1966

Thinning Methods in Slash Pine Plantations.

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KEISTER, Thomas Dwight, 1927-
THINNING METHODS IN SLASH PINE PLANTATIONS.

Louisiana State University, Ph.D., 1966
Agriculture, forestry and wildlife

THINNING METHODS IN SLASH PINE PLANTATIONS

A Dissertation

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural and Mechanical College
in partial fulfillment of the
requirements for the degree of
Doctor of Philosophy

in

The School of Forestry and Wildlife Management

by
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M.S., Louisiana State University, 1963
August, 1966

ACKNOWLEDGMENTS

The author is indebted to Dr. P. Y. Burns for his advice and help in the completion of this study and the preparation of this dissertation; to Professor A. B. Crow who supplied much of the field data; and to Drs. B. R. Farthing, N. E. Linnartz, T. Hansbrough, and W. C. Hopkins for their critical review of the manuscript.

Special thanks is extended to Mr. Peter Fogg who wrote the program for computing the competition index; to Mr. Jerry Malone and Mr. Terry Truax who wrote most of the other computer programs used; to Mr. Warren Cockerham who, along with Dr. Linnartz, prepared the description of the soils found on the study area; and to the Southern Timber Division of the Crown Zellerbach Corporation, the owners of land involved in this study.

The author is especially thankful to Dr. N. E. Linnartz who directed the crews taking the final field measurements; and to graduate students James Dear and Harvey Kennedy for their many services both in the field and in the office.

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ABSTRACT

Results of a thinning experiment initiated in 1937 in a 13-year-old slash pine (*Pinus elliottii* Engelm.) plantation growing on land of high site quality near Bogalusa, Louisiana were studied. Four thinning treatments (Light Low, Light Crown, Heavy Crown and Selection) and a control (unthinned) were compared. Each treatment included two 1/4-acre plots, and individual tree measurements were taken periodically.

The Heavy Crown and Selection treatments were applied at ages 13 and 26. The Low and Light Crown treatments were applied at ages 13, 24, and 29. One control plot, one Heavy Crown and one Selection plot were inadvertently thinned at age 30. No additional cutting has occurred. The trees were 40 years old when last measured.

No statistically significant differences in either net or gross cubic volume increment per acre were found among the treatments by age 29, but there were indications that frequent light thinnings produced more net volume per acre than heavy thinnings or no thinnings by age 40.

Residual trees inadvertently thinned on the Control plot grew rapidly, indicating that age 30 is not too late, on good sites, for slash pine to respond to thinning. Thinning stimulated tree diameter growth, and the increased growth rate was maintained longer on the more heavily thinned plots.

Increment in individual tree volume was positively correlated with crown length and crown ratio. Crown length was a better variable for predicting volume increment than was crown ratio, but neither variable had a strong effect on increment.

The average height of the trees varied with treatment; unthinned plots had the shortest average height and the Heavy Crown plots had the greatest average height. This result was thought to be a reflection of the sizes of the trees removed in thinnings rather than of growth stimulation resulting from treatment. Dominant-tree height showed little effect from treatment.

A financial analysis of the plots up to age 40 showed that thinning is financially advantageous. The Light Crown and Selection plots proved to be the most valuable. The plot that was first thinned at age 29 was more valuable than one never thinned, indicating that even deferred thinning is profitable.

Mortality was greatest on the unthinned plot; no significant differences in mortality were found among the thinned plots. Fusiform rust appeared to be an indirect cause of most mortality; those trees that died from suppression were much smaller than the average for the stand.

Random samples, totaling 158 trees, were selected from the plots in order to make a study of individual trees. Tree form class and specific gravity of the outer ten growth rings were apparently unaffected by differences in stand density. The number of suitable

pole-and-piling trees per plot was unaffected by the thinning treatment. The exterior quality, expressed in terms of the size and number of first-log knots, seemed to be slightly improved by thinning.

A competition index was developed from the sample tree data, based on the hypothesis that a tree's growth is modified by the proximity and relative sizes of the trees that surround it. It was assumed that each tree influences a circular area within a stand. When two such areas overlap, a zone of competition is established. The index of a single tree is defined as the ratio of the sum of the competition-zone areas within that tree's influence circle to the area of this circle. This competition index was inversely correlated with past growth and present crown width of the sample trees. It was concluded that this index may be useful for measuring stand density and thinning intensity and for predicting future tree growth.

INTRODUCTION

A primary objective of present-day forest management is to grow the most and the highest quality timber possible on a given site in the shortest possible time. Although it is not always possible to achieve both maximum-volume and maximum quality, the highest combination of the two is generally preferred. Maximum volume is obtained by growing a large number of trees of high volume. Maximum quality is obtained by growing the highest proportion possible of high-quality trees. The object of management then can be met by growing the greatest number of high-volume, high-quality trees.

There are differences of opinion as to the definition of a high-quality tree. The definition of such a tree is modified greatly by the use for which the tree is intended. The most important external characteristics of timber quality among coniferous species are size, good bole form, and freedom from knots and other defects. The most important internal qualities are freedom from rot, durability, rings of even width, long fibers, and high density (Anderson 1958). These attributes are important for nearly all products for which coniferous trees are used.

Tree volume is determined by the diameter and length of the tree and by the amount of taper along the length of the tree. Stand volume is the sum of tree volumes and will increase with increasing numbers of trees. Tree volume is modified by competition. That is,

the competition among individuals in the stand causes change in form, diameter, and vigor of the individual trees. Because of these changes the useable volume of the stand does not increase directly as the number of trees is increased, even though total stand volume may.

The number of trees on an area of a given size cannot be increased beyond a certain number without causing mortality within the stand. The number of trees that a given area can support depends on the tree species, the climate, soil, other site conditions, and on the size of the trees themselves. All things being equal, the number of trees will decrease as the tree size increases. Czarnowski (1961) has stated that the number of trees in a "normally" stocked stand on a given site, per unit of land area, varies inversely with the square of the mean stand height.

A forest manager must be concerned with the number of trees he can grow on the sites available to him and ways of controlling the growth of these trees so that volume production and quality will best meet the existing demand for wood. He must try to select a silvicultural system that will best meet his objective.

Tree growth is dependent on the available water, mineral nutrients, light, air, and carbon dioxide. Growth will be hindered if any of these requirements are inadequately supplied. Available light is more or less constant for a given spot on the earth's surface. Water is relatively constant (averaged over long periods of time) for a given climatic condition; although soil type has much to do with determining the amount of the total supply available for trees, and soil

and topography have great influence on the period of availability of this moisture. The available mineral nutrients are dependent on the soil complex. In other words, there is a limit to the supply of the necessary elements for growth on any given site. As the number of trees increases or as the size of the trees increases, the supply of one or more of these elements may become critical. Various silvicultural practices have been developed which attempt to favor certain plants over certain others in the struggle for a share of these elements which are so essential to growth. One of the oldest and most commonly used practices is that of thinning.

Thinnings have been defined as cuttings made in immature stands for the purpose of increasing both the rate of growth of the trees that remain and the total yield of useful material from the stand (Smith 1962). In a technical sense the term "thinning" applies to a specific type of cutting made either in an even-aged stand or within one of the many even-aged groups that make up most uneven-aged stands (Hawley 1946).

