ENVIRONMENTAL PARAMETERS AND SITE IDENTIFICATION FOR POTENTIAL EXPANSION OF THE PINE FORESTS OF EASTERN OKLAHOMA

By

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TABLE OF CONTENTS

Chapter | Page

LIST OF TABLES

Table		Page

LIST OF FIGURES

Figure | Page

CHAPTER I

INTRODUCTION

Utilization of timber from the Nation's forests is projected to increase from 13.3 billion cubic feet in 1976 to 28.3 billion cubic feet by 2030, an increase of 113 percent (USDA Forest Service, 1982). Most of the projected expansion in demand is for softwoods. In 1976, the South supplied about 40 percent of all softwood roundwood. Dependence on the South as a source of softwood roundwood supplies is projected to increase, reaching half the Nation's total supply by 2000 (USDA Forest Service, 1982).

In order to meet the growing pressures on the South's timber supplies, foresters must increase productivity by efficiently utilizing existing timber stands and searching for alternative sources. One possible solution is the expansion of the commercial forest land base. This would involve the conversion of marginal land sites or tension zone sites, specifically low quality hardwood types, to a more valuable species. Since the natural vegetation has little commercial value, forest type conversion would be a primary way to improve the productivity of these areas and increase timber supplies.

Loblolly pine (Pinus taeda L.) is the keystone of the southern pine forest products industry. Nearly half of the total southern pine inventory in the United States is loblolly. According to Wahlenberg (1960) loblolly pine is the leading forest tree species to be managed for successive timber crops in the South for four principal reasons: (1) effective natural or easy artificial regeneration on extensive areas, (2) rapid growth on a wide range of sites, (3) ease of handling products in forest and mill, and (4) steady demand and rising prices for a variety of commodities made from its wood. These factors have contributed to increased interest concerning the potential expansion of the loblolly pine range, especially in Oklahoma.

The number of loblolly plantings in Oklahoma is increasing, while interest in the state's other native southern pine, shortleaf pine (*Pinus echinata* Mill.), is declining. In southeastern Oklahoma, many landowners are realizing the investment potential of pine production and are converting hardwood stands and shortleaf pine stands to loblolly pine due to its more rapid growth. In addition, private forest industry is establishing short rotation loblolly pine plantations father north of its native range (Lambeth et al., 1984). Loblolly plantations are also beginning to appear on low quality hardwood sites in central Oklahoma, namely within the "Cross Timbers" area. According to Lantz (1977) 6.2 million acres of the "Cross Timbers" type may have a commercial timber growing potential for short rotation loblolly plantations. There is a need to gain a better understanding of the ecology of native pine forests in eastern Oklahoma in order to evaluate benefits from their potential expansion.

The present investigation has been designed to study the growth potential of loblolly pine north and west of its natural range in Oklahoma based on information from the current shortleaf pine range in the state, while pursuing the following specific objectives: (1) determine, by examination of historical records, the status of the shortleaf pine range in Oklahoma, (2) ascertain, by physical measurement, factors which have contributed to the development of the current range of shortleaf pine in Oklahoma, including isolated shortleaf pine islands, and (3) make a preliminary assessment of the potential growth of both loblolly and shortleaf pines outside of their respective ranges.

CHAPTER II

LITERATURE REVIEW

Plant - Environmental Relationships

The distribution and growth of a plant species is governed, to a large degree, by the environment. In order to understand the distribution and growth potential of a plant species, one must first look at its environment. The environment of a plant may be defined as the sum of all external forces and substances affecting the growth, structure, and reproduction of the plant (Billings, 1952). The environment provides the plant with its heat, light, water, elements, and compounds. If these are available in sufficient amounts and at the right time to satisfy the growth and reproduction requirements of any of the ecotypes or biotypes of a species, that species can grow there provided its seeds and propagules can get there (Billings, 1952).

It has long been recognized that the plant-environment system is a dynamic unit and reacts as a whole. This principle has been termed that of the holocoenotic environment (Allee and Park, 1939). Billings (1938) emphasized that successional changes in vegetation cannot be interpreted in terms of one factor, but only by considering the environmental complex as a whole. Any study of plant growth and distribution in relation to the environment must consider each factor in relation to the others of the complex (Billings, 1952). This does not mean that all factors are necessarily equal in importance, but that thay are interactive. Certain factors in any ecosystem are of overriding importance, such as moisture in a desert. Billings (1952) terms these important factors "trigger factors".

Action of the environment on the plant or plant community is not uniform or consistent. According to Billings (1952) factors in the environmental complex can be limiting and these limiting factors may be different in different parts of a species range. Liebig's Law of Minimum (Chapman, 1931, p. 107) states: "When a multiplicity of factors is present and only one is near the limits of toleration, this one factor will be the controlling one." Taylor (1934, p. 378) restated this "law" in the following fashion: "The growth and functioning of an organism is dependent upon the amount of the essential environmental factors presented to it in minimal quantity during the most critical year or years of a climatic cycle." Plant growth and distribution are limited when any factor in the environment falls below the minimum required by that particular species. Actually, a plant may be limited not only when a factor goes below the minimum but when it goes over the maximum tolerance by the plant for that factor. In any case, a single factor can often limit the growth, reproduction, or distribution of a single plant species (Billings, 1952).

Normal growth and reproduction of a plant is genetically adapted to the changes of the environment usually encountered by the plant during its life from germination to fruiting and seed dispersal. Some degree of aberrancy in the environmental cycles and totals is to be expected. A species of wide tolerance range can survive these either in space or time (Billings, 1952). Weese (1926) suggested that studies should take into account not only averages but critical years, which have a very great influence in delimiting the distribution of species at or near the borders of their range. There are limits, however, beyond which even widely distributed species cannot go. According to Billings (1952) these occur principally near the limits of distribution, and if they occur often enough they will keep the species from spreading farther. Good's (1931) Theory of Tolerance states that a plant species is able to exist and reproduce successfully only within a definite range of climatic and edaphic conditions, such a range representing the tolerance of the species to these external conditions.

Billings (1952) points out that one of the most interesting plant-environment relations that has been noted is the apparent compensation of one environmental factor for another. This usually occurs near the boundaries of a species' range and allows the individuals of the species to grow in what at first glance does not appear to be a normal habitat. An amount of a factor normally considered limiting for a species can be reduced even farther when compensated for by another factor. The substitution of elevation for latitude, allowing plants of northern distribution to grow far southward on high mountain ranges, is an example of compensation. According to Billings (1952, p. 260) the most significant types of compensation, from the standpoint of disjunct plant distributions, are those in which parent material apparently compensates for climate. "Such compensations are more striking and seemingly more common where certain climatic factors, particularly precipitation and temperature, are low, as for example in cold desert regions."

Mason (1946) states that environment occupies area independently of whether or not a species can grow in that particular environment or be restricted to it. Some species occupy all of the environment which is suited to their ecological tolerances. Other species, because of lack of sufficient time or because of barriers to the ready migration of their seeds or propagules, have not yet occupied all of the environments open to them. Of course, since environments are dynamic and continually changing, some species find their environmental areas getting smaller before they can be filled, while environments open to other species may be expanding. Sears and Couch (1932) on the examination of pollen microfossils in a peat bog in central Arkansas, concluded that an increase in southern pine fossil flora in the top layers and the enrichment of upland vegetation in Arkansas and eastern Oklahoma was the result of an increase in humidity. According to Sears and Couch (1932) Thornthwaite, in studies of climates and soil types in Oklahoma, had observed that present climatic boundaries did not correspond with the appropriate soil limits, but lay west of them. Sears and Couch (1932, p. 67) stated: "this too is quite consistent with our evidence of a recent increase in humidity, for the effect of climate on soil requires time to register." An increase in the loblolly pine range was noted by Wahlenberg (1960) for the region west of the Mississippi River, but this was due mainly to change in land use patterns.

Plant - Climate Relationships

One aspect of the environmental complex that has received considerable attention as it relates to vegetation growth and distribution is climate. According to Jackson (1962) study of the complex of climate, as expressed by conventional meteorological data, has as its primary objective the isolation of those factors, either individually or integrated in the form of an index, which are meaningfully correlated with growth and yield of the species concerned. Verney (as cited by Jackson 1962) states that

> . . . the simplest method consists in proving the existence of a positive correlation between the presence of a plant and a particular environmental factor. . . With particular reference to climate, the obvious line is to study the correlation between the area of distribution of a species and a climatic factor, simple (annual or monthly isotherm, number of days of frost, isohyet) or more complex (e.g. climatic index) (p. 4).

Jackson (1962) explains that Livingston and Shreve outlined their application of the technique as follows:

> The maximum and minimum values of each climatic condition have been determined for each vegetational area or for the distributional area of each species. . . Comparisons have been made between the positions of isoclimatic lines and the lines drawn to show the limits of botanical areas, for the purpose of discovering close correspondence. . . The parallelism that exists between the distribution of many of the closely related climatic conditions makes it difficult in some cases to determine which of the several aspects of a given condition is of the greatest importance in controlling a particular plant or vegetation (p. 4).

According to Jackson (1962) the significance of the last sentence has been all too frequently overlooked. Jackson (1962, p. 4) states that "although cogent arguments could be advanced that no element of climate is unimportant to plant growth, yet, determination of the most important factors contains the crux of the homoclime problem.

One of the earliest attempts at classifying climates in relation to vegetation was by Koppen (1884). Koppen's primary breakdown was by mean temperature of the coldest month and of the hottest months. Secondary breakdown was in terms of season and amount of precipitation. Thornthwaite and Hare (1955) stated that in spite of the wide currency it achieved, the Koppen system was always unsatisfactory, and is quite futile as a method for classifying forest climates. According to Thornthwaite and Hare (1955):

> Koppen's use of simple temperature and precipitation values to define boundaries entirely misses the point. . . The fact that a particular isopleth of mean air temperature happens to follow a soil or vegetation boundary is to a large extent fortuitous. . . Any effective system must endeavor to answer the questions, "What are the real, active processes of climatic control? And how can suitable parameters for these processes be devised? (p. 52).

Swain (1938) devised an independent classification of climate for forestry purposes. The main objectives of the system were to compare forest environments, and to determine homoclimes for exotic introductions. Being designed essentially for Australian conditions, the initial breakdown was into eight zones differentiated by duration and season of drought, which Swain defined as mean monthly rainfall below 2.00 inches. These zones were then further subdivided in terms of mean temperature of the coldest months (five sub-zones), of mean temperature of the hottest months (nine sub-zones) and annual rainfall. According to Jackson (1962) a strong criticism which can be levelled at Swain's classification is that its class-limits are very arbitrary and, more important, little account is directly taken of precipitation-effectiveness and the consequence of evaporation.

Thornthwaite (1948) in his classification, used "effectiveness of precipitation" as the primary basis of subdivision, the line of demarcation between wet and dry climates being represented by the point where precipitation exactly equals potential evapotranspiration. Potential evapotranspiration (PE) may be defined as the amount of evapotranspiration (evaporation of moisture from the soil and water transpired through the leaves of plants) that could occur if the soil of a large area having "vegetation" typical of the surroundings were kept constantly wet, that is, at or above field capacity (Rosenzweig, 1968). According to Thornthwaite (1948) PE becomes an index integrating the basic climatic factors of solar radiation as well as the dependent factor of air temperature. In terms of an annual moisture index, calculated from ratios of precipitation minus PE to PE, Thornthwaite (1948) derived nine climatic moisture types, ranging from perhumid to arid. Each of these was subdivided further into five sub-types, depending on the season and intensity of moisture deficits or surpluses contrary to the primary type. On the grounds that PE integrates both day length and mean monthly temperature, Thornthwaite used it also as an index of thermal efficiency. Adopting the equatorial PE value of 44.88 inches as a "reasonable boundary" between megathermal and mesothermal climates, other boundaries were computed as a series in descending geometric progression (Thornthwaite, 1948).

Thornthwaite's classification has been criticized by Verney (1958) who states, according to Jackson (1962, p. 7): "temperature is treated as subordinate to day length, with no attention paid to temperature extremes as effective climatic factors." According to Jackson (1962) this criticism is valid and that any system of classification involving such a plethora of factors about whose biological interactions so little is known creates a real dilemma concerning the conflicting needs for precision and manageability of the system. Jackson (1962) states that

> . . . a comparison of Swain's (1938) or Prescott's (1952) classifications with that of Thornthwaite's (1948) will show that as the number of classifying indices is increased, the system becomes more unweildy in application. Conversely, as the number of factors is reduced by more or less arbitrary rejection of the "less important" or by integration into some composite "index", the more necessary it becomes to test the validity of the rejections or basic assumptions by practical application (p. 8).

Jackson (1962) concludes that there are at least two fundamental objections to much previous work in the field of climatic classification in relation to vegetation: (1) the selection of factors for classification has been generally too arbitrary, and in many cases has been unrelated to performance of the species under consideration, and (2) the preoccupation with limits of natural distribution of a species, as a criterion, has led to confusion between the factors limiting natural range and those controlling growth. Jackson (1962) states, however, that the work of Daubenmire (1956), Hocker (1958), and Bethune (1960) are notable exceptions.

Daubenmire (1956) sought to define six different vegetation belts (ranging from *Artemesia* scrub to *Thuja-Tsuga* forest) of northern Idaho and eastern Washington in terms of the climatic classifications of Koppen, Swain, and Thornthwaite. Thornthwaite's gave the best fit of the three, and Koppen's gave the poorest. Daubenmire (1956) concluded that none of them proved adequate to define what appeared to be climatically determined vegetation regions of eastern Washington and northern Idaho and proceeded to compare these six zones in terms of monthly mean temperature/median monthly precipitation climographs for meteorological stations within each zone. Using these climographs as visual indicators of correlated statistics, Daubenmire (1956) was able to find various indices of drought which exhibited discontinuities coinciding with six of the seven ecotones studied.

Hocker's study (1958), although not concerned with any of the published climatic classifications, is of particular interest because it was the first time that a statistically-sound procedure had been used to segregate out of a wide range of alternatives, climatic indices which best differentiate the region of natural distribution. Hocker (1958) compared, by means of a discriminant function based on regression analysis, the distributional range of loblolly pine with equal area immediately outside its limits. Hocker found that there were real differences between the climate within the loblolly pine range and that outside the natural range of the species.

Bethune (1960) applied the same technique used by Hocker (1958) in relating the natural distribution of slash pine (*Pinus elliottii* Engelm.) to certain climatic factors. The components of climate which Bethune used were the average length of the frost-free period and the seasonal averages of monthly temperature and temperature range, as well as monthly precipitation and frequencies of precipitation equal to or exceeding 0.50 and 0.01 inches. Bethune's analysis demonstrated a correlation (significant at the 1 percent level) with average monthly frequency of summer precipitation equal to or more than 0.50 inches. Also significant (at the 5 percent level) were spring and fall frequencies of corresponding magnitude, although autumn precipitation was dependent upon prior removal of the negatively correlated winter frequency.

Bethune (1960) concluded that analysis of climatic factors by means of the discriminant function will show which factors are associated with the distribution of a species. This information may be useful in indicating where the species might be planted outside its natural range.

Plant - Edaphic Relationships

Soils and their relation to vegetation is another important aspect of the environmental complex. According to Blumenstock (1941) the influence of climate on the growth of plants is a predominant factor affecting their distribution; the relationship between soil formation on the one hand and vegetation and climate on the other is so close that the pattern displayed by soils maps likewise reflects climatic conditions. Both vegetation and soils are considered to be functions of gradients in the environmental factors, climate, parent material, relief, organisms and time. Jenny (1946) theorized that soil is functionally related to six independent soil forming factors by the following equation:

$$S = f(cl, r, pr, o, t, y)$$

Where S = soil properties

cl = the overall climate

r = relief

pr = initial state of soil system i.e. parent material at time zero

o = organic matter or the biotic factor

t = time

y = topographic effects

The five factors may interact with each other but are independent in the sense that one could be varied without changing the others (Jenny, 1946). Jenny and others have noted that vegetation could be expressed in a similar way i.e., the equation V = f(cl, r, p, o, t, y) already defined, with V = vegetation (Jenny, 1946; Crocker, 1952; Major, 1951).

Soils affect the growth of trees principally through soil air, soil moisture, and plant nutrients. Coile (1952) states that the productivity of soil for forest growth is conditioned by the quantity and quality of growing space for tree roots. Soil properties that may be classed under these two categories may have direct effects, both direct and indirect effects (interaction), or only indirect effects, on growth. According to Coile (1952) the soil factors that affect tree growth are:

a. Depth of surface soil (A horizon), depth to least permeable layer, or depth to mottling. These measures of quantity of growing space imply effective root depth for trees (small roots). The relationship of growth to these measurements is generally curvilinear. The net effects of increments of depth are great when depth is low. The effects of increasing depth on growth decrease beyond a certain point.

b. Total depth of soil, and soil material functions as a measure of quantity of growing space in the case of immature or poorly differentiated soil profiles.

c. Physical nature of the subsoil, least permeable layer or substratum as it influences water movement, water availability to root aeration and mechanical hindrance to roots. This factor may be exhibited with either "a" or "b" above with significant effects or interactions with tree growth. Physical properties of the subsoil that may be directly correlated with forest growth include texture, pore space distribution, imbibitional water values (an indirect measurement of the water holding capacity of the subsoil based on the difference between the moisture and xylene equivalents of the soil), water holding capacity, and changes of volume with moisture content (shrinkage and swelling).

d. Physical properties of the surface soil, notably pore space distribution and texture may under certain conditions influence water infiltration and storage which is especially important to tree growth in semi-arid regions or when precipitation is erratic.

e. Organic matter in the form of either incorporated or unincorporated humus influences the moisture regime of soils as well as their structure and porosity to air. It serves as a direct source of energy for soil organisms and as a reservoir of nitrogen and other essential plant nutrients. Excessive amounts of organic matter may reflect poor drainage and may be associated with low productivity.

f. Chemical characteristics involving nutrient supply may be a limiting factor in forest growth on deep, excessively drained silicous sands in humid climates. In such circumstances, the fertility factor is usually confounded with adverse physical soil properties and low water table.

Coile (1952) states that factors other than soil may also affect tree growth, such as:

a. Climate and length of day: These two factors are confounded for tree species that have a wide latitudinal range. The relatively rapid growth of certain species of trees in northern latitudes can be attributed in part to long days during the frostfree period which offsets the short growing season. Climate, expressed as inches of rainfall, number of frost free days per year, or defined indirectly by latitude and longitude, has been found to be correlated with growth of forests independent of soil factors.

b. Aspect and exposure: In regions or areas of marked relief, aspect of land (compass direction that a slope faces), and exposure (susceptibility of land surface to drying winds) greatly affect the local climate, as it is characterized by precipitation and temperature, wind movement (direction and rate), and evaporation. Northerly facing slopes (NW, N, and NE) are cooler and more moist than southerly facing slopes.

c. Topography and water table: The relating of topographic position of land to forest productivity is primarily indirect. Relative topographic position and distance from the soil surface to the water table both influence water supply to the soil and tree roots. This moisture supply, modified by climate and soil properties may range from excessive to insufficient.

d. Surface Geology: The permeability to water of rocks, rock formations, or unconsolidated geologic material may influence land productivity independent of the soil if the latter is shallow. (Coile, 1952).

The relationship between the same set of general soil properties and tree growth in widely separated and different regions suggests that the soil-tree relationships are basic and applicable to forest regions (Paka, 1969). However, Coile (1952) points out that soil properties which may be significantly correlated with forest growth in one region may not be significant in another region because of differences in tree species, climate, length of growing season, length of day, or action of other limiting soil factors.

Soil moisture is an important factor controlling tree growth. According to Kozlowski (1955) soil moisture is often one of the most critical factors of the edaphic complex. Water is important as a constituent of living protoplasm, a reagent in chemical reactions, a medium in which reaction occurs, and a solvent. It is also very important in the maintenance of leaf turgidity. Wilted or partially wilted leaves are ineffective photosynthetic mechanisms (Kozlowski, 1955).

Claims were made for many years that all the soil moisture in the range from field capacity to wilting point was equally available to trees. There are many observations, however, which indicate that physiological processes are profoundly influenced by drying of the soil and that very real effects on metabolism and growth of plants are manifested some time before the soil reaches wilting point (Kozlowski, 1955).

Harper (1940) found that trees adapted to the climatic environment in central Oklahoma make good growth on upland soils when the surface layer does not contain more than 25 percent of clay and the subsoil does not contain more than 30 percent of clay. In western Oklahoma satisfactory growth of trees occurs where the soil is coarser textured than that indicated above (Harper, 1940). Stoeckeler and Bates (1939) concluded that porous, coarse textured soils were most favorable for trees in regions of limited rainfall because: (1) a given amount of rainfall will penetrate to a greater depth in such soils than in finer textured ones; (2) during periods of abnormal rainfall water is stored to considerable depths where it may subsequently be available to tree roots but is not susceptible to loss through evaporation; and (3) runoff during heavy rainfall is minimized in coarse textured soils.

In coarse textured soils the moisture tension changes are relatively small from field capacity almost down to the wilting point. At the latter point the tension changes rather precipitously to permanent wilting point. Moisture tension, moisture content curves for finer textural grades of soils do not exhibit such a sharp break and indicate that water is withheld from plants with appreciably greater energy over the lower part of the available range than the upper part. In terms of energy relationships the water in such soils becomes gradually less available as the moisture content decreases from field capacity to wilting point (Kozlowski, 1955).

During any period when the forest soil cannot supply the full amount of water which the energy of potential evapotranspiration could move into the atmosphere, there is a deficiency. The magnitude of the deficiency may be so small that it has no serious effect on forest growth and behavior. On the other hand, it can become quite large, with correspondingly disastrous effects. To evaluate the deficiency, both the potential evapotranspiration (the water need) and the actual evapotranspiration (the water supply) must be known. The numerical difference between the two can be termed the water deficiency (Zahner, 1956).

As long as the soil is moist, it supplies a large portion of the difference between rainfall and the water requirements of the atmosphere. As the soil dries, however, it supplies less and less water for evapotranspiration, and the deficiency becomes greater and greater. During summer droughts, it is common for forest land in the mid-South to build up deficiencies of 15 to 20 inches of water. Because the water need is considered relatively uniform over large areas in the mid-South, water deficiencies vary primarily with current rainfall and soil storage capacities (Zahner, 1956).

Water deficits affect tree growth by modifying the rates of various internal physiological processes and conditions which control growth. Growth is reduced indirectly by interferance with various metabolic processes such as photosynthesis and nitrogen metabolism, and reduction in processes such as translocation and salt absorption. Growth is reduced directly because loss of turgor decreases cell enlargement. Water deficits not only reduce the amount of growth but also change the character of growth as seen in the thicker leaves and earlier change from spring to summer wood in trees subjected to early summer droughts (Kramer, 1962).

The internal water balance which controls growth is controlled in turn by the relative rates of water absorption and water loss. Sometimes one and sometimes the other process dominates the water balance. As a result tree growth is not always closely correlated with either rainfall or soil moisture, but sometimes with one and sometimes with the other (Kramer, 1962).

Soil temperature alone and in interaction with climatic factors influences tree growth. Near freezing soil temperatures usually stop root elongation of many species but roots of species native to warm climates cease growth at higher temperatures than do cool-climate species. High soil temperatures often limit root growth and temperatures of soil surfaces exposed to the sun are often high enough to injure roots and stem bases (Kozlowski, 1955).

Low soil temperatures often exert indirect effects on growth by influencing water uptake. Low soil temperatures reduce water absorption by retarding root growth, decreasing the rate of water movement from soil to roots, decreasing permeability of cells, increasing viscosity of protoplasm, decreasing vapor pressure of water, and decreasing metabolic activities of living root tissues (Kozlowski, 1955).

According to Kozlowski (1955) one of the most fascinating facts about tree growth is that the manner in which efficiency of physiological processes is affected in any environment varies with species. As an example, white pine (Pinus strobus L.) is much more efficient in absorbing water at low soil temperatures than is loblolly pine (Kramer, 1942; Kozlowski, 1943). These species differences may play a significant part in restricting species ranges.

Loblolly Pine

Distribution

Loblolly pine grows in the Coastal Plain and Piedmont from Delaware and central Maryland south to central Florida and west to eastern Texas. (Figure 1) It extends into extreme southeastern Oklahoma, southern and central Arkansas, and extreme southern Tennessee. Loblolly does not grow in the Mississippi River bottoms and is scarce in the deep, coarse sands of the lower Gulf Coastal Plain and sandhills of North and South Carolina. Stands of loblolly are relatively heavy in southern Delaware and Maryland, as well as in eastern Virginia and northeastern North Carolina. More southerly concentrations are found in various Gulf states with the heaviest in Louisiana. At the western limits of the range, what appears to be a drought hardy strain of loblolly pine is isolated in

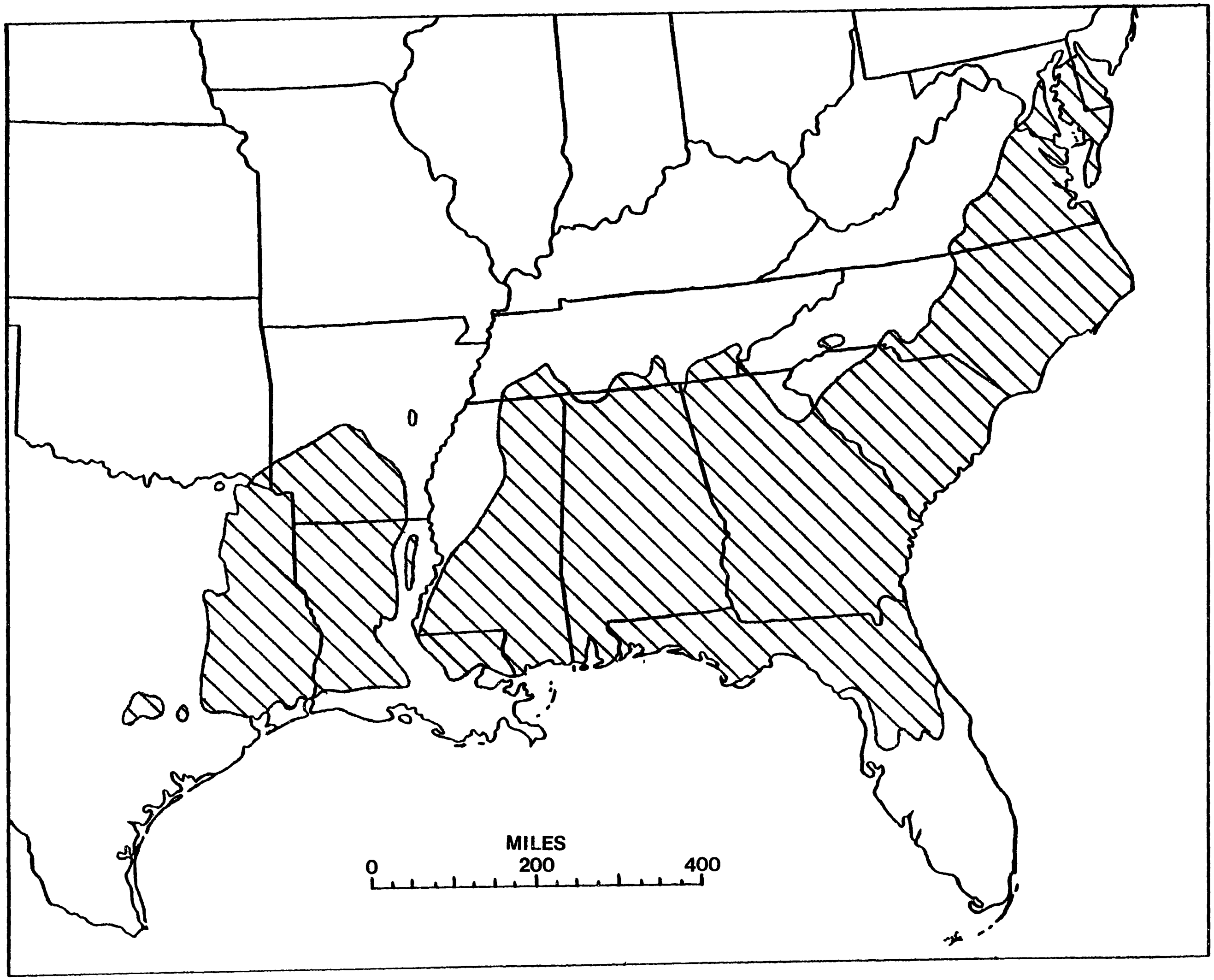

Figure 1. Distribution of Loblolly Pine in the United States (Fowells, 1965)

the so-called "Lost Pine" areas. These are in Colorado, Fayette, and Bastrop Counties, Texas, where the annual precipitation is 10 to 20 inches less than it is 200 miles farther east.

