THE RELATIONSHIP OF SOIL-SITE FACTORS
TO TOTAL HEIGHT AND YIELD OF
TWENTY-FIVE YEAR-OLD LOBLOLLY PINE
(PINUS TAEDA L.) PLANTED ON
DEEP, SANDY SOILS IN EAST TEXAS

A Thesis

by

RICHARD ORVILLE HESSLER, JR.

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ABSTRACT

The Relationship of Soil-Site Factors
to Total Height and Yield of
Twenty-Five Year-Old Loblolly Pine
(*Pinus taeda* L.) Planted on
Deep, Sandy Soils in East Texas (August 1983)

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Thinned and unthinned loblolly pine plantations at three locations in East Texas were partitioned into fifteen twenty-acre study units. Variable-plot sampling was used to determine the number of stems per acre and the diameter distribution of the study units. Total height and site factor measurements and soil samples were collected for an analysis of the effects of soil-site relations on total height. A stratified subsample was used to calculate the merchantable cubic-foot wood volume by diameter class for each location.

The regression analysis of the effects of the various soil-site factors on total height for the entire study area revealed that the depth to the least permeable horizon had the greatest (negative) effect on total height. The percentage of organic matter in the 0-6 inch (0-15 cm) soil level had a lesser, but significant (positive) relationship to total height.

Analyses of the soil-site relations for each location revealed that, in each case, the depth to the least permeable horizon, slope, and the percentage of organic matter in the 6-12 inch (15-30 cm) soil level had the highest correlations to total height of twelve screened soil-site variables. The statistical significances of those most important factors were irregular in the regression models for the three locations. The variable significance of those factors was related to the discontinuous nature of their ranges of values at each location.

Two types of cubic-foot wood volume tables were developed: local volume tables for each location and volume tables for the entire study area which separated the trees by form class and merchantable height. The calculated cubic-foot volumes, on an overall basis, had an absolute error of 3.2 percent at the 99 percent level of confidence. The correlation of basal area to merchantable volume for two locations was very high, which indicated that there was a high degree of uniformity of total height and stem taper within a given diameter class. The correlation for the third location was rather low and was related to the presence of greater variation in total height and stem taper within diameter classes.

Cubic-foot wood volume yield was calculated for each study unit using the variable-plot sampling data on stem frequencies and diameter distributions. There was a high correlation between the number of trees per acre and the merchantable cubic-foot wood volume for both the thinned and unthinned groups of study units, although the relationship was stronger for the unthinned plantations and was affected culturally by cutting practices on the thinned plantations.

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The two additional committee members, Dr. Robert Baker and Dr. Michael Longnecker provided instrumental direction in the development of the sampling scheme and incisive criticism of the manuscript.

The author is very appreciative of the cooperation between the Texas Agricultural Experiment Station McIntire-Stennis research project 6281 and forest industry. Champion International Paper Company, Owens-Illinois, Inc. and St. Regis Paper Company all granted access to their pine plantation records and timberlands for this project.

Many different graduate and undergraduate students were involved in the several stages of field work. Two fellow graduate research assistants, Jim Echols and Jon Morrissey, not only assisted with hundreds of hours of field work each, but also fostered a professional camaraderie and a stronger sense of purpose.

An especial thanks is due my parents, whose early teachings encouraged me to follow in the steps of St. Gifford.

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INTRODUCTION

Many of the considerations which form the basis for traditional growth and yield calculations have been altered or invalidated as intensive forest management has spread across the southern United States (Popham *et al*. 1979). Management practices such as mechanical site preparation and stocking regulation by thinning produce plantations that grow at rates different from natural stands. The intensity of such practices, especially the number and frequency of thinnings, if any, can have a dramatic effect on volume growth (Mann and Dell 1971).

Advances in tree improvement, harvesting systems, and utilization have overshadowed and perhaps led to the de-emphasis of growth and yield studies (Farrar 1979). The effect of soil-site relations on growth and yield of loblolly pine (*Pinus taeda* L.) has been examined on a regional basis (Coile and Schumacher 1964), but work more specific to the Western Gulf Coastal Plain is needed (Lenhart 1972). An evaluation of how end-of-rotation yield of loblolly pine planted on the deep sandy soils of East Texas is affected by modified soil-site conditions, genetically improved planting stock, and regulated planting densities would contribute to the knowledge pursuant to productive timber management (Daniels *et al*. 1979).

This thesis adheres to the style of the Journal of Forestry.

The intrinsic site productivity in all forest environments may be affected by cultural and biological factors which produce a variable volume or weight of wood production. The deep sandy soils of East Texas merit special attention for several reasons. Seedling mortality following establishment can be very high during dry, hot summers; in anticipation of high mortality, seedlings are sometimes planted at densities that would be normally too great in the absence of high mortality. Height and diameter growth may be restricted by limited soil water due to the low moisture storage capacity of sandy soils during prolonged drought. The levels of many nutrient cations are characteristically very low in the highly leached, acid, low clay content, deep, sandy soils. Most of the problems associated with intensive pine culture on the sandhills that can be addressed through modified management practices are related to the soil. The recognition of such problems allows the forest manager to treat such sites in a manner compatible with their physical limitations.

Site-specific differences demand that forest lands be managed with consideration of the most limiting peculiarity. Soil instability in some mountainous areas hampers operability where watershed protection is important. On more level terrain, impeded drainage can be a problem that must be addressed either by artificial drainage or by restricting mechanized operations during environmentally sensitive periods. On the sandhills of East Texas, the drouthiness of the soils is the foremost concern. The droughty nature of the soils cannot be corrected, but ameliorative practices can, at best, reduce the negative impact on survival and height growth. Such practices might include incorporating, rather than burning, post-harvest wood residues to increase the organic matter (and the moisture storage capacity) of the soil, the use of containerized planting stock to increase initial survival, lower planting densities per acre, and more timely thinning and prescribed burning to control better the canopy and understory competition. There would be little value in the random application of such potentially beneficial practices without first determining the relative importances of the soil-site factors which would be affected. Forest management practices can antagonistically affect a given soil-site factor. Prescribed burning may control competition and forest fire fuel accumulation while also reducing the amount of litter available for conversion to soil organic matter.

The solution to the problem has entailed identifying and quantifying those soil-site variables that affect height growth significantly. Once that determination was made, empirical yield was determined for each plantation examined using collected mensurational data. The differences in volume and weight yield of wood may be statistically correlated and, to some extent attributed to variation in site quality between loblolly pine plantations growing on deep sandy soils in East Texas. The two objectives of this study were to evaluate soil-site factors which influence height growth of loblolly pine planted on deep, sandy soils and to estimate cubic-foot wood volume yield for those loblolly pine plantations growing on deep, sandy soils in East Texas.

LITERATURE REVIEW

Soil and many other environmental factors influence the growth rate of both an individual tree and forest stands. If height growth is accepted as constant over a broad range of stocking levels on any site, one of the more important tangible measures of the potential productivity of a stand is site index. Site index is defined as the average height of dominant and codominant trees in a given stand at a specified age (Carmean 1970). Genetic and silvical properties of the tree, climate, topography, physical and chemical soil properties, and past forest management practices that have altered growth conditions originally present on the area produce a site index peculiar to a stand (Campbell 1981, Evans 1975).

The potential biological growth rate of a species as manifested by the site index, characteristic growth form, and diameter distribution of surviving trees generates the volume of wood present at any time through the life of a forest plantation (Dell et al. 1979). It is therefore necessary to establish the site index, stocking level, diameter distribution, and taper function to predict acccurately the intermediate and end-of-rotation yield of a plantation.

Height Growth

Although site index is derived from height and age, the soil-site elements that affect height growth vary considerably in relative importance from one location to another (Richards et al. 1962). On rolling or nearly level coastal plain sites, the effects of aspect, slope, and position on the slope are not as great as in mountainous areas, but still may be related to the soil formation, drainage, and movement on an area. Since many characteristics of the site affect height growth of a tree, the significance which may be attached to soil properties and management practices affecting them is limited by the extent to which the other indeterminate effects can be minimized or controlled (Feduccia _et_ _al_. 1979).

The determination of an index allows the forest manager to classify forest land by its potential productivity. In some cases, pine plantation rotation ages have been decreased to as young as 18 years to maximize certain economic criteria. The general trend toward shorter rotations makes site index curves less reliable: values for tree height from curves developed from naturally regenerated loblolly pine growing on old fields have been found to be higher at early ages and lower at older ages than for plantations on cutover forest land (Lenhart and Fields 1970, Smalley and Bower 1971). Those irregularities in growth patterns indicate that site- and age-specific curves would permit better regulation of forest management practices such as thinning regimes and initial planting densities.

Soil-Site Relations

The availabilty of water is the single most important factor limiting plant growth over much of the world. Low precipitation, high evapotranspiration, or a soil with poor water retention characteristics is often the source of the problem (Black 1968). Much of the variation in height growth of loblolly pine across the Gulf Coastal Plain can be attributed to differences in rainfall and soil textures (Willett 1978). Where the annual precipitation was in excess of 1.3 m (41 in), on sites with deep sands, more deeply-rooted slash pine (Pinus elliotii var. elliotii Engelm.) was found to outgrow loblolly pine. Coarse-textured sands allow rapid drainage of water below the rooting zone of loblolly pine. The relationship reverses with decreased rainfall because of the lower transpirational rate of loblolly pine (Shoulders and Tiark 1980).

Among a number of physically associated soil series, coarser-textured soil textural classes have lower moisture storage capacities. Thus, within an area of equivalent rainfall and seasonal distribution, the potential available moisture storage capacity (the difference in volumetric water content between total soil moisture potentials of -0.33 and -15 bars, or -0.1 and -15 bars for sandy soils) is more important than the amount and distribution of rainfall. An area with a single, homogeneous soil series has a reservoir of moisture available for use by a tree which is related to the thickness of the soil profile, in addition to the potential available moisture storage capacity peculiar to that soil texture and series (Kormanik 1966).

Particle size distribution and porosity both affect the moisture retention of a soil. Sandy soils have greater proportions of large particles and more macropore space than soils with more silt and clay. At pressure potentials below saturation (-0.1 bar), sandy soils will have a higher percentage of pores filled with air and a lower percentage filled with water (Marshall and Holmes 1979). As the silt and clay content of a soil increases, the moisture storage capacity at lower pressure potentials becomes greater than a sandier-textured soil. Finer-textured soils have less pore space filled with air, so that at pressure potentials greater than or equal to that of saturation, aeration can be restricted. Adequate aeration is essential to respiration of roots of higher plants and many soil microorganisms. Competition between the two for oxygen may be high in poorly-drained soils, but is usually not a problem with sandy soils in which water potentials often do not remain at the saturation level (Cole and Ballard 1968).

Most of the East Texas timberlands receive between 42 and 52 inches (1.1 to 1.3 m) of rain annually. It is seasonally well distributed with 20 to 28 inches (0.5 to 0.7 m) falling during the growing season from April to September (USDA, SCS 1964). Even with abundant rainfall, sandy soils that are well to excessively drained may exhibit signs of a severe moisture deficit within two weeks after a heavy rainstorm (Burns and Hebb 1972). In East Texas, much of the precipitation during the growing season falls in intermittent heavy storms (Pehl 1977). While there is normally an adequate amount of rainfall, its sporadic nature and rapid infiltration can cause moisture stress several times through a growing season. Limited availability of moisture during the late summer can reduce diameter growth of established trees, but extensive mortality occurs rarely. Newly established plantations are much more prone to inhibited growth and mortality (Arbour 1982). Of course, a 25 year-old tree transpires more water than a one year-old seedling, but the root systems of young seedlings that have not fully occupied the rooting zone can not utilize the available moisture as completely as an older root system. Seedlings are also more susceptible to damage due to high soil surface temperatures and reflected radiation (Spurr and Barnes 1980).

Available moisture within the A horizon and indirect indicators thereof, including depth to the layer of fine-textured material and percent medium sand (0.5 to 0.25 mm) were found to contribute more significantly to the prediction of site index of slash pine in the sandhills of the Florida panhandle than 21 other screened independent variables (Hebb and Burns 1975). Data in this study indicated that height growth increased as the depth to fine-textured material decreased. Height growth increases until the proximity of the impermeable B horizon begins to limit the moisture storage capacity. That depth was found to lie between one and two feet (0.3 to 0.6 m) for loblolly and slash pines in the sandhills of the southern United States (Carmean 1970).

On a Lakeland sand in northwest Florida, height growth of Choctawhatchee sand pine (Pinus clausa [Chapm.] Vasey) was closely related to topographic position within the plantation. Despite relief of only 13 feet (4.0 m) within the two-acre (0.8 ha) study area, trees were tallest at the lower and more level areas within the tract. Several profiles were examined to a depth of nearly 20 feet (6.2 m). The characterizations were as follow: sand 93 to 95 percent, pH 4.4 to 5.2, A horizon one to three inches with 1.0 to 1.8 percent organic matter, and very low in phosphorus, potassium, calcium, and magnesium (less than 1 meq/100 g of soil or only trace amounts) (Burns and Brendemuehl 1969).