There have been numerous papers written on the subject of thinning. It is commonly felt that thinning is the best way that man can control growth and stand composition. Hiley (1956) has said, "It is by thinning, more than any other operation, that a forester can control the destiny of a plantation and contribute to its financial success." Bond (1952) stated that the purpose of thinning "is to furnish each tree with room to grow, but none to waste." Some of the advantages attributed to thinning are increased diameter growth on

residual trees, decreased stand mortality, increased volume on individual stems, and increased income from early returns on invested capital. Thinning is said to influence the growth and form of trees by reducing competition and by altering the environment so that it is more favorable for the processes controlling growth of the remaining trees. Thinning tends to increase the number and size of branches, the over-all size of the crown, the size of the root system, and the taper of the trees left in the stand. The rate of growth on individual trees is increased, or at least maintained after thinning, because the greater availability of light, water, and minerals to the remaining trees favors increased rates of photosynthesis (Kramer and Kozlowski 1960).

The advantage of thinning is frequently thought to be economic rather than physiological. Fedkiw and Yoho (1960) believed that thinning should be dominated more by economic considerations than by silvicultural considerations. Among those advantages of thinning mentioned by Hiley (1930) are economic values of shorter rotations and the removal of substantial value in intermediate cuts, thereby reducing capital invested in the remaining stand.

Not all of the reports on thinning have found such favorable results. Johnson (1961) determined for slash pine (Pinus elliottii Engelm.) that "nowhere can we demonstrate much of any acceleration in diameter growth as a result of heavy thinnings, much less moderate or light thinnings, over periods as long as 10 years." Many others have found no increase in the total stand yields as a result of thinning.

Regardless of the various opinions and findings, thinning is still widely studied and practiced. Many different methods of thinning have been proposed and many different degrees of thinning intensity have been recommended over the years. Nearly every commercially important timber species in the world has had one or more thinning studies performed on it. Many of these studies are not comparable because of poor experimental design or no design at all. Many of the results are only applicable to a certain species, on a certain site, under a certain set of growing conditions. All studies share the common problems of classifying thinning intensities, comparing stand densities, and measuring site quality.

Hawley (1946) has presented four common methods of defining the types of thinning. The first of these is the low or "German" method, in which the poorest overtopped trees are removed first, followed by trees in increasingly higher crown position, depending on the degree or severity of the thinning.

The second method Hawley mentioned was the crown, or "French" method. The principle of this method is to cut from the upper crown classes in order to favor development of the most promising trees of these classes. The only trees cut from the lowest crown class (suppressed) are those trees that will not survive until the next thinning.

The third method that is discussed by Hawley is the selection method. Borggreve (1891) developed this method, in which the cuts remove a number of the largest dominant trees as well as those overtopped trees most likely to die before the next thinning.

The fourth thinning method, known as mechanical thinning, does not apply to this study and will not be discussed.

Hawley also discussed common measures of thinning intensity. The method most commonly used in Europe is one that assigns the letters from A through D (or occasionally through E) to thinnings of increasing intensity. In the United States thinnings are commonly designated as light, moderate, or heavy. Thinning intensity is often defined in terms of percentage of the number of trees, the basal area, or the volume that is removed in thinnings.

The majority of the thinning studies carried out in the United States have not continued long enough to give meaningful results. This is especially true of slash pine in the southeastern United States where slash pine has been widely planted. The first commercial planting was made in 1921-1922 by the Great Southern Lumber Company near Bogalusa, Louisiana (Mattoon 1936). Since then, more slash-pine seedlings have been planted in North America than seedlings of any other species. Many of these plantations have reached merchantable size and countless others will soon do so. Since ready markets exist for small material, it is likely that most of these plantations will be thinned one or more times before they are harvested. There have been almost no reports of long-term thinning studies on this species, and it is difficult for the forest manager to know when to thin, how to thin, what to thin, or if he should thin at all.

Hopefully, this present study will help answer some of these questions. This study is a phase of research project number 430 of the

Louisiana Agricultural Experiment Station; the project was initiated by Professor A. D. Folweiler in 1937. The objective of the study was to determine the relative yield from plantations thinned by four different methods and one that was never thinned. The first thinnings were made in 1937 when the stand was 13 years old. The study consists of ten quarter-acre plots arranged in two blocks. Each of the four treatments and the check were included on each block. The four treatments were (1) Heavy Crown (French), (2) Selection (Borggreve), (3) Light Crown (French), and (4) Light Low (German). Each tree on each plot was numbered and a record of each tree has been kept from 1937 until the present time. Professor A. B. Crow has supervised the project since 1946 and has published two papers based on this study. The first paper presented growth of the plots through age 24 (Crow 1952), and the second presented the growth through age 29 (Crow 1963).

This paper will present growth on the plots through age 40 and in addition will attempt to analyze the development of individual sample trees randomly selected in each plot. It is the author's belief that, although an attempt can be made to replicate thinning treatments, such replication is extremely difficult to accomplish. Variations in the stocking between plots receiving the same treatments, as well as the subjective way in which trees are selected for cutting, cause uncontrolled differences between plots meant to receive the same treatment. These differences may cause such variation within treatments as to hide any discrepancies that may exist among treatments. It is hoped that from this study there will be developed a method which will

enable research workers to measure objectively the amount of release given selected individual trees and to compare the growth resulting from such release by means of regression analysis.

The primary objective of this study is to compare the results of four different thinning treatments. The hypothesis that the results of different thinning treatments are reflected in the subsequent growth and development of stands was investigated, and a thorough study was made of the growth, mortality, and development of the stands since 1937.

A method is also presented whereby individual trees rather than plots may be used for future thinning studies.

Definition of Terms

In general, technical terms will be used as defined in Forestry Terminology (Society of American Foresters 1958). The terms that have received the most usage in this thesis and their definitions are listed as follows:

1. Site - An area, considered as to its ecological factors with reference to capacity to produce forests; the combination of biotic, climatic, and soil conditions of an area.

2. Site Index - An expression of forest site quality based on the height of the dominant stand at some chosen age (age 50 was used here).

3. Crown Class - A designation of trees in a forest with crowns of similar positions in the crown cover. Differentiation into crown classes is intended for application in even-aged stands. The following four crown classes are recognized.

A. Dominant - Trees with crowns extended above the general level of the crown cover and receiving full light from above and partly from the side; larger than the average trees in the stand, and with crowns well developed but possibly somewhat crowded on the sides.

B. Codominant - Trees with crowns forming the general level of the crown cover and receiving full light from above, but comparatively little from the sides; usually with medium-sized crowns more or less crowded on the sides.

C. Intermediate - Trees shorter than those in the two preceding classes, but with crowns either below or extending into the crown cover formed by codominant and dominant trees, receiving a little direct light from above, but none from the sides; usually with small crowns considerably crowded on the sides.

D. Suppressed - Trees with crowns entirely below the general level of the crown cover receiving no direct light either from above or from the sides.

4. Diameter breast high (d.b.h.) - The diameter of a tree at 4.5 feet above the average ground level.

5. Girard Form Class - the percentage ratio of the diameter inside-bark at the top of the first 16-foot log (17.5 ft. above mean ground level) to the diameter outside bark at breast height.