Loblolly pine originally occupied lowlands, bordering or within swamps, savannas, pocosins, or hammocks on a variety of moist topsoils, but was most abundant on the best quality loams, silts, clays, and peaty soils seldom flooded but with a water table 5 to 8 feet below the surface. Ashe (1915) listed its characteristic occurence in six situations as follows: (1) River swamps, as single trees with hardwoods, (2) Deep or shallow interior swamps, in small groups with hardwoods, (3) Hammocks, sparingly with other pines, (4) Well-drained uplands, in compact groups, (5) Peaty soils, with hardwoods, or in pure stands following fires, and (6) Narrow stream swamps in eastern Piedmont and scattered westward. Within the outer limits for loblolly pine, as described above, natural controls, including untimely fire, continued to restrict pine distribution, but land use had the most pronounced effect in modifying its pattern. According to Wahlenberg (1960):

> Cotton farming spread inland from the lower Coastal Plain to the Piedmont Plateau, where the peak of agricultural development was reached by 1840, with 87 percent of the land in cultivation. According to studies in Georgia about 10 percent of these Piedmont farm lands reverted to forest during the Civil War; another 30 percent was abandoned to the natural reseeding of pine during the depression of the late eighteen-eighties (Brender, 1952). . . . A large acreage of the new pine forest

> was cleared again for growing cotton during World War I, but with the advent of the boll weevil in 1920 about one-third of the new farm land was abandoned, and now roughly two-thirds of the Georgia Piedmont is once more in pine forest. When abandoned fields became available to loblolly pine it promptly invaded many sites to mingle over extensive areas with various other species, and to form numerous pure stands in the lower Piedmont. Thus, land use greatly increased the area of loblolly pine forest (p. 23-24).

This trend has been temporarily reversed in the loblolly pine belt east of the Mississippi River for three principal reasons: (1) agriculture - at least in the Coastal Plain - is now more stable, (2) better markets for pine still exist and loggers indulge in overcutting on many small tracts, and (3) organized protection has eliminated the widespread light burning that previously minimized the competition from hardwood brush (Lotti and McCulley, 1951). West of the Mississippi River the early trend toward an increase in pine area and volume continues in Arkansas, Louisiana, Texas, and Oklahoma. Much of the improvement in this general area arises from an increased application of silviculture to extensive tracts of pine land (Sternitzke and Wheeler, 1955).

Zon (1905) noted the increase of loblolly in east Texas. Zon (1905) stated:

> Of the three pines occurring naturally in eastern Texas, loblolly has the widest distribution, and the range of its possible extension is still greater. Loblolly is the first pine to take possession of the savannas or marshy praires, when the latter are

> sufficiently drained to allow tree growth. It encroaches upon the hardwood areas through its tolerance of shade in youth. Unless the hardwood stands are exceedingly dense and dark, loblolly germinates within them, grows rapidly, and crowds out all competitors. Loblolly successfully competes with shortleaf pine for occupancy, and appears even amid the longleaf pine on abandoned fields on the dry, barren sands of the uplands. Loblolly pine is adapted to a wider range of soils than any other pine in the region; this, together with its frequent and prolific seeding, rapid growth from the start, and comparative freedom from damage by hogs and fires, enables it to reproduce itself readily on cutover land. The other pines, particularly the longleaf pine, have relatively few chances to hold their own under the methods of lumbering which now prevail. . . After the virgin supply of the longleaf pine has been exhausted there will not be enough young growth to take its place, unless special pains are taken to secure regeneration, while the loblolly pine, because of its capacity to renew itself under the most unfavorable conditions and its ability to occupy new ground, promises to become the principal source of the timber supply of the region. Forty years ago longleaf pine was the most important timber tree of North Carolina; now the loblolly pine occupies that place. What happened in North Carolina, and is now to some extent common throughout all the South, is taking place in eastern Texas (p. 2).

Loblolly pine has been planted beyond its native range with some degree of success. Survival of loblolly beyond its natural range is higher than for other southern pines (Minckler, 1948; Williston, 1958, 1959, 1972; Williston and Huchenpahler, 1958; Posey, 1967; Lantz, 1977; Osterhaus and Lantz, 1978). Posey (1967) concluded that plantings in Oklahoma indicate that the adaptability of loblolly is greater than for shortleaf on certain sites west of the native pine range. Loblolly's high survival and rapid growth rates in the Ozarks of northern Arkansas give it promise as a timber tree for that region (Wheeler, Meade, and Russell, 1982). According to Gilmore (1981) loblolly has been planted extensively in the upper Mississippi River Valley due to its superior growth. This area is north of the loblolly range and includes Tennessee, Illinois, and Kentucky. However, Gilmore (1981) warned that care should be taken in planting loblolly too far north of its range and substantiated this warning by citing an example of a 30-year-old loblolly stand that was killed by three successive winters of extreme cold temperatures.

Climate

There is little quantitative information available concerning either the climate characterizing the loblolly pine region as a whole or the possible relation of climate to the natural distribution of the species. According to Hocker (1958), the work of Wakely (1944), Minckler (1950), Cummings (1952), and others indicated that even within its natural range, loblolly pine is rather sensitive to climatic influence.

The climate of the loblolly pine range is humid, with long, hot summers and mild winters. The average annual precipitation ranges from 40 inches in Delaware and east Texas to 60 inches along the Gulf Coast. Summer is usually the wettest season and autumn the driest along the mid-Atlantic Coast. In the western part of the range, rainfall is more uniformly distributed throughout the year, but summer droughts occur often enough to be a serious obstacle to regeneration of the species. According to Fowells (1965) precipitation probably limits the western extension of the loblolly pine range. During both winter and summer the area within the range of loblolly pine has a greater number of days with rain and a greater frequency (more than 0.50 inches) than the area immediately outside the range (Hocker, 1956).

The area just inside the range also has a higher average temperature in winter, thus the conclusion that temperature is the main factor limiting the northern extension of the species (Hocker, 1956). Low air temperatures damage the crown and low soil temperature retard water absorption more in loblolly pine than native northern species (Kramer, 1942). The average winter temperature ranges from 35^0 F in Delaware and 45^0 F in Arkansas and east Texas to 60^0 F in Florida, while the average summer temperature ranges from 70^0 F in Delaware to 80^0 F in Florida and east Texas. The number of frost free days range from 190 days in Delaware to 240 days in east Texas and 260 days in Florida.

Topography and Soils

The range of loblolly pine extends over two main physiographic regions, the Coastal Plain and the Piedmont.

The Coastal Plain is generally very flat near the coast but becomes rolling and hilly inland with elevations ranging up to 1000 feet in Georgia (Fowells, 1965). In the upper part of the northeastern Coastal Plain many of the best pine sites are in the valleys of small streams (Wahlenberg, 1960). Topography in the Piedmont is more rolling than in the Coastal Plain, with highly developed drainage patterns and generally heavier soils. Elevations range up to 1,500 feet. In northern Alabama and Georgia, loblolly pine grows at elevations up to and over 2,000 feet.

Loblolly pine grows on a wide variety of soils, from the flat, poorly drained, ground-water podzols of the lower Coastal Plain to the old residual soils of the upper Piedmont. It grows best in soils with poor surface drainage, a deep surface layer, and a firm subsoil (Chapman, 1923; Gaiser, 1950). Such soils are common in the lower Coastal Plain and in the flood plains of the larger rivers.

In the Coastal Plain, the productivity of the soils decreases with improvement in surface drainage. According to Wahlenberg (1960) within certain limits, poor drainage, either on the surface or within the soil, may be associated with good quality pine sites in the eastern Coastal Plain. A more precise concept of soil and site in the eastern part of the loblolly pine range requires measurement or estimates of (1) the depth of the surface soil as an indication of the space available to roots, and (2) the capacity of the subsoil to imbibe water. Wahlenberg (1960) states that this does not apply to the upper Coastal Plain west of the Mississippi River, but that they are more like the Piedmont. The imbibed water or imbibitional water value (difference in moisture and xylene equivalents of the soil) usually increases with increased "fines" (i.e., silt and clay particles) (Coile, 1942). The imbibitional water value reflects plasticity in soil, but is used largely as a measure of internal drainage and aeration. The subsoils of the Piedmont are usually finer textured than those of the eastern Coastal Plain, and as high site quality is usually associated with medium textured subsoils, it seems reasonable that the site quality of these Coastal Plain soils should increase with a rise in imbibitional water values, at least up to a point (Wahlenberg, 1960).

In the inland and Piedmont regions, where surface drainage is well developed, the physical characteristics of the soil rather than drainage, determines the availability of moisture. Site quality of Piedmont soil should generally decrease with rising values of imbibitional water and poor internal drainage (Wahlenberg, 1960). The best soils are those with a deep surface layer and a friable subsoil (Coile and Schumacher, 1953). The least productive are eroded soils where the A horizon is absent and the subsoil is plastic.

Turner (1938) studied the growth of loblolly and shortleaf pines as influenced by soil properties in the Coastal Plain region of southern Arkansas. The best sites were those located in flood plains of small streams. These sites had fine sandy loam or silt loam soils without marked profile development and with good internal drainage. Inferior sites had shallow surface soils on flat topography. Turner (1938) stated that both of the above conditions of shallow surface soil were ordinarily associated with subsoils (B horizons) having a relatively high clay content. A similar study in Texas (Chandler, Schoen, and Anderson, 1943) also found that the best sites for loblolly pine were found on flat land where the soils were immature, sandy loams and silt loams with a permeable subsoil, fair drainage, and an adequate water supply.

Associated Species

Associated species of loblolly pine vary by locality. According to Wahlenberg (1960), the Society of American Foresters listed four variants of the loblolly pine type: (1) flatwood stands with associated oaks, hickories, gums, etc.; (2) pine barren stands - formerly cutover longleaf pine areas on coarse sandy loam sites; (3) old-field stands on well-drained soils of fair quality; and (4) loblolly-shortleaf pine stands, with species mixed individually or groupwise.

In east Texas, southern Arkansas, Louisiana, and to a lesser extent in other states, mixtures of loblolly pine and shortleaf pine are found. They form the Loblolly Pine-Shortleaf Pine Type (Type 80) with shortleaf pine predominating on the drier ridges and loblolly pine on the wetter sites. Commonly associated species with these are sweetgum (*Liquidambar styraciflua* L.), hickories (*Carya* spp.), and oaks (*Quercus* spp.). When shortleaf pine predominates the mixture forms the Shortleaf Pine Type (Type 75).

Loblolly pine grows in mixtures with hardwoods throughout its range, as the Loblolly Pine-Hardwood Type (Type 82). On wet sites sweetbay (*Magnolia virginiana* L.), redbay (*Persia barbonia* (L.) Spreng), black tupelo (*Nyssa sylvatica* Marsh.), water tupelo (*Nyssa aquatica* L.), and sweetgum are prominent in the hardwood component. On drier sites southern red oak (*Quercus falcata* Michx.), white oak (*Quercus alba* L.), northern red oak (*Quercus rubra* L.), scarlet oak (*Quercus coccinea* Muenchh.), and hickories (*Carya* spp.) are the most common hardwoods.

In the Piedmont, and in the Coastal Plain at its northeastern limit in Virginia and Maryland, loblolly pine begins to be replaced by shortleaf and Virginia pine (*Pinus virginiana* Mill.). This comprises the Virginia Pine Type (Type 79).

Where moisture is comparatively plentiful, pure loblolly pine stands are widespread. In general, the main associate in the Loblolly Pine Type (Type 81) is sweetgum, but on well-drained sites shortleaf pine and the oaks (*Quercus* spp.) are frequently found with it.

Successional Trends

Loblolly pine is classed as an intolerant species, unable to survive in the understory with less than 30 to 60 percent full sunlight. It is less tolerant than the oaks and more tolerant than slash pine or longleaf pine.

The more tolerant hardwoods readily become established in the understory of loblolly pine stands, and on uplands throughout the range of loblolly pine the progress of succession is toward a hardwood, oak-hickory climax. The succession can be most clearly seen in old-field stands. Light-seeded and intolerant hardwood species, such as sweetgum, red maple (*Acer rubrum* L.), yellow-poplar (*Liriodendron tulipifera* L.), black tupelo (*Nyssa sylvatica* Marsh.), and waxmyrtle (*Myrica* spp.) are early invaders. Somewhat later the components of the climax, oaks and hickories, appear. They increase in size and number as the pine stand disintegrates between 100 and 300 years of age (Fowells, 1965).

According to Wahlenberg (1960) in the Piedmont region, the succession of dominants on abandoned lands where cultivation has given reseeding a fresh start by destroying native root systems can be outlined as follows:

Invasion stage	Dominant vegetation
Autumn following last cultivation . .	Crabgrass
During the first year	Horseweed
During the second year	Aster
Within 3 to 5 years	Broomsedge
Within 10 years	Pine
Anytime after 20 or 30 years	Hardwoods

Wahlenberg (1960) states that succession does not represent, as might be inferred, a relay of distinctly seperate stages. The reason for the sequence of dominants hinges on relative timing of events significant in the life cycle of each species and obviously, these relations vary with the differences in climate and local flora within the loblolly pine belt.

Natural succession is slower on dry coarse soil than on moist fine soil (Oosting, 1942); fewer oak and hickory seedlings are found in the Piedmont on sandy loam soil types than on silt loam and clay loam types. Existing differences in soil clearly may modify the rate of plant succession, but the soil itself does not change measurably from one vegetal stage to the next.

According to Wahlenberg (1960) in the eastern part of the loblolly pine range, a reversion of pine forests to more shade tolerant and generally less valuable native hardwoods is underway over extensive areas. This trend stems from both man-made and natural causes. The principal man caused reasons for the increasing ascendency of hardwoods are fire protection, where it succeeded without benefit of prescribed burning, and the prevailing habit of leaving hardwood associates standing everywhere pines are cut. The reversion of the pine forest to a broad-leaved type can rarely be completely reversed by any feasible action short of clearing and planting, but it must be widely arrested if pine is to be perpetuated as a commercial crop of timber (Wahlenberg, 1960).

The principal natural reasons for the increasing ascending of hardwoods involve soils, roots, and photosynthesis. According to Wahlenberg (1960) the principal reasons are: (1) Hardwoods tend to maintain the high degree of fertility needed for their best development. The litter from several species of hardwoods brings more nitrogen and calcium to the surface, favors soil fauna, and decomposes more rapidly than that from pine. (2) Hardwood roots sprout readily from residuals and develop more rapidly from seed than roots of pine, particularly where the forest floor is shaded. During drought roots of many species of hardwood have an advantage over those of pine in ramification, root hairs, and rate of early penetration. (3) For hardwoods as a class, photosynthesis is not reduced as soon by drought, nor as much by shade as for pine, and hardwoods can store up more plant food in the course of a growing season.

Principal Enemies

Wahlenberg (1960) states that in order to fully assume the responsibility to protect loblolly pine, a forester must be aware of potential damage from each of six principal harmful agents, and should acquire a working knowledge of the ones that impair the value of the forest most often, most extensively, or most seriously. According to Wahlenberg (1960) the six principal enemies of loblolly pine are:

1. Logging: After heavy partial cutting in older stands of moderate or higher density, many residual trees - intermediate and suppressed trees particularly - die from causes directly related to logging and exposure. Trees, both large and small, may be bruised or broken by logging, particularly during mechanized operations. Growth of timber may be retarded because soil is packed, and feeding roots of large trees injured by the use of heavy tractors on saturated ground.
2. Fire: Fire kills small pine seedlings and may injure seeds. Fire also may have a detrimental effect on the soil. Most damage by fire occurs in the summer.
3. Insects: Loblolly pine is attacked by a large number of insects from seed through maturity.

The insects that cause major damage throughout the loblolly range are the Southern pine beetle (*Dendroctonus frontalis*), Engraver beetle (*Ips* spp.), Turpentine beetles (*Buprestris apricans*), tip moths (*Rhyacionia* spp.), Pales weevil (*Hylobius pales*), and sawflies (*Diprion* and *Neodiprion* spp.).

4. Animals: Animals large or small, and domestic or wild, often damage loblolly pine, but seldom prevent regeneration of the species. Major damage is caused by deer, hogs, domestic stock, rabbits, gophers, and squirrels.
5. Diseases: Loblolly pines are relatively free from disease in their native habitat. Where they are reproduced naturally, pines are less subject to disease than in plantations. Major diseases that affect loblolly pine are rusts (including fusiform rust), root diseases, Littleleaf disease, heart rot, and stain and decay in wood products.
6. Climate: Climatic injuries often predispose trees to subsequent damage or death from other destructive agents already mentioned. Also damage may come from joint effects of two or more climatic elements. Major climatic elements that damage loblolly pine include lightning, wind, freezing weather, and hot, droughty weather.

Root and Shoot Growth

Among southern pines loblolly and shortleaf have the greatest quantity of absorbing roots in proportion to the top, and young loblolly has the most diffuse root system (Wakely, 1935). The roots formed by small plants like loblolly pine seedlings in their first season, or early years before they become firmly established, are vital to survival in the forest.

At normal field moisture contents, very little capillary water moves toward roots, and continual extension of the pine roots into new regions of soil is necessary for absorption of adequate quantities of soil moisture (Kozlowski, 1947). This extension proceeds more readily in some soils than in others. In well-aerated soil both roots and tops of pines usually grow best where moisture is abundant. In relatively dry soil roots tend to outgrow the tops; however, as soil approaches the permanent wilting point, root growth slows down or stops. Thus, in soils which are droughty during the middle portion of the growing season there may be two peaks of root growth, one in late spring or early summer and another in late summer or early autumn (Turner, 1936).

Within a range of favorable moisture contents, temperature seems to control root extension. The seasonal differences in the daily elongation of roots may result in part from day length, but are attributed largely to moisture changes. Barney (1947, 1951) found that roots of loblolly pine 2½ weeks old grow most rapidly at 68^0 to 77^0 F; the rates at 41^0 F and 95^0 F were less than 10 percent of the maximum rate. In winter with soil at 41^0 F or warmer the roots can grow. At 95^0 F most of the roots appeared to be dormant.

The number of roots in the A_1 horizon increases rapidly with age until stands are 20 to 30 years old. After 30 years the increase is much slower. The development of roots in the A_2 horizon follows the same trend as in the A_1 although the numbers are smaller. In the B and C horizons the number of roots remains constant after about 20 years (Coile, 1937).

The character of a soil can modify the general development of loblolly pine root systems. A taproot 4 to 5 feet long may be found on mature trees standing on deep sandy or loamy soils. On hard clay the taproot tends to be stout but short. In marshy locations lateral roots are prominent in a superficial system (Zon, 1905). When either the water table or an impenetrable hardpan confines the roots to surface layers of soil, growth is retarded and wind resistance lowered (Broadfoot, 1951).

In Arkansas two periods of marked dormancy for loblolly pine roots have been noted (Turner, 1936): December to March and July to September. The reasons appeared to be low temperature in winter and low soil moisture in summer. In the deep South the roots of loblolly pine may grow throughout the year, the high soil temperatures that preclude root growth in summer on the barren areas being confined to a thin zone near the surface (Greene, 1953).

Inadequacy of the root systems of pine seedlings increases with the shade in which they grow. Low light intensity decreases, and may even stop, root elongation in forest grown loblolly pine seedlings. The minimum intensity of light just sufficient for root growth is between 120 and 295 foot-candles (Barney, 1947, 1951).

During the first 5 to 10 years, height growth of vigorous loblolly pine seedlings average 2.5 feet per year (Brender and Barber, 1956; Wahlenberg, 1948; Wenger, 1955). Under favorable conditions, seedlings may reach 2 feet in height in the first year but the average first-year height is about 4 inches (Pomeroy and Trousdell, 1948). In Oklahoma on a tension-zone site, first year growth of loblolly plantings was 15.3 inches during a wet year and 9.4 inches during a year with normal precipitation (Osterhaus and Lantz, 1978).

Light shade apparently is beneficial in the first year, but thereafter it is not (Bormann, 1956). In Arkansas, the average annual height growth of loblolly pine is 86 to 88 percent complete by July 4 and 93 to 96 percent complete by August 1. Williston (1951) stated that rainfall seems to increase the amount, but not the period, of growth. The resumption of growth in the spring is mainly a response to rising air temperature but is also influenced by soil temperature (Kramer, 1936). It usually occurs before the date of the last killing frost in late March or early April in the northerly parts of the range (Kramer, 1943). Twenty percent or more of the year's height growth occurs each month from April to August. Growth is usually at least 80 percent complete by July 1 in all parts of the range (Kramer, 1943; Reed, 1939; Williston, 1951).

In the first year of growth of loblolly pine seedlings, moisture is evidently the most important factor for survival. In a study in North Carolina, pine seedlings in their first year did not respond to increased light at low moisture levels (Ferrell, 1953). After the first year, light becomes the most important factor. Loblolly pine seedlings in the shade do not develope root systems large enough to supply the moisture needed for survival. With ample light, root systems are larger and supply the water and nutrients needed for survival even with soil moisture as low as that within a stand (Kramer, Oosting, and Korstian, 1952; Oosting and Kramer, 1946).

Shortleaf Pine

Distribution

Shortleaf pine has the widest distribution and ranges farther north than any other southern pine. (Figure 2)

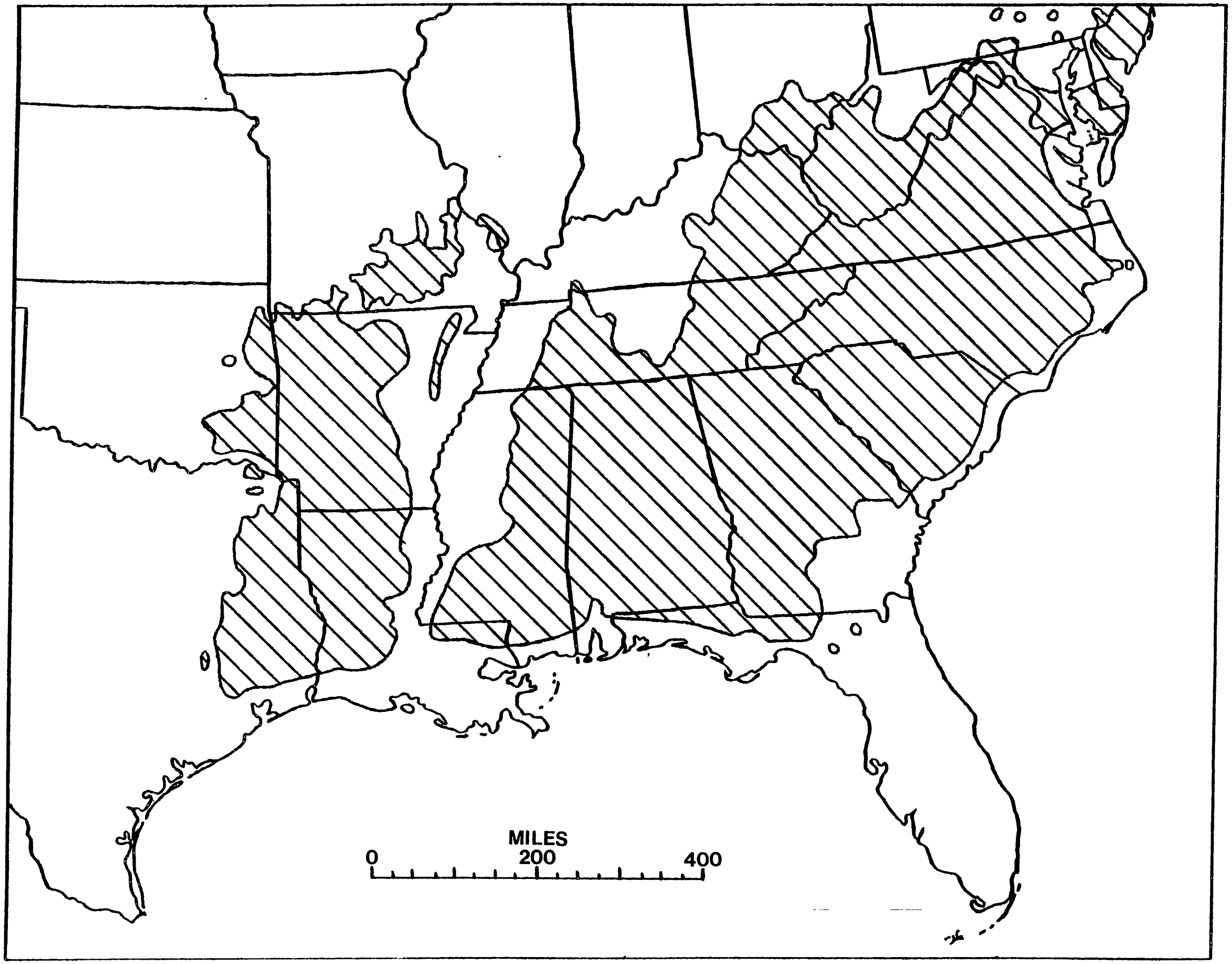

Figure 2. Distribution of Shortleaf Pine in the United States (Fowells, 1965)

It grows in 22 states from central and eastern Pennsylvania and to central Missouri in the north and from Georgia to east Texas and Oklahoma in the south (Fowells, 1965). Shortleaf pine is commercially important in the Piedmont region of Virginia, North Carolina, South Carolina, and Georgia; in the northern portions of Alabama and Mississippi; along the western foothills of the Appalachian Mountains in Tennessee, Kentucky, and West Virginia; and in eastern Texas, southeastern Oklahoma, and northwestern Louisiana. Shortleaf pine's standing inventory is about half that of loblolly with the heaviest concentration in the Ouachita Mountains of Arkansas (Sternitzke and Nelson, 1970). It is believed that the shortleaf range was once wider than it is today. In 1915 it was reported to exist in 24 states (Mattoon, 1915) and fossil pollen found in Michigan indicates that it may have once grown there (Grayson, 1954).

Climate

The average annual precipitation for the shortleaf region ranges from 40 inches in Pennsylvania, Missouri, and east Texas to 50 inches in Georgia. The number of frost free days range from 140-150 days in Pennsylvania and 160-180 days in Missouri to 240 days in Georgia and east Texas. Within the shortleaf pine region, temperatures range from a mean annual temperature of 48^0 F in New Jersey to 70^0 F in southeast Texas. The average summer temperature ranges from 70^0 F in Pennsylvania and 75^0 F in Missouri to 80^0 F in Georgia and east Texas. The 50^0 F average annual temperature line in the northeast closely parallels the northern limit of shortleaf, while in Oklahoma and Texas the 40-inch annual precipitation line marks the southwestern boundary of the range.

Topography and Soils

Shortleaf pine is found on a variety of sites ranging from wet bottomland flood plains to rocky ridge tops. In southern New Jersey shortleaf pine grows at elevations as low as 10 feet and in the mountains of the southeast it is found anywhere from the valley floors up to about 3,300 feet. Best development is attained at elevations of 600 to 1,500 feet in the Piedmont and 150 to 1,000 feet in Arkansas, Oklahoma, and Louisiana. Shortleaf will grow on all aspects.

Shortleaf's ability to grow on a great variety of soils partly accounts for its wide distribution. In the Piedmont region of the East and Southeast, site quality for shortleaf is related to the depth of the surface soil and consistence of the subsoil. Growth is good on friable subsoils, but poor on plastic subsoils. The best combination is surface soil over nine inches deep, underlain by friable subsoil (Coile, 1952).

The best shortleaf sites are fine sandy loams or silt loams without distinct profile development but with good internal drainage. These soils are found mainly in the flood plains of small streams. Poor sites are found on flat areas with shallow surface soils and on sloping land - 5 to 20 percent - which has eroded. Subsoils with a high clay content are usually present in both cases. Some sandy soils with excessive internal drainage are also very poor shortleaf sites (Coile, 1952; Turner, 1938).

Generally shortleaf pine does not grow on soils with a high calcium content or high pH. When it does grow on soils of limestone origin, the soils are usually leached and the pH is low. Shortleaf pine seedlings were found to be sensitive to high pH and high calcium levels (Chapman, 1941).

Shortleaf pine is more abundant than loblolly on the drier, better drained, and lower nutrient soils in the Piedmont. This is attributed in part to its larger root system, lower tolerance to poor soil aeration, and lower demand for soil nutrients (Zak, 1961).

Fletcher and McDermott (1957) stated that shortleaf pine in Missouri was restricted to mountainous areas and rocky, ridgetops. This is also true of its distribution in Oklahoma, especially along the fringe of its natural range. Fletcher and McDermott (1957) concluded that shortleaf's restriction to upland areas was due to natural ecological succession, man's cultural activities (such as conversion of forest to pasture) and increased fire suppression. Fletcher and McDermott (1957) also stated that shortleaf pine didn't occupy these sites because it preferred to, but because it tolerated these sites better than its hardwood associates.

