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To the Graduate Council:

I am submitting herewith a thesis written by Wayne Madison Boyd entitled "Forest Stand Projections under Conditions of Uncertainty-- A Markov Chains Approach." I recommend that it be accepted for nine quarter hours of credit in partial fulfillment of the requirements for the degree of Master of Science, with a major in Forestry.

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FOREST STAND PROJECTIONS UNDER CONDITIONS OF
UNCERTAINTY--A MARKOV CHAINS APPROACH

A Thesis

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the Graduate Council of
The University of Tennessee

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ABSTRACT

The study was conducted using hardwood diameter and mortality data from two five-year remeasurements of permanent continuous forest inventory (C.F.I.) systems. These C.F.I. plots were located on three Forestry Field Stations managed by the Forestry Department, The University of Tennessee. These three Field Stations were: Ames Plantation (located in Fayette and Hardman Counties), Highland Rim (located in Franklin County), and the Cumberland Station (located in Morgan and Scott Counties). These three Field Stations furnished four experimental forest tracts for study which were: Ames Plantation, Highland Rim, and the Morgan and Scott Counties, which were parcels of the Cumberland Field Station.

C.F.I. data were limited to diameter ranges of 5.0 to 10.5 inches. Five-year diameter distributions were established with one-half-inch diameter classes. Markov chain theory was then used to project and evaluate these distributions.

The objectives of this study were to compare present and projected hardwood diameter distributions and their resulting differences over the four experimental forest tracts. Comparisons were made among tracts, individual selected species on different tracts, and selected species within each tract. Markov chains were selected in order to quantify total stand variation in some of the major hardwood species of Tennessee.

Markov chain analysis proved to be a more useful mathematical tool of management science than was anticipated. When data were adequate, four basic categories of results were obtained: initial and projected diameter distributions, projected time periods to reach larger

diameter classes, expected time periods that trees can be expected to remain in each diameter class, and projected mortality percentages.

The analysis revealed extremely long time period projections for both entire tracts and individual species. The ability of stands to differentiate within diameter classes over entire forest tracts was, to some extent, related to tract productivity. However, where all hardwoods were concerned, Ames Plantation did not perform according to expectations. Projected mortality differences between the Morgan and Scott County forest tracts were unexpected, given their close proximity and similar species composition.

The majority of individual species performed according to traditional growth expectations. Ames Plantation possessed both the slowest and fastest growing species. Respectively, these were sweetgum (Liquidambar styraciflua) and southern red oak (Quercus falcata). Inconsistencies did exist in the sweetgum at Ames. Both growth rates and mortality levels were much less than anticipated for this species. In addition, projected growth rates revealed similarity between yellow-poplar (Liriodendron tulipifera), red maple (Acer rubrum), and chestnut oak (Quercus prinus) on the Morgan and/or Scott County forest tracts.

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CHAPTER I

INTRODUCTION

Background

In 1962 a research study to determine the factors influencing forest composition and growth was initiated by The University of Tennessee Agricultural Experiment Station. In all, 512 permanent sample plots were established on four University forest tracts. Over 15,000 acres of forest land were sampled. These forests represent a wide diversity in forest types and physiographic regions within the state. The objectives of this long-term study were as follows: "(1) relate soil and other site factors, such as aspects, topography, position, and slope, to species composition and growth rate; and (2) establish a modern timber inventory system for all forest tracts" (Tennessee Agriculture Experiment Station Research Project Hatch 107, 1962).

Related studies already have been completed under this project (Thor et al., 1969). Four of these studies included Master's theses. Martin (1966) and Summers (1968) theses' were related to site factors and stand composition, while the work of MacDonald (1964) and Martin (1970) was related to the development of a system for inventory and growth, in objective two above.

Current Study

The current study was a continuation of the above research project. It involved the study of periodic growth rates over a range of diameter classes. One growth parameter, tree diameter, was analyzed as

a factor in the dynamics of stand composition. The goal of this study was to quantify portions of the total variation that results in stand differentiation. Emphasis was placed on the more important hardwood species in Tennessee, seven of which were analyzed separately.¹ Such bench-mark information was needed to shed more light on the more complex relationships that result from growing trees interacting with each other and their environment.

Intensifying management for anticipated demands on timber resources requires adequate growth information. Since it is the young, immature stands that will respond best to silvicultural manipulation, only 5.0-10.5 inch diameter trees were included in the current study. If future stand structures of mature forests could be predicted from growth of younger stands, new and better timber management systems could be designed and planned. Diameter prediction is very important in growth predictions, but it must be recognized as only one factor in total timber productivity.

Leak (1964) listed four concerns of a forester interested in management and regulation planning: (1) species composition; (2) quality; (3) volume; and (4) diameter distributions. Of these four characteristics, Leak stated that diameter distribution was probably the least understood. Diameter growth information is especially important in natural hardwood stands of the eastern deciduous forests which contain a complex

¹These species were sweetgum (Liquidambar styraciflua), southern red oak (Quercus falcata), post oak (Quercus stellata), chestnut oak (Quercus prinus), hickory (Carya sp.), yellow-poplar (Liriodendron tulipifera), and red maple (Acer rubrum). Common names and their scientific equivalents of all species studied and all hardwood species on each forest tract are listed in Appendix A.

species composition. Projection information on growth in such stands would be very beneficial in making silvicultural recommendations, and possible species and rotational length selections.

The objectives of this study were to compare present and projected hardwood diameter distributions and their resulting differences over the four experimental forest tracts. Comparisons were made among total tracts, individual species on different tracts, and species within each tract. Diameter projections have been computed by the use of a mathematical tool of management science known as Markov chains. The theory of Markov chains allows the interpretation of diameter growth as a stochastic process.

Part of the lack of understanding in the past of diameter distributions involves their stochastic properties and nature. The markovian theory selected allows the use of a probabilistic approach based on the definition of diameter classes as states. Performance over some past time period is required. It assumes that no drastic or catastrophic changes have occurred.

It is believed that the Markov chains approach will prove to be a useful tool for more realistic stand table projections. The methods applied in this study should be especially applicable to public and private forestry agencies using C.F.I. systems. Also, such quantified information should aid in decision-making and allow for better selections among management alternatives in natural hardwood forests.

CHAPTER II

LITERATURE REVIEW

This chapter has been subdivided into reviews of research methodology and the silvics of forest stand differentiation. The management science tool, Markov chains, has received limited forestry application. Only three applications in silviculture and timber management were found by the writer. Therefore, the historical development of several management science tools used in forestry was included. The latter subdivision included past studies of forest growth and stand projections. This section was more restrictive in scope than the review of methodology and pertained to only a few selected studies. These studies illustrated: (1) factors affecting growth of the seven species currently studied; (2) hardwood diameter growth distributions and predictions; (3) changes in hardwood species composition; and (4) mortality.

I. RESEARCH METHODOLOGY

Influence of Computer Automation

The age of automation has revolutionized man's technology. It has affected every branch of resource science. Duerr (1967) listed as one of his thirteen predictions the fact that in the future automation will play a mandatory role in forest resource management. He stated that large segments and processes of forest resources will be described as systems of variables that can be measured numerically, and that mathematical equations will have been developed concerning relationships

between these variables, and that management alternatives will be "clear-cut," using such equations and tabulations. He also predicted that as product demands increase, renewable resource management will likely be greatly intensified.

As the need arises, traditional concepts change. This is true of forest management. Hall (1967) revealed a new "system" concept of forest management when he stated:

Now managers must develop entire organizations of people, land, trees, markets, and financial resources into smoothly, functioning units, defining their goals, and fitting them into a larger economic and social environment upon which they depend and which depends upon them.

Management Science Tools in Forestry

According to Ripley and Yandle (1969) such management science tools as simulation, mathematical programming, discounted cash flow, real-time management information systems, and dynamic programming are in use in forest resource management today. The advent of the computer has initiated the use of these tools to solve the more complicated problems in forest management planning and decision making.

According to Kidd (1966), the most widely used management science tool in forest management is linear programming. It was probably first introduced in forestry by Coutu and Ellertsen (1960) to solve land-use problems. Kidd and many others, such as McCurdy (1961), Curtis (1962), Loucks (1964), and Curlin and Norman (1968), have used linear programming to derive cutting schedules which solved problems involving optimum allowable cuts. With the exception of Curlin and Norman, traditional concepts of forest regulation were generally assumed in all the above studies.

Hool (1966) used dynamic programming as an approach to the same forest production control problem. His approach, however, generated silvicultural prescriptions for all possible forest conditions at different times in the planning interval. From these prescriptions, the most appropriate were selected to either maximize or minimize the return or cost of that particular management objective. Hool also claimed to be the first to use a probability approach to solve forestry problems.

Recently, interest has been stimulated in the probabilistic approach of decision-making in forestry. Suzuki (1967) conducted a probabilistic study in which the dynamics of forest change were interpreted in stochastic terms.

Thompson (1968) studied the conditions of uncertainty in forest management decisions. He investigated the compatibility of the Bayesian decision theory and problems in forest management decision making under conditions of uncertainty.

Few published studies have used the probabilistic approach of Markov chains to solve timber management problems. Hool (1966) combined Markov chains in connection with dynamic programming. He computed the risks involved in forest condition prediction with markovian theory. Leak (1969) in a recent study used a probabilistic approach in the problem of predicting the stocking of northern-hardwood regeneration. The probabilities of a tree being alive at a given future mean stand diameter were used as the initial state. From these probabilities he predicted the average number of trees required to produce one tree at some future mean diameter.

Waggoner and Stephens (1969) worked with the transition probabilities of species composition in northern hardwoods. They projected ten-year transition probabilities for a forty-year period. These forty-year probabilities were compared with the probabilities actually observed during that period. Perhaps the most significant finding of their study was the fact that forest stand projections demonstrate markovian properties over long time periods.

Growth Prediction

Before growth can be utilized as a predictor, certain assumptions must be recognized. Husch (1963) listed these assumptions as: (1) assume future growth will equal past growth; (2) assume future growth rates will follow past trends; and (3) assume future growth of a specific tree will follow the average pattern of growth established for similar trees growing under similar environmental conditions.

Traditionally, two types of growth prediction have been of interest. These were volume and diameter growth, with more emphasis on the former. Davis (1966) listed two methods of predicting volume growth: (1) indirectly, with yield tables; and (2) directly, with use of sample-plot data. Diameter-growth prediction has usually been expressed in stand-table projections. Three mensuration textbooks, Chapman and Meyer (1949), Husch (1963), and Avery (1967), all illustrated diameter movement percentage equations of the nature:

$$e = t (g/i) \text{ where:}$$

e = number of trees moving up to successive diameter classes

t = total number of trees for a particular diameter class

g = radial growth in inches for a specific time period

i = average diameter increment in inches

Regression and correlation analysis have been used extensively to determine variables related to growth and to calculate prediction equations for this growth. Other deterministic studies appear to be concerned only with site index, which includes the majority of growth-related variables (Auten, 1945; Della-Bianca and Olson, 1961; Hannah, 1968; and McClurkin, 1963). Moser and Hall (1969) stated that growth-rate equations and functions tend to be utilized more in uneven-aged stands to replace the traditional yield table.

However, regression-correlation studies have failed to account for much of the variation in growth directly attributed to "independent" site factors measured. Gingrich (1966) stated that it was difficult to find published results where more than 60 percent of growth variation was explained by site factor combinations. Thus, at present, the least-squares technique does not appear to provide a completely satisfactory approach to growth prediction.

Bonnor (1966) successfully used multi-variate analysis where the independent variables were age, site index, and number of trees per acre, and the dependent variables were mean diameter, standard deviation of diameter, and the coefficients of skewness and kurtosis. Using this equation he could construct future estimated stem-diameter distributions corresponding to different combinations of age, site index, and frequency per acre.

Prodan (1947) constructed a curvilinear equation for diameter increment of different diameter classes in a managed selection forest in Switzerland.

Leak (1969) developed an approach to quantify diameter movement in all-aged northern hardwoods. He used the multiple coefficient of determination to estimate the slope of the line while regressing number of trees and diameter at breast height (D.B.H.). De Liocourt's Law was assumed in his study.

Schaegel and Kulow (1969) recently used a Fortran IV computer program to compute future stand tables of yellow-poplar from a stand-table projection method developed by Ineson (1947).

Not much information is available on diameter-growth performance in young stands, which is basic for an economic evaluation. Teeguardin (1967) stated that there is a need for improvement in the earning-rate performance of young-growth stands. He contended that many public foresters fail to realize that forest inventory can be built up more rapidly by substituting some young-growth harvesting for old-growth harvesting.

Roe and Benson (1966) presented a simple technique for evaluating young, stand-growth. They contrasted actual diameter growth with a standard of potential growth, and actual diameters with a standard of potential diameters. By comparing both diameters and diameter growth to the potential, the stand condition could be visualized. By comparing total stands with their system, silvicultural priorities could be set.

According to Teeguardin (1967) the most unique approach in the area of young, stand-growth was developed by Clutter (1963). Clutter's

work showed that growth and yield projections could be compatible. However, he developed mathematical models to illustrate this relationship only in young pine-timber stands.

II. THE SILVICS OF STAND DIFFERENTIATION

Differences in stand growth can be a tremendously complex variable. Gilbert (1965) stated that stand differentiation was due to the variation in genotypes, phenotypes, and the interaction of one tree with another. He further stated that tree interaction varies according to the mix of individual trees and stand interaction effects. Knowledge of stand-variation differentiation ability has been studied intensely, since such stand-variation differentiation was the very foundation of early silviculture and traditional timber management.

Gilbert (1965) defined stand differentiation ability as: "The ability of a stand to differentiate into crown classes, diameter classes, and quality classes, and to vary this ability with species, age, and site." Thus, diameter growth is only one factor affecting this complex mixture.

Factors Affecting Species Growth

Foresters have continuously attempted to explain and quantify the factors affecting forest growth; various measures of site quality have received wide recognition. In addition, the variables of density, age, and species have usually been included. Traditionally, these studies relate significantly correlated site factors to site index (site quality) for a particular species. The literature cited in this section pertain

only to those species or species groups of interest in the current study: (1) oaks; (2) yellow-poplar; (3) red maple and hickory; and (4) sweetgum.

Oaks. Della-Bianca and Olson (1961) stated that soil-site studies for oaks over a wide geographic and climatic region have developed prediction equations for site index from slope position or percent, soil depth, and aspect. In their study they found a positive correlation between an increase in slope percent and the site index of black and scarlet oak.

Hannah (1968) working with white and black oak in Indiana found that slope position, shape, and aspect were important for white oak. However, only slope position was found to be significantly correlated with the site quality of black oak. Ike and Huppuch (1968) found the site index for northern red oak in the Georgia Blue Ridge Mountains to be influenced mainly by aspect and elevation. In addition, they found that site quality for chestnut oak was strongly related to slope position and steepness.

Hebb (1962) related tree growth on the Ames Plantation to various site factors that affect productivity. He found that growth of cherry-bark oak on the study area was correlated with surface drainage and basal area. McClurkin (1963) measured soil and topographic factors in white oak stands in northern Mississippi and western Tennessee and concluded from past studies that soil physical properties were better correlated with site index than chemical properties, fertility level, or indicator species. In his own study, he found the most important

variables to be percent clay in the surface soil and slope position. He concluded that practically any factor related to the availability of soil moisture or to the amount of root growing space could be significantly correlated with site quality.