Lakeland sand is an Entisol of more recent deposition than the more fertile Ultisols which are more common in Texas. The sandhills in East Texas differ from those on the Atlantic Coastal Plain and the eastern Gulf of Mexico Coastal Plain in being primarily Ultisols and Alfisols rather than Entisols and by being not as extensive in geographical distribution.

Most of the deep sands in Texas have profiles that are not as deep as Lakeland sand. Betis sand is the Ultisol analog to Lakeland sand, west of the Mississippi River, and has a sandy epipedon often as deep as those of Entisols found further east. Other Ultisols, such as Darco, Fuquay, Letney, and Troup are more extensive in Texas than Betis (USDA, SCS 1964).

On the Fuquay and Troup series (characterized by 20 to 40 inches (0.5 to 1.0 m) and 40 to 72 inches (1.0 to 1.8 m) of loamy, fine sand or fine sand respectively) loblolly pine height growth was determined to increase with greater moisture storage capacity and permeability of the B horizon (Willett 1978). Studies in southern Arkansas, northern Louisiana, and southeast Texas indicated that site index of loblolly pine increased as the A horizon depth increased to 18 inches (0.5 m). Deeper surface layers diminished the ability of the roots to exploit the moisture storage of the horizon. Surface soil thickness and texture, subsoil texture, and slope were identified as the most important site factors (Zahner 1954, 1957).

Forest soils differ from agricultural soils in having relatively higher amounts of organic matter. Organic matter can increase the moisture retention in sandy soils. At pressure potentials near field capacity, organic matter can hold 150 percent of its weight in water. Thus, each one percent increase in organic matter can increase the field capacity by 1.5 percent, conversely a decrease in organic matter can reduce the field capacity. The addition of organic matter could be expected to increase temporarily the available water holding capacity. The decomposition of organic matter would soon diminish the benefit of such an addition (Hillel 1971, Thompson and Frederick 1978). Organic matter increases the cation-exchange capacity of a soil because of its chemical components ability (principally carboxyls and phenols) to bind cations (Broadbent and Bradford 1952). The contribution of organic matter to cation-exchange capacity becomes more important in soils with low clay contents (Pritchett 1979). The organic acids and esters found in organic matter release hydrogen ions which lowers soil pH. The hydrogen ions can then replace nutrient cations attached to the soil particle matrix.

Those soil cations subject to replacement by cations in solution are termed exchangeable cations. Most of the sandy soils supporting pine forests in East Texas have very low cation exchange capacities that are highly pH dependent. Such interchanges occur without the degradation of soil solids and serve to replenish bases in the soil solution (Shoulders and McKee 1973). The more important bases are calcium, magnesium, potassium, and sodium. Once in solution, those bases, except sodium, may serve as plant nutrients. Other non-basic exchangeable cations, such as aluminum and hydrogen modify soil pH and thus affect plants in other ways (Brady 1974).

The level of soil acidity is associated with the amount of exchangeable hydrogen and aluminum cations. It has been established that the cation-exchange capacity varies with soil pH. The soil-plant relationships most affected by pH are toxicity, nutrient availability, and microbial activity (Voight 1968, Nelson et al. 1968).

Toxicity is probably not due simply to the presence of excess hydrogen cations near the roots. Hydrogen ion concentrations have been found in some cases to be greater in plant tissues than in many acid soils. Thus it may be likely that toxicity is due to the presence in the solution of oxidizes or some organic acids that are normally toxic to plant tissues

(McLean 1973). Aluminum can accumulate on the root surface and in the cortex (when present) in excessive concentration. The result is decreased root tip elongation, wilt due to decreased membrane permeability, and nutritional deficiencies of iron, potassium, phosphorus, and other elements (McLean 1965, Brady 1974)

Nutrient availability may be reduced either directly by the restriction of root growth through an acid substrate or by the reduction of exchangeable bases (Chapman 1965). Increased acidity will inhibit both ion uptake by the plant and the interchange of cations from soil particles to the soil solution.

Soil chemical and physical properties and nutrient levels interact to form a complex series of soil-site relations. The effect of the interrelationships on height growth and yield is variable. Therefore each soil parameter should be examined individually for its significance and relevance for a particular instance of growth prediction.

Merchantable Volume Equations

Tree and log volumes may be estimated by the assumption that the stem of an excurrently branched tree approximates the frustrum of a cone or paraboloid (Husch *et al*. 1972, Schmitt and Bower 1970). A single taper function is then often used to predict volumes for a number of species and wide range of sites. The flaws in those assumptions become apparent when applied to a specific data set.

The development of better procedures for volume estimation has included the use of Reinsch's algorithm for generating natural cubic spline approximations that describe stem taper functions (Liu 1980) and volume ratio models that provide ratios of merchantable to total volume, given either utilizable bole length or minimum top diameter (Cao _et_ _al_. 1980). The most efficient model for volume prediction of loblolly pine in plantations is a segmented polynomial taper equation (Max and Burkhart 1976, Goulding and Murray 1976, Goulding 1979).

Such an equation can be developed by measuring the diameter of the tree at regular intervals up the stem. The diameter used may be either diameter outside bark or diameter outside bark minus the average bark thickness which is diameter inside bark. The volume is estimated by calculating the volume of the several cylinders produced (as solids of rotation) from the diameter measurements. When the polynomial for each cylinder-segment is forced by mathematical constraints to be compatible with the polynomials for the segments above and below it on the stem of the tree, a segmented polynomial taper equation is the result (Freund and Minton 1979, Kleinbaum and Kupper 1978).

Yield Tables

Yield tables developed from even-aged stands are of three types: normal, empirical, and variable-density. They differ in the defintion of the independent stocking variable. Normal tables are based on the assumption of normal or full stocking. Empirical tables use an average stocking level, and variable-density yield tables are developed for several different stocking levels (Husch _et_ _al_. 1972). Empirical stocking is estimated by sampling and standardized to whatever stocking level is desired by distribution modeling (Matney and Sullivan 1982, Bailey and Dell 1973).

Models used to generate yield should include site index, diameter distribution, expression of dominance, crown ratio, stem volume functions, and survival (Smalley and Bailey 1974). Results from such a model, for several levels of stocking, site index, age, survival, and planting density, were used to develop variable-density yield tables for loblolly pine planted on cutover sites in the Western Gulf Coastal Plain. Predicted yields for those loblolly pine plantations exceeded observed yields by less than five percent. Total volume per acre was predicted with a mean deviation of +2.1 percent, when the surviving number of trees per acre at a given age was given. When the planted number of trees per acre was given, the mean deviation was -2.1 percent. Such deviations are determined by using randomly selected plots to test the model for goodness-of-fit (Smalley and Bower 1971). With normal and empirical models, the error of prediction may approach 100 percent if there is a significant departure from the assumption of normal or average stocking (Nelson and Bennett 1965). By clearly defining the constraints prior to construction, more site specific models can be obtained and more precise and practical application may be made possible.

MATERIALS AND METHODS

The thrust of this project was to evaluate the growth of loblolly pine on a variety of sites with deep, sandy soils and similar management regimes. There was much effort to find plantations that had a general regularity of management practices, both within themselves, and among themselves. Several practices, such as site preparation, planting density, thinning, and prescribed burning were identified as factors that could affect competition. Differences in management styles peculiar to the plantations within the study area dictated that practices such as those could not be controlled by any means. Planting density and previous thinning, if any, affect the volume of wood present at any time. Differences in both of those factors were recognized and considered in the analysis of results.

The Study Area

Soil maps, field observations, and aerial photographs indicated initially that 25 year-old loblolly pine plantations growing on deep sandy soils could be found in the following counties: Angelina, Houston, Jasper, Nacogdoches, Newton, Polk, Sabine, San Augustine, Trinity, Tyler, and Walker. That area represents a tier of counties that stretches from the Texas-Louisiana state line (in this region, the Sabine River) to the Trinity River. This region is about 50 miles (80 km) from north to south and about 150 miles (240 km) from east to west. The study area is directly north of the coastal prairie and flatwoods physiographic provinces of the coastal plain of the Gulf of Mexico.

The study area was restricted to the southern portion of the East Texas Timberlands resource area for three reasons: (1) intensive forest management in Texas began in the southeasternmost part of the state and extended later to the north and west, accordingly, there are very few loblolly pine plantations as old as 25 years outside the aforementioned counties; (2) while a physical separation of the study units within the study area was desired, the separation had to be limited to avoid confounding differences in soils and climate; and (3) the deepest sandy soils coincided roughly with the natural range of longleaf pine, which is restricted to soils developed from the Catahoula and Willis geologic formations at the northern range limit and soils formed from more recent Quaternary deposits nearer to the Gulf of Mexico. Thus, as herein defined, the study area was that part of the East Texas Timberlands on which: (1) the natural forest types were loblolly-shortleaf pine and longleaf pine; (2) intensive forest had been practiced for at least 25 years; and (3) the deepest, and presumably the most drouthy, sandy soils could be found.

Two major geologic formations are found in this sandhill region. Several other formations are limited in extent or partially underlie the major formations (Sellards et al. 1966). Nearer to the coast is the Willis formation which was deposited during the early Pleistocene era. It is noncalcareous with coarser sand than younger, coastward formations. The profiles are usually deeply weathered and often indurated by clay. Iron oxide concretions may be found locally. The Willis formation is about 100 feet (31 m) thick. Over much of the study area it is underlain by the

Fleming formation of the late Miocene era. The Fleming formation is mostly clay; beneath the Willis formation the clay is red to magenta in color, and can be found on hilltops where the Willis formation has been removed by severe erosion. At the western edge of the study area, the elevation of the Willis formation is 300 to 450 feet (90 to 140 m) above sea level. Further east where there is less topographic relief, the formation is found at 300 to 370 feet (90 to 110 m) above sea level. In Louisiana this formation is known also as Williana.

The other major geologic formation is the Catahoula formation. It extends eastward into Louisiana where it forms the Catahoula Hills. Mudstone and coarse-grained quartz sand was deposited during the early Miocene era. This formation is much thicker than the Willis formation and ranges in thickness from 300 to 600 feet (90 to 180 m). At the eastern edge of the study area it is found at elevations of 400 to 500 feet (120 to 150 m) above sea level. The topography is generally strongly dissected; occasionally cuesta, the Spanish word for steep hills or escarpments, are found. It, too is underlain by the Fleming formation, which may be seen on eroded hilltops and deep roadcuts.

Less extensive than the two major formations is the Manning formation. It was also formed during the early Miocene by deposits of quartz sand, clay, lignite, and volcanic deposits of sand and clay in some areas. The light gray sand is fine to medium grained and weathers to a medium gray. This formation is found at elevations between 200 and 350 feet (60 to 110 m) and is about 200 feet (60 m) thick.

The entire study area receives a moist tropical influence from the Gulf of Mexico. The growing season ranges in length from 250 days in the south to 240 days in the north. Pines in this area begin growing usually in early March and continue until November. Rainfall averages 48 to 50 inches (1.23 to 1.28 m) at the eastern end to 44 to 46 inches (1.13 to 1.18 m) at the western end of the study area. The rainfall is seasonally well-distributed, except for occasional droughty periods during July and August, with 22 to 24 inches (0.56 to 0.61 m) falling from April to September.

The natural upland forest types in the study area are mixtures of longleaf pine (*Pinus palustris* Mill.), shortleaf pine (*Pinus echinata* Mill.), loblolly pine, and oaks (*Quercus* sp.) (USDA, SCS 1964). There is an understory of tolerant hardwoods that will replace the subclimax pines if fire is excluded from the forest or if the pines are removed. Commercial logging began shortly before the end of the last century. Much of the pine forest was subsequently understocked or dominated by the less valuable residual hardwoods. Most of the cutover forest land remained in an unproductive state until the early 1940's when forest industry began to establish plantations on the cutover land.

Selection of Study Units

Prior to selection, several criteria were established, and all study units were to reflect the following considerations: (1) to have been planted in the spring of 1957; (2) to be growing on a ridge or upland with a sand cap at least 24 inches (0.6 m) in depth, with a soil texture of sand, loamy sand, or sandy loam; (3) to have been planted on cutover forest land, rather than old fields, to avoid irregularities stemming from varying cultivation practices; (4) to be within plantations large enough to permit the elimination of any border effect; (5) to have no intermixture of species other than loblolly pine in the plantation; and (6) to have no serious insect or disease problems. Several forest industry firms assisted in locating a number of well-suited plantations.