Associated Species

Associate species of shortleaf pine include loblolly and Virginia pines; eastern redcedar (*Juniperus virginiana* L.); black (*Quercus velutina* Lam.), blackjack (*Quercus marilandica* Muenchh.), post (*Quercus stellata* Wangenh.), and chestnut (*Quercus prinus* L.) oaks; winged elm (*Ulmus alata* Michx.); and mockernut hickory (*Carya tomentosa* Nutt.). In addition, especially on soils containing more moisture, bitternut hickory (*Carya cordiformis* (Wangenh.) K. Koch) and sweetgum are included. West of the Mississippi River, the shortleaf and longleaf (*Pinus palustris* Mill.) pines occur in mixture and often attain maximum development together. Shortleaf pine is a major component of four forest types: Shortleaf Pine (Type 75), Shortleaf Pine-Oak (Type 76), Shortleaf Pine-Virginia Pine (Type 77), and Loblolly Pine-Shortleaf Pine (Type 80) (Fowells, 1965).

Successional Trends

Shortleaf pine, like loblolly, is a pioneer species in ecological succession. Pioneer species seed into open areas following major disturbances such as fire and flooding, and due to the reduction of competition usually form dense even-aged stands. Later, hardwoods become readily established in the understory and eventually are released through openings to dominate the stand. The climax of succession for shortleaf, as is for loblolly, is toward an oak-hickory type.

Though shortleaf pine is generally classed as shade intolerant, it will grow and persist in very dense stands (Baker, 1949; Mattoon, 1915). It may be less tolerant than loblolly pine, but will endure suppression for many years, and shows greatly accelerated growth when released, even at a late age. However, it requires overhead light for best growth.

Principal Enemies

The principal enemies of shortleaf pine are generally the same as those for loblolly. Young trees, especially those in plantations are attacked and damaged by tip moths and weevils. The southern pine beetle and other beetles cause considerable damage, especially during severe droughts. Various pine sawflies defoliate trees of all sizes and cause serious growth loss.

Unlike the other southern pines, shortleaf is practically immune to fusiform rust (Siggers and Lindgren, 1947). The greatest threat to shortleaf pine is the littleleaf disease. Littleleaf disease is caused by a combination of heavy soil, periodic excessive moisture and moisture deficit, and attack on feeding roots by *Phytophthora cinnamoni*. These forces combine to impede mineral absorption, chiefly of nitrogen, and littleleaf ensues (Fowells, 1965). The disease is now a major obstacle to the management of shortleaf over much of the South (Hepting, 1961; Zak, 1961).

Shortleaf pine is quite fire resistant. Individual trees 4 to 10 inches in diameter which survived a single severe ground fire in the spring continued to increase in diameter at a normal rate even though the crowns were severely scorched (Jemison, 1943).

Root and Shoot Growth

Shortleaf pine developes a root system similar to that of loblolly, except that it is larger and terminates in a very deep taproot. Root development for shortleaf in a nursery, according to Huberman (1940), is as follows: Lateral roots appear in 40-60 days after the seed germination. Mycorrhizae appeared and lateral roots developed in 60-80 days. A corky layer appears in 80-100 days, mycorrhizae increased in 140-160 days, growing points appeared in 200-240 days, and growing points became numerous in 260-280 days.

Because shortleaf is found on dry ridges where loblolly is absent, it is sometimes believed to resist drought better than loblolly. Evidence for the greater drought resistance of shortleaf is: it absorbed more water from the soil and maintained a higher total water content in its leaves even when soil moisture was limited, and it maintained a higher solute concentration when recovering from the effects of drought (Schopmeyer, 1939). However, other observations lead to the conclusion that loblolly is more drought resistant. Permanent wilting of shortleaf pine occured before wilting of loblolly pine and survival of shortleaf was poorer than that of loblolly in planting trials (Fowells, 1965).

Average height growth of shortleaf ranges from 2.3 to 2.8 feet per year (Williston, 1951). First year heights of shortleaf seedlings planted on a tension-zone site in central Oklahoma ranged from 12.3 inches during a wet year to 8.6 inches during a year with normal precipitation (Osterhaus and Lantz, 1978).

Prolonged overstory competition is highly detrimental to young reproduction. In a study in which overstory competition was eliminated, 60 percent survival was obtained five years after germination, compared to 16 percent where the overstory was left. The tallest seedlings at five years of age were 7 inches on the untreated and 48 inches on the treated area (Liming, 1945).

In North Carolina, more than 90 percent of shoot growth in shortleaf pine took place from April through August (Kramer, 1943). In south Arkansas, reproduction from 3 to 9 feet tall completes up to 86 percent of its height growth by the first week in July and 96 percent by the end of July (Williston, 1951).

Site Evaluation

Total site evaluation is an attempt to classify all the variables that affect site and plant species requirements. Tansley (1923) defined site as the sum of the effective conditions under which the plant or plant community lives. In forestry a site may be defined as an area of land with a characteristic combination of edaphic, topographic, climatic, and biotic factors.

Site quality refers to the productive capacity of an area of land for a tree species or a mixture of species. One of the first steps for intensively managing forest land is to determine the site quality, that is, the productive capacity of the land for several alternative tree species. Then comparisons are made of potential yield and value so that the most productive and valued tree can be selected. There are different methods of classifying forest sites. According to Carmean (1975) site quality can be estimated indirectly (through plant indicators, soil-site evaluation, etc.) or directly (through site index curves, site index comparisons between species, etc.).

Ground Vegetation and Plant Indicators

The plant indicator concept is based on a cause and effect relationship where the effect is taken as a sign of the cause (Sampson, 1939). All plants are admittedly a measure of their environment, because plant production and to some extent form of growth is determined by habitat. Any plant species may indicate the nature of its surroundings, yet only a few key species of a given locality are, as a rule, sufficiently restricted by growth conditions to be helpful. Clements (as cited by Sampson, 1939) stated that the problem of using plant indicator groups is chiefly one of analyzing the factor complex, the habitat and relating the functional and structural response of both plant and community to it. According to Clements (Sampson, 1939) indicators are the dominant species which constitute a climax since they bear the unmistakable impress of the climate and other site factors in the corresponding life form.

Braun-Blanquet (Sampson, 1939) held that characteristic species are those which are logically specialized and dependent for their existence on specific organisms and factors and have high value as indicators. These species embody certain definite adjustments and demands upon the environment and as a result they must be regarded as conspicuous indicators of certain conditions of life.

Much of the basic ground work with plant indicators was laid out in the early 1900's in Finland by Cajander (1926), who is generally credited with the development of the plant indicator system. Cajander (1926) synthesized the concept of classifying the forest by type (associations), independent of any individual species. Cajander classified plant associations by those species which are abundant, those which are present but not frequent, and those which are never present. He suggested that site classification by plant indicators, in order to be practical, must be based on the climax species in areas where man has not interfered.

The fundamental hypothesis behind the use of forest (site) types are that: (1) The ground vegetation reflects the inherent quality of site better and with less variation than do forest stands, (2) Forest (site) types are to a high degree independent of the age, density, and comparison of the forest stands that may occupy an area at any given time (Coile, 1938).

Hodgkins (1960) used vegetative association as a measure of site potential for longleaf pine. Possible site indicator species were listed and then inventoried on all the test plots. A dominance factor was used to rank each species on each plot. After developing the "plant indicator scale" Hodgkins (1960) field tested it and found it acceptable for longleaf pine. Hodgkins stated that communities can be grouped into societies and associations that in turn reflect site. Hodgkins also stated that the challenge is to select the proper representative species to use as an evaluation of site quality.

Silker (1965) developed an ecological ladder using understory and overstory hardwoods for pine site evaluation in east Texas and southeastern Oklahoma. He proposed the use of hardwoods as a primary indicator rather than ground flora for the following reasons:

1. Soil moisture is usually the most important factor controlling plant adaption to a site, when other minimums are met.
2. The most critical period for soil moisture demand appears to be in the early seedling stage.
3. Groups of hardwoods are practical, natural, statistical expressions of total site factors affecting physiological minimums or maximums; species frequency and commercial bole length and form are mirror images of what the total environment may express.
4. Hardwoods used to assay a site should be common species that will occur throughout broad geologic, physiographic, and climatic provinces.
5. Hardwoods should be reliable indicators because;

> (a) most are climax plants, (b) they are less subject to rapid change than ground flora that are readily affected by fire, cutting, grazing, (c) they usually reflect an age or minimum expression of 50 to 150+ years; and they are usually conspicuous and readily identified by foresters and others.

Silker (1963, 1965) suggested that plant indicators, because of the relationship between plant associations and soil site characteristics, could be used to determine the silvicultural tool best adapted for maintaining or gaining control of the site. Silker (1963, 1965) stressed the term "total site" in an attempt to correlate all of the relationships on a site and developed a "wedge chart" to show the total site relationships and silvicultural tool adapted for controlling certain associations of undesirable hardwoods. The chart also indicated the regeneration potential for southern pine (i.e., shortleaf and loblolly pine). The associated species involved, and their competition with the southern pines, were also indicated.

Doing (1971) attempted to determine if there was an association between species which can reflect site potential for southern pine in southeastern Oklahoma. He found that certain associations are unique to a given site and determined that a significant positive or negative association of two species could be used to identify the site stratification on which the species occur. The stratifications involved were: I, the post oak-blackjack oak sites; II, the post oak-blackjack oak-hickory sites; III, the post oak-blackjack oak-hickory-red oak sites. Based on site index values for shortleaf pine (base age 50 years) from a similar study by Endicott (1971), Doing concluded that Stratification I would produce a site index of less than 50.7 feet, Stratification II would range from a site index of 50.7 feet to 54.2 feet, and Stratification III, which begins with the establishment of red oak, consists of site indexes 60.7 feet and greater.

Soil-Site Evaluation

The soil-site method of estimating site quality is based on features of the soil, subsoil and topography. According to Paka (1969), if a classification of forest sites is desired, it should be based upon fundamental and permanent features of site, namely soil and relative topographic position of the soil mass. Characteristics of the soil mass, the sub-stratum, and topography, which are related to the availability and total volume of water present for use by forests, should be the primary criteria in any classification of site. Markedly different chemical characteristics of soil may be a secondary criteria of classification (Coile, 1938).

The principal use for the soil method originally proposed was for land not supporting stands of suitable age, stocking or species for direct site determination; examples of this are cut-over or abandoned fields, very young stands, uneven-aged or partially-stocked stands, or even land which presently supports other tree species (Paka, 1969).

Carmean (1975) best describes the soil-site method as follows:

> Many site plots are located in older forest stands representing the range of site, soil, topography, and climate found within a designated forest area or region. Site index is estimated from trees on these plots using, height and age measurements or, more recently, stem-analysis techniques. Then these site index estimates are correlated with associated features of soil, topography, and climate using multiple regression methods. The resulting equations are used for calculating site-prediction tables and trend graphs for the field estimation of site index (p. 229).

According to Carmean (1975) the precision of soil-site studies depends on several key considerations: (1) site plots should represent the full range of site index, soil, topography, and climate occuring within the defined study area; (2) site quality also should have a relatively wide range; and (3) soil-site results should apply only to the particular area studied and, further, only to the particular soil and topographic conditions sampled within the study area.

An intensive study was made by Coile (1952) with regard to the relation between soil features and the site index of loblolly and shortleaf pines in the lower

Piedmont plateau of North Carolina. The study consisted of 53 plots in loblolly pine, 75 plots in shortleaf pine and 23 plots in mixed stands of the two species. Nine soil variables were tested and the data were first classified and analyzed by three topographic position classes (1) ridges, (2) middle slopes, and (3) lower slopes and bottoms. Four soil variables proved to be significant, however the following equations proved to be adequate in predicting site index:

$$S.I._L = 100.04 - \frac{75}{X_1} - 1.39X_9$$

$$S.I._S = 77.32 - \frac{45}{X_1} - 1.00X_9$$

where $S.I._L$ = site index of loblolly pine

$S.I._S$ = site index of shortleaf pine

X_1 = thickness of the A horizon

X_9 = imbibitional water value of the B horizon

On the basis of stand and soil observations in 217 areas of even-aged loblolly pine over 20 years of age in the Coastal Plain regions of South Carolina, Georgia, Florida, and Alabama, Metz (as cited by Coile, 1952) found the following soil and topographic features to be significantly correlated with height growth of loblolly pine:

1. Product of depth of A horizon and the silt content of the B horizon.
2. Product of depth of A horizon and imbibitional water value of the B horizon.

3. Product of depth of A horizon and the clay content of the B horizon.
4. Degree of surface drainage that is well, imperfectly, or poorly drained.

Gaiser (1950) reported the relationship between site index of loblolly pine and soil characteristics and drainage of the Coastal Plain region of Virginia, North Carolina, and the northeast part of South Carolina. The following variables were all significant at the 1 percent level and were found to affect the site index:

1. Depth in inches of soil from the surface to the least permeable sub layers.
2. Imbibitional water value of the subsoil.

An intensive study of the growth of shortleaf pine plantations in relation to differences in soil properties was made in a small area of Missouri by Dingle and Burns (1954). They found that site quality for shortleaf pine was strongly related to the thickness of the surface horizon and the percentage of clay of this layer. Site quality as measured by height growth was much better on soils with deep A horizon rich in clay than on those with shallow A horizon containing little clay or organic matter. The pH of the A horizon was inversely related to site quality. Sites with high organic matter and high pH were poorest. Available moisture in the upper 3" was not correlated significantly with site quality. No constant relationship of soil color to site quality could be established.

Zahner (1958) attempted to obtain basic data from which a method for evaluating site quality for loblolly and shortleaf pine could be developed on upland and terrace soils in southern Arkansas and northern Louisiana. Through regression analysis site index was related to soil and topographic variables. Soil factors that help to regulate soil moisture and soil aeration were highly correlated with site index. On mature upland soil with well-differentiated horizons, both loblolly and shortleaf pines were influenced similarly. As the thickness of the surface soil was increased up to a depth of 18" site quality also increased. Site quality decreased somewhat for deeper surface soil. Another soil variable significantly correlated was clay content of the subsoil. On immature soil with poor horizon development loblolly pine site index was associated with three factors: (1) silt content of the surface soil, (2) silt + clay content of the subsoil, and (3) surface drainage.

Paka (1969) studied the relationship between soil properties and site index of shortleaf pine in order to estimate the growing capacity of the Coastal Plain soils of southeastern Oklahoma. The study included both physical and chemical properties of the soil. Two suitable prediction equations were derived from the study:

1. Site Index = 106.2 - 0.83(slope) - 0.39(available moisture in A_2 horizons) - 0.03 (available potassium in B horizons)

r^2 =

This equation was based on twenty-one independent soil variables.

2. Site Index = $81.03 + 0.18 \frac{\text{(Silt + Clay)}}{\text{Field capacity of B}}$ X Depth of A + 0.20(% sand in A) - 437.87(% nitrogen in A) + 0.65 (Available phosphorus in A) + 2.71(C.E.C. of A) - $3.17 \frac{\text{(Silt + Clay) of B}}{\text{Depth of B}}$

r^2 =

This equation was based on thirty-six independent variables not included in derivation of the first equation.

Site Index Curves

Direct estimation of site quality by site index is based on height and age measurements from free-growing, uninjured, dominant, or dominant and codominant trees. These measurements are used with a family of height-age (site index) curves to estimate total height of trees at a specified index age. The method is simple and easy to use when suitable forest trees are available for the required height and age measurements. Such trees most commonly occur in even-aged, fully stocked stands not disturbed by past cutting, severe fires, or heavy grazing.

Site index estimates for a particular tree species are then related to tables that predict growth and yield for different stand ages and for different levels of site index. Thus, site index is a convenient way for estimating site quality and is also the intermediate step toward the ultimate goal of predicting the capability of forest land to produce wood volume. Even when adequate yield information is lacking, as is true for many species, site index still has considerable value as an index of forest land capability.

Multiple regression of height on age and site index has been used in site index curve construction. In this procedure the curve form is dictated by a selected equation form and the curves are fitted by the method of least squares. Construction of a set of site index curves by this method assumes that (1) all the factor combinations sampled produced height-age curves which are harmonic, that is, which are proportioned to each other throughout the ages of the stands, and (2) the site index given by any stand will not change during the life of that stand (Jones, 1969).

These site index curves are termed "harmonized" in reference to the mensurational technique used for their calculation. Total height and total age was measured from dominant and codominant trees on many growth and yield plots scattered throughout a particular forest region. These height and age measurements were used for calculating a single average regional height-age (site index) curve. Then curves for a range of good and poor sites were fitted proportionally to this average guiding curve (Carmean, 1975). Thus, the harmonizing technique is based on the assumption that the pattern of tree growth is the same for all site classes, localities, and soil conditions indexed in the regional yield study.

In the Ouachita Mountains of Arkansas and Oklahoma, the most common sources for harmonized shortleaf pine site index curves were Miscellaneous Publication 50 (1929) and Coile and Schumacher (1953). The Miscellaneous Publication 50 curves were constructed from average height-age data collected from 186 stands throughout the South according to the guide curve procedure described by Bruce (1926). The Coile and Schumacher (1953) curves were prepared for the Piedmont Plateau by adjusting the Miscellaneous Publication 50 curves to correct for observed overestimation of site index in young stands.

In recent years the ability of such regional harmonized anamorphic curves to accurately represent the growth patterns of individual stands has become increasingly suspect. Curtis (1964) indicated that one principal source of error in the guide curve could result from correlation of site quality and age of the sample stands. A second souce of error results from the assumption of a constant proportional relationship between the growth curves for all sites and stand conditions (Graney and

Burkhart, 1973).

According to Carmean (1975) the underlying assumptions in the anamorphic cuves are not valid and that height growth patterns vary greatly (are polymorphic) for many species that grow on contrasting sites, or that have a wide geographic distribution. Much evidence confirms the existence of polymorphic height-growth patterns for forest species growing on contrasting sites, soils, or in different portions of a forest region (Carmean, 1968). This evidence includes: (1) Comparisons of different sets of harmonized site index curves for species that range over large forest regions, (2) soil-site studies, (3) periodic height growth measurements from permanent growth study plots, and (4) newer site index curves based on stem analyses. Thus, the shape of the height-age curves potrayed in the older harmonized site index curves may not accurately represent the diverse sites and height-growth patterns actually found over the range of a particular tree species.

Stem analysis is now the method most favored for developing more accurate site index curves, and in recent years many new site curves have been published based on this method (Carmean, 1968, 1972). These new site index curves, together with internode studies have confirmed that tree growth is usually polymorphic.

Golden et al. (1981) developed height-over-age curves and derived site index prediction tables using nonlinear polymorphic regression models with data from 25-year-old, old-field loblolly plantations ranging from coastal North Carolina to southwestern Arkansas. The derived equation was recommended for general use on well-drained sites within the natural range of loblolly pine on the Piedmont and Coastal Plain south of Virginia, in old-field plantations where no severe tip damage, restrictive soil layers, or other anomalies which might affect growth are present. It was noted that plots from heavy silty clay soils of the interior flatwoods of Mississippi exhibited height growth patterns noticeably different from the overall pattern and separate tables and curves were developed for such sites.

Graney and Burkhart (1973) developed site index curves for shortleaf pine at ages 25 and 50 derived from stem analysis data collected in the Ouachita Mountain Province of Oklahoma and Arkansas. According to Graney and Burkhart (1973) the polymorphic curves derived are preferable to standard anamorphic curves for stand age less than 30 to 40 years, especially for site indices greater than 60. They stated that the polymorphic curves produce unbiased estimates for all ages and site qualities and they reduce estimation errors. Graney and Burkhart (1973) also stated that the curve shape was significantly related to site quality.

Site Index Comparisons Between Species

Many stands suitable for site index measurements may not contain the tree species for which site estimates are desired. Suitable dominant and codominant trees of several species may be present, but no usable trees of the particular desired species may occur. For such stands the tree species actually present can be used for estimating site index. Then species comparison graphs or site index ratios can be used to convert the site index of the species present to the site index of the desired species. Site index comparisons are a very useful means for extending direct site index estimations, particularly in forest areas where soil and site vary greatly, and where, for each site, the forest manager has the problem of selecting the most desirable species for management from among many possible species (Carmean, 1975).

Carmean (1975) points out that a possible source of error is that regression equations expressing site index correlations between paired species are not generally suited for solving both forward and backward. The equations use site index of one species (species 1) as the dependent variable and site index of the associated species (species 2) as the independent variable. Such an equation is suited for a forward solution of species 1 site index using observations of species 2 site index.

However, this same equation cannot be used for a backward solution - that is, an estimation of species 2 site index using observations of species 1 site index (Carmean, 1975).

Coile (1948) developed site index ratios for converting site indices of loblolly pine to shortleaf and from shortleaf to loblolly pine for the lower Piedmont of North Carolina. Through a regression analysis of the relation between the site index of the two species as influenced by (1) the site index of loblolly pine, (2) age of the stand, and (3) stand composition, the following relationship was found:

Site index (loblolly pine) = 1.13(S.I. shortleaf pine)

Site index (shortleaf pine) = 0.885(S.I. loblolly pine)

Zahner (1957) developed a graph showing the relation between site indices of loblolly pine and shortleaf pine for south-central Arkansas and north-central Louisiana. Zahner found the following relationship: Loblolly site index = 1.30(shortleaf site index) - 17.4. On poor sites shortleaf pine does nearly as well as loblolly, but as site index increases for both species, it increases in favor of loblolly pine.

Site Quality Studies

As already pointed out, one of the first steps in intensive forestland management is to determine productive capacity (site quality). This is also the first step for identifying potential sites for non-native introduction. In determining the site quality of an area an many environmental factors as possible should be considered.

Several investigators have studied site quality incorporating the "total site" concept by studying edaphic, topographic, climatic, and biotic factors in relation to site index of tree species.

Nash (1963) studied site quality of shortleaf pine sites in Missouri. An equation was developed using topographic (slope position, aspect and degree of slope) and soil factors (texture, stone content, soil consistence) in relation to their affects on soil moisture to predict site index. Nash (1963) concluded that, in general, soil moisture is a limiting factor in the growth of shortleaf pine in Missouri where site index is an expression of soil moisture availability as measured and evaluated by topographic and soil factors.

McClurkin and Covell (1965) developed equations to evaluate the productive capacity of major soil groups of Mississippi. Prediction equations were developed for loblolly pine on 12 soil groups, for shortleaf on 7 soil groups, and for longleaf on 6 groups. The equations for all the major soils groups combined for each species were as follows:

Loblolly: $$\text{Log S.I.} = 1.72882 - 0.01036(P) + 0.00615(RF) + 0.00117(DLP)$$

$$R^2 = 0.27$$

Shortleaf: $\text{Log S.I.} = 1.58959 - 0.01125(P) + 0.00795(RF) + 0.00285(D_a)$

$$R^2 = 0.29$$

Longleaf: $\text{Log S.I.} = 1.60550 + 0.00756(RF) + 0.00039(DLP)$

$$R^2 = 0.25$$

where, S.I. = site index

P = position on slope

RF = March-through-August rainfall

DLP = depth to least permeable horizon

D_a = thickness of A horizon

R^2 = coefficient of determination

Covell and McClurkin (1967) developed an equation to predict site index of loblolly pine on Ruston soils in the Southern Coastal Plain from April-through-September rainfall and thickness of the topsoil (A horizon). Covell and McClurkin stated that the equation may be useful in establishing climatic zones within the geographic area in which Ruston soils occur and may be useful in determining the effectiveness of certain soil mapping units dealing with surface soil thickness.

According to Graney and Ferguson (1971) in the Boston Mountains of Arkansas, site index of shortleaf pine at age 50 was correlated with elevation, slope type, aspect, subsoil stone content, and loss-on-ignition of the A_1 and A_{p1} horizons. These factors are interpreted as reflections of soil moisture, stand composition, and climatic properties of the sites. The regression equation developed for all soils sampled was:

$$S.I. = 65.6 - 0.80(LI) + 2.42(TS) + 2.12(Asp) - 4.09(E)$$

$$R^2 = 0.58$$

where, S.I. = shortleaf pine site index

LI = loss-on-ignition

TS = type of slope (1 = convex, 2 = linear, 3 = concave)

Asp = aspect Cos(Azimuth - 30^0)

E = elevation

R^2 = coefficient of determination

Shoulders (1976) studied the site characteristics that influence the relative performance of loblolly and slash pine plantings in Louisiana and Mississippi. The site characteristics associated with 15-year heights of dominant and codominant trees, in descending order of importance, were rainfall, slope, and soil texture. Regression equations were computed for wet, intermediate, and dry sites:

Wet sites: $R^2 = 0.80$

$$Y_L = 138.8 - 1.54(X_2) - 2.19(X_3) - 0.524(1/X_3) + 6.05(X_4) - 0.400(X_5) - 3.53(X_6) + 0.0745(X_6^2) - 0.00055(X_6^3) + 0.517(X_8) - 0.00572(X_8^2)$$

Intermediate sites: $R^2 = 0.43$

$$Y_L = 66.4 - 0.821(X_2) - 4.40(1/X_3) - 0.388(X_8) + 0.0158(X_8^2) - 0.281(X_8^3)$$

Dry sites: $R^2 = 0.82$

$$Y_L = 36.0 + 1.94(X_1) - 22.1(X_3) + 1.33(X_3^2) - 112.1(1/X_3) - 0.281(X_6) + 0.147(X_{11})$$

where, Y_L = Average 15-year height of dominant and codominant loblolly pines

X_1 = Average annual rainfall

X_2 = Average growing season rainfall

X_3 = Percent slope + 0.1

X_4 = Percent organic matter in the A_1 horizon

X_5 = Percent sand in 6-10 inch layer (Wet and Dry Sites) or A_2 horizon (Intermediate Sites)

X_6 = Percent silt in 6-10 inch layer (Wet and Dry Sites) or A_2 horizon (Intermediate Sites)

X_8 = Percent sand in 16-20 inch layer (Wet and Dry Sites) or B_2 horizon (Intermediate Sites)

X_{11} = Percent clay in 36-42 inch layer (Dry Sites only)

Shoulders and Tiarks (1980) found in Louisiana and Mississippi, that the relative performance of major southern pines can be reliably predicted from factors that determine the amount and seasonal distribution of water and its retention on site. Regression analyses showed that 46 to 60 percent of the variation in 20-year heights of dominant and codominant loblolly, slash, longleaf, and shortleaf pine on Gulf Coastal Plain soils was associated with warm and cool season rain, slope, and potential available moisture storage of the subsoil. These authors concluded that under the moisture regimes represented in the study, loblolly or slash should be taller than longleaf or shortleaf at 20 years.

These works and others indicate that the environmental factors that are of major importance in determining the growth and distribution of a species can be identified and in turn can be used as a reliable predictor of growth.

CHAPTER III

METHODS AND MATERIALS

Oklahoma comprises an area of approximately 70,000 square miles. Topographically the state is a plain which, with many interruptions, slopes from northwest to southeast. The highest point in the state, 4,978 feet above sea level, is in the Black Mesa area of northeastern Cimarron County in the panhandle. From this point the elevation decreases eastward and southward to a minimum level of somewhat less than 300 feet in the eastern portion of McCurtain County in the extreme southeast corner of the state (Rice and Penfound, 1959).