Yellow-poplar. Hebb (1962) found significant correlation between growth of yellow-poplar and topographic position, depth to mottling, and direction of exposure. Auten (1945) correlated soil depth to site quality for this species. He showed that depth to tight sub-soil and the thickness of the upper, organic-enriched mineral horizon were related to its site index. Ike and Huppuch (1968) found that the site index for yellow-poplar was associated primarily with topographic position and soil series. Della-Bianca and Olson (1961) discovered this to be the case with increasing latitude.

Red maple and hickory. Soil type and moisture condition appear to be the primary factors associated with the occurrence of red maple and hickory. Hicock et al. (1929) stated that soil moisture had more effect on red maple, hickory, and associated species than did soil type. In the United States Forest Service, Silvics of Forest Trees (1965), both species were reported to occur on a wide variety of soil textures and soil-moisture conditions. However, both were much more common where the soil moisture conditions were extreme; that is, either very wet or quite dry. Read (1952) found that red maple in the Ozarks was most prevalent on cherty and sandy soil areas.

Sweetgum. Hebb (1962) correlated topographic position and surface drainage with the height growth of sweetgum on the Ames Plantation.

Available moisture seems to be the more critical factor concerning this species. Broadfoot (1959) listed as guides in evaluation of sweetgum sites the amounts of clay and exchangeable potassium in the 36- to 48-inch soil layer; and the texture and drainage characteristics of the soil.

Diameter Growth Distributions and Tree Vigor

Diameter growth is strongly related to vigor and crown class. Weitzman and Trimble (1957) demonstrated that vigor class is related to diameter growth in oaks. Their results indicated that ten-year diameter growth of northern red oak was only related to site quality in vigor classes I and II (mainly dominant and codominant crown classes). In chestnut oak it was related in vigor classes I, II, and III, but not in IV, which was the suppressed crown class. These results indicated that the greater tolerance of chestnut oak minimized the effects of suppression.

Buchanan and Liming (1962) studied the diameter growth of black oak in well-stocked, second-growth, oak-hickory stands in southeastern Missouri. They found that not only do trees in the dominant and codominant crown classes grow faster, but that they also have a longer growing season. They discovered that 7 and 8 inch trees began growing three weeks earlier than 4 and 5 inch trees. Some of the overtopped trees actually decreased in diameter in late summer. Ninety-one percent of the year's growth occurred in May, June, and July, representing 18, 56, and 18 percent, respectively.

In a West Virginia study, Holcomb and Bickford (1952) predicted diameter growth of yellow-poplar for each vigor class by regression methods. From their predictions, they estimated the number of years necessary for trees in vigor class I to attain certain sizes. Vigor class I was used because this was the only crown class in which diameter growth was significantly correlated to d.b.h. Table 1 illustrates their findings.

Trimble (1960) found that low-vigor classes can affect the actual differences in diameter growth rate potentials among species. He stated that in going from higher to lower vigor classes, the factors of competition and tolerance increasingly mask a species' potential diameter growth. In vigor class I, he could rank the following species in terms of declining diameter growth rates: red oak, black oak, chestnut oak, scarlet oak, and white oak.

Species Composition Changes

In order to understand the complete picture of stand diameter differentiation in hardwood forests, information is needed not only on actual diameter-growth prediction, but also on the species composition changes that can be expected to occur. Given no interference, natural hardwood stands can be expected to follow the laws of natural succession and progress to the less valuable, tolerant species. But with more natural hardwood stands being placed under some type of management, an important concern is over species composition change following cutting.

Arend (1950) studied species change in well-stocked, unmanaged oak-hickory woodlots in southern Michigan. He observed a ten-year increase

TABLE 1
TIME NECESSARY FOR YELLOW-POPLAR VIGOR CLASS I TO ATTAIN
CERTAIN LARGER SIZES

Present D.B.H.	Future D.B.H. to be Attained		
	8 in. (Yrs.)	10 in. (Yrs.)	12 in. (Yrs.)
0 (seedlings)	23	29	35
2	18	24	30
4	12	19	25
6	6	13	19
8	--	7	13
10	--	--	7

SOURCE: Carl J. Holcomb and Allen C. Bickford. 1952. Growth of Yellow-Poplar and Associated Species in West Virginia. U. S. Forest Service. Northeastern Forest Expt. Sta. Sta. Paper NE-52. 26 pp.

of 18 percent in maple, ash, elm, cherry, and other miscellaneous hardwoods. In contrast, the oak-hickory species had decreased by 18 percent.

Rudolph (1956) studied an old-growth oak mixed stand in southwestern Michigan that had been undisturbed for over 100 years. He noted a large difference in the diameter distributions of white oak, black oak, and sugar maple. Oak was deficient in diameters smaller than four inches. However, sugar maple was abundant in these small d.b.h. classes. The reverse situation was true of diameters above twenty-three inches.

Wahlenberg (1956) studied species composition changes following cutting at Bent Creek, North Carolina. He found no chestnut oak or red maple that failed to sprout in harvested stands. He listed the following species in order of ability to sprout: red oak, white ash, white oak, scarlet oak, black oak, hickory, and sweet birch. Fifteen years after a thinning, he discovered that yellow-poplar and red maple had decreased 72 percent and 52 percent, respectively, as a result of increasing competition. Northern red oak had only decreased 27 percent; while chestnut oak decreased 41 percent.

Leak (1961) studied the effects of stocking on second-growth northern hardwoods on the Bartlett Experiment Forest in New England. Three stocking levels were used: low (36 square feet), medium (56 square feet), and high (94 square feet). Species changes over a twenty-five year period showed an increase in the tolerant or fairly tolerant species in the low-stocked areas. Red maple made the greatest increase, then beech, and finally sugar maple. This increase was not apparent in the medium and high-stocked levels. Hemlock increased in the high-stocked areas,

and yellow birch declined in all areas. In addition, yellow birch suffered the highest mortality.

Leak (1961) concluded that cutting will naturally favor the more intolerant species, provided a seed source is present. Many times these second-growth species are of sprout origin; in which case, the undesirable species will compete strongly with the desirable ones. If the stand closes rapidly and the density level increases appreciable, the desirable yellow-poplar, intolerant oaks, yellow birch, etc., may not survive the strong competition from their more tolerant neighbors.

Mortality

Not much has been published on mortality in natural hardwood stands. In fact, mortality has been underestimated in many cases. Flora (1967) stated that economists have traditionally disregarded mortality, to a large extent, in their benefit predictions. He supported this criticism by stating that biologically a 50-year Ponderosa pine tree has only about a 60 percent chance of surviving to age 100; whereas, past economic studies have generally implied a 100 percent chance.

Leak (1969) described survival and mortality in even-aged seedling-sapling northern hardwoods. He computed by regression methods the probability of a tree being alive at a given future mean stand d.b.h. assuming that the tree was present at a given initial stand d.b.h. From these probabilities he calculated the average number of trees, at a given initial mean stand diameter, required to produce one tree at a given future mean diameter. From these results, he judged the adequacy of stocking in seedling-sapling stands.

CHAPTER III

DESCRIPTION OF STUDY AREAS

Three forestry field stations were used as study areas: Ames Plantation, Highland Rim, and Cumberland. Each area provided a forest tract for study, with the exception of the Cumberland Forestry Field Station which included two forest tracts: one in Morgan and one in Scott County (Figure 1). All tracts are managed by the Department of Forestry, The University of Tennessee.

The three study areas are described separately below with respect to their environmental, geologic, and site conditions. These variables make forest region a major contributor to the variation in species composition and productivity, which is of interest in this study. Table 2 gives general edaphic, forest type, and climatological information for each forest tract.

I. AMES PLANTATION STUDY AREA²

Location and History

Ames Plantation is located in Fayette and Hardman Counties near Grand Junction, Tennessee. It is forty-five miles east of Memphis and forty-five miles south of Jackson (Figure 1).

²General references for the Ames Plantation description are: Ames Management Plan, 1962, and another unpublished manuscript by Barraclough, 1957.

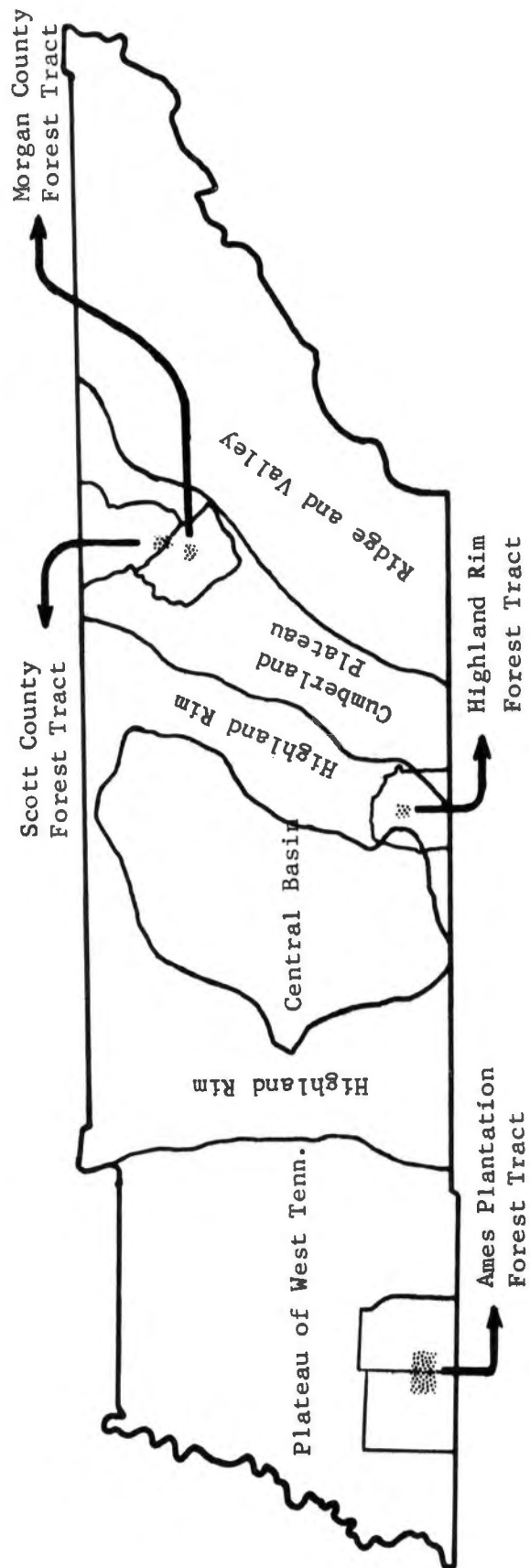


Figure 1. Location map showing the major physiographic regions of Tennessee and the four experimental forest tracts.

TABLE 2
MAJOR SOIL SERIES, FOREST TYPES, AND GENERAL CLIMATOLOGICAL INFORMATION
ON THE THREE STUDY AREAS

Study Area	Major Soil Series	Major Forest Types ^a	Annual Rainfall (In.)	Avg. Annual Temperature (°F)
Ames Plantation	Memphis, Loring, Grenada, Calloway, Henry, Lexington, Ruston, Eustis, Vicksburg, Collins, Falaga, and Waverly	Oak-Hickory and Oak-Pine	52	62
Highland Rim	Dickson, Lawrence, Guthrie, Mountview, Baxter, Green- dale, Ennis, and Lobelville	Oak-Hickory	54	59
Cumberland	Wellston, Hartsells, Johnsburg, Muskingum, Jefferson, Monongahela, Tyler, Pope, and Philo	Oak-Hickory and Oak-Pine	54	56

^aSOURCE: Herbert S. Sternitzke. 1962. "Tennessee Forests." U. S. Forest Service.
Southern Forest Expt. Sta. Forest Survey Release No. 86. 29 pp.

The University of Tennessee acquired research privileges on the Plantation in 1950 through an endowment from the Hobart Ames Foundation. Mr. Ames began land acquisition in 1903 and expanded his holdings to 18,600 acres by 1945. During this time no cutting was allowed. However, after his death in 1945, fifteen million board feet, at an estimated value of one million dollars, were removed from the area. Timber stand improvement was not conducted on the cut-over land. Since 1952, active cutting has been conducted under forest management practices. For example, Barraclough sold over 1.5 million board feet in a total of six sales.³

Climate

The area is characterized by mild winters and hot summers. The average monthly maximum temperature exceeds 70°F from April to October. Normal lows and highs are 10°F in winter and 95°F in summer. Extremes of -11°F and 106°F have been recorded. The average number of frost-free days is 200-210. Average data of the first freeze is the last day of October. The last freeze is usually recorded about the first of April.

Moist air from the Gulf Region contributes to a fairly uniform yearly rainfall pattern. Average snowfall is four to six inches annually. Severe storms are infrequent; however, hail may occur two or three times per year. Damaging glaze storms may occur every five or six years. The prevailing wind is from the Southwest with an average velocity of ten miles per hour.

³John Arthur Ewing. 1956. Planning the Ames Plantation Project, unpublished Doctoral dissertation, Harvard University, Cambridge, Massachusetts. Pp. 145-146.

Geology

A loess deposit overlies a series of sand, clay, and gravel beds that make up the old coastal-plain sediments. This old coastal plain was deposited in past geological times by a sea that covered the present Mississippi Valley. After the disappearance of this sea, wind blown silt from the west covered a large portion of what is now western Tennessee. This loess deposit has been eroded in various locations, thus exposing the old coastal plain.

Topography

The region is one of gently rolling plains with very few abrupt changes in elevation. However, many deep gullies have penetrated the loess layer. The overall elevation varies from 390 to 640 feet above sea level. This area is very typical of the land between the Mississippi Bluffs and the western valley of the Tennessee River.

Soils

Soils are derived from the loess deposits with some mixture of sands from the underlying coastal plain sediments. The following soil series are common to upland areas and are thus characteristic of upland hardwoods: Memphis, Loring, Grenada, Calloway, and Henry. Ruston and Eustis are of inferior quality and cannot support hardwood species. The following soil series are characteristic of bottomlands and thus support the better hardwoods: Vicksburg, Collins, Falaga, and Waverly. These bottomland areas are very productive from the standpoint of forest growth.

Forest Vegetation

At one time magnificent stands of virgin hardwoods covered the bottomlands of western Tennessee. Now less than 30 percent of this area is forested. On the Ames Plantation 9,541 acres are forested. Table 3 shows the delineation of the Ames forest tract by forest types and acreage. Included with the upland hardwood forest type are 286 acres of cedar-hardwood and pine-hardwood types. The bottomland hardwood type contains good quality oak and sweetgum. Sweetgum occurs over all sites, and according to Hebb (1962), has a site index range of 63 to 95 feet on ridges and bottoms, respectively.

II. HIGHLAND RIM STUDY AREA

Location and History

The Highland Rim Forestry Field Station is located in Franklin County, four miles southeast of Tullahoma, Tennessee. Franklin County is in the South-Central part of Tennessee on the undulating Cumberland Plateau and the gently sloping Highland Rim (Figure 1, page 19). The study area is located on the northern section of the Highland Rim in an area known as "the barrens."

