.). Louisiana State Univ., Baton Rouge.
19. Coile, T. S., and F. X. Schumacher. 1953. Relation of soil properties to site index of loblolly and shortleaf pines in the Piedmont region of the Carolinas, Georgia and Alabama. J. Forestry 51:739-744.
20. Cole, D. E. 1975. Comparisons within and between populations of planted slash and loblolly pine. Georgia Forestry Research Council, Macon. Res. Pap. 81.13 p.
21. Comerford, N. B., R. F. Fisher, and W. L. Pritchett. 1983. Advances in forest fertilization on the southeastern Coastal Plain. Pages 370-378 *In* IUFRO Symposium on Forest Site and Continuous Productivity (R. Ballard and S. P. Gessel, eds.). U.S.D.A. Forest Serv., Pacific Northwest Forest and Range Exp. Sta., Portland, Oreg. Gen. Tech. Rep. PNW-163.
22. Copeland, O. L., Jr., and R. G. McAlpine. 1962. Soil characteristics associated with spot die-out in loblolly pine plantations. Forest Sci. 8:12-15.
23. Daddow, R. L., and G. E. Warrington. 1983. Growth-limiting soil bulk densities as influenced by soil texture. U.S.D.A. Forest Serv., Fort Collins, Colo. Water System Development Group Rep. WSD6-TN-00005. 17 p.
24. Daniels, R. B., H. J. Kleiss, S. W. Buol, H. J. Byrd, and J. A. Phillips. 1984. Soil systems in North Carolina. North Carolina State Univ., Raleigh Agric. Res. Serv. Bull. 467. 77 p.
25. Dewit, J. N., and T. A. Terry. 1983. Site preparation effects on early loblolly pine growth, hardwood competition and soil physical properties. Pages 40-47 *In* Proc. 2nd Biennial Southern Silvicultural Research Conference (E. P. Jones, ed.). U.S.D.A. Forest Serv., Southeast. Forest Exp. Sta., Asheville, N.C. Gen. Tech. Rep. SE-24.
26. Dougherty, P. M., and C. A. Gresham. 1988. Conceptual analysis of southern pine plantation establishment and early growth. South. J. Appl. Forestry 12:160- 166.
27. Drew, M. C., and L. R. Saker. 1975. Nutrient supply and the growth of the seminal root system in barley. J. Exp. Bot. 26:77-90.
28. Duncan, D. V., and T. A. Terry. 1983. Water management. Pages 91-111 *In* Managed Slash Pine Ecosystem Symposium Proc. (E. L. Stone, ed.). June 9-11,1981, Gainesville, Fla. School of Forest Resources and Conservation, Univ. of Florida, Gainesville.
29. Eavis, B. W. 1972. Soil physical conditions affecting seedling root growth. I. Mechanical impedance, aeration and moisture availability as influenced by bulk density and moisture levels in a sandy loam soil. Plant Soil 36:613-622.
30. Ellerbe, C. M., and G. E. Smith, Jr. 1963. Apparent influence of phosphate marl on site index of loblolly pine in the Lower Coastal Plain of South Carolina. J. Forestry 61:284-286.
31. Fisher, R. F., and W. S. Garbett. 1980. Response of semimature slash and loblolly pine plantations to fertilization with nitrogen and phosphorus. Soil Sci. Soc. Am. J. 44:850-854.
32. Fox, T. R., J. A. Burger, and R. E. Kreh. 1986. Effects of site preparation on nitrogen dynamics in the southern Piedmont. Forest Ecol. Manage. 15:241-246.
33. Froelich, R. C., T. R. Dell, and C. H. Waltinshaw. 1966. Soil factors associated with *Fomes annosus* in the Gulf States. Forest Sci. 12:299- 306.
34. Froelich, R. C., E. G. Kuhlman, C. S. Hodges, M. J. Weiss, and J. D. Nichols. 1977. *Fomes annosus* root rot in the South: guidelines for prevention. U.S.D.A. Forest Serv., Southeast Area, State and Private Forestry, Atlanta, Ga. 17 p.