The climate of Oklahoma is of the continental type, with pronounced seasonal and geographic ranges in both temperature and precipitation. Climatic conditions from stations representing different sections of the state are presented in Table I (U.S. Dept. of Commerce, 1951-1980). Western sections of the state are cooler and drier; in the east showers are more frequent because of the higher frequency of moisture in the atmosphere. The average annual precipitation varies from more than 52 inches in northern McCurtain County in the southeastern part of the state to 16 inches in Texas and Cimarron

TABLE I

CLIMATIC CONDITIONS REPRESENTATIVE OF VARIOUS LOCATIONS IN OKLAHOMA
(U.S. DEPT. OF COMMERCE, 1951 - 1980)

I. Average monthly and annual precipitation (inches)

	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
Altus	0.78	0.92	1.28	2.03	4.65	2.96	1.92	2.24	2.85	2.55	1.02	0.87	24.07
Boise City	0.36	0.49	0.82	1.35	2.43	1.39	2.60	2.38	1.56	0.89	0.63	0.40	15.30
Idabel	3.04	3.42	4.36	5.40	5.67	3.69	3.55	2.62	4.53	3.84	3.83	3.47	47.42
Okla. City	0.96	1.29	2.07	2.91	5.50	3.87	3.04	2.40	3.41	2.71	1.53	1.20	30.89
Miami	1.53	1.88	3.44	3.72	5.03	4.88	3.93	3.51	4.60	3.74	2.15	2.22	40.63

II. Average monthly and annual temperature (F)

	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Altus	39.3	44.4	52.5	63.3	71.6	80.5	84.6	83.1	75.4	64.6	51.2	42.8	62.8
Boise City	34.1	38.3	44.1	54.4	63.2	73.5	78.0	75.7	68.1	57.8	43.9	36.8	55.7
Idabel	42.1	46.4	53.9	63.2	70.5	77.9	81.9	81.3	74.8	64.1	52.6	45.0	62.8
Okla. City	35.9	40.8	49.1	60.2	68.4	77.0	82.1	81.1	73.3	62.3	48.8	39.9	59.9
Miami	34.5	39.8	48.2	60.1	67.9	76.2	81.1	79.9	72.6	61.4	48.4	39.2	59.1

TABLE I (Continued)

III. Average minimum January and maximum July temperatures (F)

	Jan.	Jul.
Altus	26.1	98.2
Boise City	17.7	93.7
Idabel	30.6	94.0
Okla. City	25.4	93.5
Miami	23.8	93.0

IV. Average frost-free period

Altus	215 days
Boise City	172 days
Idabel	218 days
Okla. City	213 days
Miami	198 days

Counties, both in the panhandle. (Figure 3)

The gradual decrease in precipitation from east to west is accompanied by a change in the character of the rainfall and the regularity of its distribution throughout the seasons. Rains with a duration of several days are common in the east and long continued droughts are infrequent there. Westward there is a tendency for rains to become more and more torrential in nature and the showers are more irregularly distributed. This results in high runoff. Frequently 25 percent or more of the rainfall is of no value for increasing soil moisture. The soil is seldom if ever moist below a depth of two feet and the water available for plant growth is nearly always exhausted before the end of the growing season. Moreover, all of the moisture from light showers and much of that falling in heavier rains is intercepted by the vegetation and evaporates again without adding to the supply available for absorption (Rice and Penfound, 1959).

Throughout the state, the spring season is the period of greatest rainfall, with summer, autumn, and winter exhibiting decreasing amounts of precipitation, in that order. The length of the moist season decreases from 8 months in the east to 5 in the west, and the total amount of precipitation decreases about one-half. As a result, the conditions are progressively less favorable for forest development.

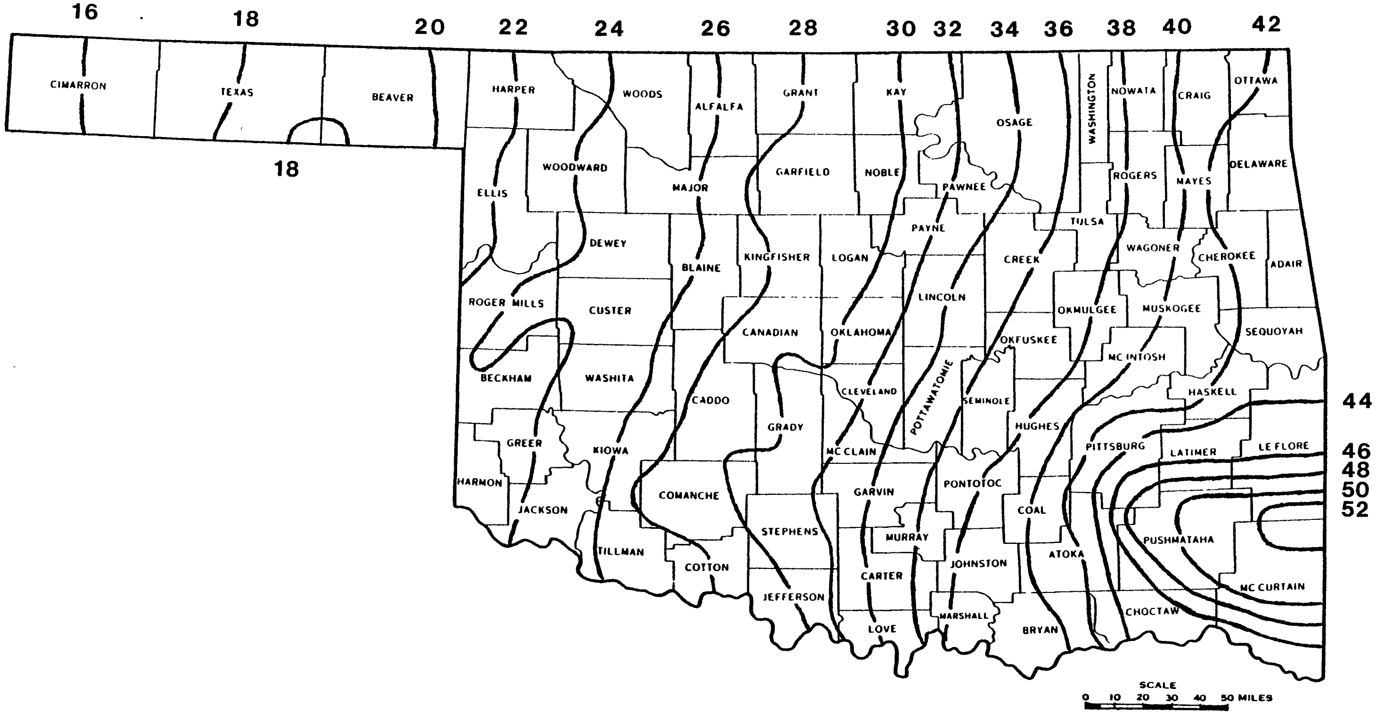

Figure 3. Average Annual Precipitation in Oklahoma (U.S. Dept. of Commerce)

The western portion of Oklahoma is characterized by greater extremes of temperature than the central and eastern sections of the state. The mean annual temperature ranges from 63^{0} F at Idabel, in the extreme southeastern corner of the state, to 56^{0} F at Boise City, in the western part of the panhandle. Temperatures of 100^{0} F or higher may be expected in Oklahoma from June to September, while maximum temperatures of 90^{0} F or higher are of record in November, January, and February. The average maximum July temperature ranges from 95^{0} F in the southeastern corner of the state and 92^{0} F in the panhandle to 100^{0} F in the extreme southwestern corner of the state. Average minimum January temperatures range from 31^{0} F at Idabel to 20^{0} F in the panhandle. The average length of the frost-free period in Oklahoma ranges from 220 days in the southeast to 200 days in the west and 180 days in the panhandle and northeastern corner of the state (U.S. Dept. of Commerce, 1951-1980).

Oklahoma has a wide diversity of vegetation since it is a border state between the temperate north and the warm temperature south and between the arid west and the humid east. (Figure 4) Deciduous forest occurs in eastern Oklahoma and is also represented along the streams westward. Numerous species which are dominants of the deciduous forest formation in Missouri, Ohio, and eastward occur in eastern Oklahoma in protected areas or where conditions are especially mesic. Among

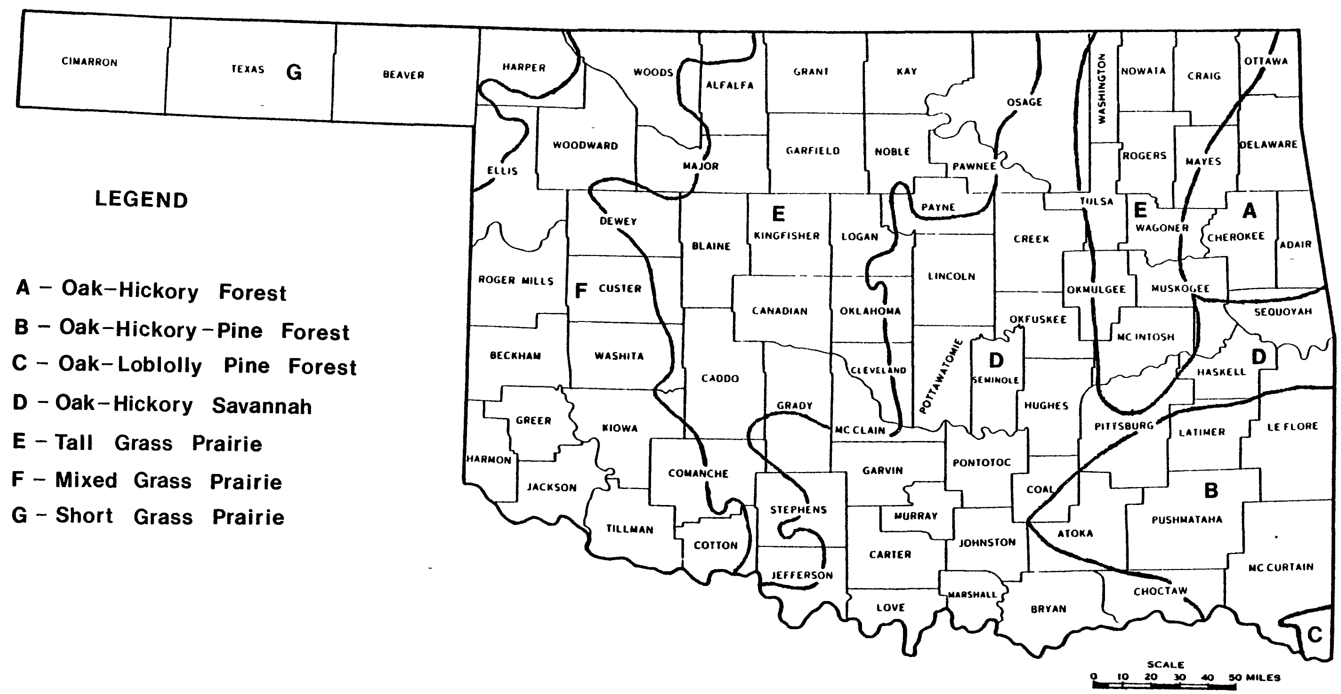

Figure 4. Vegetation of Oklahoma (Bruner, 1931; Duck and Fletcher, 1943)

these beech (Fagus spp.), maple (Acer spp.), red oak (Quercus rubra L.), linden or basswood (Tilia spp.), and ironwood (Ostrya spp.) are representative. Their occurence in Oklahoma indicates a true relationship of this woodland with the eastern deciduous forests. Oaks and hickories dominate under conditions characteristic of the region as a whole (Bruner, 1931).

According to Bruner (1931) within the boundary of the deciduous oak-hickory association of eastern Oklahoma the sub-climax Pinus species occurs over limited areas making up the oak-hickory-pine or oak-pine forest type. Bruner (1931) states that:

> Pines usually occupy only the exposed rocky ridges where the soil is poor and thin. Even here there is frequently a considerable admixture of oaks. Certain areas, however, especially in portions of McCurtain County are clothed by pure stands of pine. Such areas may be regarded as outposts of the subclimax southern evergreen forest. The oak-hickory forest characterizes the lower protected slopes, and occupies almost all of the comparatively level and more fertile portions of the region (p. 131).

Loblolly pine or the oak-loblolly pine forest type (Rice and Penfound, 1959) occurs in extreme southeastern Oklahoma, where loblolly is native only to the southeast corner of McCurtain County. However, it has been found in isolated stands north of this area in low lying areas around streams. Means (1969) found loblolly as an occassional tree in a mixed hardwood forest of the Kiamichi River Valley approximately two miles southeast of Tuskahoma, Oklahoma, in Pushmataha County.

As the moist climate of eastern Oklahoma becomes gradually drier westward, mesic communities are replaced by xeric ones. There is a change in growth-form; and the rate of growth of woody plants along streams is gradually decreased. The deciduous oak-hickory forest is replaced westward by the oak-hickory savannah,* and except for a large lobe of the subclimax prairie entering from the north, occupies sandy and rocky soils as far west as central Oklahoma. Here woodland and grassland form extensive alternes. In central Oklahoma many of the eastern species are not found and westward only scattered groups of poorly developed trees occur.

The two dominant species of the savannah are the blackjack oak (*Quercus marilandica* Muenchh.) and the post oak (*Quercus stellata* Wagenh.). The blackjack is a small, scrubby tree and is most abundant on dry, exposed hillsides or in unfavorable habitats, while the post oak makes up an increasingly greater portion of the timber on more mesic sites. Post oak exhibits much the same habit of growth as blackjack and when intermixed they attain approximately the same size. Mockernut hickory (*Carya tomentosa* Nutt.) and bitternut

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*The classical definition of "savannah" is: a xerophilous grassland containing isolated trees. However, the use of the term "savannah" in the literature cited and in this text will refer to "savannah" as: the transitional zone or ecotone between grassland and forest.

hickory (Carya cordiformis (Wangenh.) K. Koch) make up a major portion of the hickories commonly scattered among the oaks, especially in the more favorable habitats. They are usually found on soils with slightly more clay and consequently with a somewhat greater water holding capacity, and occur more commonly on north or east slopes than on south or west ones (Bruner, 1931).

Braun (1950) and Rice and Penfound (1959) considered the savannah of Oklahoma as two distinct savannahs; the eastern section being the more mesic oak-hickory savannah and the western section being the more xeric oak savannah with hickory becoming a minor component. According to Rice and Penfound (1959) the oak-hickory savannah extends from the oak-hickory forest into central Oklahoma into the grasslands of western Oklahoma. On the basis that these savannahs are relatively stable, except during major climatic shifts, and that they are perpetuating themselves through adequate reproduction Rice and Penfound (1959) concluded that the savannahs are portions of the oak-hickory forest and that their major components should be regarded as climax dominants. Rice and Penfound (1959) explain that:

> It appears that the oak savannah would metamorphose into an oak-hickory savannah in the event of a shift to a wetter climate and that it would change to grassland in the event of a change to a drier climate. . . Similarly, the oak-hickory savannah presumably would be converted into oak-forest with an increase in available

> moisture and would be transformed into an oak savannah with cumulative desication. It should be emphasized that oak savannahs and oak-hickory savannahs occur throughout the main body of the state, with a precipitation range from 25 to 45 inches. With the exception of the extreme eastern part of the state, the savannahs occur on soils of fairly coarse texture derived largely from sandstones or granites. Fine textured soils derived largely from limestones or shales support grassland vegetation. This means that almost all of Oklahoma is a broad ecotone between forest and grassland (p. 604).

Rice and Penfound (1959) further state that the climate throughout the ecotonal area cannot be said to be either a true grassland or forest climate. The deciding factor is the soil texture, apparently through its effect on water relations.

There has been an increase in the number of trees within the savannah and an increase in the area occupied by the savannah. Many islands of the savannah woodland occur in the true and mixed prairie of western sections of Oklahoma on sandstone outcrops and tongues extend across sterile ridges and along strips of infertile rocky soil to considerable distances from the margin of the community. Rice and Penfound (1959) state that a considerable extension of forest has taken place in Oklahoma through the production of ravines in grassland by accelerated erosion, and subsequent invasion by trees. Rice and Penfound (1959) also state that the current upland forests possess a greater arborescent cover than the primeval stands, especially in the oak-hickory and oak savannahs.

Study Area

The area studied includes the shortleaf pine range and pine islands of eastern Oklahoma (Figure 5) and pine plantations on the "Cross Timbers" of central and east-central Oklahoma (Figure 6). The current status of the shortleaf pine range, including the isolated shortleaf pine islands, was determined from examination of available literature published in scientific journals, past vegetation and distributional studies, public and private research and productivity reports, and observations made during sampling.

The "Cross Timbers" is the oak-hickory savannah between the eastern deciduous forest and the tall grass prairie. It extends across Oklahoma from Osage County along the Kansas state line south to Love County along the Red River. The savannah is separated rather sharply from the tall grass prairie on the west by the transition from sandstone soils to the heavier soils originating from clays and shales. Gray and Galloway (1959) described the "Cross Timbers" as:

> A large wooded area of rolling to hilly sandstone uplands extending from the Kansas line to Texas. It is an area of scrubby timber in which old growth is more or less open and park-like. Cutting and burning have caused prolific sprouting of the post and blackjack oaks to form many brushy thickets. Since the large areas lie between the eastern and central prairies they were dreaded by early travelers

Figure 5. Study Area: Shortleaf Pine Range and Shortleaf Pine Islands of Oklahoma

Figure 6. Study Area: The "Cross Timbers" of Oklahoma
(Bruner, 1931; Duck and Fletcher, 1943)

> who had to cross the timber belt on foot or on horseback - hence the name "Cross Timbers" (p. 30).

The study area is comprised of several distinct physiographic regions. (Figure 7) The Ozark Mountains occur in the northeast and extend about 85 miles from north to south and have a width of about 35 miles in the central portion. Elevations range from 600 feet in the valleys to a maximum of 1,100 feet. The rough topography has resulted from the erosion of a former plain underlaid by Mississippian cherts and limestones of the Boone formation. Streams have cut narrow, steep-sided valleys to a maximum depth of 400 feet, thus producing a mountainous topography.

Remnants of the plain persist as extensive tracts of flat, upland areas with a moderately deep, fertile soil. In other places the soil is thinner and rocky. Over the Ozarks as a whole the soil consists of a fine textured, light colored, fertile, calcareous loam on which woodland is the natural climax. On the mountain slopes there is usually a cover of coarse, resistant chert fragments which remains intact long after the out-cropping limestone has disintegrated. As a result, the slopes are very rocky with little or no surface soil although a sufficient amount of fertile soil occurs in the rock crevices to support a good growth of forest trees. The sedimentary soils of the valleys constitute only a small part of the area but, though usually somewhat

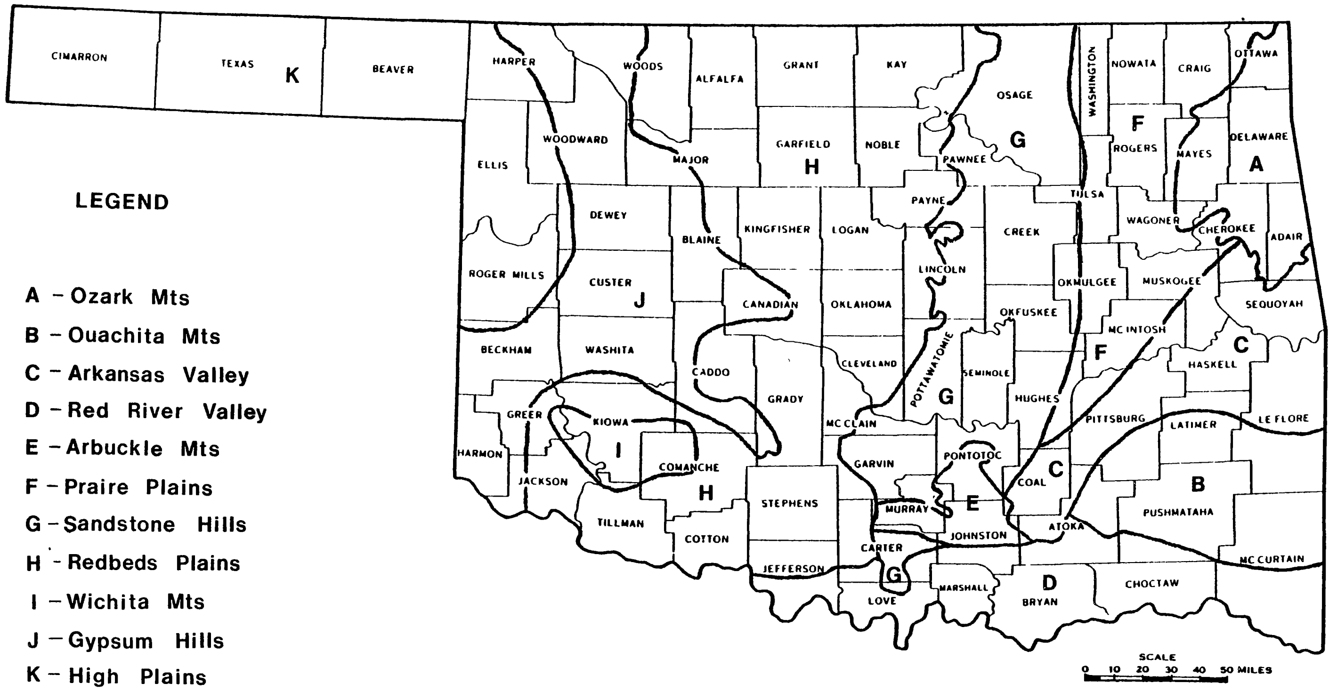

Figure 7. Physiographic Regions of Oklahoma (Bruner, 1931)

rocky, they are very fertile (Bruner, 1931).

The major soil order of the Ozarks is the Ultisols. (Figure 8) Ultisols occur in eastern Oklahoma and are usually developed in a climate which is warm and humid and has a seasonal rainfall deficiency. They generally have a horizon in which there is translocated clay or an argillic horizon with low base saturation. Precipitation usually exceeds evapotranspiration at a period during the year; consequently water moves through the soil and leaching processes occur. There is a balance between the bases released by weathering and the bases leached by water. Vegetation plays an important role in the maintenance of the bases against leaching processes. The roots of trees go deep in many soils and the bases they extract at these depths are eventually returned to the surface of the soil. Before the bases can be moved very deeply into the soil, they are again taken up by roots. Thus, the bases are held against leaching primarily by the plants. The supply of bases is partly a function of the species of plants, but the maintenance of bases in the surface horizons is at the expense of the supply in the deeper horizons (Gray and Stahnke, 1970).

The Ouachitas form the largest mountainous area and constitute the most rugged region of Oklahoma. They occupy a region nearly 50 miles wide which extends westward from Arkansas into the southeastern corner of

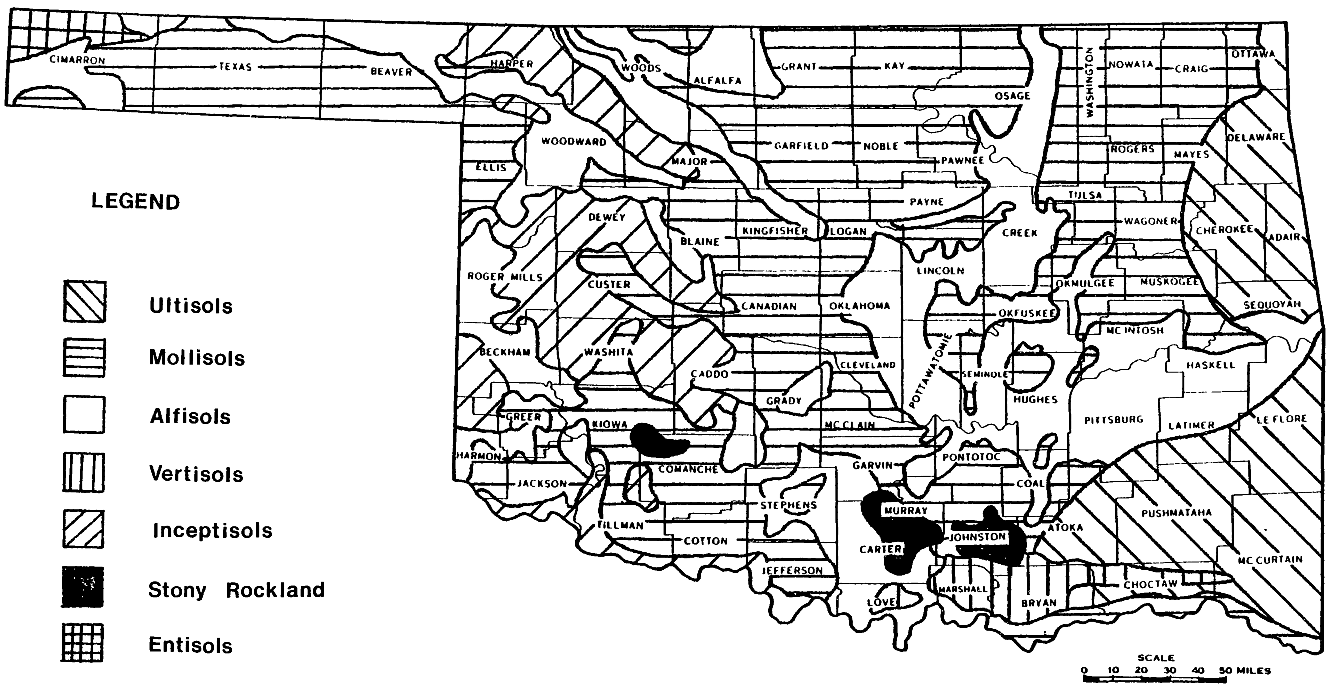

Figure 8. Soil Orders of Oklahoma (Gray and Stahnke, 1970)

the state to a distance of 90 miles. Stanley shale and Jackfork sandstone, also Mississippian strata, are the most important underlying rocks. The unequal weathering of the broken and folded bedrock has resulted in the present mountainous topography. The resistant peaks of Jackfork sandstone reach a maximum elevation of 3,000 feet above sea level. The greatest extreme of elevation is that of Rich Mountain which towers 2,000 feet above the valley floor (Bruner, 1931).

The soils of the Ouachita Mountains are for the most part neither deep nor fertile, but are thin and poorly drained. The mountains have little soil on the slopes due to the resistant nature of the Jackfork sandstone. The fine textured soils of the valleys, which have resulted for the most part from the disintegration of shales, are usually poorly drained. The nature of the forest cover throughout the area is largely determined by the depth and fertility of the soil, which accounts for the variation in the character of the vegetation on the mountain slopes (Bruner, 1931). The major soil order of the region, as in the Ozarks, is the Ultisols.

The lower Arkansas River Valley Region lies in the central part of eastern Oklahoma and separates the Ozark and Ouachita Mountains. It is 50 miles wide near the eastern boundary but in the western part decreases to a width of 20 miles. Weathering of the Pennsylvanian sandstones and shales have given rise to a rather rough topography. Broad, deep valleys have been cut by the streams into the original high plain, forming in many places very rugged hills, the relief is much less, however, than in the surrounding mountainous regions (Bruner, 1931).

The Red River Region extends 170 miles along the southeastern border of the state. The greatest width is 45 miles but most of it is much narrower. Here the lower Cretaceous sands, shales, and limestones have weathered into deep, fertile soils. Oak and pine forests are common in the eastern part while savannah occurs in the west. Owing to the fertility of the soil and favorable moisture relations much of the land is under cultivation (Bruner, 1931).

The Prairie-plains Region extends as a large, narrow tongue 150 miles southward from Kansas. It lies west of the Ozarks and extends far across the Arkansas River valley. Throughout most of its length it ranges from 30 to 60 miles in width. Broad valleys and rolling hills with escarpments facing the east characterize the area. The underlying Pennsylvanian limestones and shales have weathered into fine textured soils (Bruner, 1931). The water holding capacity is high and the ample rainfall results in the high water content which is required to support the tall grasses of the region. The greater part of the area is covered by tall grasses but where resistant bedrocks outcrop areas of woodland occur.

Mollisols constitute the major soil order of the Red River Region and Prairie-plains Region. Mollisols are soils in which there have been decomposition and accumulation of relatively large amounts of organic matter in the presence of calcium, producing calcium saturated or calcium rich forms of humus. Mollisols, therefore, must have high base saturation with abundant calcium. This requirement tends to restrict the Mollisols to sub-humid and semi-arid regions where the leaching of bases is slow or impossible, but where moisture is adequate for relatively large annual additions of organic matter. Grass is important to Mollisols because of its fibrous root system, but grass is not essential. In humid regions, under forest, calcium is rather quickly lost from the soil as a general rule. Mollisols can form if the soil fauna carries the leaf litter into the soil to decompose. Mostly, this requires calcium carbonate in some or all of the soil horizons (Gray and Stahnke, 1970). Ultisols also occur in the northern Coastal Plain of the Red River Region.

The Sandstone Hills form an extensive region which lies west of the Prairie plains and lower Arkansas River valley. It is about 50 miles wide and extends 180 miles southward from the northern boundary of the state. The Pennsylvanian shales have weathered, leaving rough, rather low hills of the more resistant sandstone. The maximum height of the hills is from 300 to 400 feet above the plain, although the average is much less. Much of the area is covered with a scrubby, transitional, oak forest but grassy areas are abundant (Bruner, 1931). This region constitutes a large part of the "Cross Timbers".

The "Cross Timbers" occupies the Arkansas Valley region, the Sandstone Hills, and extends into the Red River region. The soils of this area are coarse textured, sandy, and relatively sterile throughout the central part of the state. They have a low water holding capacity and are occupied predominantly by the savannah woodland. Northward, near the Kansas line, and again in the south there are considerable areas of finer textured soils which are occupied entirely by grasses. These areas form extensive alternes with the woodlands of the savannah (Bruner, 1931). Eastward, in the Arkansas Valley region, some fertile sedimentary soils occur in the valleys but much of the area is very rough due to the outcropping savannah sandstone and the Boggy sandstone formations.