In 1960 the 860 acres that make up the Highland Rim Forest were transferred to The University of Tennessee from the Department of Health, Education, and Welfare. Before that time it had been unused land belonging to the Arnold Engineering Development Company which was part of the Arnold Air Force Base near Tullahoma. At present, it is an active research unit of the University.⁴

⁴General references for the Highland Rim description are: Franklin County Soil Survey, 1958, and the Tullahoma and Highland Rim Field Station Files, Forestry Dept., The University of Tennessee.

TABLE 3
AMES PLANTATION FOREST TYPE DELINEATION AND ACREAGE

Forest Type	Area in Acres ^a	Percent of Total
Bottomland Hardwoods	2,577	20
Upland Hardwoods	4,200	51
Pine Plantation	<u>2,764</u>	29
	9,541	

^aThe pine plantation and total forest acreage figures came from the Ames Plantation Progress Report, 1968. The other acreage delineations were computed from percentages by Barraclough, 1957.

Climate

The area is characterized by a warm, temperate, and humid climate. It is located between two major storm paths; consequently, gentle weather changes, rather than severe ones, are more often the rule. Summers are calm, but hot. There is no distinct dry season. Prolonged hot spells occur in July and August, but the temperature rarely exceeds 95°F. Winters are generally warm. The difference between average summer and winter temperatures is only 35°F. The lowest average temperature occurs in January (41°F) and the highest in July (77°F). There are 190 frost-free days. The average date of the first and last killing frosts are October 20 and April 13, respectively.

The greatest amount of rainfall generally occurs in March (average of six inches). The driest month is October, which averages only three inches. Average annual snowfall accumulation is nine inches.

Geology

The Highland Rim is underlain by the St. Louis and Warsaw limestone groups. Fort Payne chert forms the Rim's escarpment and underlies the area known as the barrens. Some remnants of a loess silt mantle are still present. Chattanooga shale forms the dividing line between the Highland Rim and the adjoining Central Basin.

Topography

The Highland Rim and its escarpments occupy two-thirds of the County. On the west it is bounded by an escarpment that descends more than 100 feet to the adjoining Central Basin. On the east it is bounded by an escarpment that ascends more than 1,000 feet to the Cumberland

Plateau. The Highland Rim's average elevation is 970 feet above sea level, with the range being from 959 to 979.

The barrens section of the Highland Rim is gently rolling. In spite of this, drainage systems are often poorly developed. This is especially true of the study area.

Soils

The Dickson soil series occupies most of the undulating uplands, including the study area. Lawrence and Guthrie soils occupy level and depressed areas. All three series have a characteristic compact and slowly pervious subsoil. The cherty Baxter soils are principally on the steeper areas along large drainages. The cherty Greendale series is found on young colluvial deposits at the base of slopes. Ennis and Lobelville soils occur in long narrow areas on the first bottoms.

The edaphic situation on the barrens area has resulted in a very unique, but undesirable condition from the stand point of tree growth. The compact and relatively impervious subsoils found on the majority of this area are called "fragipans." Such a "pan" retards not only root development, but also the amount of available moisture.

Forest Vegetation

At the time of first settlement, practically all of Franklin County was forested. In 1958 only 55 percent had some type of forest cover. The major forest type present is Oak-Hickory, as defined by the United States Forest Service. The poorest upland soils can only support the blackjack oak-hardwood forest type. Bottomland hardwood-forest types cover areas adjacent to streams and other areas of poor drainage.

Cedar-hardwood and yellow pine-hardwood types are less extensive than those listed above. The barrens area is rather thinly wooded with species of "scrub oak," such as blackjack, black, post oak, etc. Early writings of Safford (1869) described the "scrub oaks" which occupied many square miles of the so-called barrens.

Traditionally, the forests have not been well managed. They have been subject to fire, overgrazing, and poor cutting practices. Many cull and low quality trees occupy the forests.

III. CUMBERLAND STUDY AREA

Location and History

The Morgan and Scott County forest tracts are included in the Cumberland Forestry Field Station. The Morgan County tract is located in east-central Morgan County. The Scott County tract is located fifteen miles north of the Morgan-Scott County line (Figure 1, page 19). Each tract is approximately 4,000 acres in size. The University of Tennessee acquired this property from the Bryn Mawr Mining and Land Company in 1937.⁵

The past exploitation of the area has included timber and coal mining. The majority of forest lands have been depleted of their high-quality timber and only second to poor quality remain. Most of the logging was completed in 1915-1920. Little timber management has been practiced due to inaccessibility. The area has been mined since 1950 for coal, leaving some spoil banks that have presented erosion control problems.

⁵General reference for the Cumberland description is MacDonald (1964).

Climate

The Morgan and Scott County forest tracts are in typical mountain country. Thus, they are characterized by cool winters and mild summers. The monthly mean temperature ranges from 37°F in January to 74°F in July. One or more dry spells occur in spring or fall. Rainfall is fairly constant throughout the year with monthly ranges from three inches in October to six inches in January. The average annual snowfall is over ten inches. Glaze and ice storms occur irregularly, the last being in March, 1960.

Geology

Scott and Morgan Counties lie in the Wartburg Basin of the Cumberland Mountain physiographic division of the Cumberland Plateau. In Tennessee the Plateau is underlain by Pennsylvanian rocks, mainly of the Pottsville age. The Pennsylvanian strata are divided into nine groups; the following six are in Scott and Morgan Counties: Crooked Fork, Slatestone, Indian Bluff, Graves Gap, Red Oak Mountain, and Vowell Mountain.

Topography

The Morgan and Scott County forest tracts consist of rough mountain land with numerous ridges and draws. Large sandstone outcroppings are common. The Tennessee Valley Divide runs parallel to and south of the Morgan-Scott County line. The elevation ranges from 1,400 to 2,850 feet above sea level, with abrupt changes common.

Soils

Nine soil series are present on the two tracts. The upland soils are composed of the Wellston, Hartsells, Johnsburg, and Muskingum series. Muskingum silt loam is the soil type found on over three-fourths of the area occupied by these two forests. The Jefferson soil series make up the colluvial and local alluvium land features. The Monongahela and Tyler series are located in stream terrace areas. The bottomlands are composed mainly of the Pope and Philo series.

Forest Vegetation

The Cumberland Mountain region is one of three sections of the Mixed Mesophytic Forest Regions described by Braun (1950). The two tracts fall into the Oak-Hickory and Oak-Pine forest types, as defined by the United States Forest Service. There are some pine and hemlock, but mainly hardwoods prevail. There are thirty-five species of hardwood on the area, with twelve occurring regularly. This area, like that of the Highland Rim, has been quality depleted by poor cutting practices with no consideration of stand improvement.

IV. SUMMARY OF STUDY AREAS

Forest region, with its resulting environmental and site factors, is perhaps the most important variable contributing to the major growth differences encountered throughout the State. Ames Plantation, with its longer growing season, more favorable climate, and desirable site characteristics, has the best growing conditions. The Highland Rim area has the poorest conditions for tree growth. This is largely due to the

edaphic conditions present on that area. All study areas are fairly representative of their physiographic region and major timber types, with the exception of the northern section of the Highland Rim, of which the barrens is representative.

Of the six major forest types in the State described by the United States Forest Service, only two types are covered in this study (Oak-Hickory and Oak-Pine). Those not included are: Oak-Gum-Cypress, Cedar, Loblolly-Shortleaf Pine, and White Pine. However, the two types studied account for well over one-half of the forested area of the State.

A permanent forest inventory system located on each of the four forest tracts was the source of data for this study. Table 4 provides summary information on tract establishment and size, the number of plots and pulpwood-sized species present, and the number of trees measured. All tracts have had one recurrent five-year measurement.

The Scott and Morgan County forest tracts were combined in certain sections of this study for several reasons: adjacent regional locations, similar forest types and species composition, and gains resulting from additional data for analysis. The Morgan County forest tract also has two subdivisions. These are the Brushy and Wilson Mountain forest tracts. The inventory systems on these areas were established at different times; however, the period between recurrent measurements has remained fixed at five years. These subdivisions were also combined in every section of this study and referred to simply as the Morgan County forest tract.

TABLE 4

SUMMARY OF PERMANENT FOREST SAMPLING SYSTEM ON THE FOUR FOREST TRACTS^a

Forest Tract	Year Established	No. of Plots	Forest Area (Acres) ^b	Total Area (Acres)	No. of Hardwood Species ^c	Total Stems Measured (No.)
Ames Plantation	1963	152	6,777	18,600	41	969
Highland Rim	1962	26	83	860	7	199
Morgan County:					32	1,323
Brushy Mtn.	1963	166	2,663	2,663		
Wilson Mtn.	1962	69	1,202	1,202		
Scott County	1962	99	4,289	4,289	30	636
TOTAL		512	15,014	26,853		3,127

^aSample included only trees on 1/10 acre plots; while plots were variable-radius which included 1/10 acre for pulpwood and 1/5 acre for sawtimber. Pulpwood and sawtimber threshold diameters were 5.0 and 11.0 inches, respectively.

^bPine plantations and research areas are excluded at Ames Plantation and Highland Rim, respectively.

^cIncludes species groups, such as miscellaneous hardwoods.

CHAPTER IV

METHODS AND PROCEDURES

In order to obtain diameter projection information for the different forest tracts and for species within each tract, the following methods and procedures were applied: species were selected from each forest tract; diameter frequency distributions were computed for these selected species and for the total forest tracts; a portion of these diameter frequency distributions were converted to probabilities and projected by a mathematical tool known as Markov chains.

I. SPECIES SELECTION

Several species were selected from each forest tract. Table 5 gives these species, the total number of trees measured, and the total number of trees per acre. Criteria for selection were abundance and silvicultural interests, with the majority of emphasis on the former. These criteria limited the sample of Markov chain selected species to seven, since a fairly large sample was needed for diameter projections.

II. DIAMETER FREQUENCY DISTRIBUTIONS

After all species selections were made, diameter frequency distributions were computed. All distributions were calculated on the basis of five-year periodic measurements, since all forest inventories were remeasured after this fixed time period. One-half-inch diameter-class intervals were chosen for two reasons. First, they would condense

TABLE 5

SELECTED HARDWOOD SPECIES, NUMBER OF TREES MEASURED, AND THE
NUMBER OF TREES PER ACRE

Species Selected Per Forest Tract	Total Trees Measured (No.)	Total Trees Per Acre (No.)
<u>Ames Plantation</u>		
sweetgum	111	9.27
post oak	68	6.03
southern red oak	69	5.83
winged elm	77	5.70
hickory	42	5.17
white oak	32	4.64
American elm	61	3.77
red maple	28	2.58
black oak	31	2.32
cherrybark oak	19	1.72
yellow-poplar	14	1.46
Total	552	48.49
<u>Highland Rim</u>		
post oak	86	29.35
southern red oak	24	10.32
Total	110	39.67
<u>Morgan County</u>		
chestnut oak	430	23.02
red maple	134	7.50
yellow-poplar	84	5.39
white oak	81	3.85
scarlet oak	92	3.02
northern red oak	40	2.15
black oak	52	1.89
Total	913	46.82
<u>Scott County</u>		
chestnut oak	120	14.24
yellow-poplar	114	12.93
hickory	86	10.40
white oak	66	7.27
black oak	64	6.87
red maple	35	4.55
northern red oak	38	4.34
Total	523	60.60
GRAND TOTAL	2,098	

the data to the point where each distribution would approach a regular pattern, and second, one-half inch increments over a five-year period provided sufficient sensitivity to denote any significant changes in growth patterns.

The diameter frequencies and mortality data used in the analysis of Markov chains are given in Tables 14-17, and Tables 22-28, Appendix B. Tables 14-17 are distributions of all hardwood trees on each tract. Tables 22-28 are distributions of the seven Markov chain selected species. Tables 27-28 are based on combined data for the Cumberland Field Station. Combining the Morgan and Scott County forest tracts yielded a much larger sample size for analysis. A descriptive comparison of all other species, excluding the seven used in the analysis of Markov chains, were made by forest tracts in Chapter V.

After constructing the diameter frequency distributions, each frequency was converted into a probability matrix before application of the Markov chain theory. This was done on the computer by dividing each frequency class by the total number of trees for that diameter class. Cross addition of probabilities had to add up to one:

$$\sum_{j=1}^n P_{ij} = 1, \text{ where:}$$

n = the constant time interval between inventories

j = next highest diameter class

i = initial diameter class

P = diameter class probability

Here, the P_{ij} represents the probability that a tree will move from a diameter class of i to a diameter class of j in a five-year period. It follows that each probability will be less than or equal to one, but greater than or equal to zero:

$$0 \leq P_{ij} \leq 1 .$$

The probability matrix was used as input for a Markov chain computer program specifically developed for this forestry application at The University of Tennessee Computing Center. This program is given in Appendix C.

III. APPLICATION OF MARKOV CHAIN THEORY

State Theory

Expressing the diameter distributions in one-half inch classes satisfies the basic concepts of Markov chains as defined by Howard (1960). He stated that a system occupies a state when it is completely described by the values of variables that define that state. A system makes a state transition when these describing variables change from the values specified for one state to those specified for another state. These transitions can either be discrete or continuous. The diameter distributions in this study were considered to be discrete transitions, since recurrent inventory measurements were made at fixed five-year periods. These probability distributions also satisfy the constraints of finite-state Markov chains explained by Hillier and Liefberman (1967):

1. A finite number of states.

2. The markovian property--"The conditional probability of any future 'event,' given any past 'event' and the present state, is independent of the past 'event' and depends only on the present state of the process."
3. Stationary transition probabilities.
4. A set of initial probabilities.

The markovian property, constraint 2, assumes that present diameter growth rates for each diameter class are independent, and that, the initial set of distributions are for a balanced forest, of which the structure and distribution are maintained over time. For this reason, constraint 2 would be more applicable to a forest projection, rather than a stand projection. Constraint 3 assumes that each diameter class will react and grow at the same rate over all future transition periods.

Application to Stand Table Projections

The initial diameter distribution probabilities were projected for one or more transition periods by repeated matrix squaring. Each squaring projected the distribution for one additional five-year transition period. The example below illustrates the mathematical procedures involved in just one matrix squaring.