6. Earlywood - The less dense, large-celled, first-formed part of a growth layer.

7. Latewood - The denser, smaller-celled, later-formed part of a growth layer.

8. Live-Crown Ratio - The ratio between the length of the green crown and the total height of a tree; sometimes referred to as simply "crown ratio."

9. Crown Length - The actual length of the green crown of a tree.

10. Periodic Annual Increment - The growth for any specified period divided by the number of years in the period.

11. Statistical Significance - A test of statistical significance is a measurement of the probability that an observed value may have arisen by chance. Differences between two or more statistics are said to be significant if the probability of this difference occurring by chance is .05 or less (indicated by an * in tables to follow). Differences are said to be highly significant if the probability that a chance difference of this magnitude is no more than .01 (indicated by ** in tables to follow).

12. Gross Growth - The growth in either volume or basal area over a specified period of time. The volume or basal area removed in thinnings and in unsalvaged mortality during this period is included.

13. Net Growth - Equal to gross growth minus the unsalvaged mortality.

14. Thinning - Cuttings made in immature stands for the purpose of increasing both the rate of growth of the trees that remain and the total yield of useful material from the stand.

REVIEW OF LITERATURE

Forestry literature is filled with references to thinning. There is probably no cultural operation more widely practiced. Nearly every commercially important timber species has been the subject of thinning studies. Thinning has been considered by many to be the chief method by which the forester could control the growth and regulate the composition of forest stands. Yet there is probably no other forestry operation which is more questioned or less understood than thinning.

The difficulties in understanding thinning and its effect on a forest stand arise from the complex nature of tree growth both as an individual tree and as a member of a forest community. The problem is further complicated by the fact that single species of trees often exist over a wide variety of climatic, edaphic, and other site conditions. Trees of the same species often react quite differently to the same cultural treatment practiced on different sites or at different parts of the species range.

As with most forestry operations, the first and the oldest thinning studies were carried out in Europe, but thinning studies have now been carried out in all parts of the world. The papers mentioned here are only a very few of the countless studies that have been reported, but it is hoped that these few will demonstrate similarities and dissimilarities of the results and indicate some of the many problems involved in such studies.

A basic purpose of thinning is to control the competition between trees in the stand. In order to understand thinning procedure, it must first be necessary to understand something about how trees compete. A given site will support only a limited number of trees of a certain species at a time. As the individual trees grow they compete with the other trees in the stand for light, water, nutrients, and space in which to grow. Certain of the trees will die, but as long as the remaining trees are able to increase their growth rate, the growth of the less densely stocked stand will be equal to that of a more densely stocked stand (Assmann 1953).

Competition for Light

Moller (1947) determined that forest stands always strive for full utilization of light. The ground seems always to be kept fully covered and a thinning operation in the canopy is overcome with almost equal energy on all sites. He concluded that an area will grow only so much wood, regardless of treatment, and that the total yield is more dependent on age and site than on treatment.

Gustafson (1943) found that growth in both diameter and height of white spruce /*Picea glauca* (Moench.) Voss/ and red pine (*Pinus resinosa* Ait.) was increased with increasing sunlight (up to 3/4 full light in the case of spruce, and up to full light in case of pine). This study was made on a good site where water was never limiting.

Harms (1962) measured weekly growth in 6-year-old slash pine plantations in Georgia. The trees had been planted at 6-ft, 8-ft, and

15-ft spacings. Soil moisture was measured at 2- or 3-day intervals during two growing seasons (March to October) and a weather station was set up to record climatic data. Harms found significant correlations between diameter growth and available soil moisture, maximum air temperature, evaporation, and elapsed days since January 1, but none of these factors helped to explain the difference in diameter growth between spacings. Harms attributed this difference to the interaction between light and photosynthetic surface. Photosynthetic surface, as measured by crown ratio, increased with spacing. Harms concluded that under the same light conditions individual trees on the plots of wide spacing produce more food than those at close spacings. Since competition for light had begun by the fifth year at the closest spacings, and since the rate of diameter growth changed the same on all spacings with changes in soil moisture, Harms concluded that light was a greater limiting factor than was water.

Competition for Moisture and Nutrients - Root Competition

Srogl (1940) noted that, regardless of stocking, the amount of light received by a given stand is the same, but thinning affects the amount of light available for individual trees. He believed that stand growth is more dependent upon site factors such as moisture, soil nutrients, and temperature than upon light, and therefore there is little difference in volume growth of a stand at different degrees of density in stocking. Srogl said there is no optimum density of stocking, and a stand will grow the same volume over a wide range of densities.

Lyon (1940) found in New Hampshire that eastern white pine (Pinus strobus L.), Scots pine (Pinus sylvestris L.), and northern red oak (Quercus rubra L.) growth was positively correlated with rainfall of certain seasons of the year. Lyon tested white pine, Scots pine, Austrian pine (Pinus nigra Arnold), Norway spruce /Picea abies (L.) Karst/, European larch (Larix decidua Mill.), and red oak and reported that the various species reacted differently to both temperature and moisture.

Korstian and Coile (1938) showed that the competition for soil moisture between individual components of the stand was a highly significant factor in the growth, development, and regeneration of forest stands in the Piedmont Plateau. Moyle and Zahner (1954) concluded that consideration should be given to methods of stand treatment that would conserve water and that would allow the available water to be used by the most desirable trees, since a lack of soil moisture undoubtedly limits tree growth.

There have been only a few studies made of the lateral spread of roots, but most of these have indicated that even in quite open stands the roots are likely to extend over most, if not all, of the ground space between trees. Curtis (1964), for example, found that the roots of 60-year-old ponderosa pine (Pinus ponderosa Laws.) in central Idaho had lateral roots extending over an area 5.4 times the size of the projected tree-crown area.

Smith (1964b) reported that crown width was a valuable indicator of root spread of open-grown Douglas-fir /Pseudotsuga menziesii (Mirb.) Franco/, lodgepole pine (Pinus contorta Dougl.), and several other

British Columbia tree species. The crown width was a less valuable indicator in forest-grown trees. Tree diameter was a significantly better indicator of root spread than was crown width in such trees. Smith found that only about 20 percent of the zone marked by lateral spread of roots is actually occupied by roots, and so he concluded that competition for rooting space is not likely to be as important as that for crown space in the species studied.

Lyford and Wilson (1964) reported finding horizontal roots of red maple (Acer rubrum L.) up to 25 meters long. They found that the longest roots were from the least vigorous trees. They noted three relatively distinct phases in the development pattern of roots. First is the development of the seedling root system. Next comes the differentiation and radiating extension of woody roots that bear the non-woody roots grouped as root fans. The final stage consists of a slowing of the extension of the original woody roots and the formation of adventitious roots near the stem. Thus the area of the forest floor in which maximum absorption occurs is moved progressively farther away from the stem as the stem increases in size. In the final stage of development, adventitious roots re-occupy the area near the stem, while the older roots eventually die.