35. Gardner, W. R. 1983. Soil properties and efficient water use: an overview. Pages 45-64 *In* Limitations to Efficient Water Use in Crop Production (H. M. Taylor, W. R. Jordan, and T. R. Sinclair, eds.). American Society of Agronomy, Madison, Wis.
36. Gent, J. A., Jr., R. Ballard, and A. E. Hassan. 1983. The impact of harvesting and site preparation on the physical properties of Lower Coastal Plain forest soils. Soil Sci. Soc. Am. J. 47:595-598.
37. Gent, J. A., Jr., R. Ballard, A.E. Hassan, and D. K. Cassel. 1984. Impact of harvesting and site preparation on physical properties of Piedmont forest soils. Soil Sci. Soc. Am. J. 48:173-177.
38. Gent, J. A., Jr., and L. A. Morris. 1986. Soil compaction from harvesting and site preparation in the Upper Gulf Coastal Plain. Soil Sci. Soc. Am. J. 50:443- 446.
39. Gilman, E. F., I. A. Leone, and F. B. Flower. 1987. Effect of soil compaction and oxygen content on vertical and horizontal root distribution. J. Environ. Hortic. 5:33-36.
40. Ginter, D. L., K. W. McLeod, and C. Shesrod, Jr. 1979. Water stress in longleaf pine induced by litter removal. Forest Ecol. Manage. 2:13-20.
41. Goebel, N. B., and D. H. Van Lear. 1975. Reforestation of sand hill scrub oak sites with slash and longleaf pine. Tree Planters' Notes 26:21-22.
42. Graney, D. L., and E. R. Ferguson. 1971. Site quality relationships for shortleaf pine in the Boston Mountains of Arkansas. Forest Sci. 17:16–22.
43. Greacen, E. L., and R. Sands. 1980. Compaction of forest soils: a review. Aust. J. Soil Res. 18:163-189.
44. Gresham, C. A., and T. M. Williams. 1978. Water table depth and growth of young loblolly pine. Pages 371-376 *In* Proc. Soil Moisture-Site Productivity Symposium (W. E. Balmer, ed.). Nov. 1-3,1977, Myrtle Beach, S.C. U.S.D.A. Forest Serv., Southeast Area, State and Private Forestry, Atlanta, Ga.
45. Grigsby, H. C. 1975. Performance of large loblolly and shortleaf pine seedlings after 9 to 12 years. U.S.D.A. Forest Serv., South. Forest Exp. Sta., New Orleans, La. Res. Note S0-196.4 p.
46. Haines, L. W., and J. Gooding. 1983. Site selection: slash pine versus other species. Pages 112-130 *In* Managed Slash Pine Ecosystem Symposium Proc. (E. L. Stone, ed.). June 9-11, 1981, Gainesville, Fla. School of Forest Resources and Conservation, Univ. of Florida, Gainesville.
47. Haines, L. W., and W. L. Pritchett. 1965. The effects of site preparation on the availability of soil nutrients and on slash pine growth. Soil Crop Sci. Soc. Fla. Proc. 25:356-364.
48. Hoag, R. E., and E. C. Steinbrenner. 1980. Soil survey of Weyerhaeuser lands in the Neuse District, N.C. Forestry Research, Weyerhaeuser Co., New Bern, N.C. 24 p. (120 sheets).
49. Hollis, C. A., and R. A. Schmidt. 1977. Site factors related to fusiform rust. Forest Sci. 23:69-77.
50. Hollis, C. A., W. H. Smith, R. A. Schmidt, and W. L. Pritchett. 1975. Soil and tissue nutrients, drainage, fertilization and tree growth as related to fusiform rust incidence in slash pine. Forest Sci. 21:141-148.
51. Hunt, C. B. 1972. Geology of Soils: Their Evolution,

Classification and Uses. W. H. Freeman and Co., San Francisco. 344 p.
52. Jenny, H. 1941. Factors of Soil Formation. McGraw-Hill, New York. 377 p.
53. Kellison, R. C., and J. B. Jett, Jr. 1978. Species selection for plantation establishment in the Atlantic Coastal Plain and Sandhill Provinces. Pages 196- 202 *In* Proc. Soil Moisture-Site Productivity Symposium (W. E. Balmer, ed.). Nov. 1-3,1977, Myrtle Beach, S.C. U.S.D.A. Forest Serv., Southeast Area, State and Private Forestry, Atlanta, Ga.