Given the following matrix of probabilities, the projected matrix at the end of one transition period is calculated by multiplying and adding matrix rows and columns:

Initial States		Projected States																													
<table border="1" style="display: inline-table; border-collapse: collapse;"> <tr><td style="padding: 2px 10px;">a_1</td><td style="padding: 2px 10px;">a_2</td><td style="padding: 2px 10px;">a_3</td></tr> <tr><td style="padding: 2px 10px;">b_1</td><td style="padding: 2px 10px;">b_2</td><td style="padding: 2px 10px;">b_3</td></tr> <tr><td style="padding: 2px 10px;">c_1</td><td style="padding: 2px 10px;">c_2</td><td style="padding: 2px 10px;">c_3</td></tr> </table>	a_1	a_2	a_3	b_1	b_2	b_3	c_1	c_2	c_3	X	<table border="1" style="display: inline-table; border-collapse: collapse;"> <tr><td style="padding: 2px 10px;">a_1</td><td style="padding: 2px 10px;">a_2</td><td style="padding: 2px 10px;">a_3</td></tr> <tr><td style="padding: 2px 10px;">b_1</td><td style="padding: 2px 10px;">b_2</td><td style="padding: 2px 10px;">b_3</td></tr> <tr><td style="padding: 2px 10px;">c_1</td><td style="padding: 2px 10px;">c_2</td><td style="padding: 2px 10px;">c_3</td></tr> </table>	a_1	a_2	a_3	b_1	b_2	b_3	c_1	c_2	c_3	=	<table border="1" style="display: inline-table; border-collapse: collapse;"> <tr><td style="padding: 2px 10px;">A_1</td><td style="padding: 2px 10px;">A_2</td><td style="padding: 2px 10px;">A_3</td></tr> <tr><td style="padding: 2px 10px;">B_1</td><td style="padding: 2px 10px;">B_2</td><td style="padding: 2px 10px;">B_3</td></tr> <tr><td style="padding: 2px 10px;">C_1</td><td style="padding: 2px 10px;">C_2</td><td style="padding: 2px 10px;">C_3</td></tr> </table>	A_1	A_2	A_3	B_1	B_2	B_3	C_1	C_2	C_3
a_1	a_2	a_3																													
b_1	b_2	b_3																													
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A_1	A_2	A_3																													
B_1	B_2	B_3																													
C_1	C_2	C_3																													

$$A_1 = a_1^2 + a_2b_1 + a_3c_1$$

$$A_2 = a_1a_2 + a_2b_2 + a_3c_2$$

$$A_3 = a_1a_3 + a_2b_3 + a_3c_3$$

$$B_1 = b_1a_1 + b_2b_1 + b_3c_1$$

$$B_2 = b_1a_2 + b_2^2 + b_3c_2$$

$$B_3 = b_1a_3 + b_2b_3 + b_3c_3$$

$$C_1 = c_1a_1 + c_2b_1 + c_3c_1$$

$$C_2 = c_1a_2 + c_2b_2 + c_3c_2$$

$$C_3 = c_1a_3 + c_2b_3 + c_3^2$$

Using the theorems and assumptions of finite Markov chains, as described by Kemeny and Snell (1960), the following projections were computed in the analysis:

1. Projected five-year diameter distributions for one transition period.
2. Projected number of transition periods required for trees in each diameter class to reach the 10.5 inch diameter class or larger, excluding mortality.
3. Projected number of transition periods that trees can be expected to remain in each diameter class.
4. Projected percentage by diameter class of trees dying before reaching 10.5 inches.

The analysis of Markov chains was applied to eleven diameter frequency distributions where data were judged to be sufficient. These were:

1. All hardwood pulpwood-sized trees on each of the four forest tracts.
2. Sweetgum and southern red oak on the Ames Plantation forest tract.

3. Post oak on the Highland Rim forest tract.
4. Chestnut oak on the Morgan County forest tract.
5. Hickory on the Scott County forest tract.
6. Yellow-poplar and red maple on the Morgan and Scott County forest tracts combined.

CHAPTER V

RESULTS AND DISCUSSION

The results given in this chapter follow the basic objectives given in Chapter I. These objectives included comparisons of present and projected hardwood diameter distributions and their resulting differences among: (1) total forest tracts; (2) individual species on different tracts; and (3) individual species within each tract.

I. COMPARISONS AMONG FOREST TRACTS

The results discussed in this section pertain to total forest tracts. Each tract includes all hardwood trees that represented the diameter classes studied.

Diameter Distributions and Growth Rates

Initial diameter distributions were projected one five-year transition period by Markov chains (Tables 18-21, Appendix B). The figures in these tables were not integers due to the fact that they were obtained from decimal probabilities. The accuracy of these projected stand tables cannot be evaluated until the second remeasurement.

The ranges in initial diameter frequency distributions (growth rates) varied among forest tracts. As expected, Ames Plantation possessed the greatest variability and widest ranges, while Highland Rim showed low growth rates within narrow ranges. Morgan and Scott County tracts were similar and fell between these extremes.

Markov Chain Projected Time Periods

Through the use of Markov chains, the number of five-year periods required for each diameter class to reach 10.5 inches or larger was computed for each forest tract. Table 6 gives these expected time periods and their variances.

Figure 2 graphically depicts this expected time in years. The yearly predictions excluded mortality; nevertheless, extremely long periods of time were required for living trees to reach sawtimber-size. It should be recognized that even though mortality was excluded, the extremely long time periods involved did include those suppressed, shade tolerant, and slow growing species that did not die; e.g., dogwood and other understory species. Another factor probably contributing to long time periods was the lack of active silvicultural operations on the study areas.

Very little differences in projected times were found among all tracts, with the exception of Highland Rim. Here, slow growth rates coupled with one-half-inch diameter classes caused extremely narrow diameter distributions. The net result was for the diameter distributions to become less normal and to be more like a Poisson distribution with the mean equal to the variance. Such slow growth rates were expected, given the low productivity of the "barrens" area.

An important observation can be made concerning the expected time periods for the other three tracts. All three were fairly similar in expected time across the eleven diameter classes given. This was somewhat of a surprise, since Ames Plantation would be considered as the tract possessing the best growth potential. However, given that these

TABLE 6

PROJECTED NUMBER OF FIVE-YEAR PERIODS AND VARIANCES FOR ALL HARDWOOD SPECIES
TO REACH SAWTIMBER-SIZE BY DIAMETER CLASS AND FOREST TRACT^a

Diameter Class (In.)	Ames Plantation		Highland Rim		Morgan County		Scott County	
	Pd.s	Var.	Pd.s	Var.	Pd.s	Var.	Pd.s	Var.
5.0	8.43	6.25	12.98	11.01	8.89	4.89	8.66	4.92
5.5	7.85	5.94	12.15	10.82	8.24	4.66	8.04	4.87
6.0	7.15	5.33	11.00	10.03	7.53	4.28	7.08	3.85
6.5	6.53	5.12	9.88	9.68	6.69	3.71	6.15	3.26
7.0	5.87	4.48	8.68	8.35	5.99	3.21	5.44	2.88
7.5	5.22	4.28	7.47	7.60	5.10	2.73	4.78	2.27
8.0	4.85	3.40	6.82	7.23	4.37	2.22	4.10	2.02
8.5	4.06	3.04	5.45	5.37	3.66	1.95	3.56	1.92
9.0	3.51	2.44	3.81	3.80	2.95	1.49	2.87	1.50
9.5	2.60	2.06	2.83	2.09	2.23	1.42	2.25	1.00
10.0	1.64	1.04	1.80	1.44	1.50	0.75	1.37	0.52

^aMortality data excluded.

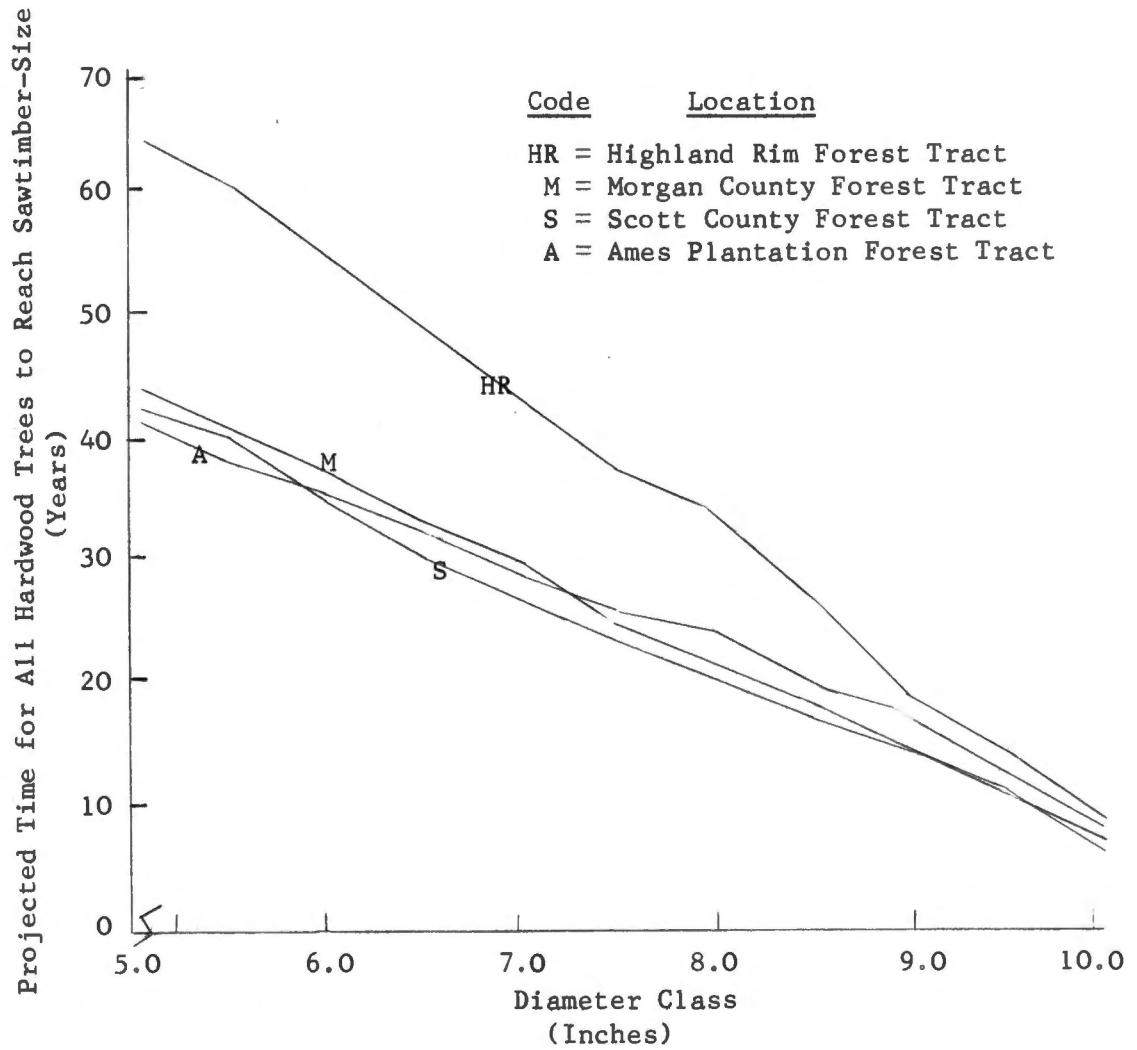


Figure 2. Projected time for all hardwood trees to reach minimum sawtimber-size at four locations.

expected time periods were computed for all hardwood species that were present in the chosen size range, the performance of a few fast growing, desirable species would tend to be masked by the many other species present on the area.

In addition to expected time periods required to reach sawtimber-size, the analysis of Markov chains also furnished the number of five-year periods that trees tend to remain in each one-half-inch diameter class. Table 7 gives these time periods for each diameter class and each forest tract.

Expected time periods projected by diameter class showed very few differences among forest tracts. In general, the growth patterns for each tract followed that portion of the traditional sigmoid-shaped, growth-response curve that was represented by the diameter range studied.

The expected time periods were averaged across all initial diameter classes and included mortality. Therefore, the summation of all time periods across diameter classes do not equal the expected time periods required to reach sawtimber-size, given in Table 6, page 41.

Projected Mortality

Markov chain theory was used to predict mortality probabilities for each diameter class on each forest tract. The chance of a tree dying before it reaches sawtimber-size is given in Table 8 and illustrated in Figure 3.

In general, the chance of a tree dying was found to be inversely related to tree diameter for all forest tracts. The probabilities among tracts were similar considering the adequacy of mortality data. However,

TABLE 7

PROJECTED AVERAGE NUMBER OF FIVE-YEAR PERIODS THAT ALL
HARDWOOD SPECIES ARE EXPECTED TO REMAIN IN EACH
DIAMETER CLASS BY FOREST TRACTS^a

Diameter Class (In.)	Avg. Expected No. of 5 Yr. Periods in Each Dia. Class			
	Ames Plantation	Highland Rim (No. of Periods)	Morgan County	Scott County
5.0	1.13	1.12	1.11	1.19
5.5	0.89	1.16	0.90	1.11
6.0	0.75	1.14	0.85	0.93
6.5	0.71	1.09	0.84	0.86
7.0	0.64	0.85	0.74	0.71
7.5	0.54	0.97	0.73	0.64
8.0	0.49	0.89	0.63	0.60
8.5	0.66	1.09	0.67	0.70
9.0	0.56	0.94	0.54	0.74
9.5	0.64	0.77	0.70	0.60
10.0	0.86	0.99	0.71	0.98

^aMortality included.

TABLE 8
MORTALITY PROJECTION FOR ALL HARDWOOD SPECIES BY DIAMETER
CLASS AND FOREST TRACT

Diameter Class (In.)	Probability that a Tree Will Die Before Reaching Sawtimber-Size			
	Ames Plantation	Highland Rim	Morgan County	Scott County
	(Percent)			
5.0	57	57	61	27
5.5	55	57	58	24
6.0	50	55	57	20
6.5	47	42	53	19
7.0	47	42	53	18
7.5	41	31	48	14
8.0	33	27	48	17
8.5	30	38	45	14
9.0	32	22	40	11
9.5	23	26	36	8
10.0	15	17	43	11

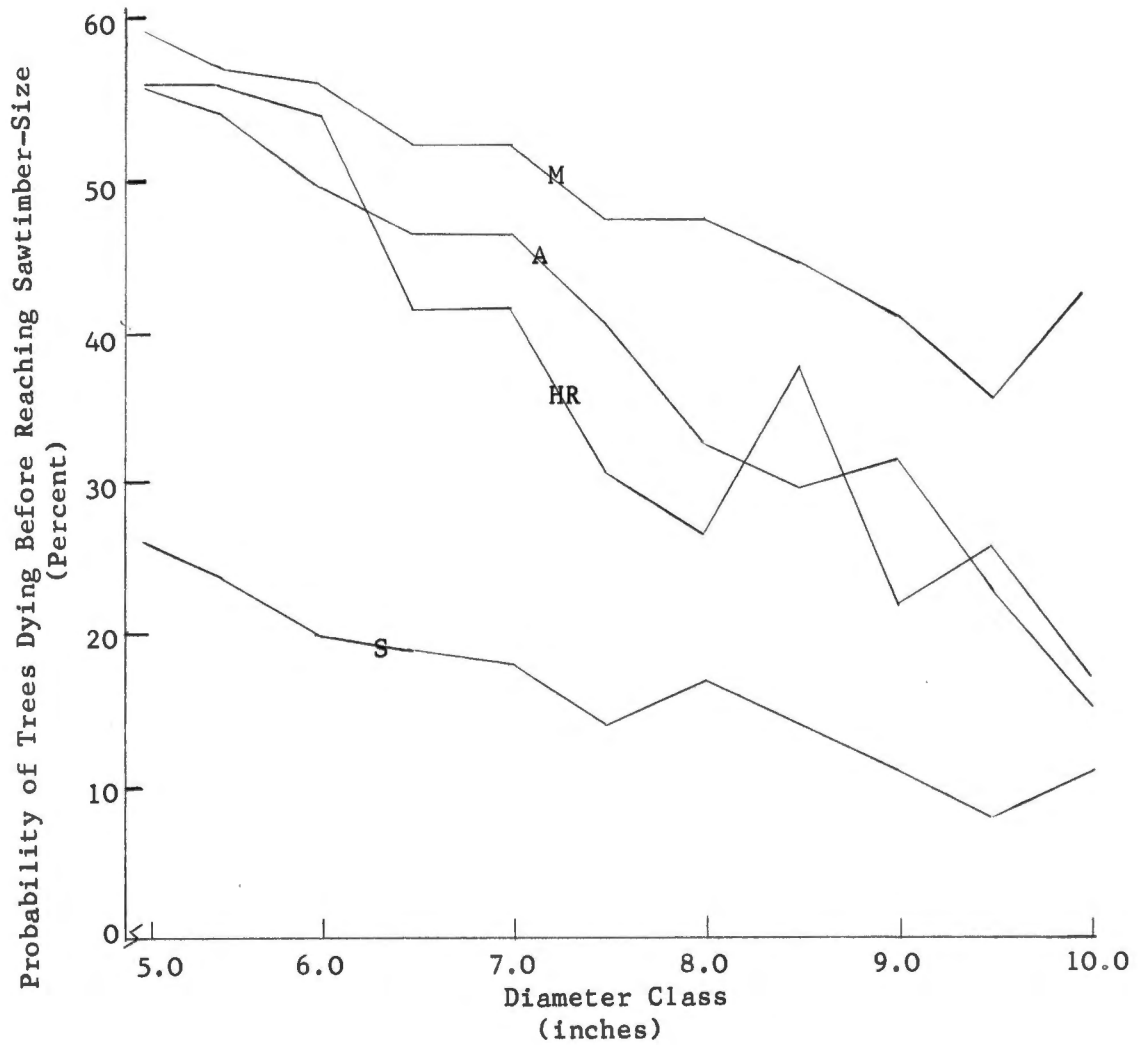


Figure 3. Projections of expected mortality for all hardwood species at four locations.

mortality on Scott County was comparatively lower than that on the other three tracts.