Description of Study Units

Three general locations were chosen, one each in Angelina, Newton, and Polk Counties, because of their adherence to the selection criteria and their physical size would permit the establishment of several study units (Figure 1). Twenty acres was found to be the minimum acreage to be valid to be used for mensurational purposes in East Texas (Hunt et al. 1970). After a preliminary survey of each location, it was found that five study units per location would be the maximum number that the physical sizes of the plantations at the three locations would allow. Since no other plantations which had a uniform adherence to the selection criteria could be found, it was thereby decided that the study area would be comprised of the 15 available study units.

The units in Newton County are in two groups that are six miles apart. Three units are on a forest road, one mile north of Mitchell Cemetary, which is two miles east of the community of Mayflower on Texas Farm Road 255 (Figure 2). The plantation is owned by St. Regis Paper Company. These units are on the top and east slope of a ridge that has a north-south orientation. The soil series on this plantation is Darco sand and loamy sand. The ridge had been cutover and had burned repeatedly prior to the establishment of the plantation. The repeated burning in the past eliminated most woody vegetation. There was no evidence of either pre-

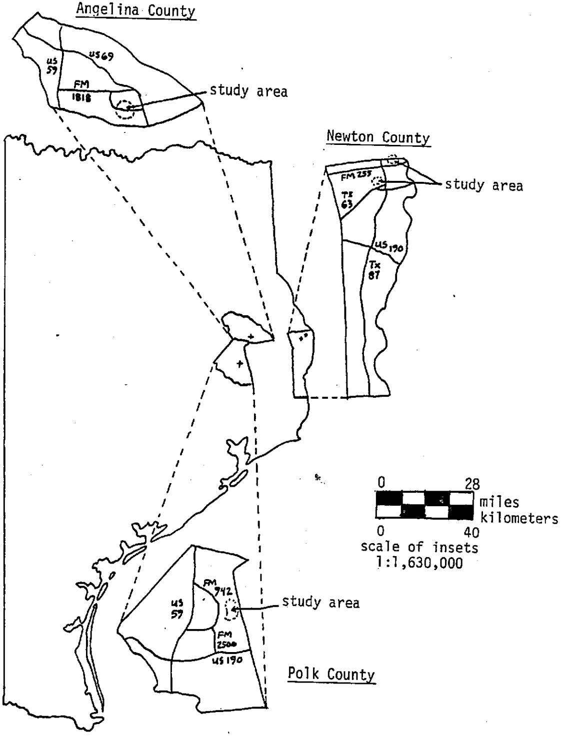


Figure 1: Map showing general locations of study units.

scribed burning or wildfire since 1957. The lack of hardwood competition and the low mortality during the early years of the plantation combined to produce a vigorous, dense stand. There was a thinning in 1980 in which every third row was removed. Some trees within the remaining rows were also removed because of their infection by fusiform rust (Cronartium quercum [Berk] Miyabe ex Shirai f. sp. fusiforme).

Two other units are two and one-half miles northwest of Weirgate (Figure 2). They are located on a broad ridgetop that has an east-west orientation. The Letney soil series with sandy and loamy sandy textures is found on the plantation. This land had also been cutover and burned before planting. There were many residual hardwood trees at the time of planting. Initial survival in the plantation was irregular. A combination of factors induced high mortality. The degree to which hardwood competition affected mortality was undeterminable. Whether or not the present level of hardwood competition was the cause or effect of high mortality, hardwood trees and sprouts were able to re-establish themselves to the detriment of the pine plantation. An examination of the signs of past prescribed burning indicated that the plantation was burned in 1978 or 1979 and once prior to that time. Sometime between the two burns, most of the larger residual hardwoods were girdled and injected with an herbicide with partial success. There was no sign of fusiform rust in the plantation, although rust-infected trees could be found in adjacent, younger slash pine plantations.

There were five units in Angelina County. The study units were in two groups within a large tract owned by Owens-Illinois that is five and one-half miles west of Zavalla on Texas Farm Road 1818, thence five miles

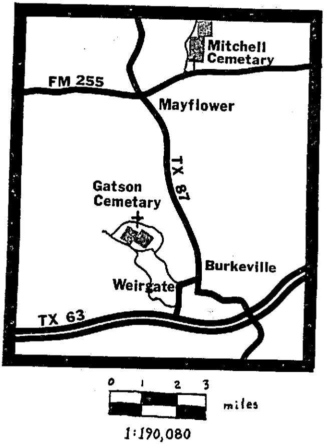


Figure 2: Map showing study units near Mayflower and Weirgate, Newton County.

south on Texas Farm Road 844. Texas Farm Road 844 ends there, from which point a network of forest roads must be travelled to reach the study units (Figure 3). Three units were on the top and slopes of a north-south oriented ridge on Owens-Illinois forest management unit number 0901. The soil series on those three units is Letney, the same series found on the study units near Weirgate in Newton County, but with sandy loams, in addition to sands and loamy sands. The degree of natural pruning and the low total crown ratios of the trees in the plantation indicated that survival was probably high through the early stages of the development of the plantation. The plantation was burned at least twice since establishment, but in some areas the prescribed burning was not effective in reducing the understory vegetation. The plantation was thinned at age 18 or 20 years. It was a selective thinning rather than a row thinning. There were numerous large, older loblolly, longleaf, and shortleaf pines that had been left as saplings or pole-size trees after the last harvest prior to the establishment of the plantation. Rust infection occurred only on scattered trees.

Two miles north of the three study units on the ridge were the other two units (Figure 3). The two study units are on Owens-Illinois forest management unit number 0801. They differed from the other units in the study because they were on an undissected flat to slightly sloping upland adjacent to Elm Creek. The Kurth soil series found on the southern one of the two units, and the Diboll series found on the northern one of the two units differ from those series found on the other study units by having more sandy loam-textured soils than loamy sands or sands, a more shallow epipedon, and seasonally restricted drainage. This plantation had low

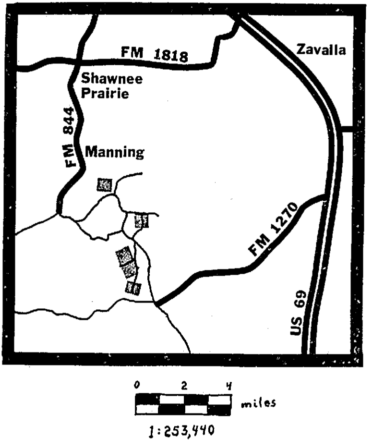


Figure 3: Map showing study units near Zavalla, Angelina County.

mortality during its early years. Prescribed burning kept hardwood competition under control. There was a selective thinning in 1978 or 1979.

Five study units were located in Polk County eight miles south of Camden on Texas Farm Road 942 to Hortense Church, thence east on a dirt road one mile to Feagin Cemetary, thence south, across Bear Creek, and east over a network of numerous forest roads (Figure 4). All of the plantations within the general location are owned by Champion International Corporation. The study units were on Champion forest management units number 21736, 21745, and 21741. All of the units were on an upland that was strongly dissected by many small ridges. There were many different slope aspects on units with more than one main ridge. The plantation was established after being cutover and burned. The burning was not effective in retarding the growth of sprouts and the residual hardwoods, or the unmerchantable pines that were left after logging. There were some areas on some units where hardwoods effectively outcompeted the planted pines. Many of the largest residual longleaf pines were killed during the southern pine bark beetle (Dendroctonus frontalis Zimm.) epidemic in the mid 1970's. At that time there were salvage and sanitation harvest operations. Aside from that, unlike the other two locations, there were no thinnings. There had been one or two prescribed burns on all of the units. Hardwood stems greater than four inches in diameter at breast height were girdled and injected with an herbicide. There was sporadic success with the reduction of competition. Those differences, especially the absence of thinning operations, necessitated that the study units in Polk County be analyzed separately, with respect to wood volume and diameter growth.

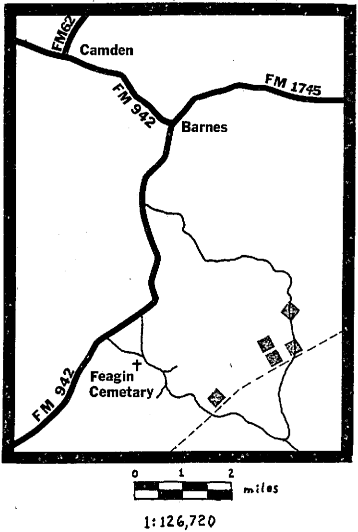


Figure 4: Map showing study units near Camden, Polk County.

Tree Parameters

On each twenty-acre unit, twenty sample points were located systematically. The trees at each sample point were tallied and measured to calculate the site index, number of trees per acre, diameter distribution of those trees, wood volume by diameter class, and yield at age 25 years. At the systematically located sample points all live, planted loblolly pine trees greater than 4.5 inches diameter at breast height (dbh) were sampled.

The sampling system used is known as variable plot sampling. In variable plot sampling, after the sample site is located, a basal area factor (BAF) is chosen to represent the number of square feet of basal area per acre a sample tree represents. In general, the principle behind the selection of a BAF is that in extremely dense young stands and in older stands with very large trees, a larger BAF is preferred to a smaller BAF. Considering all factors, a BAF of 20 was chosen.

At each sample point, turning clockwise from due north, all nearby trees were examined by looking through the BAF-20 prism to determine if they fell within their critical distances. Those for which the offset vision through the prism produced an image which was at least partially coincident were sampled. Those for which the determination of coincidence was unclear were noted and the radial distance from the sample point was measured to find if it was less than the critical distance for a tree of its diameter class, otherwise it was not sampled. For each sample tree, dbh was recorded.

A second stage of measurements followed the establishment of the sample points and dbh measurements. From the first sampling stage, frequency and diameter distributions of the trees on the unit were produced. Twenty-five subsample trees were selected systematically by diameter classes or strata in proportion to the frequencies of the diameter class in the first sample. Each of those trees was relocated; the planting spacing and the distance to the nearest competitor was recorded.

The third stage of measurements was to use an optical dendrometer to determine upper-stem diameters so that volume equations and local volume tables could be developed. The variability of such measurements necessitated the formulation of a sampling scheme that would result in the maximization of accuracy per unit effort. At each of the three locations, the relative frequencies of all represented diameter classes were calculated. Ten pre-sample trees were selected by diameter class, at each location, in proportion to the relative frequency of that class at that location. After the trees were measured, volumes were calculated. The sample size was determined by estimating the stratified population variance of the volumes of the trees within the study area. An equation incorporating the weighted stratified variance, the mean volume, and a value of Student's "t" for a desired confidence level showed that to predict the mean volume ± 5 percent, with a 99 percent confidence level, a sample size of 78 trees would be required. That sample size was doubled to 150 trees to try to reduce error further and to add to the perceived credibility of the results.

Volume equations may be developed from predicted volumes that are obtained by either the integration of upper-stem diameters and subsequent rotation of the curve to form a solid of rotation, or by determining the volumes of four-foot segments of the stem using Smalian's formula and summing the volumes of the segments. There is usually little difference in the results, so the simpler method of summing the segments was chosen (Hunt et al. 1970, Cao et al. 1980).

Volumes of trees that were randomly selected from those found at all three locations were thereby calculated. Yield tables were constructed for each unit using those volumes and diameter and frequency distributions.

Soil-Site Parameters

Each of the 25 subsample trees per study unit had associated with it two soil samples. Samples were collected from the 0-6 inch (0-15 cm) and 6-12 inch (15-30 cm) depths from a continuous soil core of the profile at a point as close as possible to the base of the subsample tree. Using a six-foot bucket auger with additional five-foot extensions, the soil profile was examined to note any incongruous soil formations and to find the depth to the least permeable horizon below which soil water would not percolate effectively. The amount of water that may percolate down through the profile can be limited by the rapid runoff of rainfall on steep slopes. A measure of the slope of the site was needed to gauge that possible influence on the availability of soil water. The degree of incline of the steepest slope downhill from the tree was chosen as the estimator that would reflect best the factors related to the overland drainage of rainfall and soil moisture, erosion, and position on the slope.

The soil samples were analyzed in the laboratory to determine the following properties: particle size distribution, percentage of organic matter, pH, potential available moisture storage capacity and cation exchange capacity using conventional techniques (Black 1965, Walsh and Beaton 1973). Particle size distribution and percent organic matter were determined for each sample because the results were to be used in statistical analyses. The other parameters were used for descriptive, not comparative purposes, so only several samples per study unit were analyzed for cation-exchange capacity and pH to confirm that the soils of the study units were similar in those characteristics. The apparatuses used to bring the soil moisture pressure potentials of the samples to simulated conditions of near saturation (-0.1 bar) and extreme drought (-15 bars) were a pressure plate and pressure table, respectively, with saturated ceramic plates on which were placed the soil samples. The equilibration of samples at the -15 bar suction level required about a week. Preliminary analyses showed that available moisture storage capacities varied little within given soil textural classes or series. If it were that soil texture limits moisture availability more than does the thickness of the coarse-textured horizon, then within a narrow textural class of soils, the depth to which soil water might percolate and be unavailable to roots would be more important. The acceptance of that premise permitted, for sampling purposes, the stratification of samples by the depth to the least permeable horizon (Cochran 1977).