54. Kormanik, P. 0. 1966. Predicting site index for Virginia, loblolly and shortleaf pine in the Virginia Piedmont. U.S.D.A. Forest Serv., Southeast. Forest Exp. Sta., Asheville, N.C. Pap. 51.27 p.
55. Kuhlman, E. G., and R. C. Froelich. 1976. Minimizing losses to *Fomes annosus* in the southern United States. U.S.D.A. Forest Serv., Southeast. Forest Exp. Sta., Asheville, N.C. Res. Pap. SE-151. 16 p.
56. Lambeth, C. C., P. M. Dougherty, W. T. Gladstone, R. B. McCullough, and 0. 0. Wells. 1984. Large scale planting of North Carolina loblolly pine in Arkansas and Oklahoma: a case of gain versus risk. J. Forestry 82:736-741.
57. Linnartz, N. E. 1963. Relation of soil and topography to site quality for southern pines in Florida parishes of Louisiana. J. Forestry 61:434 137.
58. Lorio, P. L., and R. A. Sommers. 1985. Potential use of soils maps to estimate southern pine beetle risk. Pages 239-245 *In* Proc. Integrated Pest Management Research Symposium (S. J. Branham and R. C. Thatcher, eds.) U.S.D.A. Forest Serv., Southeast. Forest Exp. Sta., Asheville, N.C. Gen. Tech. Rep. SE-56.
59. Maki, W. 1957. Site preparation. Pages 47-68 *In* Proc. 7th Industrial Forestry Seminar. School of Forestry, Yale Univ., New Haven, Conn.
60. McClurkin, D. C., and R. R. Covell. 1965. Site index predictions for pines in Mississippi. U.S.D.A. Forest Serv., South. Forest Exp. Sta., New Orleans, La. Res. Pap. SO-15. 9 p.
61. McCulley, R. D. 1950. Management of natural slash pine stands in the flatwoods of south Georgia and north Florida. U.S.D.A. Forest Serv., Washington, D.C. Circ. 845.57 p.
62. McKee, W. H. 1977. Soil-site relationships for loblolly pine on selected soils. Pages 115-120 *In* Proc. 6th Southern Forest Soils Workshop (W. E. Balmer, ed.). Oct. 19-21, 1976, Charleston, S.C. U.S.D.A. Forest Serv., Southeast Area, State and Private Forestry, Atlanta, Ga.
63. McKee, W. H., Jr. 1985. Forestry herbicide suggestions. Alabama Cooperative Extension Serv., Auburn, Ala. 10p.
64. McKee, W. H., Jr., G. E. Hatchell, and A. E. Tiarks. 1985. Managing site damage from logging. U.S.D.A. Forest Serv., Southeast. Forest Exp. Sta., Asheville, N.C. Gen. Tech. Rep. SE-32. 21 p.
65. McKee, W. H., Jr., D. D. Hook, D. S. DeBell, and J. L. Askew. 1984. Growth and nutrient status of loblolly pine seedlings in relation to flooding and phosphorus. Soil Sci. Soc. Am. J. 48:1438-1442.
66. McKee, W. H., and E. Shoulders. 1970. Depth of water table and redox potential of soil affect slash pine growth. Forest Sci. 16:399-402.
67. Miller, E. L. 1984. Sediment yield and storm flow response to clearcut harvest and site preparation in the Ouachita Mountains. Water Resour. Res. 20:471-475.
68. Miller, T. 1972. Fusiform rust in planted slash pines: influence of site preparation and spacing. Forest Sci. 18:70-75.
69. Morris, C. L., and D. H. Frazier. 1966. Development of a hazard rating for *Fomes annosus* in Virginia. Plant Dis. Rep. 50:510-511.
70. Moms, L. A. 1981. Redistribution and mobilization of nutrients as a result of harvest and site preparation of a pine flatwoods. Ph.D. disc., Univ. of Florida, Gainesville. 190 p.