The mortality differences between the Morgan and Scott County forest tracts were not expected, given that both tracts were in the same locality and had similar forest types. One explanation can be offered in the distribution of initial mortality data. Namely, the Morgan County mortality was extremely high in the larger diameter classes; whereas, Scott County was consistently lower throughout all diameter classes (Tables 16-17, Appendix B). However, this does not explain why the Morgan County initial mortality was, on the average, more than twice that of Scott County.

Another explanation might lie in mortality differences by species (Table 9). For all species studied on the Morgan and Scott County forest tracts, mortality was considerably higher on the Morgan tract for all selected species, with the exception of yellow-poplar. However, the complete answer lies in the complex interaction of differences in stocking, species composition, total stand structures, and shade tolerance ratings between the two forest tracts.

II. COMPARISONS AMONG INDIVIDUAL SPECIES ON DIFFERENT TRACTS

This section includes the results of only those seven species for which Markov chain theory was applied. The yellow-poplar and red maple data from Morgan and Scott County forest tracts were combined in order to furnish an adequate sample size.

TABLE 9
FIVE-YEAR RESPECTIVE MORTALITY AND THE NUMBER OF TREES
MEASURED FOR THE SELECTED SPECIES ON MORGAN AND
SCOTT COUNTY FOREST TRACTS

Selected Species by Forest Tract	Total Trees Measured (No.)	Five-Year Mortality (%)
<u>Morgan County</u>		
scarlet oak	92	28.3
black oak	52	21.1
northern red oak	40	10.0
white oak	81	6.0
yellow-poplar	84	5.8
chestnut oak	430	3.3
red maple	<u>134</u>	2.9
Total	913	
<u>Scott County</u>		
yellow-poplar	114	7.0
black oak	64	6.3
white oak	66	3.0
hickory	86	2.3
chestnut oak	120	0.8
northern red oak	38	0.0
red maple	<u>35</u>	0.0
Total	523	

Diameter Distributions and Growth Rates

The initial diameter distributions for the seven selected species were projected one transition period by Markov chains to obtain projected stand tables (Tables 29-35, Appendix B). Growth rates and ranges in these projected stand tables were similar to those in the initial five-year distributions.

Further stratification by species within a forest tract, in general, produced less fluctuations and more narrow diameter growth ranges per species than did the initial distributions of all hardwoods for each respective tract. However, sweetgum yielded large variability; and since it was the most abundant species on the Ames Plantation, this variability undoubtedly contributed to the total variation encountered on this tract. This variation in sweetgum can be attributed to low mortality (less than 1 percent from 1963 to 1968) and its occurrence on a wide range of sites. This is supported by the wide site index ranges for this species found on the Ames Plantation by Hebb (1962).

Southern red oak, the other species studied on the Ames Plantation, did not exhibit such large variation in growth rates. However, it may have been further stratified by the recognition of the cherrybark variety. Cherrybark oak would tend to occur on bottomland sites and southern red oak on upland sites, while sweetgum actually occurred on approximately one out of four C.F.I. plots.

Markov Chain Projected Time Periods

As in the case of all hardwood species on each forest tract, Markov chains were also used to predict the number of five-year periods

required for each diameter class to reach sawtimber-size for each of the seven selected species. Mortality, as before, was excluded from this prediction. Table 10 gives these expected time periods and their variances. Figure 4 illustrates the years required to reach sawtimber-size by species.

The species were ranked as to projected time in two distinct groupings. Sweetgum, post oak, and hickory occupied the upper group with the longest projected time. Chestnut oak, yellow-poplar, red maple, and southern red oak occupied the lower group displaying the shortest projected time.

Southern red oak on the Ames Plantation exhibited the fastest growth rate of the seven species. It was the only species studied that possessed a wide growth differential from the entire forest tract on which it occurred. This amounted to a 14-year time-span difference in the five-inch diameter class. The performance of red maple, yellow-poplar, and chestnut oak on the Morgan and/or Scott County forest tracts was unexpected. All three were very similar in projected times. Of the slow growing group, sweetgum on Ames Plantation was again a surprisingly slow performer. However, the high variances of sweetgum were much greater than the respective means. This suggests that the diameter distributions of this species were not normally distributed, an assumption of the markovian property and variance equation. Therefore, the validity of the sweetgum projections should be questioned.

As in the analysis of total forest tracts, the expected number of five-year periods that trees remained in each diameter class was also predicted for the seven individual species. Table 11 gives these expected

TABLE 10

PROJECTED NUMBER OF FIVE-YEAR PERIODS AND VARIANCES FOR MARKOV CHAIN SELECTED SPECIES
TO REACH SAWTIMBER-SIZE BY DIAMETER CLASS AND FOREST TRACT^a

Diameter Class (In.)	Ames Plantation			Highland Rim			Morgan County			Scott County			Morgan-Scott Combined		
	Southern			Post Oak			Chestnut			Hickory			Yellow-		
	Sweetgum Pd.s Var.	Red Oak Pd.s Var.	Red Oak Pd.s Var.	Pd.s	Var.	Pd.s	Oak Pd.s Var.	Var.	Pd.s	Var.	Pd.s	Var.	Poplar Pd.s Var.	Red Maple Pd.s Var.	Red Maple Pd.s Var.
5.0	13.35	42.00	5.65	2.91	14.24	13.40	8.49	2.79	15.02	14.36	7.94	5.64	7.35	4.51	
5.5	12.89	41.79	5.30	2.81	13.52	13.50	7.91	2.66	13.02	12.36	7.47	5.59	7.11	4.69	
6.0	12.80	39.72	4.83	2.74	12.40	12.15	7.16	2.54	11.07	9.78	6.86	5.05	6.46	4.20	
6.5	12.50	37.46	4.63	2.79	10.90	11.40	6.57	2.19	9.74	8.62	6.16	4.86	5.83	4.15	
7.0	10.30	34.82	3.67	2.22	10.12	11.39	5.64	1.86	8.40	8.18	5.59	4.57	5.28	3.56	
7.5	8.89	34.92	3.80	3.44	8.82	9.44	4.88	1.64	8.04	7.75	5.00	4.10	4.41	3.53	
8.0	8.71	32.81	3.71	2.43	8.01	9.17	4.25	1.26	6.21	6.00	4.21	3.62	3.82	3.16	
8.5	8.10	31.23	3.28	2.20	6.28	6.78	3.48	1.02	5.88	5.44	3.78	3.84	3.56	3.41	
9.0	8.10	31.23	2.33	2.22	4.83	6.14	2.73	0.80	3.54	2.33	3.27	3.49	2.83	2.42	
9.5	6.10	29.23	3.00	2.00	4.00	6.00	2.05	0.84	2.83	1.17	3.00	3.33	2.00	2.00	
10.0	1.20	0.24	2.00	2.00	3.00	6.00	1.29	0.37	1.40	0.56	2.00	2.00	2.00	2.00	

^aMortality data excluded.

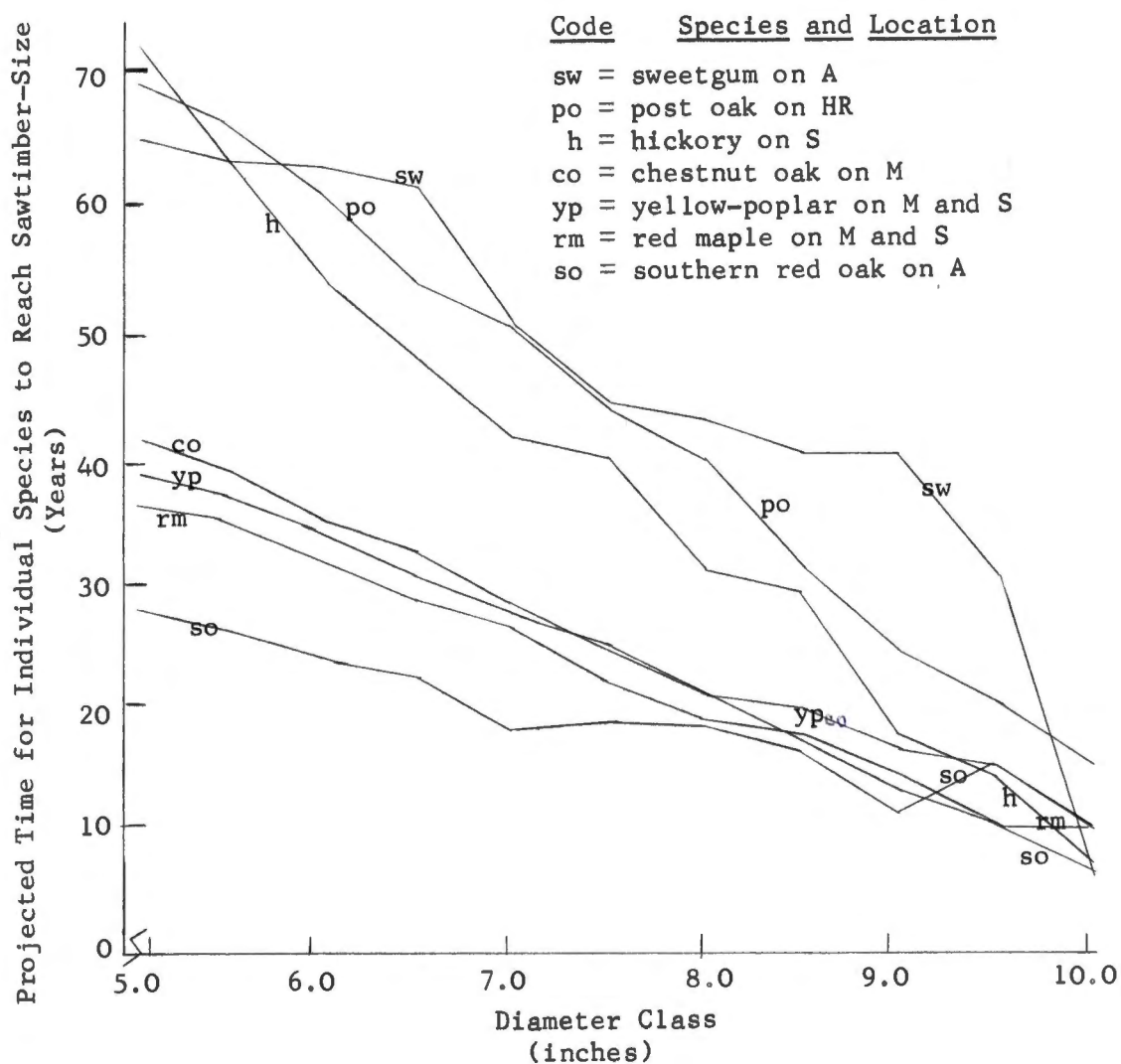


Figure 4. Projected time for individual species to reach minimum sawtimber-size at four locations.

TABLE 11

PROJECTED AVERAGE NUMBER OF FIVE-YEAR PERIODS THAT SELECTED SPECIES ARE EXPECTED TO
REMAIN IN EACH DIAMETER CLASS BY FOREST TRACT^a

Diameter Class (In.)	Ames Plantation		Highland Rim		Morgan County		Scott County		Morgan-Scott Combined		
	Sweetgum	Southern Red Oak	Post Oak		Chestnut Oak	Hickory		Yellow- Poplar	Red	Maple	
5.0	1.12	1.00	1.00		1.03	2.00		1.00		1.00	
5.5	1.09	0.57	1.31		0.78	2.17		0.89		0.71	
6.0	1.10	0.65	1.29		0.83	1.42		0.68		0.71	
6.5	1.31	0.58	1.08		0.82	1.16		0.72		0.71	
7.0	1.23	0.56	1.18		0.78	1.29		0.60		0.68	
7.5	0.93	0.34	1.16		0.77	1.05		0.68		0.72	
8.0	0.74	0.37	1.19		0.61	0.86		0.50		0.69	
8.5	1.10	0.40	1.24		0.72	1.54		0.50		0.65	
9.0	1.59	0.52	0.96		0.66	1.45		0.58		0.48	
9.5	4.00	0.27	0.82		0.74	0.48		0.72		0.62	
10.0	0.70	1.30	2.89		0.90	1.16		1.06		1.12	

^aMortality included.

number of periods. Figure 5 shows these time periods by the width of diameter class bands.

Mortality was included again in these predictions. Since such mortality tends to be inversely related to diameter, it also may contribute to the curvilinearity of the diameter movements. Even though this mortality was included, the summation of diameter class-time periods, in general, maintained the same order as those predicted time periods to sawtimber-size, discussed above.

The individual species tended to show abnormal patterns as a result of fluctuations in expected time among different diameter classes. Some of these fluctuations may have been due to lack of data; and, on the whole, were less reliable than those fluctuations encountered in the analysis of entire forest tracts.

Projected Mortality

Table 12 shows the average mortality projection for each of the seven species. The figures in this table are the odds or chances of a tree dying before it reaches sawtimber-size.