Alfisols form the major soil order of the savannah of the Arkansas River valley and Sandstone Hills regions. Alfisols are a group of soils that are usually moist and have argillic horizons with medium or high base status. They occur in climates which have a period when evapotranspiration exceeds precipitation and one or more horizons drop well below field capacity or reach wilting point. This is the normal moisture regime of soils with argillic horizons. Water movement through the solum has been adequate to remove free carbonates, but inadequate to remove a substantial part of the exchangeable bases held by the soils. The main limitations of the soils in the Alfisol order are low fertility, moderately low water holding capacity, and susceptibility to wind and water erosion (Gray and Stahnke, 1970).

Field Procedure

Site selection

Samples were taken from stands across the shortleaf pine range and from the isolated pine islands. (Figure 9) Sites were selected to provide maximum coverage of the shortleaf range and to represent the different geographic regions shortleaf occupies in Oklahoma. This allowed incorporation of a variety of the diverse climatic, edaphic, and topographic factors that are present in the eastern part of the state. Loblolly and shortleaf plantations in the "Cross Timbers" area and loblolly plantations beyond the loblolly pine range were also sampled.

Data Collection

At each site the general nature of the stand was

Figure 9. Location of Samples Taken From the Shortleaf Pine Range (sample numbers correspond with sample names given in Table XII of Appendix A)

observed, including percent of pine in the overstory, general soil conditions, presence or absence of reproduction, evidence of management, and identification of competing vegetation. The slope of the site was measured using a Suunto clinometer and the aspect (direction of slope exposure) was measured with a compass. Elevations for each site were taken from United States Geological Survey topographic maps.

Also, at each site diameters at breast height (diameter at 4.5 feet above ground level) were measured using a diameter tape and heights were measured using a Suunto clinometer. Between 5 to 10 of the interior dominant and codominant trees of the stand were measured. Trees selected were those that had developed under stand conditions; open grown and suppressed trees were avoided. The total age of each tree was determined by counting the annual rings and adding four years (estimate of time for seedling to reach 4.5 feet) from increment borings taken at breast height. A site index value for each site was obtained from the average height and age of the stand using a table constructed from site index curves. Tables developed from site index curves (base age of 25 years) by Graney and Ferguson (1973) were used for shortleaf pine and site index tables provided by the Weyerhaueser Company were used for loblolly plantations.

Soils Data

Soils information for each sample site was taken from the USDA Soil Conservation Service county soil surveys. Information recorded included depth of each horizon and total profile depth, texture of each horizon, rock fragment content (percentage of soil passing through a No. 10 (2.0 mm) sieve) for each horizon, and water holding capacity (inches per inch of soil) for each horizon. Water holding capacities for each horizon were determined by multiplying horizon depth by the percent fragment content and then by the water holding capacity (inches per inch of soil). Total water holding capacity for the total soil profile was determined by adding the calculated water holding capacities for each horizon.

Climatic Data

Climatic data was obtained from the U.S. Dept. of Commerce climatic summaries for Oklahoma. Precipitation data for 32 stations (Figure 10) and temperature data for 18 stations (Figure 11) in eastern Oklahoma were summarized from 1951 to 1980. Climatic data for each sample site was obtained by using precipitation and temperature summaries from the nearest recording station. Data summarized included average monthly and annual temperature, average monthly maximum and minimum

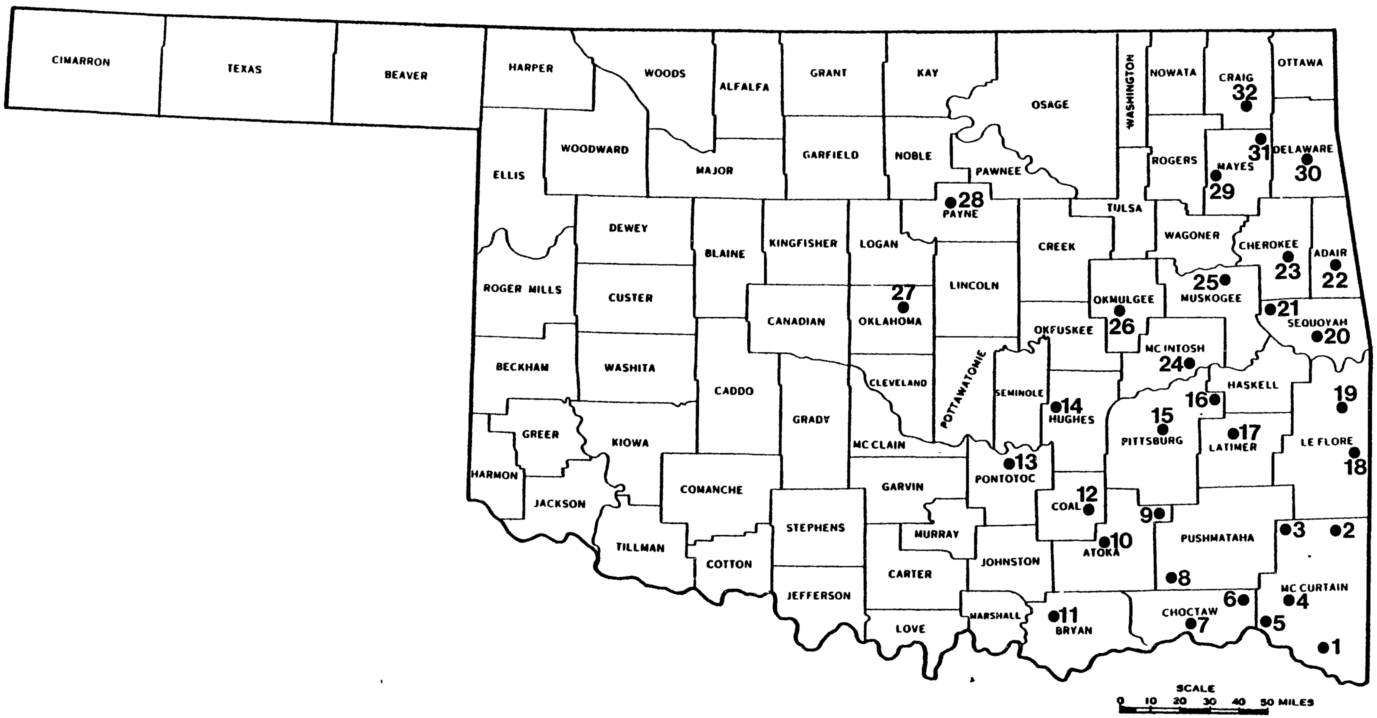

Figure 10. Precipitation Stations Utilized in the Study Area (station numbers correspond to station names given in Table II)

Figure 11. Temperature Stations Utilized in the Study Area (station numbers correspond to station names given in Tables III and IV)

temperatures, monthly and annual temperature extremes, average length of the frost free period, and monthly and annual precipitation.

A water balance to determine annual and monthly moisture deficits was computed for each site using Thornthwaite's procedure (Thornthwaite and Mather, 1955). The procedure involved computing the monthly potential evapotranspiration (PE) based on an annual heat index computed from the average annual temperature, and average monthly temperature and location (degrees latitude) of the sample site. Actual evapotranspiration (AE) for each month was determined from monthly precipitation and available water stored in the soil (obtained from Thornthwaite and Mather (1955)). AE equaled the PE when monthly precipitation exceeded the monthly PE or when (in months where PE exceeded precipitation) precipitation plus moisture supplied by the soil exceeded the monthly PE. Moisture deficits occured in months when the PE exceeded AE (precipitation plus moisture supplied by the soil). Monthly moisture deficits (PE - AE) were totaled to provide the annual moisture deficit.

Statistical Analysis

Regression studies were undertaken to study the relationship of site index of both shortleaf and loblolly pine, separately and together, to environmental factors. Simple linear correlations, Pearson and Spearman correlation procedures, were undertaken to measure the degree of association between site index and the various environmental factors and to identify the most promising factors to use in the regression analyses. The Pearson correlation procedure fits a straight line to the data, while the Spearman correlation procedure ranks the data and fits a straight line to the ranked data. An increase in the correlation coefficient ("r") produced by the Spearman correlation procedure over the "r" produced in the Pearson correlation procedure suggests a possible non-linear relationship with the variable tested.

The regression technique used in the study was the Minimum R^2 improvement (MIN R^2) technique. The MIN R^2 technique is considered superior to the step-wise regression technique in that step-wise regression may not produce the "best" n variable model (n = desired number of variables in a model). During stepwise regression a variable may be deleted in combination with certain variables in the first few steps of the technique. After the variable has been deleted it will not be reconsidered; even though it may explain a considerable amount of the variation in combination with the variables in further sequences.

The MIN R^2 technique is a sequential one which begins by determining the one variable resulting in the "best" one-variable model; that is, best in the sense that the prediction equation obtained is the one having the largest R^2 (coefficient of determination) value among all one-variable models. The model selected is also the one for which the estimated variation about the regression line is the smallest among all one-variable models.

Next the MIN R^2 technique proceeds to find the best two-variable model. From among all possible pairs of variables the procedure selects the pair for which the resulting prediction gives the largest R^2 value. The procedure also enumerates all pairs of variables which give a larger R^2 value than the best one-variable model and prints out the R^2 value and a complete analysis of each pair enumerated.

The third step selects from all possible combinations of three variables the one combination which gives the best three-variable model; that is the one with the largest R^2 value. Again, a complete analysis is given of the "best" prediction equation along with all three-variable combinations with their R^2 values which provide a larger R^2 value than the best two-variable model. Each succeeding step is performed in the same manner. The procedure may be stopped at any step when the n-variable model (n = desired number of variables) has been reached (SAS Institute, 1979).

The statistical analyses, i.e. regression and correlation studies were performed on the IBM 308 1D computer system at Oklahoma State University.

CHAPTER IV

RESULTS AND DISCUSSION

Shortleaf Pine Range

The earliest known information concerning shortleaf pine distribution in the state was provided by Fitch (1900). Fitch reported on the woodland of the Indian Territory before statehood during a survey of the area and listed the trees found there on a township by township basis. A comparison of the present distribution, including the pine islands, with information provided by Fitch (1900) indicate that pine still occurs in substantially the same general areas where it occured almost a century ago. Likewise, natural pine stands are not present where they were not recorded originally. Several pine islands were not recorded by Fitch (1900), but the ages and age distribution among the individuals of the areas indicate that the islands have been present for a considerable length of time.

The major portion of the shortleaf pine range in Oklahoma is found in the Ouachita Mountain region of the southeastern part of the state. Shortleaf ranges from the mountainous uplands of Leflore, southern Haskell, and eastern Pittsburg Counties in the north to the uplands of central Atoka County and the Coastal Plain of southern Pushmataha and McCurtain Counties in the south. In the Ozark region of the northeastern part of the state shortleaf is found on the uplands of Sequoyah, Adair, Cherokee, Delaware, and extreme eastern Ottawa and Mayes Counties.

Numerous isolated shortleaf pine islands are located beyond the contingent shortleaf pine range. These islands range in size from a few scattered trees to several hundred acres. Silker (1974) hypothesized on the origination of the pine islands in a study of the soils under the isolated islands of the Coastal Plain of Oklahoma and the "lost pines" of Texas. Silker (1974) concluded that the Alfisols and Ultisols under the pine islands were the result of fluvial deposition rather than having been weathered *in situ* from bedrock. According to Silker (1974):

> Immediately following geologic deposition there was a nearly continuous fluvial mantle (alluvial plain) that provided favorable to compensatory environments for plant migration, even into climatic tension zone areas at the western periphery (Bastrop Lost Pine Islands in east-central Texas). Plant migration moved rapidly (in geologic time) across the favorable mantle, rather than by slow soil building and genetic adaptation ("drought resistant" ecotype adaptation). Severe erosion and dissection of the mantle followed as streams were rejuvenated, leaving disjunct plant communities stranded above disjunct Alfisols and Ultisols largely undisturbed at interfluve positions (p. 63).

The northwesternmost island of the study area is located in McIntosh County, southeast of Henryetta, and the southwesternmost island is located in Bryan County, north of Bennington. The westernmost island and the westernmost record of native shortleaf pine is located north of Coalgate, along the Coal and Hughes County line (Fitch, 1900; Taylor, 1964).

Many areas of shortleaf pine in Oklahoma, especially in the eastern and southeastern portions of the state, are composed of second growth. Settlers in the late 1800's and early 1900's cleared the forest for homesteads and farmland, and harvested for lumber, poles, pulpwood, and railroad ties. Nearly all of the virgin forest had been harvested with a "cut out and get out" policy before the end of the 1930's. The current forest in Oklahoma that became established in these areas is a result of the lower quality trees passed by the original cutters (Little, 1981).

Twenty-one stands were sampled from across the native shortleaf pine range in southeastern and northeastern Oklahoma along with eight adjunct pine islands. Sample data is presented in Table XI of Appendix A.

Southeastern Sites

In the southeastern portion of the shortleaf pine range, which occuppies the Ouachita Mountains and Coastal Plain, shortleaf was found in all situations. It was found mainly on ridges and upper slopes, but was also found on bottomlands and along streams. Shortleaf occurred on all aspects with the most common occurrence on south facing slopes. Shortleaf constituted over half of the dominants of the samples with hardwoods, namely white oak (*Quercus alba*), black oak (*Quercus velutina*), southern red oak (*Quercus falcata*), and mockernut hickory (*Carya tomentosa*), comprising the remainder. Several samples were of pure pine with shortleaf making up 90 to 100 percent of the dominants in the stand. Natural regeneration was abundant in openings under the canopy in association with a dense hardwood understory. Site index values in the southeast ranged from 60 on bottomland Coastal Plain sites to 30 on the mountainous upland sites.

The most common soil series on which samples were located was the Carnasaw soil series. The Carnasaw series consists of deep, very gently sloping to steep, well-drained soils on uplands. These soils formed in material weathered from tilted shale and sandstone. A representative profile of the Carnasaw series (USDA Soil Conservation Service Soil Survey, McCurtain County) is presented in Appendix B.

Two extensive pineless areas were noted within the contingent shortleaf pine range of the southeastern part of the state. The first area was located in the Kiamichi River Valley of southern Leflore County and extended from Whitesboro to Tuskahoma. The vegetation of this area consisted of grasses on the lower areas and eastern redcedar (Juniperus virginiana), winged elm (Ulmus alata), post oak, and blackjack oak on the uplands. The main soil series under this area was the Tuskahoma soil series. The Tuskahoma series consists of shallow, moderately well drained, very slowly permeable soils that formed in material weathered from shale. Slopes range from 2 to 15 percent and these soils are droughty during the dry summer months. A typical profile of the Tuskahoma series (USDA Soil Conservation Service Soil Survey, Leflore County) is presented in Appendix B.

The second pineless area was located in Latimer County and extended from Red Oak to just east of Wilburton. The area is a valley floor with the vegetation composed mainly of grasses. The main soil series of the area is the Stigler series. The Stigler series consists of deep, moderately well drained, very slowly permeable soils that formed in clayey and loamy sediments over interbedded shale and sandstone. A typical profile of the Stigler series (USDA Soil Conservation Service Soil Survey, Latimer County) is presented in Appendix B.

Northeastern Sites

In samples of shortleaf sites in the Ozark region of northeastern Oklahoma shortleaf was found mainly on ridgetops and south and west facing side slopes. Shortleaf occurred in small patches or as individuals in a mixture of hardwoods, namely mockernut hickory, red hickory (*Carya ovalis*), northern red oak (*Quercus rubra*), and post oak, and generally comprised 50 percent or less of the dominants in the stand. Natural regeneration was rare and occurred only in openings under the canopy in association with an understory of hardwood vegetation. Site index values were between 30 and 35.

The most common soil series under the samples were the Bodine and Clarksville soil series. The Bodine series consists of very cherty or stony, strongly acid to medium acid, deep soils on uplands formed from cherty limestone. A representative profile of the Bodine series (USDA Soil Conservation Service Soil Survey, Adair County) is presented in Appendix B. The Clarksville soil consists of deep, very gently sloping to steep soils that have a stony and cherty, medium textured surface layer and a stony and cherty, moderately fine textured or fine textured subsoil. A representative profile of the Clarksville series (USDA Soil Conservation Service Soil Survey, Delaware County) is presented in Appendix B.

Pine Islands and Fringe Sites

In the pine islands and fringe areas of the contingent range, shortleaf was restricted to rough, broken landscapes and occurred only on ridgetops and side slopes with mainly a south and west aspect.

Shortleaf occurred in small patches or as individuals scattered in a mixture of post oak and blackjack oak and comprised less than 40 percent of the dominants in the stands. Little to no natural regeneration occurred in an understory composed mainly of grasses and small oaks. Site index values were generally around 25 and less. The soils under the pine islands belong to the Ultisols soil order, which is the same order that occuppies the majority of the contingent shortleaf range. The soils under the pine islands in the northeast were of the Bodine series, while the soils under the more southerly islands were of the Enders-Hector complex and the Endsaw-Hector complex with the Enders and Endsaw series being similar to the Carnasaw series.

The Enders series consists of moderately deep soils on uplands that are excessively drained and slowly permeable. They formed under trees in material weathered from shale. The Endsaw series also consists of deep, well drained, slowly permeable, gently sloping to very steep soils that formed in colluvium and material weathered from shale. They are deeper than the Carnasaw series and Enders series. The Hector series consists of shallow, well drained, moderately rapidly permeable, very gently sloping to very steep soils that formed in material weathered from sandstone. These soils are on broad ridge crests of uplands. Typical profiles of the Enders series (USDA Soil Conservation Service Soil Survey, Pittsburg County), Endsaw series (USDA Soil Conservation Service Soil Survey, Atoka County), and Hector series (USDA Soil Conservation Service Soil Survey, Pittsburg County) are presented in Appendix B.

Pine Plantations

Ten loblolly pine plantations were sampled within the Cross Timbers and shortleaf pine range and five shortleaf pine plantations were sampled beyond the shortleaf pine range. (Figure 12) Site index values for the loblolly plantations in southeastern Oklahoma ranged from 42 to 60. The higher site index values were exhibited on the soils of the Coastal Plain, while the lower site index values were on the Carnasaw soil series of the mountainous uplands. Site index values for loblolly plantations in northeastern Oklahoma ranged from 61 to 69. The highest site index was on a loamy soil adjacent to a small stream and the lower site index values were on the Clarksville soil series. Site index values for loblolly plantations on the Cross Timbers area ranged from 35, at Stillwater, to 57, at Choctaw. The plantations at Choctaw and Stillwater were located on the Stephenville soil series. The Stephenville series consists of loamy soils that are gently sloping to strongly sloping, well drained, have medium internal drainage, moderate permeability, and moderate water holding capacity. A typical profile of the Stephenville

Figure 12. Location of Loblolly and Shortleaf Plantations Sampled in the Study (sample numbers correspond with sample names given in Table XIII of Appendix A)

series (USDA Soil Conservation Service Soil Survey, Oklahoma County) is presented in Appendix B.

A second area of loblolly pine at Choctaw on the Stephenville soil series was also sampled. This area was about 5 acres in size and was the result of the natural regeneration of fifteen loblolly trees that had been planted for ornamental purposes 40 years earlier. The area could have been larger, but the advance of the regeneration was halted by a housing addition. Several different age classes of reproduction were present indicating that the regeneration was not just a chance occurrence. The average height and age of the dominants was measured to be 36 feet in 19 years, which is a site index of 45.

Site index values for the shortleaf plantations ranged from 43 to 47 in northeastern Oklahoma and from 28 to 32 in the Cross Timbers area. The shortleaf plantations sampled in the study were all located adjacent to sampled loblolly plantations. In all cases the loblolly plantations exhibited a higher site index value than did shortleaf. An example is a moderately steep site at Lamar located on the Hector soil series in an area that had been converted from post oak and blackjack oak to pine. The shortleaf pine plantation exhibited a site index of 30, while an adjacent loblolly plantation exhibited a site index of 42. Similarly, on a site in Adair County in northeastern Oklahoma located on the Clarksville soil series, the site index of shortleaf was 45 and the site index for the adjacent loblolly was 66. Data from the sampled plantations are presented in Table XII of Appendix A.

Climatic Summaries

Climatic data summarized for the study area are presented in Tables II, III, and IV, and in Appendix C. The general pattern of the average annual precipitation across the study area was the same as that exhibited for the whole state; decreasing in amount from east to west. The station receiving the most annual precipitation was Smithville with 52.57 inches and Oklahoma City was the lowest with 30.89 inches of precipitation. The greatest amount of precipitation for the majority of the stations was received in May with 6.30 inches being the highest at Daisy, and 3.47 inches at Poteau being the lowest. January was the month with the lowest precipitation for all the stations with 3.06 inches at Smithville the highest among the stations and 0.90 at Stillwater the lowest.

As mentioned earlier, it has been hypothesized that the 40-inch isohyet of annual precipitation marks the western boundary of the natural distribution of shortleaf pine. From the precipitation data compiled in this study the shortleaf pine distribution in Oklahoma corresponds with the 42-inch isohyet. (Figure 13)

TABLE II

AVERAGE MONTHLY AND ANNUAL PRECIPITATION OF STATIONS IN THE STUDY AREA - inches

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
1. Idabel	3.04	3.42	4.36	5.40	5.67	3.69	3.55	2.62	4.53	3.84	3.83	3.47	47.42
2. Smithville	3.06	3.39	5.14	5.03	5.93	4.40	4.78	3.51	4.33	4.97	3.51	4.52	52.57
3. Flashman Tower	2.76	3.28	4.63	5.75	5.90	4.16	4.25	4.32	4.77	3.95	4.11	3.77	51.65
4. Bear Mountain Tower	2.67	3.37	4.44	5.10	5.47	3.64	4.15	3.60	5.24	4.13	3.72	4.10	49.63
5. Valliant	2.45	3.10	4.12	4.76	5.35	3.63	3.63	2.77	4.98	3.62	3.60	3.60	45.61
6. Sobol Tower	2.37	2.75	4.23	5.14	6.00	3.81	3.62	3.44	5.43	4.06	3.42	3.57	47.84
7. Hugo	2.22	2.77	3.80	4.72	5.66	4.52	3.05	3.44	5.15	3.94	3.33	2.96	45.56
8. Antlers	2.20	2.75	3.65	5.10	5.94	3.97	3.17	3.23	5.27	3.91	3.18	3.02	45.39
9. Daisy 2E	1.96	2.69	3.84	5.43	6.30	4.48	4.32	3.51	5.70	3.81	3.36	2.66	48.06
10. Atoka	1.64	2.30	3.14	5.01	4.65	4.16	3.14	2.77	5.70	3.73	2.58	2.32	41.14
11. Durant	1.73	2.25	3.34	4.63	4.96	3.75	2.60	2.54	5.60	3.47	2.80	2.18	39.85
12. Coalgate	1.66	2.16	3.93	4.92	5.17	3.86	3.03	2.82	5.19	3.81	2.97	2.24	41.76
13. Ada	1.36	1.88	2.90	3.77	5.63	3.73	2.69	3.09	4.01	3.92	2.55	1.94	37.47
14. Holdenville	1.32	1.68	2.98	4.37	5.60	3.83	3.46	2.66	4.00	3.54	2.40	1.83	37.67
15. McAlester	1.62	2.26	3.85	4.54	5.62	3.73	3.41	3.25	4.96	3.90	3.07	2.38	42.59
16. Quinton	1.62	2.10	3.69	4.33	5.56	4.03	3.80	3.10	4.41	3.61	3.24	2.36	41.85

TABLE II (Continued)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
17. Wilburton	1.91	2.56	4.00	4.91	5.58	3.99	4.36	3.25	4.97	3.80	3.61	2.98	45.92
18. Heavener	2.25	2.72	4.15	4.93	5.52	4.00	3.56	3.35	4.52	3.30	3.69	3.22	45.21
19. Poteau	1.84	2.68	4.12	4.70	5.92	3.47	3.68	3.30	4.22	3.19	4.02	2.93	44.07
20. Sallisaw	1.78	2.48	3.80	4.47	5.47	4.33	3.55	3.17	4.41	3.86	3.41	2.47	43.20
21. Tenkiller Ferry Dam	1.70	2.34	3.65	4.62	5.33	4.47	3.27	3.19	4.32	3.53	2.91	2.44	41.77
22. Stilwell	1.96	2.57	3.70	4.61	5.63	4.48	3.73	3.35	4.31	3.28	3.25	2.71	43.58
23. Tahlequah	1.78	2.41	3.64	4.56	5.47	4.64	3.39	3.06	4.34	3.41	3.20	2.46	42.36
24. Eufaula	1.53	2.07	3.97	4.74	5.63	3.98	3.69	2.81	4.20	3.27	3.03	2.36	41.28
25. Muskogee	1.65	2.17	3.22	4.66	4.95	4.32	3.21	3.08	4.22	3.35	2.94	2.28	40.05
26. Okmulgee	1.63	1.79	3.03	4.52	5.08	4.71	3.05	2.63	3.80	2.89	2.63	2.02	37.78
27. Oklahoma City	0.96	1.29	2.07	2.91	5.50	3.87	3.04	2.40	3.41	2.71	1.53	1.20	30.89
28. Stillwater	0.90	1.20	2.19	2.58	5.08	3.92	3.79	2.83	3.93	2.90	1.78	1.22	32.32
29. Pryor	1.54	1.77	3.08	3.90	4.88	4.67	3.06	3.40	4.16	3.77	2.78	2.04	39.05
30. Jay	1.72	1.97	3.55	4.38	5.20	5.39	3.69	3.56	4.60	3.78	3.21	2.30	43.35
31. Grand River Dam	1.55	1.94	3.10	3.96	4.86	5.01	3.66	3.35	4.47	3.45	2.79	2.05	40.19
32. Vinita	1.53	1.81	3.54	4.07	5.35	4.87	3.38	3.61	4.75	3.72	2.96	2.14	41.73

TABLE III

AVERAGE MONTHLY TEMPERATURE OF STATIONS IN THE STUDY AREA - ^{0}F

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1. Idabel	42.1	46.4	53.9	63.2	70.5	77.9	81.9	81.3	74.8	64.1	52.6	45.0
2. Smithville	39.0	42.8	51.2	60.8	67.9	75.4	79.4	78.3	71.9	61.7	50.1	42.1
3. Antlers	40.6	45.0	53.0	62.7	69.7	77.4	81.8	81.0	74.2	63.6	51.9	43.4
4. Durant	40.8	45.7	52.1	63.5	70.9	78.8	83.1	82.4	75.0	64.9	52.7	42.8
5. Atoka	41.2	46.0	53.5	63.0	70.7	77.6	81.9	81.2	74.4	64.5	52.7	43.9
6. Ada	39.5	44.7	52.4	62.5	69.7	77.7	82.7	81.5	74.6	64.4	51.8	43.5
7. Holdenville	38.7	44.1	51.7	62.2	69.7	77.5	82.7	81.8	74.6	64.1	51.0	42.9
8. McAlester	38.1	43.1	51.3	61.9	69.5	77.5	82.7	81.7	74.2	63.3	50.8	42.0
9. Wilburton	39.5	44.5	52.0	62.1	69.2	77.0	81.8	80.6	73.6	62.9	50.9	42.9
10. Poteau	39.9	44.6	52.5	62.8	70.0	77.7	82.7	81.5	74.5	63.8	51.9	43.7
11. Eufaula	39.1	44.4	52.6	63.3	70.6	78.2	84.3	82.5	75.1	64.8	51.9	43.5
12. Sallisaw	38.4	43.4	51.3	62.2	69.7	77.4	82.1	81.0	74.2	63.4	50.7	42.2
13. Tahlequah	37.4	41.7	49.9	61.1	68.2	76.0	80.7	80.0	72.9	62.1	49.5	40.8
14. Muskogee	37.6	42.7	51.1	62.1	69.6	77.4	82.6	81.4	74.1	62.9	50.3	41.5
15. Okmulgee	37.3	43.1	52.3	62.3	69.3	77.2	81.8	80.9	73.5	63.1	50.4	42.0
16. Oklahoma City	35.9	40.8	49.1	60.2	68.4	77.0	82.1	81.1	73.3	62.3	48.8	39.9
17. Stillwater	35.3	40.5	48.8	60.4	68.4	77.0	82.1	81.0	73.1	61.9	48.9	39.8
18. Grand River Dam	35.8	40.5	49.1	60.7	68.6	76.8	81.8	80.5	72.8	62.2	49.1	40.1

TABLE IV

AVERAGE LENGTH AND PROBABILITIES OF THE FROST FREE PERIOD OF STATIONS IN THE STUDY AREA

	Average	1 Year in 10	2 Years in 10	5 Years in 10	8 Years in 10	9 Years in 10
1. Idabel	218	239	236	220	197	196
2. Smithville	196	215	211	194	182	169
3. Antlers	205	220	213	203	193	187
4. Durant	225	244	240	226	202	197
5. Atoka	216	240	234	213	202	194
6. Ada	221	242	236	220	203	198
7. Holdenville	220	237	233	221	204	195
8. McAlester	214	234	226	214	199	195
9. Wilburton	197	216	215	195	179	175
10. Poteau	213	232	226	213	198	193
11. Eufaula	227	247	240	233	205	204
12. Sallisaw	207	228	224	206	192	179
13. Tahlequah	194	218	205	194	179	166
14. Muskogee	215	231	226	216	202	195
15. Okmulgee	208	228	224	204	193	188
16. Oklahoma City	213	236	225	217	202	194
17. Stillwater	203	223	217	201	192	183
18. Grand River Dam	204	221	214	203	187	178

Figure 13. Comparison of the 42-inch Annual Precipitation Isohyet with the Shortleaf Pine Distribution in Oklahoma

Fletcher and McDermott (1957) found that the 17-inch isohyet of winter precipitation (November - April) defined the northwestern extremity of shortleaf pine in Missouri, suggesting the essentiality of adequate winter moisture. The 17-inch isohyet for winter precipitation (October - March) as compared to the shortleaf pine range in Oklahoma is presented in Figure 14. The general pattern displayed by the 17-inch isohyet for winter precipitation corresponds to that displayed by the shortleaf distribution in the state.