71. Morris, L. A., and W. L. Pritchett. 1983. Effects of site preparation on forest soil properties. Pages 243-251 *In* Proc. IUFRO Symposium on Forest Site and Continuous Productivity (R. Ballard and S. P. Gessel, eds.). U.S.D.A. Forest Serv., Pacific Northwest Forest and Range Exp. Sta., Portland, Oreg. Gen. Tech. Rep. PNW-163.
72. Morris, L. A., W. L. Pritchett, and B. F. Swindel. 1983. Displacement of nutrients into windrows during site preparation of a flatwoods forest. Soil Sci. Soc. Am. J. 47:591-594.
73. Nambiar, E. K. S., G. D. Bowen, and R. Sands. 1980. Root regeneration and plant water status of *Pinus radiata* D. Don seedlings transplanted to different soil temperatures. J. Exp. Bot. 30:1119-1131.
74. Nash, A. J. 1963. A method for classifying shortleaf pine sites in Missouri. Missouri Agric. Exp. Sta., Columbia, Res. Bull. 824.53 p.
75. National Atlas of the United States of America. 1970. Geological Survey, U.S. Dep. of Interior, Washington, D.C.
76. National Cooperative Soil Survey Staff. 1975. Soil Taxonomy. U.S.D.A. Soil Conservation Serv., Washington, D.C. Handb. No. 436.754 p.
77. Neary, D. G., L. A. Morris, and B. F. Swindel. 1984. Site preparation and nutrient management in southern pine forests. Pages 121-144 *In* Forest Soils and Treatment Impacts, Proc. 6th North American Forest Soils Conference (E. L. Stone, ed.). June 1983, Knoxville, Tenn. Dep. of Forestry, Wildlife and Fisheries, Univ. of Tenn., Knoxville.
78. Oak, S. W. 1985. Adaptation of littleleaf disease hazard rating for use in forest management in South Carolina National Forests. Pages 246-251 *In* Proc. Integrated Pest Management Research Symposium (S. J. Branham and R. C. Thatcher, eds.). U.S.D.A. Forest Serv., South. Forest Exp. Sta., New Orleans, La. Gen. Tech. Rep. SO-56.
79. Pausell, L. K. 1969. The ecology of upland hardwoods of the Ozarks and Ouachitas. Pages 117-135 *In* The Ecology of Southern Forests, 17th Forestry Symposium Proc. (N. E. Linnartz, ed.). Louisiana State Univ., Baton Rouge.
80. Perry, T. 0. 1964. Soil compaction and loblolly pine growth. Tree Planters' Notes 67:9-11.
81. Phillipson, J. J., and M. P. Coutts. 1977. The influence of mineral nutrition on the root development of trees. II. The effects of specific nutrient elements on growth of individual roots of Sitka spruce. J. Exp. Bot. 28:864-871.
82. Pritchett, W. L. 1979. Properties and Management of Forest Soils. John Wiley and Sons, New York. 500 p.
83. Prouty, W. F. 1952. Carolina Bays and their origin. Geol. Soc. Am. Bull. 63:167-224.
84. Pruitt, A. A. 1947. A study of the effects of soils, water table and drainage on the height growth of slash and loblolly pine on the Hofmann Forest. M. S. thesis, North Carolina State Univ., Raleigh. 93 p.
85. Ralston, C. W. 1951. Some factors related to growth of longleaf pine in the Atlantic Coastal Plain. J. Forestry 49:408-412.
86. Ralston, C. W., and R. L. Barnes. 1955. Soil properties related to the growth and yield of slash pine plantations in Florida. Soil Sci. Soc. Am. Proc. 19:84-85.
87. Roth, E. R., E. R. Toole, and G. H. Hepting. 1948. Nutritional aspects of the littleleaf disease of pine. J. Forestry 46:578-587.