The mortality percentages followed the patterns of tolerance fairly closely. The more intolerant species should have shown the greatest mortality. This was the case for the majority, with the exception of sweetgum and post oak. Yellow-poplar, probably the most intolerant species studied, had the highest projected mortality percentage. Chestnut oak and southern red oak were similar in mortality. As expected, the more tolerant species of hickory and red maple showed relatively lower mortality percentages.

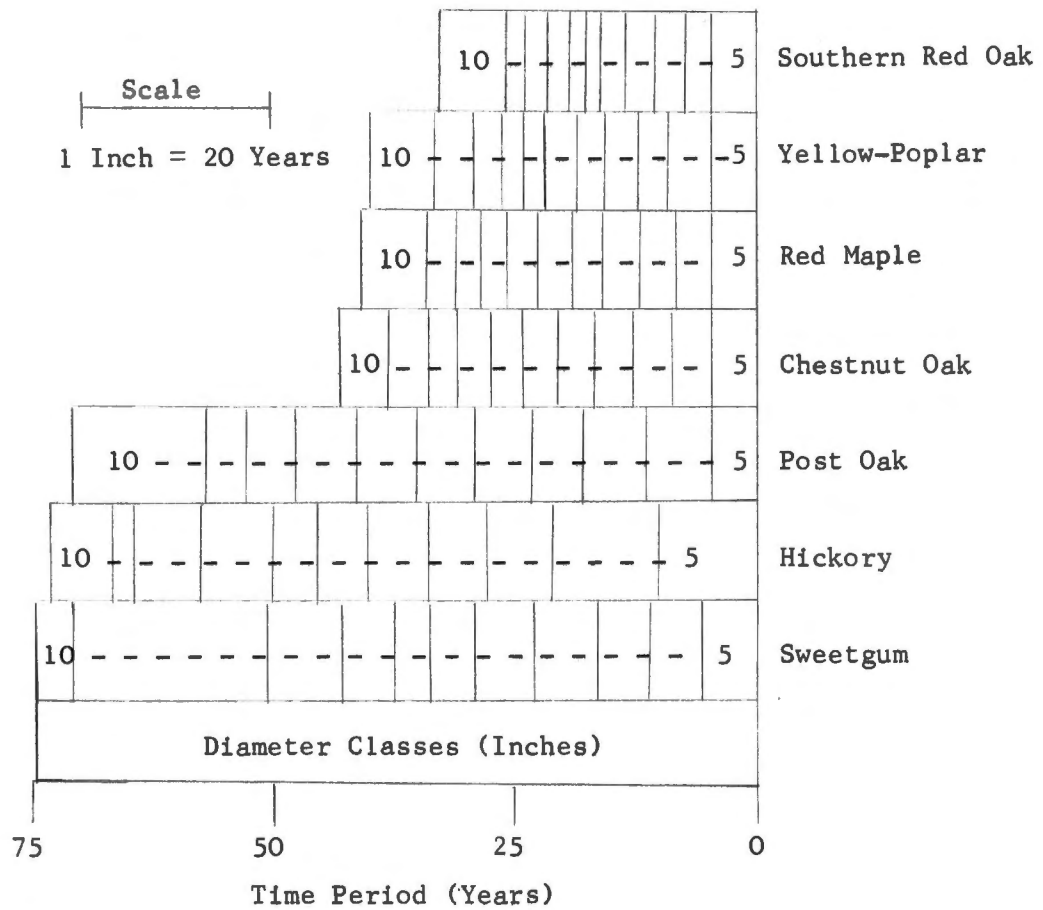


Figure 5. Diameter growth movements by diameter class and projected differences among seven selected species.

TABLE 12
MORTALITY PROJECTION FOR SELECTED SPECIES BY FOREST TRACT^a

Forest Tract	Selected Species	Percent Chance of Mortality
Ames Plantation	sweetgum	1.4
	southern red oak	22.0
Highland Rim	post oak	3.4
Morgan County	chestnut oak	23.5
Scott County	hickory	17.4
Morgan-Scott Combined	yellow-poplar	28.5
	red maple	6.2

^aPercentages are averages from all diameter classes.

One surprising note concerns the mortality of post oak on the Highland Rim. Being classified as a relatively intolerant oak, this species should have showed more mortality than these data revealed. Part of this discrepancy may have been due to the understocked, poor growing condition of the "barrens" area.

III. COMPARISONS AMONG INDIVIDUAL SPECIES WITHIN EACH TRACT

This section deals with those selected species which, by reason of lack of data or silvicultural interest, were not included in the analysis of Markov chains. Here, growth and mortality comparisons by forest tract were the main issue. The results that follow were often based on a small sample size, and therefore, may be inadequate for conclusive comparisons. Table 13 lists these growth and mortality data.

Ames Plantation Forest Tract

Yellow-poplar and cherrybark oak maintained the greatest average diameter growth (1.3 inches). Unfortunately, however, these two desirable species were poorly represented in sample size with only 14 and 19 trees, respectively. Black and white oak were second in growth with 1.2 inches. Following these three species, the growth rate dropped appreciably to 0.7 inches for the three species of post oak, winged elm, and hickory. Red maple was growing surprisingly slow (0.6 inches); however, it did show one of the largest diameter growth ranges (0.0-2.5 inches). Other species having a large range of diameter growth included yellow-poplar (0.0-3.0 inches) and white oak (0.0-2.5 inches). Cherrybark oak did not

TABLE 13

FIVE-YEAR DIAMETER GROWTH RATES AND RANGES, TOTAL NUMBER OF
TREES MEASURED, AND MORTALITY PERCENTAGES BY
SELECTED SPECIES AND FOREST TRACT

Selected Species by Forest Tract ^a	Average Five-Year Growth ^c and Range ^b Average (In.)	Range (In.)	Total Trees Measured (No.)	Five-Year Mortality (%)
<u>Ames Plantation</u>				
American elm	0.5	0.0-1.0	61	21.3
post oak	0.7	0.0-1.5	68	14.8
yellow-poplar	1.3	0.0-3.0	14	14.3
black oak	1.2	0.0-2.0	31	13.8
winged elm	0.7	0.0-1.5	77	11.7
hickory	0.7	0.0-2.0	42	9.5
red maple	0.6	0.0-2.5	28	3.6
cherrybark oak	1.3	0.0-2.0	19	5.3
white oak	1.2	0.0-2.5	32	0.0
<u>Highland Rim</u>				
southern red oak	0.8	0.5-1.5	24	8.3
<u>Morgan County</u>				
scarlet oak	0.7	0.0-2.0	92	28.3
black oak	0.7	0.0-2.0	52	21.1
northern red oak	0.8	0.0-2.0	40	10.0
white oak	0.6	0.0-2.0	81	6.0
yellow-poplar	1.0	0.0-2.0	84	5.8
red maple	0.8	0.0-2.0	134	2.9
<u>Scott County</u>				
yellow-poplar	0.8	0.0-2.5	114	7.0
black oak	0.9	0.0-2.0	64	6.3
white oak	0.6	0.0-1.5	66	3.0
chestnut oak	0.8	0.0-2.0	120	0.8
northern red oak	1.0	0.0-2.0	38	0.0
red maple	0.7	0.0-1.5	35	0.0

^aSpecies used were not included in analysis of Markov chains.

^bGrowth measurements were for a diameter class range of 5.0-10.5 inches.

show a relatively high range (0.0-2.0 inches); however, this may have been due to the fact that the growth data were based only on 19 trees.

Mortality percentages over the five years between inventories were greatest for American elm (21.3) and lowest for white oak (0). Post oak and yellow-poplar were similar with 14.8 and 14.3, respectively. Next to white oak, red maple was lowest with only 3.6 percent. Cherrybark oak mortality was only 5.3 percent, which again, could have been influenced by small sample size.

Highland Rim Forest Tract

Southern red oak and post oak were the only selected species on this tract; however, combined they represented over one-half of all the species measured on the tract. Since post oak has already been discussed in earlier sections, only southern red oak will be mentioned here. The average five-year diameter growth rate was very low (0.8 inches). This was quite different from the high growth rate observed for southern red oak on the Ames Plantation (2-1/2 to 3 inches). Mortality for the five-year period was 8.3 percent.

Morgan County Forest Tract

All species listed under the Morgan County forest tract were present on the Ames forest tract, with the exception of scarlet oak and northern red oak. Those species common to both tracts (black oak, white oak, yellow-poplar, and red maple) showed, on the average, a one-half-inch higher periodic growth rate on the Ames Plantation, except for red maple. This species was growing 0.2 inches more on the Morgan tract. The red maple growth range was greater at Ames, but the majority of trees

failed to maintain the growth rate measured on the Morgan tract.

Scarlet oak and northern red oak on the Morgan tract were maintaining growth rates of 0.7 and 0.8 inches, respectively. Yellow-poplar was maintaining the best periodic growth rate at 1.0 inches.

Mortality percentages were greatest in scarlet oak (28.3), which was also the highest mortality for any of the four tracts. Black oak mortality was 21.1 percent. This was nearly 8 percent higher than the black oak mortality on the Ames Plantation. For species common to both the Morgan and Ames Plantation tracts, mortality was consistently higher on the Morgan tract, with the exception of yellow-poplar.

Scott County Forest Tract

In general, diameter growth rates and ranges on this tract were very similar to those on the Morgan tract. However, as mentioned in previous sections, large mortality differences were found between these two tracts. Mortality percentages were consistently less on the Scott County tract for all selected species, with the exception of yellow-poplar which was about equal to that on the Morgan tract.

CHAPTER VI

SUMMARY

A mathematical tool of management science, Markov chains, was used to quantify anticipated diameter growth and mortality as they contribute to stand variation found in selected hardwood stands in Tennessee. The objectives of this study were to compare present and projected hardwood diameter distributions and their resulting differences over four experimental forest tracts. Comparisons were made among total tracts, individual species on different tracts, and species within each tract.

Diameter and mortality data were obtained from a five-year remeasurement of permanent C.F.I. plots located on experimental forests. The four tracts studied were: Ames Plantation, Highland Rim, Morgan County, and Scott County.

These tracts presented an opportunity of studying a wide range in potential productivity. Ames Plantation represented the best growing conditions, while Highland Rim typified the poorest conditions. Morgan and Scott Counties offered an intermediate comparison between these two extremes.

In order to obtain diameter projection information for the different forest tracts and for species within each tract, the following methods and procedures were applied: species were selected from each forest tract; diameter frequency distributions were computed for these selected species and for the total forest tracts; and a portion of these diameter frequency distributions were converted to probabilities and projected by

Markov chains. Where data were adequate, results were obtained in four basic categories: projected diameter distributions for one transition period; projected time periods to larger diameter classes; projected time periods that trees can be expected to remain in each diameter class, and projected mortality percentages.

I. REVIEW OF MAJOR FINDINGS

The ability of stands to differentiate within diameter classes over entire forest tracts was, to some extent, related to tract productivity. The analysis revealed extremely long time period projections, per se, for all tracts. Highland Rim exemplified this fact in the following manner. It had the longest projected time for five-inch trees to reach sawtimber-size (approximately 20 years longer than the other three tracts). In addition, Highland Rim exhibited the slowest diameter growth rates. Ames Plantation, however, did not perform according to expectations in those cases where all hardwoods were considered. It did not exceed the Morgan and Scott County forest tracts in projected time to sawtimber-size.

Although in close proximity, the Morgan and Scott County forest tracts surprisingly showed the largest projected differences in mortality. Scott County exhibited the lowest projected mortality, in comparison to all other tracts. Projected mortality differences were small among the remaining three tracts. It was not completely clear why Scott County had such low mortality projection; however, the answer probably resulted from differences in stocking, species composition, and initial mortality within species common to both tracts.

The majority of selected species performed, on their respective locations, according to traditional growth expectations. Again, the projected time required to reach sawtimber-size was extremely long.

Sweetgum and southern red oak, the two most abundant species on the Ames Plantation, performed contrary to what was anticipated. Southern red oak was the fastest growing species and the only one studied that maintained an important positive growth rate differential on the forest tract on which it occurred. Sweetgum, on the average, exhibited very slow growth and maintained a negative growth rate differential on the Ames Plantation. Perhaps, due to the variety of site conditions on which sweetgum occurred at Ames, it revealed both slow and fast growing trees. Adding to this variability was extremely low mortality. The net result was an extremely high variation, which questions the validity of its Markov chains.

II. CONCLUSIONS

The goal of this study has been to interpret the uncertainties of diameter growth as a stochastic process by a theoretical model known as Markov chains. All indications are that with adequate data Markov chains can be applied to the traditional forestry problem of forest stand projections. This type of analysis seems more applicable to either natural, unmanaged stands where large variability exists or to large diverse forest tracts that have C.F.I. systems.

Although long expected time periods were projected in this study, the implications to timber management are not as discouraging as these projections might suggest. For example, foresters are more concerned

regarding future products that are derived from that portion of the stand that grows faster than one standard deviation to the right of the mean. In this study, 16 percent of trees within the diameter range selected should grow faster than one standard deviation of the projected means, and thus, may account for the majority of ultimately selected crop trees.

With adequate data, Markov chains appear to be a good tool for quantifying mortality. For example, the strong inverse relationship found in this study between projected mortality and diameter-size class implies the need for more intensive management and early thinnings to capture such mortality.

III. RECOMMENDATIONS

Results from this study indicate several suggested recommendations. The markovian property of forest stand projection should be documented with the second C.F.I. remeasurements. All projected stand tables should be checked for accuracy with 1972 and 1973 growth data.

Recommendations for additional research include the following:

1. According to Watt (1968), accurate predictions are possible with stochastic models when a small population is used. Thus, more research could be conducted with Markov chains to include further stratification. Stratification could include the variables of site, age, crown class, stocking, vigor class, and/or tree grade.

2. Further research could be conducted to expand the range of projected time periods in order to integrate them with the financial maturity of commercially important species.

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LITERATURE CITED

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APPENDICES

APPENDIX A

COMMON NAMES OF ALL SPECIES AND THEIR SCIENTIFIC EQUIVALENTS,

CODED BY FOREST TRACTS

Location Code ^a	Common Names ^b	Scientific Equivalents ^c
A,M,S a A	.. red maple sugar maple boxelder	<u>Acer rubrum</u> L. <u>Acer saccharum</u> Marsh. <u>Acer negundo</u> L.
M,S,	yellow buckeye	<u>Aesculus octandra</u> Marsh.
M	serviceberry	<u>Amelanchier arborea</u> Michx.
S M,S A	yellow birch sweet birch river birch	<u>Betula alleghaniensis</u> Britton. <u>Betula lenta</u> L. <u>Betula nigra</u> L.
A,HR,M,S	.. hickory	<u>Carya sp.</u> Nutt.
A	redbud	<u>Cercis canadensis</u> L.
A,M,S	dogwood	<u>Cornus florida</u> L.
A,M	persimmon	<u>Diospyros virginiana</u> L.
M,S	American beech	<u>Fagus grandifolia</u> Ehrh.
A,M,S A,M,S	white ash green ash	<u>Fraxinus americana</u> L. <u>Fraxinus pennsylvanica</u> Marsh.
A,M,S	black walnut	<u>Juglans nigra</u> L.
A,M,S	.. sweetgum	<u>Liquidambar styraciflua</u> L.
A,M,S	.. yellow-poplar	<u>Liriodendron tulipifera</u> L.
A,S	osage orange	<u>Maclura pomifera</u> Raf.
M,S	magnolia	<u>Magnolia sp.</u> L.
A,M	red mulberry	<u>Morus rubra</u> L.
A,HR,M,S	blackgum	<u>Nyssa sylvatica</u> Marsh.
A,M	Ironwood	<u>Ostrya virginiana</u> Mill.
M,S	sourwood	<u>Oxydendron arboreum</u> L.