Soil Series Descriptions

The criteria by which each of the three locations within the study area was selected were chosen, in part, to ensure the comparability of the soil series found on each of the five study units per location. Five different soil series are found, collectively, on the study units: Betis, Darco, Letney, Diboll, and Kurth.

The Betis series is classified as belonging to the sandy siliceous, thermic Psammentic Paleudult family and is characterized as a deep, somewhat excessively drained, rapidly permeable, sandy upland soil with slopes up to 12 percent. The solum is a fine sand or loamy fine sand to a depth greater than 80 inches (2 m). Until 1978, Betis was classified as Lakeland (a deep, sandy Entisol common in central Florida). Since that date soils west of the Mississippi River previously classified as Lakeland have been reclassified as one of several new series. The former Lakeland soils within the study area were reclassified as Betis because although the soils appeared to be Entisols, taxonomically they were Ultisols. The taxonomic paradox was resolved by placing Betis within the Psammentic group of Ultisols. Psammentic refers to the sandy particle-size class of the pedon which, as an Ultisol, also has an argillic horizon. Although the argillic horizon of Betis may be at a depth of 30 feet (9.8 m) or more, a typic Entisol would not have such a horizon, even at that depth.

The Darco series is a loamy, siliceous, thermic Grossarenic Paleudult. This deep, well drained, rapidly permeable upland soil is classified as Grossarenic because of the presence of a 40 to 80 inch (1 to 2 m) thick sandy particle-size class epipedon. The texture of the epipedon is sandy or loamy sand.

The Letney series belongs to the family of loamy, siliceous, thermic Arenic Paleudults. The upland soils are deep, well drained, and moderately rapidly permeable. This series differs from Darco by having a sandy epipedon that is only 20 to 40 inches (0.5 to 1 m) thick.

The Kurth series is classified as a fine loamy, siliceous, thermic Aquic Glossudalf. The series consists of deep, moderately well-drained, slowly permeable soils. The soils are found on nearly level to strongly sloping, broad interstream divides. A typical pedon has 8 to 34 inches (0.2 to 0.8 m) of fine sandy loam underlain by strong brown and red sandy clay loam.

The Diboll series is a fine silty, siliceous, thermic Glossic Natraqualf. The series consists of deep, somewhat poorly drained, nearly level and gently sloping soils on uplands. A characteristic pedon has a loamy or sandy loam surface layer about 29 inches (0.7 m) thick over loam streaked by clay loam to a depth of 43 inches (1.1 m) below which is a firm siltstone.

RESULTS AND DISCUSSION

There were two primary objectives in this study: (1) to evaluate the influence of soil-site relations on height growth of twenty-five year-old loblolly pine planted on deep, sandy soils; and (2) to develop cubic-foot wood volume and yield estimates for those loblolly pine plantations. First, soil and site characteristics had to be examined and scrutinized to establish which relationships and interrelationships had a significant, if not noticeable effect on height growth. That required separate analyses for each of the three locations. Several variables displayed a stratification of values that was associated with one or more of the three locations. When the data was not partitioned, there was a confusing variablity that was due, not to a continuous nature of the data, but to the presence of discrete strata peculiar to locations. After the stratification of the data by location, many previously masked relationships appeared. Following the recognition of those relationships, the data was examined closely for plausible explanations which supported each statistically significant relationship. There was no obvious or remote reason for some of the relationships. The statistical significance of such relationships was probably due, not to any particular biological phenomena, but rather to a lack of independence among the variables. Multiple regression analysis techniques were then applied to the data. Different equations along with different explanations of the soil-site relations which affected height growth were developed for each of the three locations.

The development of volume and yield tables required a much more complex methodology. The results were gleaned from the data more easily than the results from the regression analysis of height growth, but were not generally statistically comparable. The procedures performed well on an overall basis; most of the results were straightforward and classical in substance. The local volume tables were developed by regression analysis of the relationship of diameter at breast height to calculated cubic-foot wood volume. Other volume tables were developed by including the form class and merchantable height of the subsample trees. Empirical yield was estimated using by the variable-plot sampling data and the local volume tables.

Soil Characteristics

Two particle size analyses were associated with each sample tree. It was found at all locations that the percentage of sand in the 0-6 inch (0-15 cm) level was strongly correlated ($r = 0.71$) to the percentage of sand in the 6-12 inch (15-30 cm) level. Since the percentage of sand in a sample is related directly to the soil texture, the textures of the two levels were usually the same. In general, a comparison of any pair of soil samples showed that although the samples were usually texturally identical, the 0-6 inch (0-15 cm) sample had slightly more sand, slightly less clay, and the same percentage of silt. That was due to the eluviation of clay from the upper level of the profile. The relationship was the same at all three locations (Table 1).

The selection criterion specifying soil textures was met for the entire study area. At each location, analytically determined soil textures

TABLE 1

Average soil particle size distribution.

	0-6 inch level			6-12 inch level		
	sand	silt	clay	sand	silt	clay
	-----percent------			-----percent------		
Newton Co.	86.2	7.4	6.4	85.5	7.5	7.0
Angelina Co.	79.0	14.5	6.5	77.7	14.1	8.1
Polk Co.	90.5	3.8	5.6	90.5	3.4	6.1

were reflective of earlier soil series mapping efforts. The location in Newton County had almost equal numbers of samples that were sands and loamy sands; there was one anomalous sandy loam. That soil sample was collected from a small ridgetop depression with no overland drainage. The textures of the two study units on the Letney soil series were predominantly loamy sands, while the textures of the other three units which were on the Darco series were mostly sands.

There was much more variation in the textures at the Angelina County location. Sands, loamy sands, and sandy loams were present in roughly equal proportions. That was due to the differences among the three soil series at the location, whereas the location in Newton County had two similar series and the location in Polk County had only one very homogeneous soil series.

The textural classifications of the Betis soil series at the location in Polk County were mostly sands, with a few loamy sands, and one sandy loam. The uniformity of texture was due to the presence of only one soil series and to the relatively small area in comparison to the other two locations within which the five study units were located (Table 2).

The percentage of organic matter was determined for the two soil levels. Analysis showed that the average percentage of organic matter in the 0-6 inch (0-15 cm) was twice as great as the average percentage in the 6-12 inch (15-30 cm). The relationship was true for all three locations. For the minimum and maximum percentages of organic matter per location, the general relationship was not so strong (Table 3). Samples which had a large amount of organic matter in the 0-6 inch (0-15 cm) soil level had usually a similarly large amount in the 6-12 inch (15-30 cm) soil level.

TABLE 2

Soil textural classifications.

	sand	loamy sand	sandy loam	total
	------------number of	samples	------------	
Newton Co.	60	64	1	125
Angelina Co.	30	54	41	125
Polk Co.	101	23	1	125
total	191	141	43	375

Samples which had a small amount (less than 1.0 percent organic matter) in the upper soil level had a similarly low amount in the lower soil level.

For all three locations there were weak, negative correlations between the percent organic matter in one level to the percent sand in the same level. Within a location, the correlation was stronger when samples of the same series were compared.

There was tremendous variation in the depth to the least permeable horizon. Depth to the argillic horizon ranged from 0 to over 16 feet (0 to over 4.9 m). The minimum sandcap criterion was violated by 15 percent of the 375 sample points (Table 4).

At the Polk County location, the minimum depth was 2.3 feet (0.7 m). It was at this location that the deepest sands were found [the soil series present on these study units, Betis sand, is characterized by an argillic horizon at a depth greater than 80 inches (2 m)]. The physical limit of the soil auger used to examine the profile was reached at a depth of 16 feet (4.9 m), so the depth to the argillic horizon was not determined for many sample points at that location. Pine roots were found as deep as 16 feet (4.9 m), so trees in the plantations were able apparently to obtain moisture even at that depth.

In correspondence to the characterizations of the soil series, there were only six sample points at the Newton County location for which the depth to the least permeable horizon was less than two feet (0.6 m). Darco soil series has an argillic horizon at a depth less than 80 inches (2 m). On study units where that series was present, only a sample point in a small ridgetop depression, mentioned earlier, had no sandy or loamy sand textured horizon. Although the maximum depth to the least permeable hori-

TABLE 3

Soil organic matter content.

	0-6 inch level			6-12 inch level		
	avg.	min.	max.	avg.	min.	max.
	percent					
Newton Co.	1.64	0.27	5.47	0.94	0.13	3.01
Angelina Co.	1.76	0.60	3.33	0.88	0.35	2.21
Polk Co.	1.26	0.48	2.85	0.64	0.20	2.13

TABLE 4

Depth to the least permeable horizon.

	depth		
	avg.	min.	max.
	----------feet---------		
Newton Co.	5.1	0.0	12.4
Darco	4.9	0.0	12.4
Letney	5.3	1.6	9.8
Angelina Co.	2.6	0.3	7.3
Letney	2.3	0.3	7.3
Kurth	2.1	0.8	4.2
Diboll	3.9	1.0	6.2
Polk Co.	9.8	2.3	16.0
Betis	9.8	2.3	16.0

zon was greater for Darco, the average was higher for Letney, which has generally a more shallow argillic horizon. The other five sample points where the depth was less than two feet (0.6 m) were on the Letney soil series. Letney is characterized by a layer of loamy sand 14 to 42 inches (0.4 to 1.1 m) thick over a relatively impermeable sandy clay loam.

The Letney series was also present on three ridgetop study units in Angelina County. It was on those units that the widest range of depths were found (Table 4). The two other units were on a broad, interstream, upland divide that had seasonally impeded drainage. The Kurth and Diboll series differ from the soil series at the other locations because of their associated occasional permeability and drainage problems. The commonality was in the average depth of the sand or loamy sand which, regardless of reduced infiltration in winter or early spring, produced a susceptiblity to late summer moisture stress.

The available moisture storage capacity (AMSC) [or available water holding capacity (AWHC)] was calculated for a variable number of samples for each location. The number of samples was determined by the stratification of the variable depth to the least permeable horizon into three-foot (0.9 m) thick strata. Thus, at the location in Polk County where the depth was as great as or greater than 16 feet (4.9 m), there were six three-foot (0.9 m) strata; 0.0-3.0 feet (0.0-0.9 m), 3.1-6.0 feet (1.0-1.8 m), 6.1-9.0 feet (1.9-2.8 m), 9.1-12.0 feet (2.0-3.7 m), 12.1-15.0 feet (3.7-4.6 m), and over 15.1 feet (4.6 m). At the other locations where the depths to the argillic horizon were not as great, there were proportionally fewer strata. The values obtained for available moisture storage capacity were intended originally to be used as an independent variable for the prediction of total height. However, due to the variability of the results obtained, the results were used for empirically comparative, rather than statistical, purposes. Most of the observations fell within the bounds of available moisture storage capacity described in the literature as characteristic of their respective soil series (Table 5).

TABLE 5

Average soil moisture retention, by soil series, by the depth to the least permeable horizon (DLPH).

soil series	(DLPH)	percent moisture	percent moisture	percent moisture	percent moisture
	ft	-0.1 bar	-15 bars	AWHC	AWHC, SCS
Darco	4.5	9.3	0.66	8.6	5.0-9.0
	6.9	7.2	1.50	5.7	5.0-9.0
	12.4	7.9	0.83	7.1	5.0-10.0
Letney	1.5	15.0	0.73	14.3	6.0-10.0
	2.4	13.0	0.33	12.7	6.0-10.0
	7.3	13.0	0.33	12.0	6.0-10.0
	9.8	10.8	0.68	10.1	6.0-10.0
Diboll	4.4	15.8	0.82	15.0	10.0-20.0
Betis	2.8	8.8	1.30	7.5	5.0-9.0
	4.5	5.4	1.12	4.3	5.0-9.0
	7.6	7.5	0.87	6.6	5.0-9.0
	11.0	4.5	0.15	3.0	5.0-9.0
	13.5	5.2	0.77	4.4	5.0-9.0
	16.0+	4.8	1.08	3.7	5.0-9.0

Site Characteristics

The steepest incline downhill from each sample tree was measured and recorded as the slope percentage most representative of the surface and subsurface drainage of water on that microsite. The range of slopes was nearly the same for all three locations (Table 6). Although the average slope percentages within each location were much the same, the average slope percentage for the Newton County location was significantly less than the average for the Angelina County location which was significantly less than the average for the Polk County location (Table 7). Those results were obtained by using Student's t-test to compare pairs of means. A comparsion of the differences between means which used Fisher's least significant difference (LSD) test showed only a significant difference between Newton and Polk Counties.

The planting spacing was measured for each study unit. Nominal planting density ranged from 1210 to 1815 trees per acre (490 to 735 trees per ha). Mortality and thinning at two locations reduced substantially the number of trees per acre remaining at age 25 years (Table 8).