The roots of planted slash pine trees have been found to draw nutrition from soil as far as 19 ft from the tree only two years after planting; five years after planting, such trees were feeding from as far away as 32 ft (Pritchett and Robertson 1960). A recent study has indicated that roots of longleaf pine (Pinus palustris Mill.) may

extend out 55 ft or more from the base of the tree; this distance is dependent on the age of the tree and the elevation of the tree in relation to the elevation of the source of nutrients (Hough *et al*. 1965).

Chapman and Bulchis (1940) determined, from a study of mature longleaf pine, that retarded growth of individual trees is largely due to root competition. When such competition is removed the suppressed individuals respond immediately with an increased growth rate. They believed that the distance that roots are able to spread from the bole of the tree is the factor that finally limits increases in growth rate. They found that crown-length was a reliable indicator of potential volume growth of a tree after release and that a crown 40 feet long gives the qualities most desirable in a reserve tree.

Competition for Space

Competition for space actually involves a composite of all forms of competition that exist between the trees in a forest stand. Growing space has been shown to have a profound effect on the growth and development of the trees in a forest stand. Growing space is often expressed in terms of stocking or stand density.

Cilliers and VanWyk (1938) established that, for two suppressed even-aged stands of maritime pine (*Pinus pinaster* Ait.) growing in South Africa, the basal-area increase in each stand was directly proportional to the growing space in the respective stands. Craib (1947b) reported that growing space exerts an almost precise mathematical influence upon tree growth. Simmons and Schnur (1937) determined that

the mortality rate and the basal-area-growth rate of loblolly pine (<u>Pinus taeda</u> L.) stands were correlated with stand density; while Deetlefs (1954), using regression analysis, showed that relationships exist between stand density, crown size, and basal-area growth. Deetlefs found that tree growth decreased with increasing stand density so that loblolly pine trees make more than twice as much basal-area growth at densities of 60 ft^2 of basal area than at 140 ft^2 of basal area.

Wenger <u>et al</u>. (1958) determined that cubic-foot growth in natural loblolly pine stands was related to site, stand density, and age. They found that volume growth in young stands increased with increasing density on good sites, but decreased with increasing density on poor sites. In older stands the volume growth increased with increasing density on all sites, but to a lesser degree on the poorer sites.

Ware and Stahelin (1948a, b) described a plantation spacing study begun in 1932 in which loblolly, slash, and shortleaf (<u>Pinus echinata</u> Mill.) pines were planted at spacings ranging from 4 ft up to 16 ft between trees. After 14 years, the closest spacing had produced the most and the widest spacing the least wood. Slash pine had out-produced loblolly pine at close spacing, but the reverse was true at wide spacing. Crowding retarded and wide spacing stimulated both the diameter and volume growth of loblolly more than that of slash pine.

Bennett (1963a, b) reported that slash pine gives better yields at closer spacings on the better sites, but on the poorest sites spacing has little effect. He stated that mean-annual growth (in cords per

acre) culminates between the ages of 18 and 25 on the better slash pine sites and earlier when spacing is close. Growth culminates latest on the poorest sites regardless of spacing.

Nelson (1952) found that mutual competition in slash pine plantations had begun the third year when spacing was 6 ft. By the end of the seventh year a plantation with 12-ft spacing had a one-inch advantage in diameter over one with 6-ft spacing.

Other studies have shown that diameter is directly related to plantation spacing, while volume and basal area are inversely related to plantation spacing (Little and Somes 1958; Harms and Collins 1965). Russell (1958) found that a 14-year-old slash pine plantation was making better annual cord-volume growth with 4-ft spacing than with 5-ft, 6-ft, or 13-ft spacing; and Williams (1959) reported that an unthinned plantation of shortleaf pine had made greater growth in basal area by age 21 than had any thinned stands.

Laessle (1965) made a study of the relationship between spacing and competition in natural stands of sand pine /Pinus clausa (Chapm.) Vasey/. Results from his study indicated that most stands less than 23 years old have their stems either aggregated or essentially randomly distributed. Older stands tend to become more regularly spaced.

Zinke (1962) noted that lodgepole pine trees influenced various properties of the soil surrounding the trees. The area of this influence was circular and was roughly proportional to the crown areas projected onto the soil surface. Individual trees had maximum influence under the crown canopy and this influence decreased outward from the bole of the tree.

Baker (1953), after studying ponderosa pine in northern California, concluded that growth, in a biological sense, is not much affected by variation in number of trees per acre, but it is greatly affected in an economic sense. The degree of effect is more a matter of products, markets, and prices than anything the biologist can ascertain in computations of gross increment.

Most studies have shown height to be little affected by stand density. Kramer and Kozwolski (1960) stated that height growth is little affected over a wide range of densities, possibly because a small, more or less fixed amount of carbohydrate is used in height growth. Bennett (1960a) found no correlation between height growth of slash pine and the stand density or spacing. Zahner and Whitmore (1960) found that height growth of loblolly pine was not stimulated by heavy thinnings, and Limstrom and Deitschman (1953) reported finding a significant response in diameter growth but not in height growth of shortleaf pine subjected to varying intensities of thinning.

However, Shirley and Zehngraff (1942) found that height growth of 16- to 18-year-old red pine increased with increasing density. They claimed that 37 percent of the variation in height was due to spacing or factors associated with spacing. Turner (1943) also found height growth of loblolly and shortleaf pine was better in denser stands and attributed this to more available nitrogen in proportion to the supply of available carbohydrates. It seems likely, however, that the height growth of most species, and especially the southern pine species, is not greatly affected by stand density except at the most extreme ranges of density.

The influence of an individual tree on the surrounding site and on the other trees in the stand is basic to the theory of thinning. It is assumed that an individual tree's growth can be controlled to a certain degree by releasing the tree from the competition of the surrounding trees. If all the residual trees are released from some of their competition by thinning, then the total growth on these trees should increase, and those trees that would have died in the struggle for light, water, and nutrients will be salvaged and used. The problem is to determine the amount of competition to which a tree can be subjected before its growth is slowed and how much release is needed in order for growth to increase. It has been customary to measure competition in terms of density of stocking. Stocking is often defined as the number of trees on an area of a given size. Individual trees are assumed to be regularly spaced over this area, either with square or triangular spacing. Such regular spacing may not exist; however, in older stands of ponderosa pine, such spacing usually does occur (Cooper 1961).

Stocking or stand density has been measured in many ways other than a tree count. Some of these ways are described in the next section.

Measuring Stand Density

Many different methods have been proposed for expressing stand density so that it may be used to describe the condition of a stand. Gingrich (1965) defined stocking as a qualitative term referring to "the degree of adequacy of a stand condition to meet a timber management

objective." He defined stand density as "a quantitative term expressing some volume or areal unit, or simply a tree count that reflects the degree of crowding of stems within the area stocked."

Smith and Bailey (1964) discussed the difference between stocking and stand density. They defined stocking as a term applied primarily to the proportion of area occupied by trees, which can be measured by the percentage of stocked quadrants and by crown closure. Stand density is different from stocking since it should describe the degree of crowding of individual trees within the portion of the area actually stocked with trees.

Vezina (1964) stated that expressions of density should be developed which would use only the factors of number of trees, or spacing, or crown width, and diameter or height.