Location Code ^a	Common Names ^b	Scientific Equivalents ^c
a	ponderosa pine	<u>Pinus ponderosa</u> Laws.
A,M,S	sycamore	<u>Platanus occidentalis</u> L.
A	cottonwood	<u>Populus deltoides</u> Bartr.
A,M,S	black cherry	<u>Prunus serotina</u> Ehrh.
A,M,S	. white oak	<u>Quercus alba</u> L.
A	swamp white oak	<u>Quercus bicolor</u> Willd.
A,HR,M,S	. scarlet oak	<u>Quercus coccinea</u> Muenchh.
A,HR	.. southern red oak	<u>Quercus falcata</u> Michx.
A	. cherrybark oak	<u>Quercus falcata</u> var. <u>pagodaefolia</u> Ell.
A,HR,M,S	blackjack oak	<u>Quercus marilandica</u> Muenchh.
A	swamp chestnut oak	<u>Quercus michauxii</u> Nutt.
A	water oak	<u>Quercus nigra</u> L.
A	pin oak	<u>Quercus palustris</u> Muenchh.
A	willow oak	<u>Quercus phellos</u> L.
M,S	.. chestnut oak	<u>Quercus prinus</u> L.
A,M,S	. northern red oak	<u>Quercus rubra</u> L.
A,AR,M	shumard oak	<u>Quercus shumardii</u> Buckl.
A,HR,M	.. post oak	<u>Quercus stellata</u> Wangenh.
A,HR,M,S	. black oak	<u>Quercus velutina</u> Lam.
A,M,S	black locust	<u>Robinia pseudoacacia</u> L.
A,S	black willow	<u>Salix nigra</u> Marsh.
A,M,S	sassafras	<u>Sassafras albidum</u> Nutt.
a	hemlock	<u>Tsuga canadensis</u> L.
A,S	. American elm	<u>Ulmus americana</u> L.
A,M	. winged elm	<u>Ulmus alata</u> Michx.

^aA = Ames Plantation; HR = Highland Rim; M = Morgan County; S = Scott County. Those species without a location code did not occur on the study areas, but were cited in the literature review.

^b. = individually selected species; .. = Markov chains selected species. All species without a dot code were included only in analysis of entire forest tracts.

^cNomenclature from Harlow and Harrar (1958).

. APPENDIX B

TABLE 14

CHANGE IN DIAMETER DISTRIBUTIONS OF ALL HARDWOODS
FOR A FIVE-YEAR GROWTH PERIOD AMES FOREST TRACT

1968 D.B.H.

	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10+	M	TOTAL
5.0	12	40	24	9	4	2		1					10	102
5.5		29	55	24	17	5	1	4					16	151
6.0			22	52	28	11	14		2				12	141
6.5				24	38	21	8	7	3	3			9	113
7.0					14	25	13	13	3	2	1		13	84
7.5						14	26	23	7	5	2	2	13	92
8.0						1	16	42	23	6	5		5	98
8.5								14	19	17	8	1	3	62
9.0									12	20	13	1	6	52
9.5								1		11	22	9	5	48
10.0											7	11	2	20
10+												2	4	6
														969

TABLE 15

CHANGE IN DIAMETER DISTRIBUTIONS OF ALL HARDWOODS
FOR A FIVE-YEAR GROWTH PERIOD HIGHLAND RIM FOREST TRACT

1967 D.B.H.														
	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10+	M	TOTAL
5.0	1	6	2											9
5.5		4	10		1								1	16
6.0			4	12	2								4	22
6.5			1	10	11	7							1	30
7.0					7	11	3	1					3	25
7.5						7	8	7	1				1	24
8.0						1	7	7	3					18
8.5							1	7	12	1			1	22
9.0								1	2	7	2	1		13
9.5										2	5	1	1	9
10.0											4	5	1	10
10+													1	1
1962 D.B.H.														<u>199</u>

TABLE 16

CHANGE IN DIAMETER DISTRIBUTIONS OF ALL HARDWOODS
FOR A FIVE-YEAR GROWTH PERIOD MORGAN COUNTY FOREST TRACT

1967 D.B.H.												
	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10+
5.0	12	54	31	12	3							12
5.5	1	32	77	47	16	2	2					10
6.0		1	38	84	36	16	2	2				14
6.5			2	36	64	47	19	3				8
7.0					28	51	23	13	1			9
7.5						20	47	30	5	6	1	5
D.B.H. 8.0							13	54	24	13	2	9
8.5								13	39	28	6	2
9.0									9	37	30	3
9.5										14	26	17
10.0											8	16
10+											1	2
												3
												6
												1323

TABLE 18

TEN-YEAR PROJECTED STAND TABLE FOR ALL HARDWOODS
AMES FOREST TRACT

1973 D.B.H.

	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10+	M	TOTAL
5.0	1.4	12.4	21.1	18.2	13.4	6.6	4.5	3.1	1.2	0.7	0.2	0.1	19.1102.0	
5.5		5.6	19.1	30.0	25.1	15.5	11.6	7.5	3.9	2.5	0.9	0.2	29.2151.0	
6.0			3.4	19.2	26.5	21.5	15.6	16.3	7.3	4.3	1.8	0.3	24.8141.0	
6.5				5.1	14.4	19.0	14.8	17.7	8.3	6.9	4.3	1.2	21.2113.0	
7.0				2.3	8.1	11.4	17.0	10.1	7.7	5.1	1.7	20.6	84.0	
7.5					2.4	8.2	19.9	15.8	12.5	9.3	4.8	18.9	92.0	
D.B.H. 8.0				0.3	2.9	16.7	22.0	22.8	16.5	5.0	11.8	98.0		
8.5							3.5	8.7	15.0	17.1	9.2	8.4	62.0	
9.0								0.4	2.8	9.2	16.7	12.1	10.8	52.0
9.5								0.5	0.3	2.8	12.9	23.2	8.4	48.0
10.0										2.4	14.8	2.7	20.0	
10+												6.0	0.0	
TOTAL	1.4	18.0	43.7	72.4	81.8	73.5	68.9	102.6	80.4	84.4	87.3	78.6	176.0	

TABLE 19

TEN-YEAR PROJECTED STAND TABLE FOR ALL HARDWOODS
HIGHLAND RIM FOREST TRACT

1972 D.B.H.

	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10+	M	TOTAL
5.0	0.1	2.2	4.3	1.1	0.6								0.7	9.0
5.5		1.0	4.3	5.5	1.4	0.4	0.1						3.2	16.0
6.0			1.1	6.2	5.3	3.7	0.2	0.1					5.4	22.0
6.5			0.5	3.9	6.8	9.2	3.7	2.5	0.3				3.1	30.0
7.0					2.0	6.5	5.7	5.0	1.5				4.3	25.0
7.5						2.5	5.8	7.5	5.6	0.9	0.2	0.1	1.6	24.0
8.0						0.7	3.4	5.5	5.5	1.9	0.5	0.2	0.4	18.0
8.5						0.1	0.7	3.5	5.8	7.0	2.4	1.0	1.4	22.0
9.0								0.5	0.9	2.7	5.0	2.9	1.0	13.0
9.5										0.4	3.1	3.7	1.7	9.0
10.0											1.6	7.0	1.4	10.0
10+												1.0		
TOTAL	0.1	3.2	10.3	16.6	16.1	23.0	19.6	24.5	19.6	13.0	12.7	16.0	24.3	

TABLE 20

TEN-YEAR PROJECTED STAND TABLE FOR ALL HARDWOODS
MORGAN COUNTY FOREST TRACT

1972 D.B.H.

	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10+	M	TOTAL
5.0	1.5	14.6	31.5	30.6	15.7	7.5	2.7	0.5	0.3					19.0124.0
5.5	0.3	6.3	29.1	51.1	37.5	25.9	10.1	3.9	1.4	0.3	0.1			20.9187.0
6.0		0.4	8.8	33.7	45.3	42.7	22.8	10.3	2.0	2.0	0.9	0.1	0.1	24.1193.0
6.5			0.8	8.1	27.6	44.0	37.1	28.9	7.8	5.5	0.9	0.1	0.1	18.2179.0
7.0					6.3	20.4	28.8	28.9	12.5	9.4	2.0	0.3		16.4125.0
7.5						3.5	13.6	31.3	23.2	18.5	7.3	2.8		13.8114.0
D.B.H.							1.5	13.3	26.8	30.6	18.0	6.3		18.5115.0
8.5								1.7	9.5	27.4	27.8	13.8		17.8 98.0
9.0									1.0	12.2	25.0	26.5		17.4 82.0
9.5										3.1	11.5	32.3		17.2 64.0
10.0											1.8	19.6		14.7 36.0
10+														6.0
TOTAL	1.7	21.3	70.2	123.5	132.3	144.0	116.6	118.8	84.5	109.0	95.3	107.7		198.0

TABLE 21

TEN-YEAR PROJECTED STAND TABLE FOR ALL HARDWOODS
SCOTT COUNTY FOREST TRACT

1972 D.B.H.

	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10+	M	TOTAL
5.0	1.4	10.3	13.5	12.7	6.8	2.3	1.4	0.1					4.5	53.0
5.5	0.5	12.3	19.9	25.9	19.2	10.1	7.6	2.6	0.9	0.3	0.0	0.1	6.5	106.0
6.0		0.6	5.9	18.0	22.3	18.4	15.2	6.9	2.5	0.9	0.1	0.2	3.1	94.0
6.5				4.5	11.3	18.7	18.6	16.6	8.3	4.0	1.2	0.5	4.4	88.0
7.0				0.4	2.0	9.6	16.6	26.7	15.1	7.7	3.2	1.8	5.1	88.0
7.5						1.3	4.9	18.7	22.6	13.9	8.8	2.2	2.5	75.0
D.B.H. 8.0							0.3	5.3	14.5	11.7	14.5	5.2	4.5	56.0
8.5								1.4	9.5	11.0	19.9	10.9	3.3	56.0
9.0								2.8	5.8	18.4	21.2	2.9	51.0	
9.5									1.1	9.0	22.2	1.7	34.0	
10.0										0.8	10.0	1.2	12.0	
10+												1.0		
TOTAL	1.9	23.2	39.3	61.4	61.6	60.4	64.5	78.4	76.1	56.3	75.9	75.3	39.8	

TABLE 22

CHANGE IN DIAMETER DISTRIBUTIONS OF SWEETGUM
FOR A FIVE-YEAR GROWTH PERIOD AMES FOREST TRACT

1968 D.B.H.

	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10+	M	TOTAL
5.0	1	4	2	1				1						9
5.5		5	7		1	2		1						16
6.0			7	8	2	2			1				1	21
6.5				6	5									11
7.0					3	3	1	1						8
7.5						3	4	1	1		1			10
8.0							3	7	2		1			13
8.5									2	2				4
9.0									2	2				4
9.5								1		6	1	1		9
10.0											1		5	6
10+														

														111

TABLE 23

CHANGE IN DIAMETER DISTRIBUTIONS OF SOUTHERN RED OAK
FOR A FIVE-YEAR GROWTH PERIOD AMES FOREST TRACT

1968 D.B.H.												
	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10+
5.0	1	2	3	1								7
5.5		1	6	4							2	13
6.0			1	3	2	2					1	9
6.5			1	4	2	2	1	1				11
7.0								1	1			3
7.5							2	3	1			7
8.0								2	3			5
8.5									2	1	3	6
9.0											2	4
9.5										2		2
10.0											1	2
10+												
												69

TABLE 24

CHANGE IN DIAMETER DISTRIBUTIONS OF POST OAK
FOR A FIVE-YEAR GROWTH PERIOD HIGHLAND RIM FOREST TRACT

1967 D.B.H.

	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10+	M	TOTAL
5.0	3	1												4
5.5	3	5	1											9
6.0		3	6										1	10
6.5			3	4										13
7.0			4	4	1									9
7.5			1	3	1									5
8.0			1	4	5	1								11
8.5					4	9								13
9.0						5	1							6
9.5							3							3
10.0							2	1						3
10+														---
														86

TABLE 25

CHANGE IN DIAMETER DISTRIBUTIONS OF CHESTNUT OAK
FOR A FIVE-YEAR GROWTH PERIOD MORGAN COUNTY FOREST TRACT

1967 D.B.H.													
	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10+	M TOTAL
5.0	1	13	14	2									1 31
5.5		5	33	20	5								2 65
6.0			6	27	17	5	1						3 59
6.5				8	21	14							1 44
7.0					5	19	10	5					2 41
7.5						5	17	16	2		1		1 42
8.0							4	23	14		1		2 44
8.5								2	18	12	1		3 33
9.0									1	18	15		3 34
9.5										4	14	7	2 25
10.0											2	7	2 11
10+												1	1 1
													430

1962

D.B.H.

TABLE 26

CHANGE IN DIAMETER DISTRIBUTIONS OF HICKORY
FOR A FIVE-YEAR GROWTH PERIOD SCOTT COUNTY FOREST TRACT

1967 D.B.H.

	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10+	M	TOTAL
5.0	1	1												2
5.5		7	5	1										13
6.0			3	4	1									8
6.5				2	6									8
7.0					2	3	2	1					1	9
7.5						4	2	2						8
8.0							1	1	1					3
8.5								4	3					7
9.0									4	2	4		1	11
9.5										3	7			10
10.0											2	5		7
10+														
														86

1962

D.B.H.

CHANGE IN DIAMETER DISTRIBUTIONS OF YELLOW-POPLAR
FOR A FIVE-YEAR GROWTH PERIOD MORGAN-SCOTT COUNTY FOREST TRACTS

89

TABLE 28

CHANGE IN DIAMETER DISTRIBUTIONS OF RED MAPLE
FOR A FIVE-YEAR GROWTH PERIOD MORGAN-SCOTT COUNTY FOREST TRACTS

1967 D.B.H.

	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10+	M	TOTAL
5.0		2	5	2	1								1	11
5.5		4	7	9	2		1						1	24
6.0			3	7	10	2	1						1	24
6.5				5	11	6	5	2						29
7.0					1	10	5							16
7.5						2	7	4	2	3				18
8.0							1	3	2	4			1	11
8.5								4	3	2	2	1		12
9.0									1	3	2	1		7
9.5											5	5		10
10.0											1	1		2
10+												1		1
														165

1962

D.B.H.