An additional competition variable was measured. The distance to the nearest competitor (DNC) was defined as the horizontal distance to the nearest tree that had been in a competitive crown position, relative to a sample tree, since the establishment of the plantation. The distance to the nearest competitor was usually related to the maximum negative deviation from the nominal planting spacing (the closest actual planting spacing), was reflective of a localized plantation establishment failure, or was associated with reductions due to thinning or mortality. In other cases, the nearest competitor was a residual pine or hardwood that had had

TABLE 6

Downhill incline from sample trees.

	average slope	minimum slope	maximum slope
	------------	percent	------------
Newton Co.	5.08	0.0	16.0
Angelina Co.	5.73	0.0	20.0
Polk Co.	6.81	0.0	20.0

TABLE 7

Student's t-test and Fisher's LSD test for average slope percentages.

	average slope	t-value	LSD groupings
Newton Co.	5.08		A
Newton vs Angelina		-2.35*	
Newton vs Polk		-6.65*	
Angelina Co.	5.73		A B
Angelina vs Polk		-3.63*	
Polk Co.	6.81		B

* significant at 95 percent level of confidence

TABLE 8

Planting density, stand density, and percent of planted trees remaining.

location	study unit	nominal planting density	average present stand density	remaining percent
		-------trees/acre--------		
Newton Co.	1	1210	147	12
	2	1210	142	12
	3	1815	182	10
	4	1815	250	14
	5	1815	226	12
Angelina Co.	1	1210	190	16
	2	1210	143	12
	3	1210	140	12
	4	1210	215	18
	5	1210	171	14
Polk Co.	1*	1360	288	21
	2*	1360	256	19
	3*	1360	239	18
	4*	1360	252	18
	5*	1360	270	20

* these study units were unthinned.

an obvious competitive impact on the planted sample tree. The distance to the nearest competitor was measured because it offered a better indication of the present competitive stress of a sample tree than parameters such as planting density, survival, or stand density estimates derived from point sampling data. Both the average distance to the nearest competitor and the average number of trees per acre were strongly correlated to diameter breast height (Table 9).

As the average distance to the nearest competitor decreased, average dbh decreased ($r = 0.50$). Average dbh decreased as the average number of trees per acre increased. The sample trees at the locations in Newton and Angelina Counties followed those trends. Among the five study units, at each of the two locations, as the result of different thinning practices, there was wide variation in the number of trees per acre and the average dbh. At the Newton County location, the average number of trees per acre per study unit ranged from 142 to 250 (335 to 600 trees per ha). The range was 140 to 215 stems per acre (335 to 520 stems per ha) at the Angelina County location. A regression analysis of relationship of the number of trees per acre to average dbh, revealed a strong correlation ($r = 0.95$, $R^2 = 0.90$) which, in view of the different thinning practices at those two locations, however statistically significant, had a not purely biological basis. The stocking levels at the Polk County location ranged from 231 to 288 trees per acre (555 to 690 trees per ha). The statistically significant, biologically-unaltered relationship was even stronger than that of the other two locations. The same regression analysis of the data from the Polk County location produced a coefficient of determination (R^2) of 0.99. The study units in Polk County, as a group, had the highest number

TABLE 9

Effect of spacing on diameter (dbh) and basal area (BA), by location, by study unit.

location-study unit		trees/acre	BA	dbh	DNC	spacing
			----------average----------			
		number	sq. ft.	in.	------ft.-----	
Angelina Co.	3	140	69	9.5	10.2	10.0
Newton Co.	2	142	62	8.9	10.9	9.9
Angelina Co.	2	143	68	9.3	9.2	9.8
Newton Co.	1	147	68	9.2	10.7	9.7
Angelina Co.	5	171	75	8.9	11.3	9.0
Newton Co.	3	182	74	8.6	10.5	8.7
Angelina Co.	1	190	77	8.6	10.5	8.5
Angelina Co.	4	215	77	8.1	9.8	8.0
Newton Co.	5	226	84	8.3	9.1	7.8
Polk Co.	3	231	77	7.7	6.0	7.7
Newton Co.	4	250	74	7.4	8.6	7.4
Polk Co.	4	252	72	7.2	7.1	7.4
Polk Co.	2	256	68	7.0	7.4	7.4
Polk Co.	5	270	69	6.8	5.9	7.2
Polk Co.	1	288	66	6.4	4.7	6.9

of trees per acre, highest percentage of survival, and the least average distance to the nearest competitor. Those factors combined to produce the smallest average diameter of the three locations.

Soil-Site Relations and Height Growth Regression Analysis

Data on twelve soil-site variables and three location indicator variables from 375 sample trees on 15 study units from three locations were screened for statistical correlation to total height at age 25 years. The absolute value of the simple correlation coefficients (r) of height to the soil-site and location variables ranged from 0.0008 for the percentage of clay in the 0-6 inch (0-15 cm) soil sample to 0.58 for the Polk County location indicator variable (Table 10).

A multiple regression analysis which used all independent variables showed that the full, unpartitioned model explained a significant amount of the variation in the data (Table 11). The soil-site and indicator variables predicted a significant amount of the variation in total height of the 375 sample trees. However, the calculation of the sums of squares resulted in a singular, non-invertible X'X matrix (sums of squares of independent variables). That problem was solved by the creation of a generalized inverse using one of many possible solutions to the normal equations of the model.

The singularity was caused by the colinearity of several groups of variables; the values of the organic matter for the two soil levels, the percentages of the three particle size classes for both of the soil levels, the depth to the least permeable horizon and the available water index, (WI), which was the product of the depth to the least permeable hori-

TABLE 10

Correlation between height and soil-site variables.

	Newton Co.	Angelina Co.	Polk Co.	Overall
DLPH	-0.12	+0.12	-0.26	-0.49
--percent-- slope	-0.30	+0.25	-0.03	-0.09
OM, 0-6 in.	+0.28	-0.04	+0.08	+0.27
OM, 6-12 in.	+0.22	-0.09	+0.12	+0.26
sand, 0-6 in.	-0.14	+0.30	+0.17	-0.21
silt, 0-6 in.	+0.17	-0.29	-0.12	+0.25
clay, 0-6 in.	-0.03	-0.20	-0.16	0.00
sand, 6-12 in.	-0.11	+0.21	+0.12	-0.24
silt, 6-12 in.	+0.16	-0.21	-0.04	+0.29
clay, 6-12 in.	-0.30	-0.11	-0.19	+0.03
AMSC	-	-	-	+0.47
WI (DLPH*AMSC)	-	-	-	-0.14
Newton Co.	-	-	-	+0.28
Angelina Co.	-	-	-	+0.30
Polk Co.	-	-	-	-0.58

TABLE 11

Regression analysis of all soil-site and three indicator variables for the entire study area.

source	df	SS	MS	F	p-level	R^2
model	14	16619	1187	17.06	0.0001	0.40
error	360	25047	70			
total	374	41666				

zon and the available moisture storage capacity (AMSC), for a given sample point, and the three indicator variables were linear combinations of one another. For that reason, a substantially reduced model was tested for its predictive value for total height.

Variables were eliminated from the full model with the intent being to remove most of the colinearity. The reduced model had four soil-site variables. It was recognized that some of the discarded variables did contribute to the prediction of total height, but because either the variables had a high correlation coefficient in relation to one of the four included variables or the statistical significance for the prediction of total height was very low, their addition would have resulted only in the complication of and not the improvement of the model (Table 12).

The coefficient of determination for the reduced model was lower than that of the full model, which might suggest that the reduced model was less appropriate, however, the increase in the F-statistic of the reduced model indicates a reduced probability of incorrectly rejecting the null hypothesis (committing a type I error). The significance of the model notwithstanding, a more complete understanding of the soil-site relations was reached by testing the individual significances of the coefficients of the independent soil-site variables with Student's t-test (Table 13).

The depth to the least permeable horizon (DLPH) had the greatest influence on total height. The statistical significance of the depth to the least permeable horizon was empirically well-supported by the data. The percentage of organic matter in the 0-6 inch (0-6 cm) soil level was also highly significant. The percentages of sand, 0-6 inch (0-15 cm) level and slope had only empirical and theoretical significances. They were both

TABLE 12

Regression analysis of selected soil-site variables for the entire study area.

source	df	SS	MS	F	p-level	R^2
model	4	10980	2745	33.10	0.0001	0.26
error	370	30685	83			
total	374	41665				

TABLE 13

Assessment of the coefficients of individual soil-site variables in the reduced model for the entire study area.

source	t-value	p-level
slope	0.27	0.79
DLPH	-9.27	0.0001
OM, 0-6 in.	3.36	0.001
sand, 0-6 in.	0.37	0.71

statistically non-significant at the tested level of significance. Among the three locations there were three recognizable strata of depths to the least permeable horizon. Thus, while that variable was highly significant, some of the effect was associated with the strata peculiar to the three locations. For that reason, the data from the entire study was partitioned by location so the location effect could be removed from the analysis.

After the data was partitioned into three groups, simple correlations for all soil-site variables were calculated (Table 10). Some of the simple correlations coefficients for any one location did not have the same positive or negative relationships that were found in the correlation coefficients for the entire study area. An examination of the data disclosed that inconsistencies in the signs of the correlation coefficients were related to the stratification of values for some soil-site variables by location. The slope percentage had a positive correlation to total height at the Angelina County location, in contrast to the negative correlation overall and for the other two locations. A series of interactions at the Angelina County location resulted in shorter trees on more level areas. The ranges in values and the means for the soil-site variables differed for each location. The differences in the mean values of the variables at each location meant that not all variables would have a uniform effect on the total height of the trees at the three locations. Six soil-site variables were selected for each location. The variables were selected from twelve screened variables on the basis of their magnitude of correlation to total height and their degree of non-colinearity with other variables. The combination of variables was different for each location, but three variables, percentage slope, depth to the least permeable horizon, and percentage organic matter, 6-12 inch (15-30 cm) level, were common to the reduced models for all locations. The three common variables had irregular effects on total height. The irregularities were due to the non-continuous nature of the data.

The independent soil-site variables used in the regression analysis for the data from the Newton County location were the six variables with not only relatively high simple correlations to total height, but those which also had relatively low simple and partial correlation coefficients among themselves. One covariate was also used in the multiple regression analysis. The covariate was selected by standardizing the data, so that the variables had means equal to zero and sample variances equal to one, and screening the array of covariates for those which were relatively large and non-colinear with the other covariates and soil-site variables. The chosen covariate was percentage sand, 0-6 inch (15-30 cm) level by percentage sand, 6-12 inch (15-30 cm) level. The two variables had a simple correlation of +0.71. That simple correlation was high, but since neither variable was included in the model and the standardized covariance was much larger than any other non-colinear covariate, it was selected as the covariate that could contribute the greatest predictive value to the model. The negative correlations of the slope percentage and the depth to the least permeable horizon support the hypothesis that on steeper slopes, the overland drainage of moisture would be more rapid and that greater depth to the least permeable horizon would permit deeper infiltration of moisture (Larson 1971). Such effects, in combination, would diminish the amount of water available for transpiration. The positive correlations of the percentages of silt and organic matter in both the 0-6 inch (0-15 cm) and 6-12 inch (15-30 cm) soil levels are indicative of the complementary relationship of the sand and silt content of a soil (in this range of soil textures, a less sandy soil has a greater available moisture storage capacity) and the substantial moisture storage capacity of organic matter. All seven variables had a relationship to total height that was related to the moisture availability of the site.

Regression analysis of the data indicated that the model predicted a significant amount of variation in total height (Table 14). While the F-value was significant, the coefficient of determination (R^2) was only 0.14. The coefficient of determination is defined as the model sums of squares divided by the corrected sums of squares and indicates the fraction of total variation that can be explained by the model. However, it is not a measure of the appropriateness of the linear model. Such a low coefficient of determination was the result of the omission of some significant independent variables.

The model failed to represent perfectly the "true model" for two main reasons: (1) the biological nature of the data produced a variability in numerous unknown or unquantifiable factors that was uncontrollable; and (2) some factors that were recognized as quantifiable and possibly important, such as elevation, rainfall, and evapotranspiration were not measured. Factors such as those that were quantifiable, were not used because of difficulties related to accurate measurement. The indiscriminate inclusion of independent variables can usually increase the coefficient of determination, but meaningful interpretation of the results becomes increasingly difficult (Snedecor and Cochran 1980). With that recognition,

TABLE 14

Regression analysis of six soil-site variables and one covariate, Newton County location.

source	df	SS	MS	F	p-level	R^2
model	7	1162	166	2.78	0.01	0.14
error	117	6989	60			
total	124	8151				

the seven independent variables were tested for the significances of their respective coefficients in the model. The coefficients for the percentage slope and the depth to the least permeable horizon had the lowest probabilities (of committing a type I error, or incorrectly rejecting the null hypothesis) that their observed test statistics could exceed the tabular test statistics for the data (Table 15). The other five variables were found to be significant only at high probabilities (of committing a type I error) that their test statistics could be exceeded by their respective tabular test statistics.