A simple tree count is probably one of the most commonly used expressions of stand density. This is especially used in plantation studies, where the age is known and where stem distribution is thought to be especially regular. Bennett (1960a), for example, used simply the number of trees per acre to show the effect of density on diameter in young slash pine plantations. Bonnor (1964) expressed stand density as number of trees per acre and found that this density did not influence the correlation of stem diameter with crown width and tree height. Bonnor pointed out that density is a stand parameter and the other measurements were individual tree parameters.

Many writers have proposed the use of number of trees per acre combined with tree diameter as a better measure of stand density.

Probably the best known method is the one proposed by Reineke (1933), who developed the equation

$$\log N = -1.605 \log D + K$$

where:

N = number of trees per acre,

D = diameter of tree of average basal area, and

K = a constant for a given species.

Mulloy (1943) found Reineke's index to be independent of both age and site and therefore met the requirements of a density index. Meyer (1942) used this index to express the density of loblolly pine stands. Simmons and Schnur (1937) used Reineke's index to express density when developing equations to show the effect of stand density on mortality and growth of loblolly pine; however, they used the average density rather than the maximum density.

Wahlenberg (1952) plotted the current average diameter growth of yellow-poplar trees (Liriodendron tulipifera L.) over the average density of the stand ten years after thinning. He used a modified form of Reineke's index, where $\log N = 3.864 - 1.4987 \log D$. MacKinney and Chaiken (1935) also modified Reineke's index for use with loblolly pine. Their equation for determining the number of trees per acre on fully stocked stands is $\log N = - 1.707 \log D + 4.1588$.

Langdon (1961) found that Reineke's index accounted for more of the variation in volume yield in slash pine than either number of trees per acre or basal area per acre, and therefore he used it as an expression of stand density.

Chisman and Schumacher (1940) developed the concept of tree-area ratio, which allocated the area of an individual tree in a stand according to the tree's diameter. They presented an equation,

$$Y = b_o + b_1x + b_2x^2$$

where:

Y = the ground area of a tree in the stand

x = the individual tree diameter, and

b_o, b_1, b_2 are constants.

Deetlefs (1953) and Stahelin (1949) both used this method to express stand density.

Another common way of expressing stand density is to consider both the number of trees and the mean height of the stand. Wilson (1946) found that the number of trees in a uniformly-stocked, even-aged stand of any species could be expressed by the equation

$$N - 43560/ (hf)^2$$

where:

N = the number of trees,

h = the average height of the stand, and

f = certain fraction of the height appropriate to the species.

The constant "f" decreases with the tolerance of the species.

Gevorkiantz (1947) presented a modification of a formula developed by H. A. Ferguson (1933), in which the value of (hf) of Wilson's formula is equivalent to SH with S equal to the spacing in percent of upper height, and H equal to the upper height (average height of 100 tallest trees).

Braathe (1955) discussed the value of a density index based on the average spacing between trees as a percent of upper height. He concluded that such an index is valuable for research and demonstration and may also serve as a simple thinning guide. (See also Braathe 1957). Day and Bennett (1962) used height as a basis for deriving a numerical expression of stocking and concluded that the method proposed by Braathe is a valid measure of density in slash pine plantations.

Davis (1935) determined that spacing in feet per inch of diameter breast high is nearly a constant for any given basal area. Cottam and Curtis (1956) described density as the number of individuals distributed over a certain area and suggested that the mean area per individual is the reciprocal of density. The square root of the mean area is then a direct indication of spacing.

Another common method of describing the density or degree of stocking of a stand is to compare it to a normal stand. The normal forest stand as an ideal was developed in Europe, where it is considered equivalent to a fully stocked stand, in which all space is effectively occupied but in which ample room is available for development of crop trees, and where the soil and sunlight are fully utilized (Bickford et al. 1957). Most of the normal yield tables in the United States are based on single measurements of untreated plots in even-aged, "fully-stocked" stands.

The theory is that each species on a given site has a certain ideal or normal stocking at any given age. Stands either under- or overstocked will approach this norm with age. Gevorkiantz (1937) and

Duerr (1938) discussed the use of Gehrhardt's formula (Gehrhardt 1930) to determine how an understocked stand will approach normality. Gehrhardt's formula was given as:

$$g = dG\ (1 + K - Kd),$$

where:

g = the growth of an understocked stand on a particular site and at a certain age,

G = the growth of a normal stand on that site and at that age,

d = the density of the stand as a percentage of a normal stand on that site and at that age, and

K = a species constant which varies between 0.6 and 1.1 depending on the tolerance of the species.

Wellwood (1943) developed a theory that second-growth stands of loblolly pine have a measurable trend towards normality of stocking with increasing age. He used Chisman and Schumacher's "tree-area ratio" as an index to measure normality of stocking. He developed the algebraic expression:

$$N = 0.324 + 0.0040(S) + 0.0713(C) - 0.0003(SC) - 5.537(1/A - 0.0426(S/A) + 1.085(C/A) - 0.0010\ (SC/A)$$

where:

N = normality of stocking,

S = site index,

A = age, and

C = percentile class.

When the age and site-index are known and the normality of stocking has been computed by the tree-area method, the value for C may be computed by the formula:

$$C = \left[A\,(N - .324 + .0040S) + 5.537 + .0426S\right] \Big/ \left[A\,(.0713 - .0426S) + 1.085 - .0010S\right]$$

Normality at a subsequent date can be found by using the C- value determined and the new age.

Gevorkiantz (1944) believed that a true normal stand exists which has a definite measurable structure. He stated that in normal stands the rate of growth for both height and diameter is bound by a definite relationship and for any given change in average height there is a definite change in average diameter. He developed a formula which, he believed, reflected the structural pattern of normal stand development. This formula is:

$$AD = (AH)^b / C$$

where:

A = stand age,

H = average stand height,

D = the average stand diameter,

C and b = constants for species and tolerance.

Czarnowski (1956, 1961) presented an "index of crowding" which equals 1 when the stand density gives the optimum crown ratio of 1/3. This crown ratio of 1/3 is considered to be optimum for best growth in both Scots pine and loblolly pine. He theorized that the number of trees in a normal stand is equal to $N'P/H^2$, where N' is the actual

number of trees on a unit area of size P, and H is the mean stand height. N' is constant for a given site quality, according to Czarnowski, if the normal stand is defined as the normal number of trees per surface unit, and where the term normal means that the stand has a certain density determined by the crown-length ratio. The "index of crowding" is the ratio of the actual number of trees to the normal number. Czarnowski also used as a measure of stand density the ratio of actual stand volume to maximum stand volume; this ratio he called "compactness factor."

Wiley (1959) said that normal yield tables are of no use in managed stands. Instead he believed that managed stands are fully stocked when the crowns are touching but not interlaced and that a correlation exists between the crown diameter and the d.b.h. of the tree. The crown diameter (in feet) for the tree of average d.b.h. can be squared and divided into 43,560 to find the number of trees per acre in a fully stocked stand.