TABLE 29

TEN-YEAR PROJECTED STAND TABLE FOR SWEETGUM
AMES FOREST TRACT

1973 D.B.H.

	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10+	M	TOTAL
5.0	0.1	1.7	2.6	1.4	0.9	0.7	0.0	0.4	0.6	0.5			0.1	9.0
5.5		1.6	4.5	2.7	1.4	2.3	0.9	0.6	1.0	0.5	0.2		0.3	16.0
6.0			2.3	7.0	5.1	2.0	1.0	0.4	1.0	0.5	0.2		1.3	21.0
6.5				3.3	4.6	1.9	0.6	0.6						11.0
7.0					1.1	2.0	1.8	1.2	1.0	0.5	0.4			8.0
7.5						0.9	2.1	2.5	1.9	1.0	0.8	0.8		10.0
D.B.H. 8.0							0.7	1.6	5.0	4.5	0.4	0.8		13.0
8.5								0.2	1.0	2.3	0.2	0.2		4.0
9.0								0.2	1.0	2.3	0.2	0.2		4.0
9.5								0.7	0.5	4.5	0.8	2.5		9.0
10.0											0.2	5.8		6.0
10+														
TOTAL	0.1	3.3	9.5	14.4	13.0	9.8	7.2	8.5	13.0	16.7	3.4	10.4	1.8	

TABLE 30

TEN-YEAR PROJECTED STAND TABLE FOR SOUTHERN RED OAK
AMES FOREST TRACT

1973 D.B.H.

	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10+	M	TOTAL
5.0			0.1	1.0	2.1	1.0	1.0	0.3	0.6	0.3			0.7	7.0
5.5				0.7	2.5	1.3	1.3	0.5	1.9	1.3			3.4	13.0
6.0			0.1	0.4	0.2	0.8	1.7	2.6	1.0	0.0	0.0	0.3	2.0	9.0
6.5			0.1	0.4	0.2	0.8	1.7	3.2	1.5	1.0	0.5	0.5	1.6	11.0
7.0											1.5	0.2	1.2	3.0
7.5								0.8	2.2	0.5	2.0	1.2	0.2	7.0
8.0									0.7	0.3	2.5	0.7	0.7	5.0
8.5											3.5	2.0	0.5	6.0
9.0											1.0	2.0	1.0	4.0
9.5											1.0	1.0		2.0
10.0											0.5	1.5		2.0
10+														
TOTAL	0.0	0.0	0.1	1.8	5.3	2.7	3.8	5.1	11.2	5.0	13.0	9.6	11.5	

TABLE 31

TEN-YEAR PROJECTED STAND TABLE FOR POST OAK
HIGHLAND RIM FOREST TRACT

1972 D.B.H.

	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10+	M	TOTAL
5.0		1.0	2.0	0.6	0.3								0.1	4.0
5.5		1.0	3.2	3.0	0.8	0.4	0.0	0.1					0.5	9.0
6.0			0.9	3.2	2.8	1.8							1.3	10.0
6.5				0.7	4.1	4.4	2.4	1.5						13.0
7.0					1.8	2.6	2.4	1.6	0.7					9.0
7.5						0.5	1.7	1.9	1.0					5.0
8.0						0.6	2.1	3.6	3.8	0.8	0.2			11.0
8.5								1.2	2.8	7.5	1.5			13.0
9.0										5.7	0.3			6.0
9.5										2.0	1.0			3.0
10.0										1.3	1.7			3.0
10+														
TOTAL	0.0	2.0	6.0	7.5	9.7	10.3	8.5	9.8	8.3	8.3	10.7	3.0	1.9	

TABLE 32

TEN-YEAR PROJECTED STAND TABLE FOR CHESTNUT OAK
MORGAN COUNTY FOREST TRACT

1972 D.B.H.

	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10+	M	TOTAL
5.0		1.4	8.5	10.8	6.0	1.8	0.2							2.2 31.0
5.5		0.4	5.9	20.3	20.0	11.5	1.8	0.6						4.5 65.0
6.0			0.6	7.7	16.7	17.6	6.4	4.5	0.6	0.0	0.1			4.9 59.0
6.5				1.5	6.4	13.9	10.8	7.9	0.7	0.0	0.3			2.5 44.0
7.0					0.6	4.6	9.8	13.4	6.8	1.8	0.8			3.2 41.0
7.5						0.6	3.6	11.8	14.4	6.9	2.1	0.6		2.1 42.0
D.B.H.							0.4	3.5	14.2	15.8	7.1	0.6		2.4 44.0
8.0								0.1	1.6	12.2	14.9	4.0		0.2 33.0
8.5														
9.0										3.4	13.2	14.6		2.7 34.0
9.5										0.6	4.8	17.0		2.5 25.0
10.0											0.4	8.3		2.4 11.0
10+												1.0		
TOTAL	0.0	1.8	15.0	40.2	49.7	50.0	32.9	41.7	38.3	40.7	43.8	46.2		29.6

TABLE 33

TEN-YEAR PROJECTED STAND TABLE FOR HICKORY
SCOTT COUNTY FOREST TRACT

1972 D.B.H.

	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10+	M	TOTAL
5.0	0.5	1.0	0.4	0.1										2.0
5.5		3.8	4.6	3.3	1.4									13.0
6.0			1.1	2.5	3.6	0.3	0.2	0.1					0.1	8.0
6.5				0.5	2.8	2.0	1.3	0.7					0.7	8.0
7.0					0.4	2.2	1.9	2.2	1.1				1.2	9.0
7.5						2.0	1.7	2.8	1.5					8.0
8.0							0.3	0.9	1.1	0.2	0.4		0.1	3.0
8.5								2.3	2.8	0.5	1.1		0.3	7.0
9.0									1.5	1.3	4.0	2.9	1.4	11.0
9.5										0.9	4.1	5.0		10.0
10.0											0.6	6.4		7.0
10+														
TOTAL	0.5	4.8	6.1	6.4	8.2	6.5	5.4	9.0	8.0	3.0	10.1	14.3	3.7	

TABLE 34

TEN-YEAR PROJECTED STAND TABLE FOR YELLOW-POPLAR
MORGAN-SCOTT COUNTY FOREST TRACTS

1972 D.B.H.

	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10+	M	TOTAL
5.0		1.2	2.2	3.0	2.0	1.8	0.7	0.2	0.1	0.1				2.6 14.0
5.5		1.4	3.6	7.2	5.9	7.1	3.2	1.4	0.9	0.8	0.1			3.6 35.0
6.0			0.5	2.4	2.9	4.6	3.4	2.3	0.7	0.7				1.6 19.0
6.5				1.1	3.2	5.8	5.7	5.5	3.0	3.9	0.8	0.2		2.8 32.0
7.0					0.8	2.3	2.8	3.9	2.8	3.9	1.3	0.4		0.7 19.0
7.5						0.5	0.9	2.8	4.0	4.8	2.2	0.9		0.9 17.0
8.0								0.3	2.5	3.7	4.3	2.2		3.0 16.0
8.5								0.1	1.6	2.4	4.2	3.3		1.5 13.0
9.0									1.0	1.6	5.4	5.9		2.1 16.0
9.5										0.6	1.6	2.3		2.6 7.0
10.0												0.5	1.5	2.0
10+														
TOTAL	0.0	2.6	6.2	13.7	14.8	22.2	16.7	16.5	16.7	22.4	20.3	16.6	21.2	

TABLE 35

TEN-YEAR PROJECTED STAND TABLE FOR RED MAPLE
MORGAN-SCOTT COUNTY FOREST TRACTS

1972 D.B.H.

	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10+	M	TOTAL
5.0		0.3	1.2	2.6	3.1	1.5	0.9	0.1					1.3	11.0
5.5		0.7	2.0	5.1	6.8	3.7	2.7	0.9	0.2	0.4			1.5	24.0
6.0			0.4	2.1	4.5	8.2	5.3	1.2	0.4	0.7			1.2	24.0
6.5				0.9	2.6	8.6	7.1	3.7	2.1	3.2	0.3	0.2	0.5	29.0
7.0					0.1	1.7	4.7	3.6	2.0	3.5			0.5	16.0
7.5						0.2	1.4	3.7	2.8	4.4	2.7	2.1	0.6	18.0
D.B.H. 8.0							0.1	1.3	1.2	1.7	3.1	2.5	1.1	11.0
8.5								1.3	1.4	2.0	3.5	3.8		12.0
9.0									0.1	0.4	2.8	3.6		7.0
9.5											2.5	7.5		10.0
10.0											0.5	1.5		2.0
10+													1.0	
TOTAL	0.0	1.0	3.6	10.6	17.0	23.9	22.2	15.8	10.3	16.2	15.5	22.2	6.7	

APPENDIX C

MARKOV CHAIN COMPUTER PROGRAM

```

DIMENSION LAB(20),Z(13,13),AM(13,13)
DIMENSION P(13,14),PS(13,13),E(11),V(11),VIJ(11,11),
AN(11),AB(11,13),A(11,22)
DO1I=1,11
1  AN(I)=4.5+I*.5
99  WRITE(6,21)
    DO2I=1,8
    READ(5,20)((LAB(J),J=1,20)
20  FORMAT(20A4)
22  WRITE(6,23)(LAB(J),J=1,20)
23  FORMAT(21X,20A4)
    DO25I=1,12
    READ(5,24)L1,L2,L3,(P(I,J),J=1,14)
24  FORMAT(/,2A4,A3,F3.0,13F5.0)
25  WRITE(6,26)L1,L2,L3,(P(I,J),J=1,14)
26  FORMAT(31X,1H|,/,21X,2A4,A3,F3.0,12F5.0,F6.0)
    READ(5,27)A1
27  FORMAT(/,75X,F4.0,/)
    II=1
    DO61I=1,13
    Z(1,I)=0.
    DO61J=1,11
61  Z(1,I)=Z(1,I)+P(J,I)
    WRITE(6,28)(Z(1,I),I=1,13),A1
28  FORMAT(31X,1H|,/,26X,'TOTAL',F3.0,12F5.0,F6.0)
    DO4I=1,11
    P(12,I)=0.
    P(13,I)=0.
    IF(P(I,14).NE.0..AND.P(I,14).NE.P(I,13)) GO TO 2
    WRITE(6,3)
3  FORMAT(1H1,'NOT ENOUGH DATA')
    GO TO 99
2  DO4J=1,13
49  AM(I,J)=P(I,J)/(P(I,14)-P(I,13))
    P(I,J)=P(I,J)/P(I,14)
4  CONTINUE
    P(13,13)=1.
    P(12,12)=1.
    P(12,13)=0.
    P(13,12)=0.
    WRITE(6,29)
29  FORMAT(///,' THE PROBABILITY TRANSITION MATRIX IS',/)
    WRITE(6,30)(AM(I),I=1,11)
30  FORMAT(30X,11F5.1,' 10+ M TOTAL',/,30X,75(1H-))
    DO31I=1,11
31  WRITE(6,32)AN(I),(P(I,J),J=1,13)
32  FORMAT(/,25X,F5.1,1H|,13F5.2)
    WRITE(6,33)((P(I,J),J=1,13),I=12,13)
33  FORMAT(/,27X,'10+',1H|,13F5.2,/,29X,'M',1H|,13F5.2)
    DO5I=1,13
    DO5J=1,13

```

```

      PS(I,J)=0.
      DO5K=1,13
5      PS(I,J)=PS(I,J)+P(I,K)*P(K,J)
      WRITE(6,65)
65     FORMAT(1H1,'STAND TABLE AFTER 10 YEARS',/)
      WRITE(6,30)(AN(I),I=1,11)
      DO200J=1,13
200    Z(13,J)=0.
      DO62I=1,12
      E(I)=0.
      DO62J=1,13
      Z(I,J)=PS(I,J)*P(I,14)
      Z(13,J)=Z(13,J)+Z(I,J)
62     E(I)=E(I)+Z(I,J)
      DO64I=1,11
64     WRITE(6,81)AN(I),(Z(I,J),J=1,13),E(I)
81     FORMAT(/,25X,F5.1,1H|,14F5.1)
      WRITE(6,82)((Z(I,J),J=1,13),I=12,13)
82     FORMAT(/,27X,'10+',1H|,13F5.1,/,25X,
      "TOTAL",1H|,14F5.1)
      DO7I=1,11
      DO8J=1,11
8      P(I,J)=-P(I,J)
7      P(I,I)=P(I,I)+1.
      N=11
104    IF(I)99,102,101
102    DO113I=1,N
      DO103J=1,N
103    A(I,J)=-AM(I,J)
113    A(I,I)=A(I,I)+1
      GO TO 110
101    DO9I=1,N
      DO9J=1,N
9      A(I,J)=P(I,J)
110    N2=N+N
      N1=N+1
      DO10I=1,N
      DO11J=N1,N2
11     A(I,J)=0.
      IN=I+N
10     A(I,IN)=1.
      DO14I=1,N
      X=A(I,I)
      I1=I+1
      DO14J=I1,N2
      A(I,J)=A(I,J)/X
      DO14K=1,N
      IF(K.EQ.I)GO TO 14
      A(K,J)=A(K,J)-A(K,I)*A(I,J)
14     CONTINUE
      DO12I=1,N

```

```

      E(I)=0.
      DO12 J=N1,N2
12    E(I)=E(I)+A(I,J)
      DO13 J=1,N
      JN=J+N
      DO13 I=1,N
13    VIJ(I,J)=A(I,JN)*(2.*A(J,JN)-1.)-A(I,JN)*A(I,JN)
      DO15 I=1,N
      V(I)=0.
      DO16 J=1,N
      JN=J+N
      V(I)=2.*A(I,JN)*E(J)+V(I)
      IF(I.EQ.J)V(I)=V(I)-E(I)
16    CONTINUE
      V(I)=V(I)-E(I)*E(I)
15    CONTINUE
      DO18 I=1,N
      DO18 J=N1,13
      AB(I,J)=0.
      DO18 K=1,N
      KN=K+N
18    AB(I,J)=AB(I,J)+A(I,KN)*P(K,J)
      WRITE(6,21)
      DO37 I=1,N
37    WRITE(6,35)(A(I,J),J=N1,N2)
35    FORMAT(1H0,13F7.2)
21    FORMAT(1H1)
      WRITE(6,60)
60    FORMAT(////)
      DO38 I=1,N
38    WRITE(6,35)(VIJ(I,J),J=1,N)
      WRITE(6,60)
      DO40 I=1,N
40    WRITE(6,35)E(I)
      WRITE(6,60)
      DO41 I=1,N
41    WRITE(6,35)V(I)
      WRITE(6,60)
      IF(II)106,106,105
105   DO42 I=1,N
42    WRITE(6,35)(AB(I,J),J=N1,13)
6     CONTINUE
106   II=II-1
      GO TO 104
      END

```

VITA

Wayne Madison Boyd, son of Paul Calvin Boyd and Louise (Officer) Boyd, was born in Cleveland, Tennessee, on October 9, 1946. He attended elementary school and high school in Cleveland, and graduated from Bradley Central High School in 1964. He entered The University of Tennessee in 1964 and received the degree of Bachelor of Science in Forestry in June, 1968. In September, 1968, he entered the Graduate School of The University of Tennessee, holding a teaching assistantship. In August, 1970, he received his Master of Science degree in Forest Management.

He is married to the former Kathryn Ann Berney of Knoxville, Tennessee.