The regression equation for the Angelina County location used six soil-site variables and two covariates. At this location, in contrast to the Newton County location, the percentage of slope had a positive correlation with total height. There were two study units that were on level to gently sloping terrain with two soil series that exhibited seasonally restricted drainage. An increase in slope would result in increased soil drainage in association with a better-drained soil series, with an increased soil oxygen level, that would not restrict root growth in the early spring. oxygen level. The positive correlation of the percentage of silt in the 6-12 inch (15-30 cm) soil level was highly correlated (r=-0.74) to the percentage of sand for that level and to the percentage of sand for the 0-6 inch (0-15 cm) soil level (r=-0.84). The negative correlation of the percentage of clay in the 0-6 inch (0-15 cm) level to total height was related to the impeded drainage of the finer-textured soil series which had shorter total heights than the coarser-textured soils at this location. The depth to the least permeable horizon had a negative correlation (r = -0.12) that was equivalent to that of the Newton

TABLE 15

Assessment of the coefficients of the eight variables in the model for the Newton County location.

source	t-value	p-level
slope	-0.27	0.02
OM, 0-6 in.	1.25	0.21
silt, 0-6 in.	0.65	0.51
DLPH	-1.57	0.12
OM, 6-12 in.	0.45	0.65
silt, 6-12 in.	0.10	0.92
sand, 0-6 in. X sand, 6-12 in.	0.50	0.62

County location, even though the average depth was 2.6 feet (0.8 m) and the average at the Newton County location was 5.1 feet (1.6 m). The percentage of organic matter in the 6-12 inch (15-30 cm) soil level had a weak, negative correlation to total height for which there was not an apparent biological reason. The two covariates were the percentage of sand in the 0-6 inch (0-15 cm) soil level multiplied by (1) the percentage of slope and (2) the percentage of sand in the 6-12 inch (15-30 cm) soil level. The negative correlation of (1) was related to the shorter total heights of the sample trees on the steepest, sandiest sites. The positive correlation of (2) was related to the shorter total heights of the sample trees on the finer-textured soils and the tallest total heights of the trees on the sandier, more level sites.

The regression model which used all eight variables predicted a significant amount of variation in the dependent variable (Table 16). The coefficient of determination ($R^2 = 0.18$) was slightly greater than that of the Newton County location. There was much variation in the dependent variable for which the eight independent variables offered no predictive value. The percentage slope variable and its nearly colinear covarviate, slope * percentage of sand in the 0-6 inch (0-15 cm) soil level contributed significantly more to the prediction of total height than the other independent variables (Table 17).

Six soil-site variables and two covariates were used for the regression analysis of the data from the Polk County location. Sample trees at this location were much shorter than those at the other two locations. The average total height was 44.8 feet (13.8 m). The averages for the Newton and Angelina County locations were, respectively, 57.8 feet (17.8

TABLE 16

Regression analysis of six soil-site variables and two covariates, Angelina County location.

source	df	SS	MS	F	p-level	R^2
model	8	1714	214	3.15	0.003	0.18
error	116	7891	68			
total	124	9605				

TABLE 17

Assessment of the coefficients of the eight variables in the model for the Angelina County location.

source	t-value	p-level
sand, 0-6 in.	1.28	0.20
slope	2.76	0.01
silt, 6-12 in.	1.63	0.10
DLPH	-0.57	0.57
clay, 0-6 in.	0.85	0.40
OM, 6-12 in.	-0.01	0.99
sand, 0-6 in. X slope	-2.59	0.01
sand, 6-12 in.	1.60	0.11

m) and 58.2 feet (17.9 m). The average depth to the least permeable horizon (DLPH) [9.8 feet (3.0 m)] was substantially greater than the average for either of the other two locations (Table 4). The simple correlation of the depth to the least permeable horizon to total height (r=-0.26) was the highest of the 12 screened independent variables. The weakness of the predictive value of the independent variables was shown by the relatively low F-statistic produced by the eight-variable regression model (Table 18). The F-statistic failed to indicate that the average height was related to the eight variables at the alpha=0.05 level of significance. However, when the probability of incorrectly rejecting the null hypothesis that the model had no predictive value was raised to alph=0.10, the model displayed statistical significance.

Of the eight independent variables, only the depth to the least permeable horizon had a coefficient of sufficient magnitude to reject the null hypothesis at even a slightly reasonable level of significance (alpha=0.20). The rejection of the null hypothesis for the other variables would have required that the probability of committing a type I error be raised to between 0.26 and 0.84 (Table 19). As the probability of committing a type I error increases, the probability of failing to reject the null hypothesis when it is indeed false (type II error), is reduced. There was a greater concern, in this analysis, for reducing the likelihood of a type I error rather than reducing the probability of a type II error, id est, it was more important to not falsely identify a soil-site variable as significant in the regression than to exclude a significant variable from the regression. Although the coefficients of determination for each location were, in absolute terms, rather low, the lower predictive value of the equations for the Polk County location may have been related to the greater importance of undetermined variables, such as rainfall and evapotranspiration, which at this, the most western of the three locations, have probably their greatest influence on the soil moisture regime and height growth.

TABLE 18

Regression analysis of six soil-site variables and two covariates, Polk County location.

source	df	SS	MS	F	p-level	R^2
model	8	1076	134	1.85	0.07	0.11
error	116	8418	73			
total	124	9494				

The collective and individual location results from the regression analyses indicate that greater depths to the least permeable horizon are associated consistently with shorter average total height. Other soil-site factors, including slope, soil texture, and organic matter have irregular and sometimes insignificant effects on total height. The poor performance of all of the models: unpartitioned, full; unpartitioned, reduced; partitioned, full; and partitioned, reduced; indicated that, for a thorough understanding, many other variables mentioned previously should be considered and included in any future models which would study the soil-site relations of loblolly pine planted on the deep, sandy soils of East Texas.

TABLE 19

Assessment of the coefficients of the eight variables in the model for the Polk County location.

source	t-value	p-level
DLPH	-1.35	0.18
OM, 6-12 in.	0.64	0.52
clay, 6-12 in.	-1.14	0.26
OM, 0-6 in.	0.53	0.60
sand, 0-6 in.	0.65	0.52
slope	0.29	0.77
DLPH X slope	-0.19	0.85
sand, 0-6 in. X sand, 6-12 in.	-0.27	0.79

Volume Table Development

Two types of volumes tables were developed from the collected dbh and upper-stem diameter data. A local volume table was developed for each general location in the study area using trees of stratified, systematically selected diameters at breast height (dbh) from 20 variable-plot sample points from each of the five study units and a series of upper-stem diameter measurements for each selected subsample tree. Fifty subsample trees per location were allocated in proportion to the relative frequencies of the diameter classes. The merchantable, outside bark volume was calculated for each of the 50 trees. A FORTRAN computer program was used to: fit the 50 trees to diameter classes; calculate average merchantable, outside bark volume to a 2-inch minimum upper-stem mid-bolt diameter per diameter class; and develop a regression equation which predicted the volume of an individual tree as a function of its basal area (Hunt et al. 1970). The regression equation predicted tree volumes for diameter classes within the range of the data, and beyond that up to the 20-inch diameter class.

The volume equations for the Newton and Angelina County locations performed very well; the coefficient of determination (R^2) was about 0.95 for both those locations. The strength of those two equations was related to a greater uniformity of form class (Girard 1933) (stem diameter at 17.5 feet (5.4 m) divided by the stem diameter at 4.5 feet (1.4 m)) and and merchantable heights within diameter classes (Table 20). Those two factors were associated with the relative homogeneity of stand density and possibly with the microsite conditions within the study units.

The merchantable volume prediction equation for the Polk County location performed poorly in comparison to the other two equations (Table 20). The lack of predictive strength was due to a more irregular distribution of form classes and merchantable heights within the diameter classes. Although this location had a comparitively greater uniformity of some soil-site factors, most notably soil texture, in general, the most harsh site conditions were found at this location. The most significant soil-site factor, depth to the least permeable horizon, had the most extreme deleterious values (some of which were truncated at a value of 16 feet (4.9 m) because of sampling difficulties) for the three locations. Thus, while it was that the range of site index at this location was much the same as the other two locations, there was a sufficient number of (microsite) dominant trees that were not dominant in the broader context of a

TABLE 20

Merchantable volume tables and equations for three locations.

DBH	Newton Co.	Angelina Co.	Polk Co.
	---------------cu. ft.**	----------	
5	4.1	3.0	4.8
6	5.8	5.0	6.1
7	7.7	7.3	7.8
8	10.0	9.9	9.6
9	12.6	12.9	11.7
10	15.5	16.3	14.1
11	18.7	20.0	16.7
12	22.2	24.0	19.6
13	26.0	28.4	22.7
14	30.1	33.2	26.0
15	34.5	38.3	29.7
16	39.2	43.8*	33.5*
17	44.2	49.6*	37.6*
18	49.5	55.8*	42.0*
19	55.2*	62.3*	46.6*
20	61.1*	69.2*	51.4*

* estimate outside the range of the data for the location

** diameter outside bark volumes to a 2-inch merch. top

Table 20. Continued.

<u>Newton</u> <u>Co</u>.

$V = 27.8734 * (DBH^2 * 0.005454) + 0.2767$

$R = 0.9751$

$R^2 = 0.9508$

<u>Angelina</u> <u>Co</u>.

$V = 32.3257 * (DBH^2 * 0.005454) - 1.3588$

$R = 0.9714$

$R^2 = 0.9436$

<u>Polk</u> <u>Co</u>.

$V = 22.8257 * (DBH^2 * 0.005454) + 1.6479$

$R = 0.4054$

$R^2 = 0.1643$

large plantation, such that the site index was not adequately reflective of the worst microsites of the study units. For that reason, the variability of microsite index was not controlled sufficiently in the sampling of trees for volume calculations.

The problem of microsite variability was addressed by compiling the merchantable tree volume for each location and then sorting the sample trees by Girard form class and merchantable height (4-foot bolts). The data indicated that a few outlying sample trees had a form class less than 75 or greater than 90, but over 90 percent of the sample trees had a form class within those bounds. Volume tables were constructed for form classes 75 or less, 80, 85, and 90 or greater. The merchantable heights of the sample trees ranged overall from six to 17 bolts (24.5 to 68.5 feet, including a 0.5-foot stump). Within any given diameter class the range was usually no more than four bolts (16.0 feet) (Table 21). There were a few tree volumes that did not fit the expected increase in volume, within a diameter class, with an increase in merchantable height.

The sample trees for volume calculations were selected to minimize the variance of volume within the diameter classes, rather than to be able to determine volumes for every possible combination, so there were missing combinations of DBH by bolt height. The presample for volume calculations indicated that a sample size of 78 trees should have permitted the prediction of the mean volume, overall, or for any diameter class, with a positive or negative deviation of less than five percent at the 99 percent level of significance. The sample size was doubled to increase that predictive strength. The number of trees used to determine the percent error of merchantable volume was less than the sample size (n=150, n'=146) be-

TABLE 21

Merchantable volume tables, by form class, by merchantable height in four-foot bolts.

FORM CLASS 75 OR LESS

DBH	bolts											avg. vol.(#)
	6	7	8	9	10	11	12	13	14	15	16	
in.						cu. ft.*						
5	2.4	2.4										2.4 (6)
6		2.8	3.5	3.8								3.4 (3)
7			5.8	-	6.0	-	8.1					6.6 (3)
8			6.3	7.5	-	8.1						7.3 (3)
9								10.5				10.5 (1)
10												- (-)
11							13.3	18.3				16.7 (2)
12									23.8	-	24.1	24.0 (2)

Basis = 21 trees

* volume to 2-inch minimum top, d.o.b.

TABLE 21. Continued.

FORM CLASS 80

DBH	bolts									avg. vol.(#)
	7	8	9	10	11	12	13	14	15	
in.					cu. ft.*					
5		2.7	3.1							2.9 (3)
6		3.6	4.6	4.2	6.2					4.4 (8)
7	4.1	5.0	6.0	6.6	8.2					6.1 (8)
8		7.5	7.9	8.6	9.0	8.6				8.6 (8)
9				10.5	11.7					10.9 (3)
10				14.0	-	-	15.0			14.5 (2)
11			12.9	18.1	-	-	-	19.5		16.8 (3)
12						21.2	-	-	25.8	23.5 (2)
13							24.1	24.6		28.8 (3)

Basis = 40 trees

* volume to 2-inch minimum top, d.o.b.

TABLE 21. Continued.