Temperatures were rather uniform across the study area with the average July temperature ranging from 84.3^0 F at Eufaula to 79.4^0 F at Smithville, and the average January temperature ranging from 35.3^0 F at Stillwater to 42.1^0 F at Idabel. The average length of the frost free period ranged from 194 days at Tahlequah to 227 days at Eufaula.

Linear Correlation Studies

Site index values (25) of shortleaf and loblolly pine, together and separately, were correlated with sixty-six independent variables (Table V) using the Pearson and Spearman Correlation Procedures in an attempt to identify the most promising variables to use in the regression analyses. No significant increases in the correlation coefficients ("r") were found by using the Spearman Correlation Procedure, thus indicating linear

Figure 14. Comparison of the 17-inch Winter Precipitation (October - March) Isohyet with the Shortleaf Pine Distribution in Oklahoma

TABLE V

LIST OF ENVIRONMENTAL VARIABLES USED IN THE STUDY

X_3 = percent slope
X_4 = cos(aspect - 30^0)
X_5 = elevation
X_6 = degrees longitude
X_7 = degrees latitude
X_8 = average annual precipitation
X_9 = average cool season precipitation (Oct-Mar)
X_{10} = average warm season precipitation (April-Sept)
X_{11} = average January precipitation
X_{12} = average February precipitation
X_{13} = average March precipitation
X_{14} = average April precipitation
X_{15} = average May precipitation
X_{16} = average June precipitation
X_{17} = average July precipitation
X_{18} = average August precipitation
X_{19} = average September precipitation
X_{20} = average October precipitation
X_{21} = average November precipitation
X_{22} = average December precipitation
X_{23} = average annual temperature
X_{24} = average minimum temperature for January
X_{25} = average maximum temperature for July
X_{26} = average maximum temperature for August
X_{27} = length of frost free period
X_{28} = average annual potential evapotranspiration
X_{29} = average annual actual evapotranspiration
X_{30} = average annual moisture deficit

TABLE V (Continued)

X_{31} = average June moisture deficit
X_{32} = average July moisture deficit
X_{33} = average August moisture deficit
X_{34} = average September moisture deficit
X_{35} = total soil depth
X_{36} = total available water in the soil profile
X_{37} = depth of the A horizon
X_{38} = available water in the A horizon
X_{39} = depth of the B horizon
X_{40} = available water in the B horizon
X_{41} = depth of the A plus B horizons
X_{42} = available water in the A plus B horizons
X_{43} = warm season potential evapotranspiration (April-Sept)
X_{44} = cool season potential evapotranspiration (Oct-Mar)
X_{45} = May potential evapotranspiration
X_{46} = June potential evapotranspiration
X_{47} = July potential evapotranspiration
X_{48} = August potential evapotranspiration
X_{49} = September potential evapotranspiration
X_{50} = October potential evapotranspiration
X_{51} = November potential evapotranspiration
X_{52} = average January temperature
X_{53} = average July temperature
X_{54} = average August temperature
X_{60} = July plus August potential evapotranspiration
X_{61} = average January plus February precipitation
X_{62} = average August plus September moisture deficit
X_{70} = average January - May precipitation
X_{71} = average January - April precipitation

TABLE V (Continued)

X_{72} = average February - May precipitation
X_{73} = average January - March precipitation
X_{74} = average February - April precipitation
X_{75} = average March - May precipitation
X_{76} = average February plus March precipitation
X_{77} = average March plus April precipitation
X_{78} = average April plus May precipitation
X_{79} = average July - September precipitation
X_{80} = average August plus September precipitation

relationships.

Six independent variables suggested relationships (less than 0.20 probability level used) with the site index of loblolly pine, however, none were significantly correlated. (Table VI) This was probably due to the low number of observations for loblolly in the study. Forty-four independent variables suggested relationships (less than 0.20 probability level used) with the site index of shortleaf pine with fourteen of these significant at the 0.05 probability level and fourteen significant at the 0.01 probability level. (Table VII) Thirty independent variables suggested relationships (less than 0.20 probability level used) with the site index of shortleaf and loblolly considered together with one significant at the 0.05 probability level and seventeen significant at the 0.01 probability level. (Table VIII)

Percent slope had a strong negative correlation with the site index of loblolly and shortleaf pine, separate and together. Zahner (1958) found the site index of both loblolly and shortleaf pine decreased as slope increased. Similar results were also found by Gaiser (1950), Linnartz (1963), Shoulders (1976), and Shoulders and Tiarks (1980). Aspect, elevation, and degrees latitude and longitude were the other physiographic factors which were correlated with the site index of shortleaf and shortleaf and loblolly considered together.

Soil factors that were correlated with site index

TABLE VI

INDEPENDENT VARIABLES RELATED TO LOBLOLLY SITE INDEX (SIGNIFICANT AT THE 0.20 LEVEL)

Variable	"r"
X_3 = slope	-0.47426
X_{16} = average June precipitation	0.45694
X_{34} = average September moisture deficit	-0.57807
X_{35} = total soil depth	0.55874
X_{37} = depth of the A horizon	0.51691
X_{47} = July potential evapotranspiration	-0.52314

TABLE VII

INDEPENDENT VARIABLES RELATED TO SHORTLEAF SITE INDEX
(SIGNIFICANT AT THE 0.20 LEVEL)

Variable	"r"
X_3 = slope	-0.68486**
X_4 = cos(aspect - 30^0)	-0.31392**
X_5 = elevation	-0.44827**
X_6 = degrees longitude	-0.46599**
X_7 = degrees latitude	-0.43040*
X_8 = average annual precipitation	0.32663
X_9 = average cool season precipitation (Oct-Mar)	0.36932*
X_{11} = average January precipitation	0.53717**
X_{12} = average February precipitation	0.47117**
X_{20} = average October precipitation	0.25428
X_{22} = average December precipitation	0.39923*
X_{23} = average annual temperature	-0.29750
X_{25} = average maximum temperature for July	-0.59005**
X_{26} = average maximum temperature for August	-0.43204*
X_{27} = length of the frost free period	-0.39142*
X_{28} = average annual potential evapo- transpiration	-0.32796
X_{30} = average annual moisture deficit	-0.26578
X_{33} = average August moisture deficit	-0.29170
X_{34} = average September moisture deficit	-0.30677
X_{37} = depth of the A horizon	0.45526**
X_{38} = available water in the A horizon	0.29421
X_{41} = depth of the A plus B horizons	-0.27275
X_{42} = available water in the A plus B horizons	-0.28303

*denotes significant at the 0.05 probability level

**denotes significant at the 0.01 probability level

TABLE VII (Continued)

Variable	"r"
X_{43} = warm season potential evapotranspiration (April-Sept)	-0.63249**
X_{44} = cool season potential evapotranspiration (Oct-Mar)	-0.39588*
X_{45} = May potential evapotranspiration	-0.27027
X_{46} = June potential evapotranspiration	-0.29033
X_{47} = July potential evapotranspiration	-0.65104**
X_{48} = August potential evapotranspiration	-0.42327*
X_{49} = September potential evapotranspiration	-0.28927
X_{50} = October potential evapotranspiration	-0.42120*
X_{51} = November potential evapotranspiration	-0.41564*
X_{53} = average July temperature	-0.59911**
X_{54} = average August temperature	-0.50224**
X_{60} = July plus August potential evapotranspiration	-0.57322**
X_{61} = average January plus February precipitation	0.50892**
X_{62} = average August plus September moisture deficit	-0.38462*
X_{70} = average January - May precipitation	0.36602*
X_{71} = average January - April precipitation	0.37018*
X_{72} = average February - May precipitation	0.31055
X_{73} = average January - March precipitation	0.41267*
X_{74} = average February - April precipitation	0.30950
X_{75} = average March - May precipitation	0.23680
X_{76} = average February plus March precipitation	0.34818*

*denotes significant at the 0.05 probability level

**denotes significant at the 0.01 probability level

TABLE VIII

INDEPENDENT VARIABLES RELATED TO LOBLOLLY AND SHORTLEAF SITE INDEX (SIGNIFICANT AT THE 0.20 LEVEL)

Variable	"r"
X_3 = percent slope	-0.64585**
X_4 = cos(aspect - 30^0)	-0.49483**
X_5 = elevation	-0.61120**
X_6 = degrees longitude	-0.59211**
X_7 = degrees latitude	-0.58864**
X_{11} = average January precipitation	0.27115
X_{12} = average February precipitation	0.21747
X_{23} = average annual temperature	-0.28646
X_{25} = average maximum temperature for July	-0.55294**
X_{26} = average maximum temperature for August	-0.40954**
X_{27} = length of the frost free period	-0.25249
X_{28} = average annual potential evapo- transpiration	-0.29059
X_{37} = depth of the A horizon	0.49117**
X_{38} = available water in the A horizon	0.28122
X_{39} = depth of the B horizon	0.22471
X_{41} = depth of the A plus B horizons	-0.45161**
X_{42} = available water in the A plus B horizons	-0.39656**
X_{43} = warm season potential evapo- transpiration (April-Sept)	-0.48232**
X_{44} = cool season potential evapo- transpiration (Oct-Mar)	-0.59141**
X_{45} = May potential evapotranspiration	-0.28708
X_{46} = June potential evapotranspiration	-0.20324
X_{47} = July potential evapotranspiration	-0.53731**
X_{48} = August potential evapotranspiration	-0.25513

*denotes significant at the 0.05 probability level

**denotes significant at the 0.01 probability level

TABLE VIII (Continued)

Variable	"r"
X_{49} = September potential evapotranspiration	-0.22767
X_{50} = October potential evapotranspiration	-0.60559**
X_{51} = November potential evapotranspiration	-0.60070**
X_{53} = average July temperature	-0.45501**
X_{54} = average August temperature	-0.33294*
X_{60} = July plus August potential evapotranspiration	-0.42703**
X_{61} = average January plus February precipitation	0.24528

*denotes significant at the 0.05 probability level

**denotes significant at the 0.01 probability level

include total soil depth; depths of the A, B, and A plus B horizons; and water holding capacities of the A and A plus B horizons. Total depth of the soil profile showed a strong positive relationship with site index of loblolly pine. The depth of the A horizon exhibited a strong positive correlation with site index of loblolly and shortleaf, separate and together. Coile (1952) suggests that depth of the surface soil is a measure of the well aerated space for root development above more restrictive soils. According to Zahner (1958) site index for both loblolly and shortleaf pines consistently increases with increasing surface soil thickness. Similar results were found by Coile and Schumacher (1953), McClurkin and Covell (1966), and Covell and McClurkin (1967). The water holding capacity of the A and A plus B horizons exhibited a positive relationship with the site index of shortleaf and shortleaf and loblolly together, and a strong positive relationship was found between the depth of the B horizon and site index of shortleaf and loblolly together.

Climatic factors that correlated with site index include various measures of monthly precipitation, temperature, and monthly potential evapotranspiration. Precipitation of single winter months and various combinations of winter months exhibited the strongest correlations with site index of loblolly and shortleaf pine. The sum of the precipitation for January and February exhibited the highest positive correlation. A significant negative correlation was shown between July and August maximum and average temperature and site index of shortleaf and shortleaf and loblolly together. July and August potential evapotranspiration also exhibited a significant negative correlation with site index, as did the sum of the two months.

Regression Analysis

Regression analysis was performed on the independent variables that correlated with site index from the linear correlation studies using the MIN R^2 procedure. Loblolly and shortleaf were subjected to the procedure separately and together. The three resulting models were all composed of the same three independent variables; percent slope, depth of the A horizon, and the January plus February precipitation. The "best" three variable models found were:

Loblolly:

$$Y = 14.6022 + 4.9196(X_{61}) + 2.2326(X_{37}) - 0.9438(X_3)$$

$$R^2 = 0.79$$

Shortleaf:

$$Y = 11.7748 + 3.4011(X_{61}) + 1.1247(X_{37}) - 0.4915(X_3)$$

$$R^2 = 0.70$$

Shortleaf and Loblolly:

$$Y = 16.8886 + 2.7129(X_{61}) + 1.6418(X_{37}) - 0.7556(X_3)$$

$$R^2 = 0.58$$

where, Y = site index

X_3 = percent slope

X_{37} = depth of the A horizon

X_{61} = January plus February precipitation

Considerably higher R^2 values were obtained by considering loblolly and shortleaf separate than by considering the two species together. This indicated a possible difference in the regression lines of the two species. Covariance analysis, incorporating a dummy variable for species, was undertaken to determine if there was a species difference. The first test of the covariance analysis tested the hypotheses of no difference in the slope of the regression lines of the two species. Results of the first test are presented in Table IX. No significant interactions were found between the two species and the independent variables, thus indicating no significant difference in the slopes of the regression lines of loblolly and shortleaf. The second test of the covariance analysis tested the hypothesis of no differences in levels of the regression lines of the two species. Results of the second test, presented in Table X, indicate that a significant difference existed in the levels of the regression lines of loblolly and shortleaf. The regression line for loblolly occurred at a higher level than that for shortleaf, thus indicating that for a given set of values for the independent variables (slope, depth of the A horizon, and January plus February

TABLE IX

COVARIANCE ANALYSIS - TEST OF H_0: NO SIGNIFICANT DIFFERENCE IN SLOPES OF THE REGRESSION LINES OF LOBLOLLY AND SHORTLEAF PINE

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F
MODEL	7	7169.9160	1024.2737	30.48	0.0001
ERROR	36	1209.9704	33.6103		
TOTAL	43	8379.8863			

SOURCE	DF	TYPE I SS	F VALUE	PR > F	DF	TYPE III SS	F VALUE	PR > F
W	1	4027.3158	119.82	0.0001	1	1.7807	0.05	0.8193
X3	1	1742.2588	51.84	0.0001	1	570.6873	16.98	0.0002
X37	1	525.6953	15.64	0.0003	1	697.6795	20.76	0.0001
X61	1	705.5253	20.99	0.0001	1	849.6193	25.28	0.0001
X3*W	1	81.6871	2.43	0.1277	1	56.6633	1.69	0.2024
X37*W	1	59.1391	1.76	0.1930	1	75.9727	2.26	0.1414
X61*W	1	28.2946	0.84	0.3650	1	28.2946	0.84	0.3650

W = species

TABLE X

COVARIANCE ANALYSIS - TEST OF H_0: NO SIGNIFICANT DIFFERENCE IN LEVELS OF THE REGRESSION LINES OF LOBLOLLY AND SHORTLEAF PINE

SOURCE	DF	SUM OF SQUARES	MEAN SQUARE	F VALUE	PR > F
MODEL	4	7000.7952	1750.1988	49.49	0.0001
ERROR	39	1379.0912	35.3613		
TOTAL	43	8379.8864			

SOURCE	DF	TYPE I SS	F VALUE	PR > F	DF	TYPE III SS	F VALUE	PR > F
W	1	4027.3158	113.42	0.0001	1	2135.1888	60.38	0.0001
X3	1	1742.2588	49.27	0.0001	1	862.2394	24.38	0.0001
X37	1	525.6953	14.87	0.0004	1	749.1745	21.19	0.0001
X61	1	705.5254	19.95	0.0001	1	705.5254	19.95	0.0001

W = species

precipitation) the site index of loblolly pine will be higher than that for shortleaf.

From the covariance analysis a final prediction equation was derived for determination of site index of loblolly and shortleaf pine for the study area:

$$Y = 27.6793 - 17.8802(W) + 3.5357(X_{61}) + 1.3224(X_{37}) - 0.5236(X_3)$$

$$R^2 = 0.84$$

where, Y = site index

W = 0 for loblolly; 1 for shortleaf

X_3 = percent slope

X_{37} = depth of the A horizon

X_{61} = January plus February precipitation

The three independent variables included in the final model all affect the growth of loblolly and shortleaf in the study area mainly through their actions and interactions upon the moisture regime of the sites. The negative correlation of site index with slope indicates that site index values decrease with increasing slope. Slope influences the moisture of the site through its affect on the infiltration rate of precipitation into the soil, surface flow, and subsurface flow. Generally, on steep slopes the infiltration rate of water into the soil will be lower than for an area with a more gentle relief, due mainly to the action of gravity on the water. This results in more precipitation being removed through surface flow from sites with steeper slopes. More moisture is also removed from sites with steeper slopes than on gentle slopes through subsurface flow. This is due to gravity and a decrease in infiltration rates down through the soil profile, which results from an increase in finer soil particles and a decrease in soil porosity. The degree of slope also influences the amount of moisture lost from the site through evaporation. More moisture will be lost from steeper slopes, depending upon the season and aspect, through evaporation due to the amount and angle at which solar radiation is received.

The positive correlation between site index and depth of the A horizon indicates that site index values increase with increasing depth of the surface soil in the study area. According to Zahner (1958) the depth of the surface soil is a measure of the soil available for occupancy by small roots. Since the majority of pine roots are located in the surface soil, sites with deeper soil surfaces provide a greater amount of space for root growth, and consequently, a greater volume of soil providing air, water, and nutrients.

The positive correlation between site index and the precipitation for January and February indicates that site index should increase with higher amounts of precipitation received in these months. It was believed that the amount of precipitation received in the growing season was probably more influential on pine growth in

Oklahoma than precipitation received during the winter. A graph of the monthly precipitation of stations representing the extremities of the study area (Figure 15) shows that the amount of precipitation received for months during the growing season is rather uniform, while the amount of precipitation received during the winter months varies greatly across the study area. The importance of the precipitation received during the winter months is mainly through the recharging of the soil after accumulated summer deficits and providing enough moisture for the initial growth flush of pine in the spring. Precipitation received during the growing season is important in determining the amount of growth of pine during that season, but only if the amount of winter precipitation received has been adequate enough to recharge the soils.

The variables that have been identified in the model explain a considerable amount of the variation in the growth of pine across the study area, however, they may not totally explain the reasons for the distribution of shortleaf pine in the state. Obviously, shortleaf pine can grow beyond its natural range due to evidence supplied by plantations growing on the "Cross Timbers". Also, the site index values for the shortleaf plantations were higher than for many of the sites in the contingent range. Natural regeneration can also occur on the "Cross Timbers", as demonstrated by several plantations in

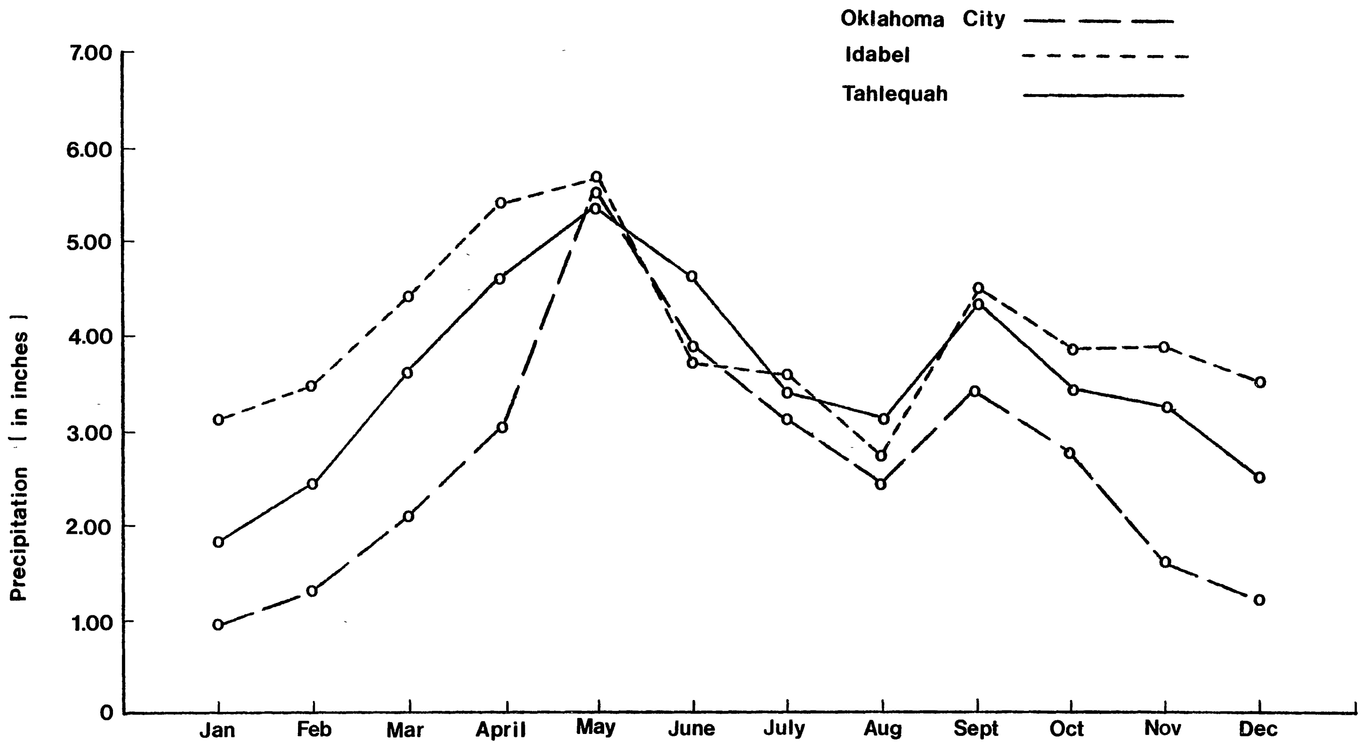

Figure 15. A Comparison of the Monthly Precipitation Received at Stations Representing the Extreme Reaches of the Study Area

the study. Thus, there are factors other than the ones identified in the model that have contributed to the current shortleaf distribution.

One factor that affects distribution is soil texture. Shortleaf occurs over two extensive areas of rough, broken, mountainous terrain, namely the Ozark and Ouachita Mountains. In the Ozarks shortleaf occurs mainly on silty loam soils weathered from limestone, while in the Ouachitas and pine islands it occurs on loam and sandy loam soils weathered from sandstone. Shortleaf rarely occurs on fine textured clayey soils weathered from shales, as evident from its absence in the Arkansas River Valley, the two pineless areas noted earlier, and the areas surrounding the pine islands. The occurrence of shortleaf on coarse textured soils reflects the more favorable moisture regime that occurs on these soils. The roots of shortleaf are able to penetrate to greater depths in coarser textured soils than in clayey soils due mainly to the increased porosity. Similarly, precipitation penetrates to a greater depth in coarse soils, consequently during droughty conditions the water stored at these depths may subsequently be available to tree roots but is not susceptible to evaporation. Also during droughty conditions, the water is not held as tightly by the soil particles, thus it is easily attainable by roots. Therefore, coarse textured soils are more favorable to the growth, survival, and regeneration of shortleaf pine throughout its range.

Competition is another factor that influences distribution. The major situation that shortleaf occuppies across the state is mainly on ridgetops and south and west facing side slopes. This is similar to results found by Fletcher and McDermott (1957) who concluded that shortleaf occuppies these sites because it is here that pine is best able to meet the competition of its associated hardwoods. Shortleaf does not grow on these sites because it prefers to, but because it tolerates the conditions of these sites better than its hardwood associates. Obviously, shortleaf pine will grow faster and taller on sites which are richer in nutrients and have more moisture. However, these better sites are also proportionately better for hardwoods and pine seedlings cannot meet the competition of the hardwood sprouts. Thus, the succession toward a hardwood climax is facilitated on moist, mesic sites. This is evident by the relative decrease or absence of shortleaf pine on north and east facing slopes and on lower slopes.

In the Ozarks the minor contribution of shortleaf to the composition of the stands and the small amount of natural regeneration present indicate that the forests of the Ozarks are probably in the later stages of natural succession moving toward a hardwood climax. In the Ouachitas shortleaf makes up a considerable portion of the stands indicating that natural succession has not progressed as far as in the Ozarks. This is due largely to past forest practices by early settlers and annual fires that occurred over extensive areas during open range, thus allowing shortleaf pine migration into these disturbed areas.

The influence of man has also contributed to the present shortleaf pine distribution. Land use practices, such as clearing of land for pasture, has assisted in altering distribution. Increased fire suppression in recent decades has also played an imortant role. Fire is essential for pine establishment through reduction in competition of associate species, exposure of mineral soil which facilitates seed germination, and opening of the canopy to allow penetration of light.

Potential for Pine Plantations

The relative performance of both loblolly and shortleaf plantations in the study indicate that pine plantations can be established and survive in the environment that exists in the "Cross Timbers". Three of the plantations in the "Cross Timbers", the loblolly and shortleaf plantations at Lamar and the loblolly plantation at Choctaw, were established within the past twelve years. Graphs of the yearly precipitation received at these sites during the time of plantation establishment as compared to the normal yearly precipitation for these areas is presented in Figures 16 and 17.

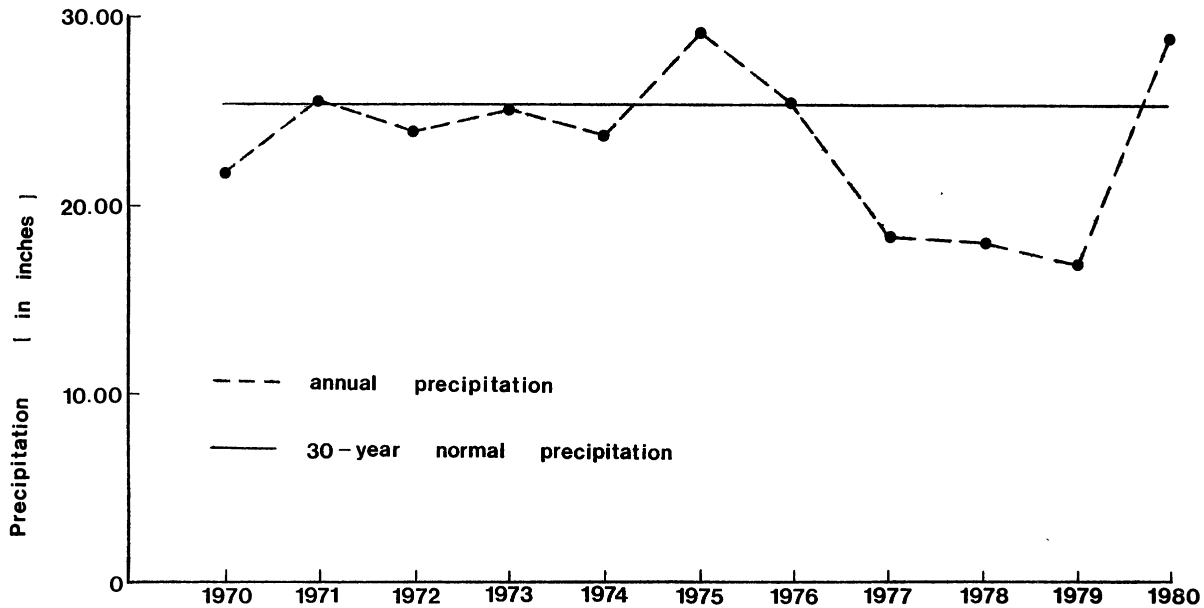

Figure 16. The Yearly Precipitation Received at Choctaw During Plantation Establishment as Compared with the 30-year Normal.