Krajicek and Brinkman (1957) reported that the development of the tree crowns can be used as an index of stand density. They presented a "crown-competition factor" which was the sum of the proportion of the area occupied by each tree crown. They found a strong correlation between stem diameter and crown area and stated that, once this relationship for open-grown trees is known, the crown competition factor can be found by multiplying the number of trees of each diameter by the open-grown crown area appropriate to that diameter and then summing the products for all diameters in the stand. This factor was said to be independent of site index, age, and

diameter distribution in oak stands in Iowa. (See also Krajicek *et al*. 1961, and Vezina 1962, 1963a, b). Smith *et al*. (1961) also used the relationship between diameter and crown width to measure density. By determining this relationship for fully open-grown trees, they found it possible to estimate the number of open-grown trees of a given diameter that would fully occupy a stand. The number of trees would vary directly with the ratio of diameter to crown width or average square spacing. They found that in open-grown stands which fully occupy the sites (trees with maximum crown area) this ratio equals 2 and in fully stocked stands the ratio is 1.

Briegleb (1952) reported that young Douglas-fir trees utilize space in proportion to their diameter and height and that crown width and crown length are both related to the diameter and height of the tree. He presented a measure of stand density in which the number of trees expressed as a percent of normal for the average diameter of the stand, was linearly correlated with the stand height expressed as a percent of normal height for the tree of average diameter. Stands having a specified average diameter will require fewer short trees than tall ones to stock an acre adequately. He based all his studies on comparison with normal yield tables.

Nelson and Brender (1963) tested four different methods of expressing stand density in even-aged stands of loblolly pine. The four methods were: (1) Stahelin's percent of full stocking, (2) total basal area, (3) Reineke's "stand density index," and (4) the initial merchantable cubic-foot volume. Essentially, the same amount of the

variation in annual cubic-foot growth was explained by each of the four methods when combined with age, site, and certain interactions in a regression equation.

Smith (1964a) discussed the problem of defining a "normal" forest stand. He suggested that a comprehensive system of describing changes in stand structure is needed in order to determine the influence of various levels of thinning. He took issue with those who use crown analysis to determine stand structure because these people often fail to recognize the extent to which crown-spread is controlled by variation in stand density. The major handicap to using crown measures to define stand density, according to Smith, is that there is an approximate limit beyond which the crown of a tree of a given diameter will not spread, even when the tree is fully open-grown. He noted that for a given stocking there is a constant ratio between crown width and diameter that increases as stocking decreases (Smith 1963); he felt that control of crown development was the key to the growing of forest crops to meet desired goals of quality or growth rate.

Curtin (1964) studied the requirements of a density measure for even-aged stands of Tasmanian oak (Eucalyptus obliqua L'Herit). He represented the two extremes of density conditions by open-grown trees on the one hand and by dominant and co-dominant trees growing in a state of intense competition on the other. For the open-grown trees he found that crown width was linearly related to stem diameter independent of height. In dense stands he found that the mean dominant height was an important additional variable in the relationship. He used these

three variables to develop an index of stand density for the species that was independent of both age and site quality.

Ward (1964) developed a "crown competition index" and found that he could explain from 40 to 50 percent of the variation in live-crown ratio of individual dominant and codominant red oak trees with this index. The index value was defined as the sum of the ratio of a numerical expression of the crown class of each competing tree to its horizontal distance from the sample tree. Competing trees were defined as those trees that directly contributed to the shading of the crown of the sample tree. An estimate of the average live-crown ratio produced with increasing stand age in response to different levels of density was obtained from a multiple regression relating live-crown ratio to the crown competition index and sample tree height. Ward's basic assumption was that crown competition between trees was directly proportional to the numerical values that he assigned to individual crown classes and inversely proportional to the distance between the trees. He felt that the usual expressions of spacing actually have very little significance because the important factor of crown class is ignored.

Arnold (1949) developed a "crown-area index" (the product of crown width and crown length) and found that it could account for from 70 to 90 percent of the variation in basal-area growth of western white pine (*Pinus monticola* Dougl.). He found this index better than either growing space ratio (the quotient of crown spread in feet divided by diameter breast high in inches) or the percent of live crown.

However, the length and width of the tree crown that Arnold used for his index are themselves modified by stand density.

Measuring and Defining Thinning Treatments

Evidently trees have considerable influence on one another so that the growth, vigor, and form of any individual tree depends, to a great extent, on the size and proximity of other trees. The aim of thinning, then, is to control this influence to the greatest advantage. The problem is to determine how to best accomplish this aim. As has been shown, a great many methods have been presented in an attempt to measure the influence between trees in stands, but the problem remains; how many trees, and which trees, can best be removed from the stand in order to reach a desired growth rate or a desired quality? Is it economically sound to remove part of the growing stock before the stand matures? The answer to these questions have been sought in hundreds of thinning studies throughout the world.

Any scientific study, in order to be meaningful, should be repeated under differing conditions. With thinning studies such replication is very hard to achieve, since it is so very difficult to describe a thinning treatment in such a way that it can be repeated.

Wicht (1936) gave a thorough discussion of the problems of classifying thinning types and intensities. He noted that such classifications must be free from ambiguity and must be applicable to all types of conditions. He presented a method for classification which he felt was superior to other methods in use at that time. First he

separated trees into crown-height classes, since crown height can be measured. He then divided these classes into three stem-quality classes (perfect, less perfect, and imperfect). This second division is quite subjective. He felt that thinning type should be characterized by:

1. Time of first thinning,
2. Type of thinning (which tree classes are removed),
3. Grade or degree of thinning, and
4. Length of interval between thinning.

The thinning intensity could best be determined by the spacing between trees and the height of the trees. As an example, he suggested spacing as a percent of total height.

Welander (1940) mentioned three kinds of thinning that have been widely used in thinning studies. The first type he described as low thinning, in which the average diameter of the trees removed is less than the average diameter of the residual trees. Next he described crown thinning, in which the average diameter of the trees cut and the trees left is the same. Finally, he discussed selection thinning, in which the average diameter of the trees removed is larger than that of the residual trees. He made no mention of the degree of thinning desired, although he did not approve of the selection type of thinning since it exposed the residual stand to excessive storm damage.

Philippis (1946) proposed the classification of trees by the degree of dominance or suppression and the use of this classification as a basis for thinning even-aged stands. He presented a classification

which he found was especially adapted to even-aged stands of fir and beech (Fagus sp.) in the Appennines Mountains of Italy. His system contained four major tree classes:

1. Predominant or superdominant,
2. Dominant,
3. Intermediate, and
4. Dominated.

Class 3 was subdivided into sub-dominant and sub-dominated classes, and class 4 was subdivided into dominated and suppressed.

Moller and Holmsgaard (1947) reported the results of a thinning experiment in Denmark that was begun in 1930. The treatments were described as:

1. A light thinning from below,
2. Heavy Danish thinning, in which trees were removed either from below or above so long as the best formed trees were favored and the crowns were free, and
3. A selection thinning from above.

Singh (1948, 1955) felt that the number of trees involved was all-important in defining a thinning treatment. He wrote that thinning intensity should be determined by the number of trees left after thinning and not by the number or the class of treees removed. He also believed that the ruling factor in tree classification should be the "freedom" of the crown and not the degree of dominance which is "neither defined or understood." He did not suggest a way in which crown freedom could be measured.