FORM CLASS 85

DBH	bolts												avg. vol.(#)
	6	7	8	9	10	11	12	13	14	15	16	17	
in.	---------------------cu. ft.*---------------------------												
5	2.2			2.6									2.4 (2)
6				3.4			5.8						4.6 (2)
7			5.2	6.8	-	7.2	7.2	8.7					7.2 (8)
8				7.9	9.4	10.4	8.8	10.5					10.7 (8)
9					10.6	-	-	13.5					11.8 (5)
10			11.0	-	17.3	13.6	-	15.9	15.3				14.8 (6)
11							21.2	19.6	18.4	23.0	-	26.1	21.6 (5)
12							19.4	-	24.3				22.6 (3)
13							24.2	-	28.4				26.6 (2)
14									33.0				33.0 (1)
15													- (-)
16								38.6	35.6				37.1 (2)
17													- (-)
18								48.1					48.1 (1)

Basis = 45 trees

* volume to 2-inch minimum top, d.o.b.

TABLE 21. Continued.

FORM CLASS 90

DBH	bolts									avg. vol.(#)
	9	10	11	12	13	14	15	16	17	
in.					cu. ft.*					
5	3.6									3.6 (1)
6										- (-)
7			6.7	6.1						6.6 (4)
8			9.2	10.1	9.7					9.7 (8)
9		10.1	-	-	13.7	14.6	15.3	15.8		13.9 (7)
10			17.9	-	16.7	18.1	18.0	19.6		17.6 (10)
11					19.4	21.9	-	-	23.5	21.0 (4)
12					24.0	25.8	-	25.8		25.2 (3)
13							33.9	33.3		33.5 (3)
14					35.2	-	32.4			33.0 (3)
15										- (-)
16							41.2			41.2 (1)

Basis = 44 trees

* volume to 2-inch minimum top, d.o.b.

cause, for each location, diameter classes represented by single trees had no variance component to be used for the weighted stratified variance (Cochran 1977). For each location, the percent error varied slightly from the desired five percent level, but on an overall basis, the deviation was ±3.2 percent at the 99 percent level of confidence and ±2.4 percent at the 95 percent level of confidence (Table 22). Those deviations were calculated from 150 sample trees, with no separation by form class or height, which would have certainly reduced further the percent error of merchantable volume prediction.

TABLE 22

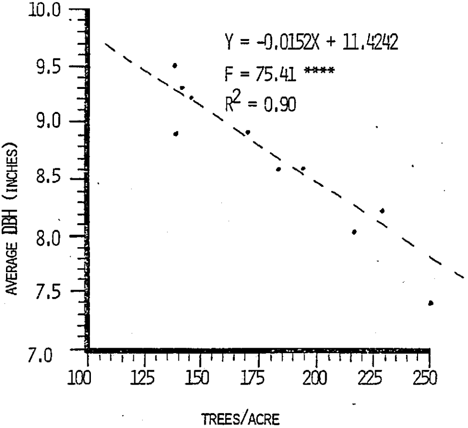
Comparison of percent error of merchantable volume.

location	n'	mean volume	level of confidence	volume error	volume error
		cu. ft.	percent	cu. ft.	percent
Newton Co.	48	14.8	95	0.58	3.9
			99	0.78	5.2
Angelina Co.	49	19.0	95	0.68	3.6
			99	0.81	4.3
Polk Co.	49	8.2	95	0.44	5.4
			99	0.59	7.2
overall	146	14.9	95	0.36	2.4
			99	0.48	3.2

Yield Table Development

Empirical yield was calculated for each of the 15 study units by using a FORTRAN computer program which used the output local volume table per location described earlier and the diameter class frequencies derived from variable-plot sampling on each study unit (Hunt et al. 1970). The yield tables were separated into two groups: (1) those for the thinned study units at the Newton and Angelina County locations; and (2) those for the unthinned study units at the Polk County location. It was recognized that, in particular, the thinned study units resulted in highly empirical estimates for which comparisons could be made only with the caveat that the average dbh, number of stems, and basal area per acre were largely the result of undeterminable and variable past thinning practices. Even so, the classic inverse relationship of the number of stems per acre and average dbh was very strong (Table 9) (Figure 5). Study units with greater numbers of stems per acre had trees with smaller diameters at breast height. Stand density ranged from 140 to 250 stems per acre (345 to 620 stems per hectare). The average cubic wood volume ranged from 1770 to 2400 cubic feet per acre (130 to 175 cubic meters per hectare). The average merchantable volume per acre for all but one pair of study units were within one standard deviation each, of each other (Table 23). The empirical yield estimates for the thinned plantations are presented in Appendix A.

The five study units at the Polk County location had much less variation of stand characteristics. They had the same classic, inverse relationship of the number of stems per acre and the average dbh (Figure 6).



**** SIGNIFICANT AT THE ALPHA = 0.001 CONFIDENCE LEVEL

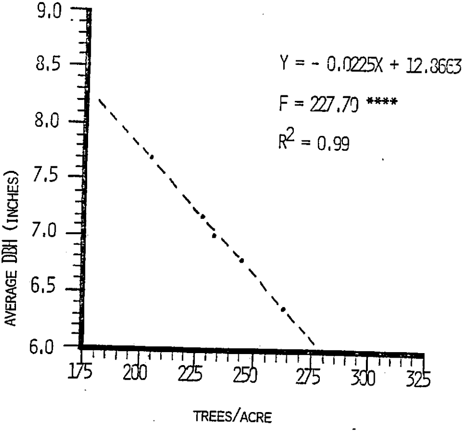
Figure 5: Relationship of the number of stems per acre to average DBH for ten thinned study units.

TABLE 23

Comparison of Site index, basal area, average volume per tree and yield for ten thinned study units.

County location	study unit	site index	trees/ acre	basal area	avg. DBH	avg. vol.	avg. vol./ acre
		25 yr	no.	sq. ft.	in.	---cu.	ft.---
Angelina	3	68	140	69	9.5	14.5	2040
Newton	2	69	142	62	8.9	12.4	1770
Angelina	2	73	143	68	9.3	14.0	2000
Newton	1	75	147	68	9.2	13.2	1930
Angelina	5	60	171	75	8.9	12.7	2180
Newton	3	62	182	74	8.6	11.5	2100
Angelina	1	69	190	77	8.6	11.7	2220
Angelina	4	60	215	77	8.1	10.2	2190
Newton	5	60	226	84	8.3	10.7	2420
Newton	4	61	250	74	7.4	8.6	2140

Stand density ranged from 230 to 290 stems per acre (570 to 720 stems per hectare). The cubic volume for all five study units was about 2000 cubic feet per acre (145 cubic meters per hectare) (Table 24). The empirical yield estimates are presented in Appendix A.



**** SIGNIFICANT AT THE ALPHA = 0.001 CONFIDENCE LEVEL

Figure 6: Relationship of the number of stems per acre to average DBH for five unthinned study units.

TABLE 24

Comparison of site index, basal area, volume, and yield of five unthinned study units, Polk County location.

study unit	site index	trees/ acre	basal area	avg. DBH	avg. vol.	avg. vol./ acre
	25 yr.	no.	sq. ft.	in.	---cu.	ft.---
3	50	231	77	7.7	9.0	2150
4	61	252	72	7.2	8.2	2050
2	52	256	68	7.0	7.7	1970
5	50	270	69	6.8	7.5	2030
1	53	288	66	6.4	6.8	1970

SUMMARY AND CONCLUSIONS

The soil-site factor which had the greatest effect on total height was the depth to the least permeable horizon. For the range of values present on the entire study area, an increase if one foot (30 cm) in the depth to the least permeable horizon of a soil profile, corresponded to a decrease of 1.1 feet (34 cm) in total height of twenty-five year-old loblolly pine planted on deep, sandy soils.

The percentage of organic matter in the 0-6 inch (0-15 cm) soil level had a stronger, positive relationship with total height. Although that relationship was numerically stronger, it was not as statistically significant as the relationship of the depth to the least permeable horizon to total height. Results from this study showed that total height was 2.5 feet (80 cm) greater for each one percent increase in organic matter. That relationship, along with several other weaker relationships, had a statistical relationship to total height that was likely not entirely causal. Forest stands which grew on areas which had soil-site relations that were both quantifiably and unquantifiably better or worse than average would produce accordingly more or less biomass which would be later transformed into soil organic matter. Thus arose the presently unresolvable dilemma of cause or effect. The numerous potential interrelationships among both the measured and undetermined soil-site factors demanded, with respect to the range of soil-site conditions within the study area, that the data be examined further in a more discrete manner.

Further analysis of the data for each of the three locations revealed that for each location a different combination of soil-site factors had significant effects on total height at age 25 years. The variable effects of the soil-site factors appeared to be related to differences in the ranges of values per location for the significant factors.

The percentage slope and the depth to the least permeable horizon had significant effects on total height at the Newton County location. The relationship of slope to height indicated, while there were also underlying correlations between slope and soil texture and organic matter, that sample trees on steeper slopes were significantly shorter than sample trees on more level terrain. The depth to the least permeable horizon had a negative effect on total height. This relationship indicated, for the range of values within this location, that the greater the depth to which soil water might infiltrate freely, the greater would be the difficulties a tree would have obtaining soil water for transpiration.

The depth to the least permeable horizon also had a negative correlation with total height at the Angelina County location, but was not statistically significant. Earlier studies on this particular soil-site relationship (Carmean 1970, Zahner 1954,1957) found that height growth increased as the depth to the least permeable horizon decreased, until the proximity of an impermeable B horizon began to limit the moisture storage capacity of the profile. That depth was reported as being between one and three feet (0.3 to 0.9 m). It would appear, at this location where the average depth was 2.6 feet (0.8 m) that localized shallowness of the deep, sandy soils can limit height growth. The two significant soil-site factors at this location were slope and the covariate of slope by the percentage of sand in the 0-6 inch (0-15 cm) soil level. The negative relationships of both of these variables indicated that trees growing on steeper slopes, particularly those on sandier-textured soils, were significantly shorter than trees growing on more level sites with a greater proportion of finer-textured soil particles.

The Polk County location had the highest average values of the three locations for the depth to the least permeable horizon and percentages of sand in the two soil levels. The variation of most soil-site factors was greater at this location. Those two facts, coupled with the shorter average total height and a greater coefficient of variation for height hindered the development of an equivalently efficient and significant model of the effects of the soil-site factors on total height. Of the twelve screened soil-site variables, only the depth to the least permeable horizon had statistical significance at a minimal level of confidence of 80 percent. The statistical significance of that variable in the height prediction model was not as great as its significance in the overall model or the models for the other two locations, but its simple correlation to height was about twice as great as its correlation at the other locations.

The results indicated, by location and collectively, that total height of twenty-five year-old loblolly pine planted in East Texas on coarse-textured soils with sandy epipedons greater than two feet (0.6 m) is limited most by the depth to the least permeable horizon. Other factors, including slope, organic matter, and sand content, influenced total height primarily on sites with relatively extreme values for those factors.

The same factors which influenced height growth also affected tree and stand cubic-foot wood volumes. Within a given diameter class, cubic-foot wood volume is the result of two characteristics: height, either total or merchantable; and stem taper. It has long been established that trees growing on poorer sites will reach their maximum annual increment of diameter or height at an older age than trees growing on better sites. The sample trees at the Polk County location had an average total height of 45 feet (13.8 m), whereas at the other two locations the average height was 58 feet (17.8 m). Thus it was that the trees at the Polk County location had grown more slowly and had a more uniform stem taper. The trees of the 5-, 6-, and 7-inch diameter classes that were predominant at that location had substantially greater volumes than trees of those sizes at the other locations. However, at the other locations, the planting spacing, present spacing, average dbh, and average height were much greater, so the average cubic-foot volume per tree was also greater.

The local volumes tables were developed by fitting the calculated volumes of the 50 subsample trees per location to a regression equation which used dbh as the independent variable to predict outside-bark, merchantable cubic-foot volume. The equations for the Newton and Angelina County locations predicted volume very well; the coefficients of determination were both over 0.90. However, the equation for the Polk County location performed rather poorly. For that location, the coefficient of determination was only 0.16. Although the coeffifcient of determination is a measure of the fraction of the total sums of squares attributable to the model sums of squares, many large (on a percentage basis), negative deviations in the volumes of small trees may be offset by small (on a percentage basis), positive deviations in the volumes of large trees (USDA, For. Serv. 1929). Even so, the relatively poor performance of the equation for the Polk County location was related probably to the much greater (and often unquantified) microsite variation.

More refined volume tables were developed from the 150 subsample trees by sorting the trees by Girard form class, diameter class, and merchantable height in four-foot bolts. These tables have a broader range of applicability than the local volume tables. Within a given diameter class, a tree with a higher form class should have a greater cubic-foot volume. There were some irregularities in that relationship in the smaller diameter classes (less than 8 inches dbh), but there were marked increases in cubic-foot volume with increases in form class of the larger trees.