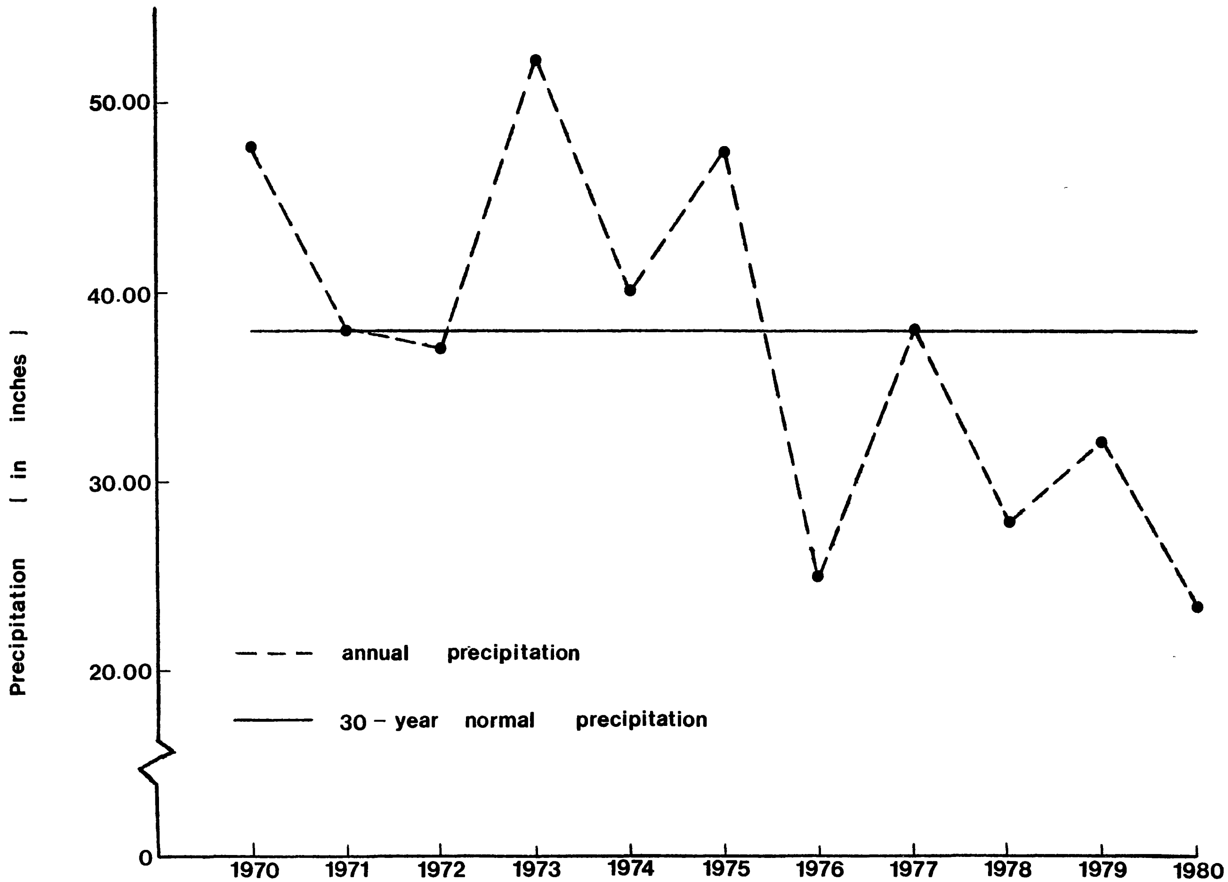

Figure 17. The Yearly Precipitation Received at Lamar During Plantation Establishment as Compared with the 30-year Normal.

The plantations at Lamar were established in 1973. The total precipitation received at Lamar during 1973 was 52.57 inches, 14.9 inches above normal, with 22.9 inches received during March - June. Above average rainfall occurred in 1974 and 1975 followed by a period of drier years with 1980 being the driest year where only 23.68 inches of precipitation was received, 13.99 inches below normal. The loblolly plantation at Choctaw was established in 1972 with 24.0 inches of precipitation, 1.4 inches below normal, occurring. This was followed by years in which below normal precipitation occurred; except 1975 with 29.2 inches of precipitation; with 1979 as the driest year with 16.7 inches, 8.7 inches below normal. The establishment of the plantation at Choctaw during low moisture conditions and the survival of the plantations at Lamar and Choctaw demonstrates the ability of young plantations to become established and survive under conditions that exist on the "Cross Timbers".

Further evidence of the ability of loblolly pine to grow and survive beyond its native range was indicated from the examination of several plantations, not included in the analysis, beyond the study area in western Oklahoma. Two loblolly plantations were examined near Carter, which is 20 miles southwest of Elk City and about 330 miles west of the native loblolly pine range in the state. The average annual precipitation received in this area is about 23 inches. The first plantation covered about five acres and was 25 years in age. The average height of the dominants in the plantation was 39.1 feet; a site index of 39. The second plantation, which occurred on a slightly steeper slope, was 30 years-old and covered eight acres. The average height measured in this plantation was 37.0 feet; a site index of 31.

Both plantations at Carter were located on the Nobscot soil series. This series consists of light-colored soils that formed in deep sands on choppy-surfaced uplands that are undulating to dunelike in places. A typical profile of the Nobscot series (USDA Soil Conservation Service Soil Survey, Jackson County) is presented in Appendix B.

A 27 year-old loblolly plantation was also examined at Blair, just north of Altus and 300 miles west of the native loblolly pine range in the state. This area receives about 24 inches of annual precipitation. The five acre plantation had an average height of 39.0 feet, which is a site index of 36. The plantation at Blair was located on the Springer soil series. The soils of the Springer series are soils of uplands that formed under tall grasses in old alluvium that had been modified by wind. A typical profile of the Springer series (USDA Soil Conservation Soil Survey, Greer County) is presented in Appendix B.

From the study in can be concluded that the major factors of the environment which affect the growth of pine in Oklahoma are those which relate to the soil moisture regime. It can also be concluded that loblolly should grow faster and exhibit a higher site index for a given set of conditions than shortleaf. Sites that could potentially support pine production are those which have a coase textured soil, a fairly deep A horizon, and are level to gently sloping. Based on these site characteristics and additional criteria (total soil depth greater than 24 inches, clay layer not present above 30 inches, etc.) the total number of acres for each county represented in the study area which have the potential to produce pine was identified. This information is presented in Table XIII of Appendix A. Site index maps utilizing the growth prediction model and the precipitation data from across the study area were developed for various classes of slope percentage and A horizon depths. These are presented in Appendix D.

CHAPTER V

SUMMARY AND CONCLUSIONS

As the demand for timber products increases, foresters are faced with the problem of increasing productivity and searching for alternative sources. One possible solution is the expansion of the forest growing land base through conversion of sites supporting low quality vegetation to a more valuable species. In Oklahoma approximately 6.2 million acres of low quality hardwoods exist which may have the potential to support loblolly and shortleaf pine.

The present investigation has been designed to study the growth potential of both loblolly and shortleaf pine beyond their respective ranges. The major objectives of the study are as follows:

1. determine, by examination of historical records, the status of the shortleaf pine range in Oklahoma,
2. ascertain, by physical measurement, factors which have contributed to the development of the current range of shortleaf pine in Oklahoma, including isolated pine islands,

3. make a preliminary assessment of the potential growth of both loblolly and shortleaf pines outside of their respective ranges.

The study area included the native shortleaf pine range in eastern Oklahoma, native isolated shortleaf pine islands, and loblolly and shortleaf plantations growing on the "Cross Timbers" area of east central and central Oklahoma. Twenty-eight samples were taken from the shortleaf pine range and isolated pine islands and fifteen loblolly and shortleaf plantations were sampled on the "Cross Timbers". Site index values (base age = 25 years) were determined from the dominants and codominants of the sampled stands. Site index is a measure of the site potential for specific geographic or genetic strains of a species. Site index is also a measure of all effective factors of site: climate, edaphic, physiographic, and biotic.

Vast differences existed in the environmental conditions present through the study area, which in turn caused differences in site index. Linear correlation studies and regression analyses were undertaken to determine which environmental factors present in the study area were of major importance in determining the growth of loblolly and shortleaf pines in Oklahoma. Regression analysis indicated that the growth of shortleaf and loblolly pine is most strongly related to slope steepness, depth of the A horizon, and the average amount of precipitation occurring in January and February. A suitable prediction equation was derived to determine site index of loblolly and shortleaf pine for the "Cross Timbers" and the shortleaf pine range. The equation is as follows:

$$Y = 27.6793 - 17.8802(W) + 3.5357(X_{61}) + 1.3224(X_{37}) - 0.5236(X_3)$$

where, Y = site index

W = 0 for loblolly; 1 for shortleaf

X_3 = percent slope

X_{37} = depth of the A horizon

X_{61} = January plus February precipitation

From the study the following major conclusions can be drawn:

1. The present natural distribution of shortleaf pine in Oklahoma is decreasing, with the exception of the southeastern part of the state. This is due to natural succession, increased fire suppression, and current land use practices.
2. The major environmental factors (slope, depth of the A horizon, and January and February precipitation) which were found to determine the growth of loblolly and shortleaf pine in Oklahoma are those that affect the soil moisture regime. This agrees with past site quality studies cited in the literature review (Nash, 1963; McClurkin and Covell, 1965; Covell and

McClurkin, 1967; Graney and Ferguson, 1971; Shoulders, 1976; and Shoulders and Tiarks, 1980) which found that the site factors which determined the soil moisture regime were the most influential in determining pine growth.

a. Slope affects the soil moisture of a site through its influence on infiltration. An increase in slope results in a decrease in site index. Similar results were found by Nash (1963), McClurkin and Covell (1965), Graney and Ferguson (1971), and Shoulders (1976).

b. The depth of the A horizon affects the soil moisture regime by providing a space for water storage. An increase in the A horizon depth results in an increase in site index. This agrees with results found by Coile (1952), Dingle and Burns (1954), Zahner (1958), and Covell and McClurkin (1967).

c. The importance of the precipitation received during January and February on the soil moisture regime is through replenishing the soil with moisture needed for the spring growth flush after accumulated moisture deficits. The decrease in the amount of precipitation received during January and February across Oklahoma from east to west results in a decrease in site index from east to west. The importance of winter precipitation on pine growth and distribution was also stressed by Fletcher and McDermott (1957), Nash (1963), and Shoulders and Tiarks (1980).

3. The relative performance of existing plantations on the "Cross Timbers" indicates that pine can be established and survive beyond its present range in Oklahoma. The best sites for plantation establishment are those with little to no slope and have a deep, sandy soil with a deep A horizon.
4. For a given set of environmental conditions at a particular site, the site index of loblolly pine should be higher than that for shortleaf pine. This agrees with results found by Coile (1948), Zahner (1957), and Shoulders and Tiarks (1980).

Results of this study should provide a better understanding of the ecology of the native pines of Oklahoma and their potential for expansion into marginal areas. It is hoped that the growth prediction model will serve as a valuable tool for assisting landowners in identifying sites which have potential for pine production. Furthermore, it is hoped that this study has provided a better understanding of Oklahoma's land base and has identified needs for future research endeavors.

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APPENDIX A

STAND DATA

TABLE XI

STAND DATA FOR THE SHORTLEAF PINE RANGE SAMPLES
AND THE SHORTLEAF PINE ISLAND SAMPLES

	Height		DBH			Site	Soil
	Average	Range	Average	Range	Age	Index (25)	Series
Contingent Range Samples:							
1. Eagletown	94.4	90 - 100	18.3	16.0 - 20.7	57	60	Felker
2. Plunketville	67.6	64 - 69	12.3	10.4 - 13.2	59	39	Carnasaw
3. Bethel	53.6	51 - 64	12.4	10.5 - 13.3	42	37	Carnasaw
4. Corrinne	57.0	53 - 60	10.9	9.6 - 12.1	51	34	Carnasaw
5. Antlers	44.6	42 - 47	10.6	9.8 - 11.4	33	36	Carnasaw
6. Lane	55.3	49 - 61	12.2	10.6 - 14.2	54	32	Bosville
7. Stringtown	46.1	41 - 50	11.3	9.8 - 13.4	51	26	Carnasaw
8. Daisy	53.6	44 - 64	13.5	10.6 - 18.5	52	31	Carnasaw
9. Nashoba	60.7	55 - 65	16.8	14.5 - 20.5	65	31	Clebit
10. Zafra	70.0	64 - 72	13.2	12.1 - 13.9	54	45	Sherless
11. Hodgens	61.0	55 - 68	12.5	10.1 - 13.8	59	34	Carnasaw
12. Poteau	41.5	32 - 47	15.3	13.7 - 16.8	58	19	Carnasaw
13. Red Oak	45.5	40 - 54	12.1	10.5 - 13.7	45	29	Carnasaw
14. Talihina	51.6	48 - 60	9.6	9.0 - 11.0	47	32	Denman

TABLE XI (Continued)

	Height		DBH			Site	Soil
	Average	Range	Average	Range	Age	Index (25)	Series
15. Hartshorne	49.7	42 - 56	15.9	15.0 - 16.5	64	23	Enders
16. Wilburton	52.9	47 - 60	17.7	15.2 - 20.8	94	18	Carnasaw
17. Quinton	31.4	29 - 34	9.3	7.8 - 10.0	37	23	Enders
18. Stilwell	64.2	61 - 66	12.1	11.2 - 13.6	65	33	Bodine
19. Peggs	49.4	47 - 51	13.6	11.9 - 15.1	45	31	Clarksville
20. Jay	50.3	46 - 53	13.7	11.0 - 15.8	75	21	Clarksville
Pine Island Samples:							
21. Marble City	52.1	46 - 56	12.4	13.0 - 16.6	43	35	Bodine
22. Porum	40.3	40 - 42	14.1	12.2 - 16.8	71	16	Endsaw
23. Enterprise	37.1	34 - 42	12.2	10.1 - 14.6	41	24	Hector
24. Henryetta	39.8	34 - 42	13.7	10.2 - 16.9	44	25	Endsaw
25. Crowder	33.8	31 - 43	10.3	8.5 - 12.3	64	13	Enders
26. Stuart	56.1	55 - 60	15.9	14.6 - 17.4	66	28	Hector
27. Coalgate	39.5	36 - 45	13.6	11.9 - 14.6	59	18	Endsaw
28. Atoka	50.1	43 - 57	11.3	9.8 - 12.9	56	27	Enders

TABLE XII

STAND DATA FOR THE LOBLOLLY AND SHORTLEAF PINE PLANTATION SAMPLES

	Height		DBH			Site	Soil
	Average	Range	Average	Range	Age	Index (25)	Series
Loblolly Plantation Samples:							
1. Eagletown	30.6	27 - 33	7.9	6.5 - 8.4	12	57	Felker
2. Valliant	68.9	67 - 71	12.1	10.4 - 13.4	30	59	Ruston
3. Nashoba	21.2	18 - 24	6.9	5.8 - 7.6	12	42	Carnasaw
4. Choctaw	30.9	29 - 32	8.7	7.6 - 9.3	12	57	Stephenville
5. Choctaw	35.7	33 - 42	9.0	8.3 - 12.3	19	45	Stephenville
6. Lamar	17.3	17 - 19	4.3	3.5 - 5.1	10	42	Hector
7. Stillwater	38.3	36 - 41	10.1	9.6 - 10.5	27	35	Stephenville
8. Masena	24.3	22 - 27	5.1	3.5 - 6.1	8	69	Elsah
9. Westville	22.7	18 - 27	5.3	4.2 - 6.1	8	66	Dickinson
10. Jay	27.0	23 - 30	7.3	6.6 - 7.6	10	61	Clarksville
Shortleaf Plantation Samples:							
11. Lamar	14.0	13 - 16	3.1	2.5 - 3.7	10	30	Hector
12. Stillwater	30.5	31 - 38	9.3	8.0 - 11.4	27	28	Stephenville
13. Masena	17.6	14 - 24	3.8	3.3 - 4.5	8	47	Elsah
14. Westville	16.9	13 - 20	3.3	2.2 - 4.2	8	45	Dickinson
15. Jay	20.2	16 - 24	4.2	3.7 - 4.6	10	43	Clarksville

TABLE XIII

THE NUMBER OF ACRES PER COUNTY IN THE STUDY AREA THAT HAVE THE POTENTIAL FOR PINE PRODUCTION

County	Total Acres	Potential Pine Production Acres	Per Cent of County
1. Adair	364,160	252,366	69%
2. Atoka	634,880	244,344	38%
3. Bryan	594,560	206,692	35%
4. Carter	535,680	226,028	42%
5. Cherokee	483,840	284,272	59%
6. Choctaw	508,800	183,123	36%
7. Cleveland	347,800	172,780	50%
8. Coal	336,640	87,032	26%
9. Craig	488,960	62,457	13%
10. Creek	622,000	206,480	33%
11. Delaware	457,600	331,870	73%
12. Garvin	520,960	182,336	35%
13. Grady	698,880	339,472	49%
14. Haskell	366,470	36,575	10%
15. Hughes	518,400	178,120	34%
16. Jefferson	483,200	99,054	20%
17. Johnston	420,480	156,920	37%
18. Latimer	471,680	349,766	74%
19. Leflore	1,012,480	700,522	69%
20. Lincoln	622,720	233,428	37%
21. Logan	478,080	93,055	19%
22. Love	312,320	133,716	43%
23. Marshall	269,440	105,991	39%
24. Mayes	432,640	92,092	21%
25. McClain	366,720	171,838	47%

TABLE XIII (Continued)

County	Total Acres	Potential Pine Production Acres	Per Cent of County
26. McCurtain	1,167,846	945,955	81%
27. McIntosh	460,800	119,273	26%
28. Murray	271,360	39,488	15%
29. Muskogee	520,960	76,928	15%
30. Nowata	369,280	34,240	9%
31. Okfuskee	397,440	166,427	42%
32. Oklahoma	451,200	202,480	45%
33. Okmulgee	448,000	87,122	19%
34. Osage	1,476,480	226,965	15%
35. Ottawa	309,120	81,327	26%
36. Pawnee	378,240	59,050	16%
37. Payne	444,800	101,120	23%
38. Pittsburg	869,760	192,224	22%
39. Pontotoc	460,160	141,455	31%
40. Pottawatomie	513,920	199,552	39%
41. Pushmataha	910,720	601,041	66%
42. Rogers	456,320	135,161	30%
43. Seminole	404,480	209,721	52%
44. Sequoyah	454,555	129,395	28%
45. Stephens	571,520	170,145	30%
46. Tulsa	376,320	82,602	22%
47. Wagoner	360,192	109,340	30%
48. Washington	272,000	35,503	13%
Total of Study Area:	24,694,863	9,459,556	38%

APPENDIX B

SOIL SERIES DESCRIPTIONS

BODINE SOIL SERIES (USDA SOIL CONSERVATION SERVICE SOIL SURVEY, ADAIR COUNTY)

A1 - 0 to 3 inches, light brownish-gray (10YR 6/2) very cherty silt loam, dark grayish-brown (10YR 4/2) when moist; weak, fine and medium, granular structure; friable; rapidly permeable; many roots; chert fragments, ½ inch to 8 inches across and 30 to 75 percent by volume, slightly acid, pH 6.1; gradual wavy boundary.

A2 - 3 to 14 inches, very pale brown (10YR 8/3) very cherty silt loam, pale brown (10YR 6/3) when moist; weak, fine and medium, granular structure; friable; permeable; many roots in upper part; chert fragments 40 to 80 percent by volume; medium acid, pH 6.0; gradual, wavy boundary.

B1 - 14 to 20 inches, very pale brown (10YR 7/3) very cherty light silty clay loam, yellowish-brown (10YR 5/4) when moist; weak, fine, subangular blocky structure; friable; rapidly permeable; chert fragments 60 to 90 percent by volume; strongly acid, pH 5.1; gradual, irregular boundary.

B2t - 20 to 36 inches + chert bed; reddish yellow (5YR 6/6) silty clay loam coating on chert fragments and in interstices, yellowish-red (5YR 5/6) when moist; coarsely mottled in places with very pale brown and strongly brown; weak, fine, subangular block structure; slightly hard when dry, friable when moist; roots can penetrate through crevices and interstices; volume of angular chert and rock increases with increasing depth and makes up 95 percent or more of the total volume; very strongly acid, pH 4.5.

CARNASAW SOIL SERIES (USDA SOIL CONSERVATION SERVICE SOIL SURVEY, McCURTAIN COUNTY)

A1 - 0 to 3 inches, very dark grayish-brown (10YR 3/2) loam; moderate, medium and fine, granular structure; very friable; many fine and medium roots; about 6 percent fine quartzite and thin fragments of sandstone; medium acid; clear, wavy boundary.

A2 - 3 to 9 inches, yellowish-brown (10YR 5/4) loam; weak, medium and fine, granular structure; very friable; many fine and medium roots; about 12 percent fine, gravelly quartzite and thin, flat sandstone fragments; strongly acid; clear, wavy boundary.

B21t - 9 to 15 inches, yellowish-red (5YR 5/8) silty clay loam; strong, medium and fine, subangular blocky structure; friable; common fine and medium roots; nearly continuous clay films on ped faces; few, fine, flat shale fragments and few, fine, rounded sandstone fragments; very strongly acid; gradual, smooth boundary.

B22t - 15 to 37 inches, yellowish-red (5YR 4/8) silty clay; strong, medium, subangular blocky structure; friable, common fine roots; nearly continuous clay films on ped faces; many peds coated with red (2.5YR 4/6) stains; few, thin, shale fragments; very strongly acid; gradual, smooth boundary.

B3t - 37 to 42 inches, yellowish-red (5YR 4/8) silty clay; many, fine and medium, distinct, strong-brown (7.5YR 5/8) and red (2.5YR 4/6) mottles; moderate fine, blocky structure; friable; common fine and few medium roots; patchy clay films on ped faces; about 20 percent by volume, sandstone and shale fragments; strongly acid; clear, irregular boundary.

C - 42 inches, fractured shale bedrock laminated with layers of sandstone; brown and reddish coatings along fractures and cleavage planes, shale and sandstone bedrock tilted 30^{0} from a horizontal plane.

CLARKSVILLE SOIL SERIES (USDA SOIL CONSERVATION SERVICE SOIL SURVEY, DELAWARE COUNTY)

A1 - 0 to 2 inches, dark grayish-brown (10YR 4/2) stony silt loam, grayish brown (10YR 5/2) when dry; about 40 percent stones and chert, by volume; weak, fine, granular structure; slightly hard, very friable; slightly acid; clear, smooth boundary; horizon 1 to 3 inches thick.

A2 - 2 to 10 inches, grayish brown (10YR 5/2) stony silt loam, light gray (10YR 7/2) when dry; about 40 percent stones and chert by volume; weak, fine, granular structure; slightly hard, very friable; strongly acid; gradual, smooth boundary; horizon 6 to 18 inches thick.

B1 - 10 to 20 inches, strong brown (7.5YR 5/6) very stony silty clay loam, reddish-yellow (7.5YR 6/6) when dry; about 60 percent stones and chert, by volume; moderate fine, subangular blocky structure; hard, friable; clay films; very strongly acid; gradual, smooth boundary; horizon 3 to 14 inches thick.

B2t - 20 to 40 inches, strong brown (7.5YR 5/6) very stony silty clay loam, reddish-yellow (7.5YR 6/6) when dry; a few, coarse, brown and gray mottles; about 70 percent stones and chert, by volume; moderate, fine, subangular blocky structure; hard, friable; thin continuous clay films on chert particles and soil particles; very strongly acid; gradual, smooth boundary; horizon 12 to 30 inches thick.

B3 - 40 to 60 inches, chert beds and interlayers of brownish-yellow (10YR 6/6) stony and cherty silty clay loam or cherty silty clay; mottled with strong brown, yellowish-red, and gray, about 80 percent chert, by volume; moderate, very fine, blocky structure; hard, friable; clay films on chert and ped surface; very strongly acid.

ENDERS SOIL SERIES (USDA SOIL CONSERVATION SERVICE SOIL SURVEY, PITTSBURG COUNTY)

A1 - 0 to 2 inches, light brownish-gray (10YR 6/2) fine sandy loam, dark grayish-brown (10YR 4/2) when moist; weak fine and medium, granular structure; numerous surface stones 10 to 20 inches in diameter; friable when moist; pH 5.0; clear boundary; 1 to 4 inches thick.

A2 - 2 to 4 inches, light gray (10YR 7/2) fine sandy loam, pale brown (10YR 6/3) when moist; weak, fine, granular structure; numerous sandstones; friable when moist; pH 4.5; gradual boundary; 2 to 4 inches thick.

A3 - 4 to 9 inches, pale brown (10YR 6/3) and yellowish-red clay loam in ped interstices; moderate, fine, blocky structure; ped faces partly coated with pale brown fine sandy loam; patchy clay films; few sandstones; very firm when moist; extremely hard when dry; pH 4.5; clear boundary; 3 to 7 inches thick.

B2t - 9 to 24 inches, red (2.5YR 5/6) clay, red (2.5YR 4/6) when moist; few, distinct, yellowish-brown mottles; strong, medium, blocky structure; continuous clay films; very firm when moist, extremely hard when dry; pH 5.0; wavy boundary; 8 to 20 inches thick.

R - 24 to 36 inches +, partly weathered, light olive gray shale.

ENDSAW SOIL SERIES (USDA SOIL CONSERVATION SERVICE SOIL SURVEY, ATOKA COUNTY)

A1 - 0 to 4 inches; dark-grayish brown (10YR 4/2) fine sandy loam; weak medium granular structure; very friable; fragments of sandstone less than 75 millimeters in diameter make up 10 percent by volume; medium acid; clear smooth boundary.

A2 - 4 to 9 inches; yellowish-brown (10YR 5/4) fine sandy loam; weak medium granular structure; very friable; fragments of sandstone less than 75 millimeters in diameter make up 10 percent by volume; medium acid; clear smooth boundary.

B21t - 9 to 28 inches; red (2.5YR 4/6) clay; moderate fine blocky structure; very firm; thick clay films on faces of peds; fragments of sandstone less than 75 millimeters in diameter make up 2 percent by volume; very strongly acid; clear smooth boundary.

B22t - 28 to 40 inches; yellowish-red (5YR 5/6) clay; with many coarse prominent yellowish-brown (10YR 5/6) mottles; weak medium blocky structure; very firm; thick clay films on faces of peds; fragments of sandstone less than 75 millimeters in diameter make up 2 percent by volume; very strongly acid; clear smooth boundary.

B3 - 40 to 48 inches; mottled yellowish-red (5YR 5/6), gray (10YR 5/1), and yellowish-brown (10YR 5/6) clay; weak coarse blocky structure; very firm; few clay films on faces of peds; very strongly acid; gradual wavy boundary.

Cr - 48 to 60 inches; pale yellow (5YR 8/3) soft shale; slightly acid; tilted 10 degrees from the horizontal.

HECTOR SOIL SERIES (USDA SOIL CONSERVATION SERVICE SOIL SURVEY, PITTSBURG COUNTY)

A1 - 0 to 3 inches; brown (10YR 4/3) fine sandy loam; weak medium granular structure; very friable; about 10 percent coarse fragments of sandstone; strongly acid; clear smooth boundary.

A2 - 3 to 6 inches; brown (10YR 5/3) fine sandy loam; weak medium granular structure; very friable; about 10 percent coarse fragments of sandstone; strongly acid; clear smooth boundary.

B2 - 6 to 18 inches; strong brown (7.5YR 5/6) loam; weak medium subangular blocky structure; friable; about 10 percent coarse fragments of sandstone; very strongly acid; abrupt irregular boundary.

R - 18 to 22 inches; hard fractured sandstone.

NOBSCOT SOIL SERIES (USDA SOIL CONSERVATION SERVICE SOIL SURVEY, JACKSON COUNTY)

A_1 - 0 to 4 inches, grayish-brown (10YR 5/2, dry; 4/2, moist) fine sand; single grain (structureless); loose when dry; noncalcareous (pH 6.0); wavy boundary.

A_2 - 4 to 25 inches, light-brown (7.5YR 6.5/4, dry; 6/4, moist) fine sand; single grain (structureless); loose when wet or dry; noncalcareous (pH 6.0).

A_3 - 25 to 40 inches, red (2.5YR 5/6, dry; 4/6, moist) fine sandy loam; porous, massive (structureless); hard when dry, friable when moist; noncalcareous (pH 6.5); gradual boundary.

C_1 - 40 to 84 inches, light-red (2.5YR 6/6, dry; 5/6, moist) fine sandy loam with htin lenses of fine sand; hard when dry, friable when moist; noncalcareous (pH 6.5).