Stahelin (1949) considered the basal area of a fully-stocked stand at a given average diameter to be the best standard for expressing stand density for thinning purposes. He found that the relationship of total basal area per acre to the d.b.h. of the tree of average basal area varied little with site and age in fully-stocked stands of loblolly and slash pine under 60 years of age.

Mitchell (1952) also proposed spacing as the key to a measure of thinning intensity. He related space between trees to diameter. He claimed that dominant southern pines, regardless of species, age, or site, require the same minimum growing space if the diameters are the same. This minimum space can be determined by adding a constant (4 in the instance of southern pines) to the diameter in inches and then by squaring the results. He believed that the principle of diameter-plus-a-constant gave a scientific basis for evaluating over- or under-stocking and for accurately prescribing the amount of growing stock to leave in order to meet management objectives.

Becking (1953) agreed with Wilson (1946) that spacing and height were related, and he presented a formula for measuring the degree of thinning. This formula is $d = S(h/100)$ where d is the degree of thinning, S is mutual spacing between trees as a percent of their top height (h). Becking considered trees to be triangularly spaced rather than having the square spacing as proposed by Wilson and Mitchell. With the assumption of regular triangular spacing the number of trees remaining in a hectare after a certain degree of thinning could be objectively calculated from the formula $N = 10,000/(0.5\ d^2 \sqrt{3})$.

Although the selection of trees to cut was subjective, this method allows the thinning intensity to be repeated in subsequent thinnings.

Hummel (1954) also suggested that stand density should be expressed as a percent of top height. He assumed square spacing and defined top height as the average height of trees whose basal areas correspond to the mean basal area of the largest 250 trees per hectare. Using the old European thinning grades of A, B, C, etc., he assigned a value of 1.0 to a spacing equivalent to 20 percent of top height. Thinning grade A then has a value of 4.0, grade B a value of 2.5, grade C a value of 1.5, grade D a value of 0.75, and grade E a value of 0.5.

MacDonald (1954) was more concerned with thinning type than with thinning intensity. He recommended a heavy crown thinning, leaving only 100 dominant trees per acre, as the most desirable method of thinning.

Hiley and Lehtpere (1955) presented a method for calculating numerical thinning schedules for conifers. The method was based on the principle that, if current annual increment in a plantation is unaffected by the grade of thinning (Assmann 1953), the ring widths must be inversely proportional to the bole area per acre. Bole area was defined as the total area of cambium on the main stem of the trees and was proportional to the number of trees per acre times the mean height times the mean diameter. Thinning grades were based on the thickness of the annual rings, which in turn were dependent on age and bole area.

Morriss (1958) wrote that, because of the wide variation in soil capabilities and the natural density of stocking accompanying advancing

age, systems of determining densities left after thinning should be based on site and age. He recommended thinning to a residual basal area which is a percentage of the basal area normal for a given species, site, and age. This would permit more attention to be given to the quality of the trees left than is allowed by systems based on spacing.

Vuokila (1960) presented the results of a 28-year-old thinning study where intensity was classified as either light or heavy, and method was classified as low or crown thinning. This type of classification is common in thinning studies in the United States. (See Bornbusch 1944; Daniel and Barnes 1959; Fahnestock and Wellner 1940; Foiles 1956; Hanzlik 1925; and others). Other common methods of classification relate the terms light, medium, and heavy to grade letters (Hummel 1947, 1954) or to basal area cut (Green and Pruett 1963). Thinnings in plantations are commonly classified in terms of square spacing (Adams 1936; Hansen 1933; Cheo 1946; and others).

Much recent work has been concerned with finding a more objective method of defining thinnings, but there has been little success. It has been stated that it is impossible to define a thinning grade which can be widely applied both qualitatively and quantitatively (Johnston and Waters 1961). Vezina (1963b) noted that all early methods of grading thinnings depended on initial stand density and therefore should not be used to compare thinnings. Vezina presented a thorough discussion of the relative merits of several of the methods mentioned earlier in this review and gave preference to an expression that used a ratio of crown width to diameter.

Newnham (1964) developed a method of defining thinning intensity using three major classes. Class I was a "moderate low thinning" and called for removal of all trees with diameters less than the mean diameter of the stand minus one standard deviation. Class II, designated "severe low thinning," required the removal of trees in the intermediate crown class whose diameters were less than the mean diameter minus 1/2 standard deviation, but larger than the mean diameter minus one standard deviation. Class III, named a "crown or selection thinning," required the removal of a small number of codominant trees whose diameters were greater than the mean diameter plus .75 standard deviation, but less than the mean diameter plus one standard deviation.

<u>Results and Effects from Thinning Southern Pines</u>

Objective measures of thinning type and intensity are being studied, but apparently no completed thinning studies have used a truly objective measure for either the type or the intensity of thinning. Probably one great impediment to thinning research is the difficulty of defining a range of thinning regimes by mathematical functions suitable for statistical analysis (Dawkins 1960). In spite of this difficulty a large number of thinning experiments have been performed and the results published.

Kramer and Kozlowski (1960) wrote that thinning produces increased diameter growth on the remaining trees. Decreasing stand density is accompanied by increases in average diameter, volume in stems, volume growth per stem, volume of branches per tree, the ratio of branches to

stem, the size of crown, and the amount of needles per tree. They noted that thinning influences the growth and form of trees by reducing competition and by altering the environment so that it is more favorable for the processes controlling the growth of the remaining trees.

Changes in the growth of trees following thinning are produced by a reduction in competition for moisture and soil nutrients. Bassett (1964) found that 30-year-old loblolly pine thinned to 125 ft^2 of basal area would make continuous diameter growth when the amount of available water in the surface foot was greater than 65 percent. If available water was less than 40 percent, tree growth stopped. A similar plot thinned to 55 ft^2 of basal area grew continuously even at the lower water levels. Bassett believed that heavy thinning leaves large areas in the soil free of growing roots; these areas serve as water reserves. Zahner and Whitmore (1960) found that five years after thinning loblolly pine, the remaining trees, even at the widest spacing (100 trees per acre), were no longer free from competition because their roots had filled the available soil area. They found that diameter growth was related to crown and root development and to available soil moisture. Widely spaced trees continued diameter growth for a longer period during the summer than did closely spaced trees.

Effects of Thinning on Growth and Yield

Of primary interest to most forest managers is the effect that thinning has on the growth and yield of the forest stands. Most of the studies reviewed have considered this effect.

One of the earliest thinning studies in southern pine was reported by Akerman (1928). This study originated in 1912 in a 17-year-old loblolly pine stand. The study involved eight plots; four were thinned with what was described as a C-grade thinning; the rest were not thinned. Akerman stated that the over-all volume growth after 15 years was greatest on the thinned plots. He also found greater total volume on the thinned plots and more even distribution of trees over the area of the thinned plots.

The value of heavy early thinnings that remove all trees competing directly with the final crop trees was stressed by Bull (1934, 1935) He pointed out that low thinning, even when very severe, does little to stimulate growth of residual loblolly pine trees. (See also Bull 1936).

Frothingham (1942) presented the results of thinning pine near Biltmore, North Carolina. In general, the effect of thinning was to increase the mean annual growth and quality of the thinned stands over that of the unthinned stands.