Empirical yield tables were constructed using the local volume table for each location and the variable-plot sampling data from each study unit. The classic inverse relationship between stand density and average dbh was true for both the thinned and unthinned study units.

The yield estimates were not calculated for statistical comparisons with other yield tables; the differences in past forest in past forest management practices; but rather for the establishment of a data base for future studies of the growth and yield of loblolly pine planted on these and other similar sites. Since these plantations were established, a much broader array of management practices has come into widespread use. There is often intensive site preparation and debris burning prior to planting. Planting densities are much lower today. Young plantations adjacent to some of the study units have as few as 725 trees per acre (1800 trees per hectare). Both of the objectives of this study needed to be fulfilled so that in the future the effects of intensive forest management can be monitored and practices modified, if necessary to accomodate the different soil-site relations of loblolly pine planted on the deep, sandy soils of East Texas. Technological advances cannot remedy all social problems. New findings in technology and science, however, can ease the difficulties associated with increasing production with decreasing capital. Forest management has recognized the diminishing land base available for resource management and has begun to find answers to the problem. The problem is not restricted to the United States, indeed it is greater elsewhere in the world, and is of such a magnitude, that simple solutions are not possible. The only way the problem may be resolved is by incremental and seemingly infintesimal contributions to man's ability to efficiently utilize the available resources.

The intent of this study was to provide such a contribution. Urbanization is making daily incursions on the acreage available for timber management. The calculated response of timber growers is to seek to maximize production on the available land base. That land base tends to be increasingly comprised of land, such as the sandhills of East Texas, that is not well-suited to uses other than forestry.

The utilizable wood and fiber production of a site can approach the potential productivity of biomass if the soil-site relations, silvics of a tree, and the silviculture of the forest are clearly understood. The silvics and silviculture of loblolly pine are understood more fully than the soil-site relations of the species. The increase in utilizable wood volume production per unit effort should be greater if, as the weakest member of the triad, the knowledge of soil-site relations were improved instead of one of the other two members. The number and variation of soil-site factors is very large, so the number and range of factors was necessarily limited in this study. Soil-site factors were selected for their theoretical and previously-found significance, and ability to be quantifiably measured, and interpretive value.

Mensurational characteristics of loblolly pine plantations growing on deep, sandy soils were examined, in addition to the soil-site relations, to provide a more complete treatise describing the physical manifestations of the biological conditions peculiar to these areas. The volume tables that were developed from trees growing on those sites have a broad range of applicabilty. The merchantable volume of any loblolly pine within the ranges of diameter, height, and stem taper should be accurately predicted by the volume tables, even if the tree has grown on a dissimilar site or is not twenty-five years old. The empirical yield estimates are quite specific to those sites and the forest management practices found therein. They cannot as such be compared directly to yield estimates from plantations with other conditions, but may serve as indicators of potential cubic-foot wood volume production for similar sites.

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APPENDIX A

YIELD FOR THINNED PLANTATIONS.

Table A-1. Empirical yield for thinned plantations.

Weirgate, Newton County, Texas

study unit 1

Site Index, age 25: 75 , age 50: 116

dbh in.	trees/acre no.	basal area sq. ft.	cubic-foot volume for O.B. top of 2 inches
5	30	4.1	132
6	19	3.7	98
7	15	4.0	128
8	15	5.2	159
9	9	4.0	126
10	16	8.7	252
11	13	8.6	251
12	15	11.8	345
13	6	5.5	157
14	4	4.3	125
15	3	3.7	94
16	1	1.4	31
17	0	0.0	0
18	1	1.8	31
	147	66.8	1929

Arith. mean dbh = 8.6 inches
Quadratic mean dbh = 9.1 inches

Table A-1. Continued.

Weirgate, Newton County, Texas

study unit 2

Site Index, age 25: 69, age 50: 108

dbh in.	trees/acre no.	basal area sq. ft.	cubic-foot volume for O.B. top of 2 inches
5	15	2.0	63
6	23	4.5	124
7	11	2.9	91
8	30	10.5	302
9	19	8.4	240
10	17	9.3	269
11	11	7.3	209
12	7	5.5	149
13	5	4.6	119
14	4	4.3	118
15	0	0.0	0
16	1	1.4	30
17	1	1.6	30
18	1	1.8	30
	145	64.1	1774

Arith. mean dbh = 8.6 inches
Quadratic mean dbh = 9.0 inches

Table A-1. Continued.

Mayflower, Newton County, Texas

study unit 3

Site Index, age 25: 62, age 50: 95

dbh in.	trees/acre no.	basal area sq. ft.	cubic-foot volume for O.B. top of 2 inches
5	38	5.2	157
6	15	2.9	92
7	28	7.5	213
8	30	10.5	301
9	19	8.4	240
10	14	7.6	209
11	11	7.3	208
12	12	9.4	267
13	8	7.4	208
14	5	5.3	148
15	2	3.2	59
	182	74.7	2102

Arith. mean dbh = 8.2 inches
Quadratic mean dbh = 8.7 inches

Table A-1. Continued.

Mayflower, Newton County, Texas

study unit 4

Site Index, age 25: 61, age 50: 95

dbh in.	trees/acre no.	basal area sq. ft.	cubic-foot volume for O.B. top of 2 inches
5	33	4.5	133
6	44	8.6	260
7	71	19.0	546
8	64	22.3	637
9	15	6.6	190
10	17	9.3	252
11	5	3.3	94
12	1	0.8	31
	250	74.4	2143

Arith. mean dbh = 7.2 inches
Quadratic mean dbh = 7.4 inches

Table A-1. Continued.

Mayflower, Newton County, Texas

study unit 5

Site Index, age 25: 60, age 50: 93

dbh in.	trees/acre no.	basal area sq. ft.	cubic-foot volume for O.B. top of 2 inches
5	18	2.4	71
6	44	8.6	274
7	42	11.2	340
8	44	15.4	438
9	32	14.1	402
10	21	11.4	334
11	11	7.2	200
12	9	7.1	199
13	4	3.7	99
14	2	2.1	66
	227	83.5	2423

Arith. mean dbh = 8.0 inches
Quadratic mean dbh = 8.2 inches

Table A-1. Continued.

Zavalla, Angelina County, Texas

study unit 1

Site Index, age 25: 69, age 50: 108

dbh in.	trees/acre no.	basal area sq. ft.	cubic-foot volume for O.B. top of 2 inches
5	42	5.7	113
6	11	2.2	53
7	23	6.1	173
8	15	5.2	150
9	38	16.8	493
10	25	13.6	408
11	21	13.8	414
12	12	9.4	290
13	5	4.6	130
	192	77.4	2224

Arith. mean dbh = 8.1 inches
Quadratic mean dbh = 8.6 inches

Table A-1. Continued.

Zavalla, Angelina County, Texas

study unit 2

Site Index, age 25: 73, age 50: 112

dbh in.	trees/acre no.	basal area sq. ft.	cubic-foot volume for O.B. top of 2 inches
5	0	0.0	0
6	26	5.1	137
7	14	3.7	110
8	15	5.2	152
9	33	14.6	430
10	21	11.4	359
11	14	14.6	283
12	12	9.4	286
13	6	5.5	165
14	1	1.1	42
15	1	1.2	42
	143	71.8	2006

Arith. mean dbh = 9.0 inches
Quadratic mean dbh = 9.6 inches

Table A-1. Continued.

Zavalla, Angelina County, Texas

study unit 3

Site Index, age 25: 68, age 50: 105

dbh in.	trees/acre no.	basal area sq. ft.	cubic-foot volume for O.B. top of 2 inches
5	15	2.0	51
6	11	2.2	57
7	15	4.0	123
8	12	4.2	127
9	30	13.2	391
10	18	9.8	299
11	10	6.6	202
12	17	13.4	408
13	6	5.5	171
14	2	2.1	69
15	3	3.7	104
16	1	1.4	35
	140	68.1	2037

Arith. mean dbh = 9.1 inches
Quadratic mean dbh = 9.4 inches

Table A-1. Continued.

Zavalla, Angelina County, Texas

study unit 4

Site Index, age 25: 60, age 50: 93

dbh in.	trees/acre no.	basal area sq. ft.	cubic-foot volume for O.B. top of 2 inches
5	22	3.0	73
6	25	4.9	136
7	60	16.0	463
8	47	16.4	481
9	32	14.1	432
10	12	6.5	188
11	6	4.0	127
12	5	3.9	129
13	2	1.8	65
14	3	3.2	98
	214	73.8	2192

Arith. mean dbh = 7.7 inches
Quadratic mean dbh = 8.0 inches

Table A-1. Continued.

Zavalla, Angelina County, Texas

study unit 5

Site Index, age 25: 60, age 50: 93

dbh in.	trees/acre no.	basal area sq. ft.	cubic-foot volume for O.B. top of 2 inches
5	17	2.3	63
6	12	2.4	70
7	29	7.7	219
8	34	11.9	342
9	37	16.3	467
10	14	7.6	239
11	8	5.3	162
12	8	6.3	204
13	4	3.7	123
14	3	3.2	83
15	3	3.7	125
16	2	2.8	84
	171	73.2	2181

Arith. mean dbh = 8.5 inches
Quadratic mean dbh = 8.8 inches

APPENDIX B

YIELD FOR UNTHINNED PLANTATIONS.

Table B-1. Empirical yield for unthinned plantations.

Camden, Polk County, Texas

study unit 1

Site Index, age 25: 53, age 50: 81

dbh in.	trees/acre no.	basal area sq. ft.	cubic-foot volume for O.B. top of 2 inches
5	113	15.4	541
6	56	11.0	346
7	70	18.7	547
8	32	11.2	307
9	7	3.1	88
10	8	4.4	115
11	0	0.0	0
12	1	0.8	28
	287	64.6	1972

Arith. mean dbh = 6.3 inches
Quadratic mean dbh = 6.4 inches

Table B-1. Continued.

Camden, Polk County, Texas

study unit 2

Site index, age 25: 52, age 50: 80

dbh in.	trees/acre no.	basal area sq. ft.	cubic-foot volume for O.B. top of 2 inches
5	62	8.4	305
6	57	11.2	348
7	63	16.8	485
8	47	16.4	458
9	12	5.3	147
10	8	4.4	115
11	5	3.3	84
12	0	0.0	0
13	0	0.0	0
14	1	1.1	27
	255	66.9	1969

Arith. mean dbh = 6.8 inches
Quadratic mean dbh = 6.9 inches

Table B-1. Continued.

Camden, Polk County, Texas

study unit 3

Site Index, age 25: 50, age 50: 72

dbh in.	trees/acre no.	basal area sq. ft.	cubic-foot volume for O.B. top of 2-inches
5	56	7.6	284
6	37	7.3	230
7	36	9.6	276
8	34	11.9	320
9	39	17.2	448
10	19	10.4	272
11	13	8.6	214
12	3	2.4	53
13	1	0.9	26
14	0	0.0	0
15	1	1.2	26
	239	77.1	2149

Arith. mean dbh = 7.4 inches
Quadratic mean dbh = 7.7 inches

Table B-1. Continued.

Camden, Polk County, Texas

study unit 4

Site Index, age 25: 61, age 50: 95

dbh in.	trees/acre no.	basal area sq. ft.	cubic-foot volume for O.B. top of 2 inches
5	33	4.5	162
6	74	14.5	444
7	56	15.0	442
8	46	16.0	452
9	31	13.7	374
10	8	4.4	120
11	3	2.0	59
	251	70.1	2053

Arith. mean dbh = 7.0 inches
Quadratic mean dbh = 7.2 inches

Table B-1. Continued.

Camden, Polk County, Texas

study unit 5

Site Index, age 25: 50, age 50: 72

dbh in.	trees/acre no.	basal area sq. ft.	cubic-foot volume for O.B. top of 2 inches
5	70	9.5	359
6	88	17.3	540
7	33	8.8	268
8	41	14.3	403
9	33	14.6	389
10	3	1.6	35
11	2	1.3	34
	270	67.4	2028

Arith. mean dbh = 6.6 inches
Quadratic mean dbh = 6.8 inches

VITA

Richard Orville Hessler, Jr. was born in Huntsville, Alabama on 23 March 1959. He is the eldest of four children born to Richard and Virginia Hessler. He graduated as the valedictorian of Buckhorn High School, New Market, Alabama in May 1976. Later that year, he entered the University of Tennessee, and began working as an undergraduate research assistant in the Department of Forestry. He found seasonal employment through his undergraduate years with the U.S. Forest Service in California, Hiwassee Land Company in Tennessee, and Resource Management Service, Inc. in Alabama. The degree of Bachelor of Science in Forestry was conferred upon him by the University of Tennessee in December 1980. Since that date, he worked as a research assistant at the Forest Science Laboratory at Texas A&M University. Currently he is a candidate for the degree of Master of Science in Forestry at that university. His permanent address is 240 Nance Mtn. Rd., Gurley, Alabama 35748.

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