SPRINGER SOIL SERIES (USDA SOIL CONSERVATION SERVICE SOIL SURVEY, GREER COUNTY)

A_p - 0 to 8 inches, brown (7.5YR 5/4) loamy fine sand; dark brown (7.5YR 3/4) when moist; weak, granular structure; very friable when moist, soft when dry; pH 7.0; plowed boundary. 4 to 16 inches thick.

A12 - 8 to 19 inches, brown (7.5YR 5/4) loamy fine sand; dark brown (7.5YR 3/4) when moist; moderate, fine, granular structure; very friable when moist, soft when dry; pH 7.0; gradual boundary. 4 to 12 inches thick.

B2t - 19 to 33 inches, reddish-brown (5YR 5/4) sandy loam; dark reddish-brown (5YR 3/4) when moist; moderate, coarse, prismatic structure; friable when moist, hard when dry; clay films on faces of peds; pH 6.5; gradual boundary. 12 to 20 inches thick.

B3 - 33 to 42 inches, yellowish-red (5YR 5/6) loamy fine sand; yellowish-red (5YR 4/6) when moist; weak, coarse, prismatic structure; gradual boundary. 6 to 14 inches thick.

C - 42 to 50 inches +, yellowish-red (5YR 5/6) loamy sand; yellowish-red (5YR 4/6) when moist; structureless; pH 7.0.

STEPHENVILLE SOIL SERIES (USDA SOIL CONSERVATION SERVICE SOIL SURVEY, OKLAHOMA COUNTY)

A1 - 0 to 4 inches, grayish-brown (10YR 5/2) fine sandy loam, very dark grayish-brown (10YR 3/2) when moist; weak, fine, granular structure; soft when dry, very friable when moist; nuetral; clear boundary; horizon 3 to 6 inches thick.

A2 - 4 to 14 inches, light brown (7.5YR 6/4) light fine sandy loam, dark brown (7.5YR 4/4) when moist; massive; soft when dry; friable when moist; medium acid; clear boundary; horizon 6 to 14 inches thick.

B2t - 14 to 26 inches, yellowish-red (5YR 5/6) sandy clay loam, yellowish-red (5YR 4/6) when moist; weak, fine, subangular blocky structure; hard when dry, firm when moist; medium acid; gradual boundary; horizon 7 to 15 inches thick.

B3 - 26 to 40 inches, red (2.5YR 5/6) sandy clay loam, red (2.5YR 4/6) when moist; massive; hard when dry, friable when moist; medium acid; gradual boundary; horizon 12 to 16 inches thick.

R - 40 to 45 inches +, light red (2.5YR 6/6) soft sandstone, red (2.5YR 4/6) when moist; medium acid.

STIGLER SOIL SERIES (USDA SOIL CONSERVATION SERVICE SOIL SURVEY, LATIMER COUNTY)

A1 - 0 to 11 inches; dark grayish brown (10YR 4/2) silt loam; weak fine granular structure; friable; many fine roots; few dark brown concretions; strongly acid; gradual wavy boundary.

A2 - 11 to 22 inches; brown (10YR 5/3) silt loam; few fine faint yellowish-brown mottles; weak medium granular structure; friable; common fine roots; common dark brown concretions; strongly acid; gradual wavy boundary.

B21t - 22 to 35 inches; yellowish-brown (10YR 5/4) silty clay; common medium distinct pale brown (10YR 6/3), brownish yellow (10YR 6/6), red (2.5YR 4/6), and gray (10YR 6/1) mottles; moderate medium blocky structure; very firm; clay films on faces of peds; few black and dark brown concretions; medium acid; diffuse wavy boundary.

B22t - 35 to 55 inches; yellowish-brown (10YR 5/6) silty clay; many medium and coarse distinct pale brown (10YR 6/3), dark brown (10YR 3/3), and gray (10YR 6/1) mottles; moderate medium blocky structure; very firm; clay films on faces of peds; few dark brown and black concretions; medium acid; diffuse wavy boundary.

B3 - 55 to 72 inches; coarsely mottled yellowish-brown (10YR 5/6), brown (10YR 4/3), and gray (10YR 6/1) silty clay; weak coarse blocky structure; very firm; few clay films on faces of peds; few medium dark brown and black concretions; slightly acid.

TUSKAHOMA SOIL SERIES (USDA SOIL CONSERVATION SERVICE SOIL SURVEY, LEFLORE COUNTY)

A1 - 0 to 5 inches; dark grayish brown (10YR 4/2) stony loam; moderate fine granular structure; friable; fragments of sandstone make up 15 percent of the volume; medium acid; abrupt smooth boundary.

B2t - 5 to 10 inches; brown (10YR 4/3) clay; many fine distinct yellowish-red mottles and few fine faint dark grayish brown mottles; moderate medium blocky structure; firm; continuous clay films on faces of peds; few fine fragments of shale; medium acid; gradual wavy boundary.

B3 - 10 to 15 inches; dark gray (10YR 4/1) shaly clay; common fine distinct yellowish-red mottles; weak medium blocky structure; firm; thin patchy clay films on faces of peds; fragments of shale make up 25 percent of the volume; medium acid; gradual irregular boundary.

Cr - 15 to 30 inches; gray (10YR 5/1) soft shale bedrock that has thin layers of shaly clay; tilted 40^0 from horizontal; nuetral.

APPENDIX C

CLIMATIC DATA

TABLE XIV

THE AMOUNT OF MONTHLY AND ANNUAL PRECIPITATION IN WHICH TWO YEARS IN TEN WILL RECEIVE LESS THAN OR EQUAL TO FOR STATIONS IN THE STUDY AREA - inches

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
1. Idabel	1.19	1.81	2.08	2.79	2.62	0.96	1.23	0.65	1.95	1.67	1.67	1.66	40.31
2. Smithville	0.95	1.99	2.94	3.00	3.00	1.55	1.60	1.03	1.80	0.89	1.69	2.38	43.46
3. Flashman Tower	1.16	1.61	2.32	3.38	3.04	1.52	1.64	1.96	2.25	0.85	1.98	2.03	41.21
4. Bear Mountain Tower	1.32	1.59	2.02	2.85	3.23	1.63	1.30	0.89	1.81	1.10	1.50	2.07	40.56
5. Valliant	1.13	1.52	1.66	2.94	3.01	1.32	1.26	0.71	1.58	0.75	1.17	1.28	33.00
6. Sobol Tower	0.98	1.69	2.15	2.23	2.27	1.34	1.15	1.57	2.30	1.32	1.19	1.94	38.88
7. Hugo	0.93	1.30	1.16	2.52	3.30	2.04	0.66	0.94	1.89	0.58	1.19	0.58	37.49
8. Antlers	0.82	1.35	1.85	2.29	2.99	1.27	0.79	1.23	1.82	0.81	1.16	1.46	35.95
9. Daisy 2E	0.71	1.34	1.46	2.22	3.13	1.54	1.58	1.05	2.62	0.32	1.13	1.12	37.07
10. Atoka	0.50	0.99	1.35	2.79	3.33	1.22	1.04	0.62	3.03	0.50	0.46	0.70	32.53
11. Durant	0.56	1.07	1.26	1.89	2.87	1.79	0.58	0.73	2.16	0.51	0.75	0.99	34.28
12. Coalgate	0.51	1.00	1.60	3.04	2.95	2.30	1.05	0.95	1.94	0.79	0.77	0.97	33.27
13. Ada	0.42	0.83	1.12	2.44	2.98	1.75	0.71	1.28	1.32	0.88	0.86	0.87	26.87
14. Holdenville	0.20	0.76	1.14	1.71	3.34	2.18	1.31	1.05	1.15	0.70	0.51	0.85	27.91
15. McAlester	0.50	1.11	1.63	2.42	3.64	1.46	0.83	0.92	1.49	0.50	0.98	1.28	32.79
16. Quinton	0.71	0.99	1.61	2.06	2.40	1.41	1.13	1.13	1.52	0.75	1.01	1.11	32.18

TABLE XIV (Continued)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
17. Wilburton	0.68	1.10	1.91	2.43	3.07	1.78	1.41	1.63	2.52	0.92	1.50	1.52	38.26
18. Heavener	0.91	1.07	1.88	2.75	2.60	1.13	1.65	0.90	1.79	0.79	1.64	1.64	35.16
19. Poteau	0.81	1.09	1.98	2.32	3.19	1.32	1.00	1.57	2.02	1.09	1.56	1.45	32.16
20. Sallisaw	0.79	1.17	1.60	2.07	3.05	1.96	1.13	1.18	1.75	0.71	1.29	0.98	35.22
21. Tenkiller Ferry Dam	0.79	1.05	2.05	3.06	3.21	2.57	1.38	1.47	1.35	0.59	0.68	1.11	33.39
22. Stilwell	0.93	1.45	1.69	3.02	2.67	2.01	0.96	1.59	1.83	0.73	1.14	1.21	37.04
23. Tahlequah	0.75	0.96	1.98	2.57	3.12	2.94	0.78	1.62	1.18	0.73	0.85	0.77	32.88
24. Eufaula	0.65	1.06	1.87	3.12	3.09	1.69	0.66	1.20	1.37	0.76	0.93	1.13	32.04
25. Muskogee	0.83	0.90	1.41	3.10	2.67	2.23	0.75	1.40	1.60	0.80	0.92	1.44	32.53
26. Okmulgee	0.62	0.89	1.35	2.67	3.25	2.07	0.76	1.32	0.83	0.95	0.68	0.77	27.98
27. Oklahoma City	0.26	0.69	0.85	2.06	2.08	1.34	1.21	1.24	0.99	0.84	0.10	0.45	24.17
28. Stillwater	0.15	0.33	0.72	1.88	2.03	1.38	1.06	1.03	0.77	0.69	0.34	0.41	24.12
29. Pryor	0.69	0.79	1.21	2.04	3.05	2.56	0.85	1.68	0.68	0.91	0.92	0.82	31.87
30. Jay	0.78	1.01	1.78	2.20	2.42	2.47	1.06	1.63	1.01	1.36	0.90	1.21	32.83
31. Grand River Dam	0.67	1.18	1.29	2.13	2.18	1.70	0.89	1.51	0.84	0.95	0.81	1.18	32.22
32. Vinita	0.78	0.98	1.28	2.53	3.07	2.54	1.27	1.33	1.04	1.04	0.79	0.81	31.67

TABLE XV

THE AMOUNT OF MONTHLY AND ANNUAL PRECIPITATION IN WHICH TWO YEARS IN TEN WILL RECEIVE GREATER THAN OR EQUAL TO FOR STATIONS IN THE STUDY AREA - inches

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
1. Idabel	4.90	5.09	7.05	9.09	8.47	6.71	6.62	5.21	7.11	6.17	6.45	4.21	52.34
2. Smithville	4.46	4.70	7.07	7.79	9.99	6.99	7.88	6.25	7.53	8.89	6.58	5.58	62.97
3. Flashman Tower	4.00	4.62	6.03	8.73	9.28	6.15	6.84	6.14	7.90	6.72	7.08	4.60	58.17
4. Bear Mountain Tower	3.72	5.00	6.42	7.89	7.48	4.69	8.09	6.33	8.23	7.24	5.93	5.85	55.26
5. Valliant	4.04	6.38	5.23	6.55	8.26	5.49	7.67	5.43	7.06	5.54	6.26	5.91	50.31
6. Sobol Tower	4.15	4.38	5.87	9.62	9.64	5.11	7.55	5.74	8.03	5.33	6.06	5.04	53.17
7. Hugo	3.39	4.31	5.59	6.53	9.70	7.54	5.73	5.96	8.82	6.19	5.26	4.07	49.96
8. Antlers	3.36	4.02	4.97	7.82	8.58	6.11	6.32	4.55	8.99	6.96	5.30	3.97	50.76
9. Daisy 2E	2.95	3.84	5.31	7.75	9.64	7.32	6.01	5.74	9.48	7.13	6.20	3.80	57.32
10. Atoka	2.75	3.59	4.60	6.80	6.41	6.56	4.97	6.29	8.31	6.33	5.49	3.76	49.55
11. Durant	2.92	3.78	4.89	7.30	7.73	5.64	3.74	4.24	8.23	5.75	4.51	2.68	46.62
12. Coalgate	2.52	2.98	6.02	6.87	7.54	5.77	4.52	4.72	8.28	6.15	5.26	3.38	48.25
13. Ada	2.01	3.09	4.50	5.27	6.88	5.46	4.38	5.63	6.93	7.19	4.26	3.33	45.00
14. Holdenville	2.06	2.56	4.18	6.93	9.52	5.49	5.60	3.85	6.00	5.36	3.34	2.87	47.49
15. McAlester	2.82	3.65	5.48	6.79	7.30	6.84	5.56	6.00	7.82	7.22	4.88	3.96	51.28
16. Quinton	2.52	2.96	5.47	6.44	7.72	6.73	5.22	5.01	7.24	6.03	5.25	3.60	52.81

TABLE XV (Continued)

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Total
17. Wilburton	3.02	3.52	5.58	7.49	7.92	6.31	6.75	4.05	7.07	6.32	5.67	4.51	54.18
18. Heavener	3.32	4.24	6.05	7.84	8.80	6.43	5.11	6.09	6.98	5.66	6.12	5.02	54.28
19. Poteau	2.47	3.89	6.35	6.88	9.27	5.63	6.47	4.91	6.55	5.22	6.93	4.61	50.18
20. Sallisaw	2.58	3.72	5.20	6.77	8.67	6.01	5.30	5.01	7.03	6.11	4.80	4.28	57.73
21. Tenkiller Ferry Dam	2.79	3.49	4.75	6.61	7.18	6.01	5.38	4.78	7.38	5.86	4.73	4.13	49.77
22. Stilwell	3.18	3.62	4.93	6.07	7.17	7.34	5.27	5.15	5.36	5.58	4.94	4.50	51.79
23. Tahlequah	2.51	2.97	4.57	6.68	8.45	6.61	4.98	4.61	5.38	5.49	5.17	4.34	52.56
24. Eufaula	2.23	2.97	5.81	6.46	7.52	5.72	5.52	5.42	7.48	4.97	4.66	3.93	48.96
25. Muskogee	2.37	2.82	4.64	5.97	6.84	5.56	5.10	5.16	7.36	6.62	4.41	3.73	48.43
26. Okmulgee	2.72	2.96	3.94	5.73	7.36	7.39	4.71	4.27	7.52	5.39	4.47	2.65	46.30
27. Oklahoma City	1.47	2.05	3.21	5.22	7.85	6.68	5.05	3.75	6.51	4.66	3.81	1.97	37.42
28. Stillwater	0.99	2.02	2.91	4.83	6.63	6.08	5.23	3.78	6.23	4.54	3.12	1.66	33.04
29. Pryor	2.22	2.50	4.21	5.38	6.25	6.58	5.35	5.07	6.65	6.20	4.42	3.07	46.49
30. Jay	2.34	3.08	5.31	6.00	7.41	7.93	6.29	5.04	8.04	6.68	4.72	3.24	54.85
31. Grand River Dam	2.08	2.43	4.51	5.27	6.21	7.58	5.76	4.27	7.45	5.43	3.93	2.80	50.55
32. Vinita	2.16	2.72	4.92	5.84	6.87	6.99	4.88	6.27	9.29	5.76	5.94	3.39	50.26

TABLE XVI

THE TEMPERATURE FOR EACH MONTH FOR STATIONS IN THE STUDY AREA IN WHICH TWO YEARS IN TEN WILL HAVE A DAILY TEMPERATURE IN THE MONTH THAT IS GREATER THAN OR EQUAL TO - ^{0}F

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1. Idabel	77	80	88	88	93	100	104	106	101	93	83	79
2. Smithville	74	79	81	86	91	99	105	106	100	93	81	75
3. Antlers	78	82	89	88	92	99	105	106	102	94	84	76
4. Durant	79	82	88	90	94	103	107	109	102	96	84	79
5. Atoka	77	82	90	89	92	98	105	105	101	97	83	78
6. Ada	76	80	88	90	94	98	105	105	100	95	82	75
7. Holdenville	77	81	88	89	83	100	106	107	102	95	82	76
8. McAlester	76	80	87	90	91	99	106	107	101	95	83	76
9. Wilburton	76	80	86	90	93	101	106	107	103	94	84	76
10. Poteau	76	81	87	89	93	100	107	107	103	94	83	75
11. Eufaula	75	80	89	90	91	99	108	107	102	95	81	77
12. Sallisaw	75	79	87	90	92	99	105	106	101	93	82	76
13. Tahlequah	74	79	85	89	92	99	107	106	101	95	81	75
14. Muskogee	74	79	88	90	92	98	105	106	101	93	81	76
15. Okmulgee	75	82	88	91	92	99	106	105	101	95	83	76
16. Oklahoma City	73	78	87	92	95	100	104	105	102	95	81	73
17. Stillwater	73	77	88	90	96	99	104	106	102	96	80	72
18. Grand River Dam	72	80	87	90	93	99	106	106	99	92	80	75

TABLE XVII

THE TEMPERATURE FOR EACH MONTH FOR STATIONS IN THE STUDY AREA IN WHICH TWO YEARS IN TEN WILL HAVE A DAILY TEMPERATURE IN THE MONTH THAT IS LESS THAN OR EQUAL TO - ^{0}F

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
1. Idabel	7	10	20	30	41	51	57	57	44	31	16	11
2. Smithville	0	8	15	26	35	45	52	53	38	27	13	6
3. Antlers	3	10	17	29	39	49	55	55	41	28	16	12
4. Durant	4	12	16	31	39	52	59	56	44	31	18	9
5. Atoka	3	12	18	30	40	49	58	56	42	31	16	9
6. Ada	0	8	14	28	40	50	57	56	42	32	16	8
7. Holdenville	2	10	12	29	40	52	60	58	45	32	16	8
8. McAlester	0	9	14	28	39	51	56	55	43	30	17	7
9. Wilburton	0	8	14	26	36	47	53	50	39	28	17	7
10. Poteau	1	9	18	29	39	49	55	54	42	28	18	7
11. Eufaula	2	9	15	30	42	52	58	56	44	33	17	7
12. Sallisaw	1	9	14	28	38	49	56	54	41	30	14	7
13. Tahlequah	-3	5	12	23	34	46	51	52	38	26	13	4
14. Muskogee	1	9	14	29	40	50	57	56	43	31	15	5
15. Okmulgee	0	7	11	27	37	50	53	52	40	27	13	3
16. Oklahoma City	2	9	12	28	39	50	54	55	40	28	14	5
17. Stillwater	2	8	12	28	38	49	53	54	41	27	13	4
18. Grand River Dam	-3	2	12	25	35	48	54	54	41	28	13	0

APPENDIX D

PREDICTED SITE INDEX MAPS

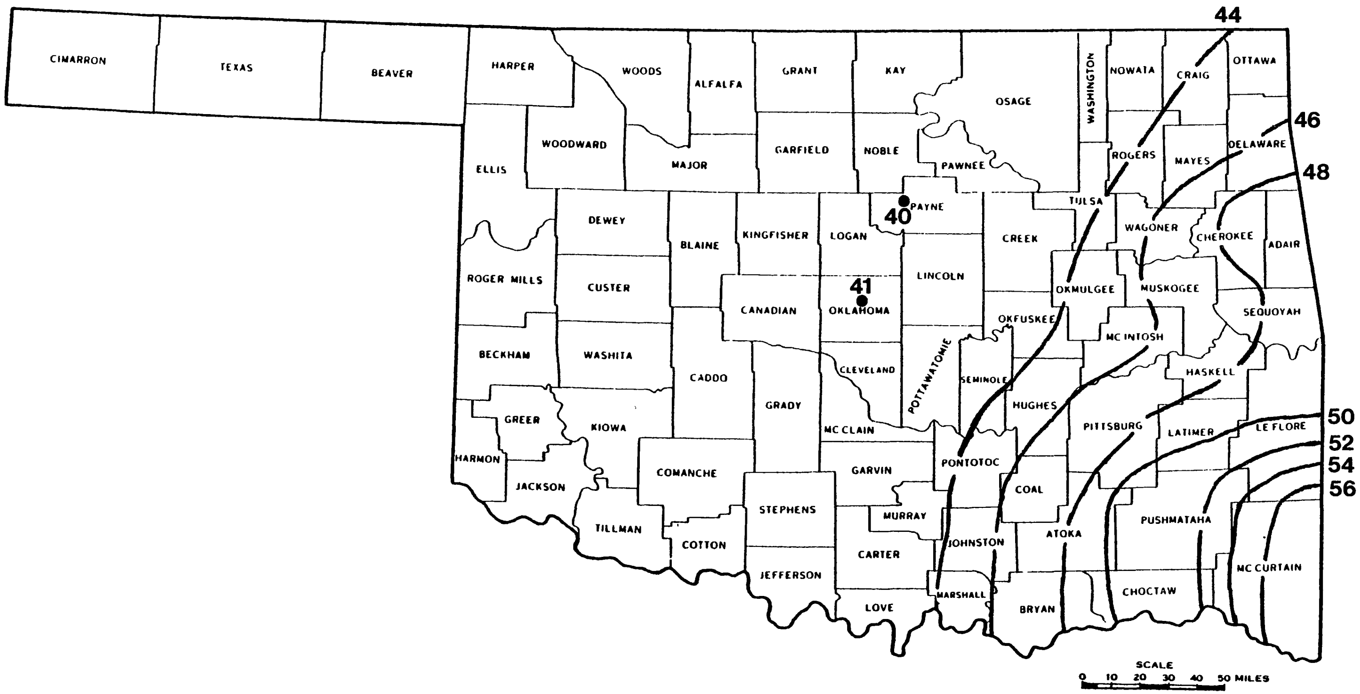

Figure 18. Predicted Site Index Values of Loblolly Pine with A Horizon Depth = 6 Inches and Slope = 5%

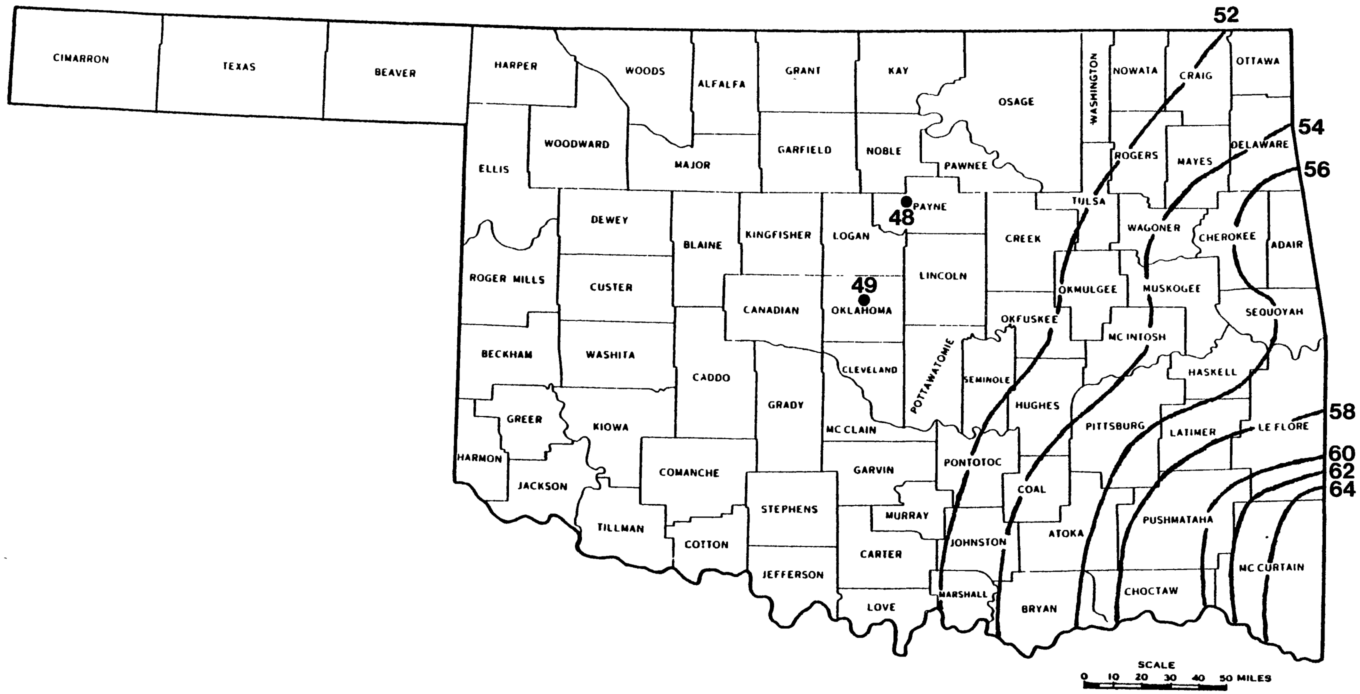

Figure 19. Predicted Site Index Values of Loblolly Pine with A Horizon Depth = 12 Inches and Slope = 5%

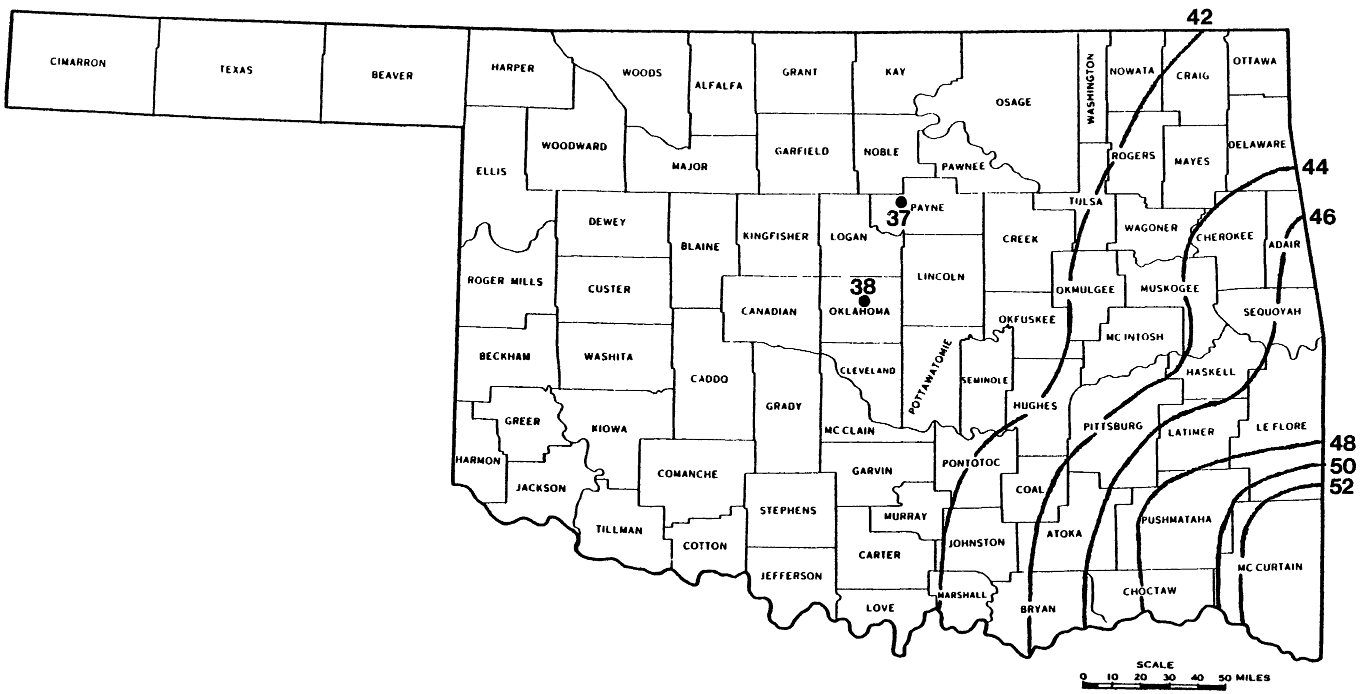

Figure 20. Predicted Site Index Values of Loblolly Pine with A Horizon Depth = 6 Inches and Slope = 10%

Figure 21. Predicted Site Index Values of Loblolly Pine with A Horizon Depth = 12 Inches and Slope = 10%

Figure 22. Predicted Site Index Values for Shortleaf Pine with A Horizon Depth = 6 Inches and Slope = 5%

Figure 23. Predicted Site Index Values of Shortleaf Pine with A Horizon Depth = 12 Inches and Slope = 5%

Figure 24. Predicted Site Index Values of Shortleaf Pine with A Horizon Depth = 6 Inches and Slope = 10%

Figure 25. Predicted Site Index Values of Shortleaf Pine with A Horizon Depth = 12 Inches and Slope = 10%

VITA

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