88. Row, C. 1960. Soil-site relations of old-field slash pine plantation in Carolina sandhills. J. Forestry 58:704-707.
89. Schmidt, R. A., T. Miller, R. C. Holley, R. P. Belanger, and J. E. Allen. 1988. Relation of site factors to fusiform rust incidence in young slash and loblolly pine plantations in

the Coastal Plain of Florida and Georgia. Plant Disease 72:710-718.
90. Schultz, R. D. 1973. Site treatment and planting method alter root development of slash pine. U.S.D.A. Forest Serv., Southeast. Forest Exp. Sta., Asheville, N.C. Res. Pap. SE-109.11p.
91. Schultz, R. P. 1976. Environmental change after site preparation and slash pine planting on a flatwoods site. U.S.D.A. Forest Serv., Southeast. Forest Exp. Sta., Asheville, N.C. Res. Pap. SE-156.
92. Shoulders, E. 1982. Comparisons of growth and yield of four southern pines on uniform sites in the Gulf Coastal Plain. Pages 75-100 *In* Predicting Growth and Yield in the Mid-South, 31st Forestry Symposium Proc. (J. E. Hotvedt and B. D. Jackson, eds.). Louisiana State Univ., Baton Rouge.
93. Skaggs, R. W., J. W. Gilliam, T. J. Sheets, and J. S. Barnes. 1980. Effect of agricultural land development on drainage waters in the North Carolina Tidewater Region. Univ. of North Carolina, Chapel Hill Water Resources Institute Rep. 159.164 p.
94. Smalley, G. W. 1979. Classification and evaluation of forest sites on the Southern Cumberland Plateau. U.S.D.A. Forest Serv., South. Forest Exp. Sta., New Orleans, La. Gen. Tech. Rep. SO-23. 59 p.
95. Smalley, G. W. 1980. Classification and evaluation of forest sites on the Western Highland Rim and Pennyroyal. U.S.D.A. Forest Serv., South. Forest Exp. Sta., New Orleans, La. Gen. Tech. Rep. SO-30. 120 p.
96. Smalley, G. W. 1982. Classification and evaluation of forest sites on the Mid-Cumberland Plateau. U.S.D.A. Forest Serv., South. Forest Exp. Sta., New Orleans, La. Gen. Tech. Rep. SO-38.58 p.
97. Smalley, G. W. 1983. Classification and evaluation of forest sites on the Eastern Highland Rim and Pennyroyal. U.S.D.A. Forest Serv., South. Forest Exp. Sta., New Orleans, La. Gen. Tech. Rep. SO-43. 123 p.
98. Smalley, G. W. 1984. Classification and evaluation of forest sites in the Cumberland Mountains. U.S.D.A. Forest Serv., South. Forest Exp. Sta., New Orleans, La. Gen. Tech. Rep. SO-50. 84 p.
99. Smalley, G. W. 1986. Classification and evaluation of forest sites on the North Cumberland Plateau. U.S.D.A. Forest Serv., South. Forest Exp. Sta., New Orleans, La. Gen. Tech. Rep. SO-60. 74 p.
100. Soil Survey of Jones County, North Carolina. 1981. National Cooperative Soil Survey, Washington, D.C. 98 pages (13 sheets).
101. St. John, T. V., 0. C. Coleman, and C. P. P. Reid. 1983. Growth and spatial distribution of nutrient-absorbing organs: selective exploitation of soil heterogeneity. Plant Soil 71:487-493.
102. Stone, E. L. 1975. Soils and man's use of land. Pages 1-9 *In* Forest Soils and Forest Land Management, Proc. 4th North American Forest Soils Conference (B. Bernier and C. H. Winget, eds.). Aug. 1973, Quebec, Canada. Laval Univ. Press, Quebec.
103. Stransky, J. J. 1981. Site preparation effects on soil bulk density and pine seedling growth. South. J. Appl. Forestry 5:176-180.
104. Swank, W. T., N. B. Goebel, and J. D. Helvey. 1972. Interception loss in loblolly pine stands of the South Carolina Piedmont. J. Soil Water Conserv. 27:160-164.
105. Taylor, H. M., G. M. Roberson, and J. J. Parker, Jr. 1966. Soil strength-root penetration relations for medium- to coarse-textured soil materials. Soil Sci. 102:18-22.
106. Terry, T. A. 1978. Factors related to the growth of intensively managed loblolly pine *(Pious taeda* L.) on selected soils in the North Carolina Lower Coastal Plain. Ph.D. disc., North Carolina State Univ., Raleigh. 163 p.
107. Terry, T. A., and R. G. Campbell. 1981. Soil management considerations in intensive forest management. Pages 98-106 *In* Forest Regeneration, Proc. Symposium, Engineering System for Forest Regeneration Systems. American Society of Agricultural Engineers, St. Joseph, Mich. Publ. 10-81.
108. Thames, J. L. 1962. Loblolly best but seed source important in erosion control planting in north Mississippi. Tree Planters' Notes 55:21-22.
109. Thomthwaite, C. W. 1948. An approach toward a rational classification of climate. Geographical Rev. 38:55-95.
110. Tiarks, A. E., and E. Shoulders. 1982. Effects of shallow water tables on height growth and phosphorus uptake by loblolly and slash pines. U.S.D.A. Forest Serv., South. Forest Exp. Sta., New Orleans, La. Res. Note SO-285.5 p.
111. Tuttle, C. L., M. S. Golden, and R. S. Meldahl. 1983. Effects of surface soil removal on selected soil properties and loblolly pine seedlings after the first growing season. Pages 18-22 *In* Proc. 2nd Biennial Southern Silvicultural Research Conference (E. P. Jones, Jr., ed.). U.S.D.A. Forest Serv., Southeast. Forest Exp. Sta., Asheville, N.C. Gen. Tech. Rep. SE-24.
112. Ursic, S. J. 1961. Lethal root temperatures of 1-0 loblolly pine seedlings. Tree Planters' Notes 47:25-28.
113. Van Rees, K. C. J., and N. B. Comerford. unpublished data, Univ. of Florida, Gainesville.
114. Vitousek, P. M., and P. A. Matson. 1985a. Disturbance, nitrogen availability and nitrogen losses in an intensively managed loblolly pine plantation. Ecology 66:1361-1376.
115. Vitousek, P. M., and P. A. Matson. 1985b. Intensive harvesting and site preparation decrease soil nitrogen availability in young plantations. South. J. Appl. Forestry 9:120-124.
116. Vomocil, J. A., and W. J. Flocker. 1961. Effect of soil compaction on storage and movement of soil air and water. Trans. ASAE 4:242-246.
117. White, E. H., and W. L. Pritchett. 1970. Water table control and fertilization for pine production in the flatwoods. Florida Agric. Exp. Sta., Gainesville Tech. Bull. 743.41 p.
118. Wiggins, J. E., Jr. 1978. Soil-tree growth correlation and site classification. Pages 87-92 *In* Proc. Soil Moisture-Site Productivity Symposium, (W. E. Balmer, ed.). Nov. 1-3, 1977, Myrtle Beach, S.C. U.S.D.A. Forest Serv., Southeast Area, State and Private Forestry, Atlanta, Ga.
119. Wilhite, L. P. 1976. Slash, loblolly, longleaf and Sonderegger pines 20 years after planting on Leon sand in northeast Florida. U.S.D.A. Forest Serv., Southeast. Forest Exp. Sta., Asheville, N.C. Res. Pap. SE-153. 30 p.
120. Yde-Anderson, A. 1970. Discussions on *Fomes annosus.* Pages 177-184 *In* Proc. 3rd International Conference on *Fomes annosus,* Session 4. U.S.D.A. Forest Serv., Southeast. Forest Exp. Sta., Asheville, N.C.
121. Zahner, R. 1954. Estimating loblolly pine sites in the Gulf Coastal Plain. J. Forestry 52:448-449.
122. Zahner, R. 1958. Site-quality relationships of pine forests in southern Arkansas and northern Louisiana. Forest Sci. 4:162-176.
123. Zobel, B. 1982. Loblolly pine - in retrospect. Pages 1-6 *In* Proc. Symposium on Loblolly Pine (East Region). Dec. 8-10, 1982, Raleigh, N.C. School of Forest Resources, North Carolina State Univ., Raleigh.