A rather unique method of thinning was proposed by Craib (1947a,b). In a series of annual thinnings, he reduced a plantation from 1200 trees per acre at the time of planting down to 50 trees per acre by the end of the ninth year. Under the conditions found in South Africa, the suppression of dominant trees comes at an early age over a wide range of stand densities. Craib reported that the longer thinning is delayed, the greater will be the loss in total volume increment thereafter.

Stahelin and Ware (1948) reported the results of a study started in 1927 on a 3-year-old well-stocked stand of loblolly pine. Two plots were thinned at age three to 16-ft and 6-ft spacing while a third plot was left as a control with 3000 trees per acre. They concluded, after thinning all plots at age 20, that the light thinning yielded more volume than either the heavy thinning or the control plot.

Another study that included a pre-commercial thinning in slash pine followed 10 years later by a commercial thinning was made by Gruschow (1949). Plots that had received a light pre-commercial thinning (to 700 trees per acre) gave a greater yield in cord volume than did plots receiving a heavy (to 200 trees per acre) or a moderate (to 400 trees per acre) pre-commercial thinning or plots that had received no pre-commercial thinning at all. The heavy pre-commercially thinned plot had made the best diameter growth, but there were so few trees on this plot that a commercial thinning was not possible.

Minckler and Dietschman (1949, 1953) presented data from a thinning study established in a 13-year-old loblolly pine plantation in southern Illinois. Two plots were thinned to reduce the average basal area from 126 ft^2 to 81 ft^2. The rough, poorly formed dominant and codominant trees were removed in the thinning. Two plots were not thinned. Little difference in either basal area or volume growth was found between the thinned and unthinned plots when the plots were remeasured four years later.

In a review of slash pine management practices, McCully (1950) noted that slash pine tends to stagnate, and the expression of dominance

is slow. However, trees respond promptly to thinning, even after severe suppression, if they are given enough growing space. He described thinning studies in Georgia in which thinning had no apparent effect on the growth of the 100 largest trees per acre. McCully concluded that heavy cuts (up to one-half the volume) at the time of the first thinning leaves the stand in better condition for future development than does a thinning of less intensity. He noted that response to release is slow if the live crown length is less than 30 percent of the total height, and therefore thinning should be aimed at developing or maintaining crown lengths which are 30 to 40 percent of the total height.

Chapman (1951) made a study of thinning in 20-year-old longleaf pine stands in Louisiana. He concluded that such stands should not be thinned to a basal area of less than 80 ft^2 nor allowed to remain above 120 ft^2. Gaines (1951) reported the results of a thinning study established in Alabama in a 22-year-old stand of longleaf pine. Fifteen years after thinning the basal-area and volume increment were greater on the unthinned plots than on plots thinned to spacings of 15 ft, 12 ft, and 10 ft. Diameter growth of the largest trees on each plot decreased as the spacing decreased, but basal-area and volume growth of the stands increased with decreased spacing.

Results from the Maxwell thinning plots near Urania, Louisiana, were presented by Mann (1952a, b). These plots, established in a natural loblolly pine stand, were thinned for the first time at age eight with a pre-commercial thinning. Commercial thinnings of several kinds and intensities were later tried. Until age 33 the unthinned

control plot made the greatest periodic cord-volume growth, but after this age the mortality from the merchantable size classes reduced the growth on this plot below that of any of the thinned plots, so that the more lightly thinned of the thinned plots made the best growth.

An examination of the results of a combination plantation spacing and thinning study, established in slash and loblolly pine plantations in Alabama, revealed that pine planted at 6-ft-square spacings increased in diameter but decreased in basal area with increasing thinning intensity (Livingston 1952). Stands thinned at age 12 gave a greater volume yield than those not thinned until age 19. These results were influenced by the fact that plots thinned at age 12 were on a better site than those not thinned until age 19. It was concluded that on sites similar to those in the study area, slash pine is capable of maintaining rapid growth in denser stands than is loblolly pine.

Chapman (1955) found that a loblolly pine stand which had been periodically thinned since age 26 produced more merchantable cubic-foot volume by age 43 than did a similar stand that was never thinned. When the value of the products produced was considered, the thinned stand out-produced the unthinned stand by nearly 82 percent.

Data from 21 slash pine plantations in Georgia indicated that diameter growth varied directly with spacing, while yield was correlated with mortality and site index (Bennett 1956). Although differences in cord-volume growth between different spacings were not great, the length of time required to produce sawtimber differed greatly. The number of forked trees seemed to be greater with the wider spacing.

Limstrom and Deitschman (1953) described a comparative study of thinning methods in a 14-year-old shortleaf pine plantation in Indiana. Two methods of thinning (above and below) and three different intensities (to residual basal areas of 80, 100, and 120 ft^2) were used. After three growing seasons there were no differences in growth attributable to method, but differences in diameter growth were found between plots thinned to different residual densities. Volume growth was similar on all plots, but basal-area growth was greatest on the most intensely thinned plots and least on the unthinned control plots.

Guttenberg (1954), after thinning a 44-year-old stand of loblolly and shortleaf pine, determined that intermediate, codominant, and dominant trees are capable of good response to release even when they are well past the age when the first thinning is usually made.

Evans and Gruschow (1954) discussed a longleaf pine thinning study in which plots in a 25-to-35-year-old stand were thinned to residual densities ranging from 400 to 100 trees per acre. Residual trees were selected by a "space-selection" method, by which the largest and most vigorous trees were left at reasonably uniform spacing. No relationship was found between the residual basal area and the volume growth after thinning, so they concluded that optimum volume growth is possible over a wide range of densities.

A 62-year-old stand of loblolly pine that had been thinned from below at 5-year intervals since age 21 had greater annual volume growth on plots kept thinned to 120 ft^2 of basal area than on either plots kept thinned to 110 ft^2 of basal area or on plots never thinned at all (Moyle

1956). However, McMinn (1963) concluded that thinning did not greatly increase the merchantable wood production of slash pine stands, although thinning did make merchantable wood available sooner.

Nelson (1961) found that cubic-foot growth in thinned loblolly pine stands was significantly related to age, site, stand density (expressed by a method proposed by Stahelin 1949), and total basal area (see also Nelson and Brender 1963). Gruschow and Evans (1959), using Stahelin's method for measuring the stand density in slash pine stands, determined that cubic-foot volume growth was associated with age, residual stand density, and the site. Maximum growth per acre was realized at something less than full stocking.

Bennett (1963b) concluded, after studying plantations of several pine species, that thinnings, prior to the period of stand stagnation, do not increase total cubic-foot yields. However, thinnings do result in growth being added on fewer stems which then reach merchantable size earlier. Maximum total cubic-foot yield is obtained with closer spacings, while early sawtimber yields are produced by wider spacings. Bennett wrote that spacing is a function of the owner's objective.

Apparently, thinning has relatively little effect on the total amount of wood that can be grown on a given site. However, this effect depends in part on the density of the stand before thinning, the thinning intensity, the age of the stand, the site on which the stand is growing, and on the species involved.

Thinning has considerably more effect on the growth of individual trees within the stand. In addition to the effect on tree diameter and

volume growth, thinning affects the development of the crown. Gruschow and Evans (1959), for example, found a slight correlation between stand density and the change in live-crown ratio and a much stronger correlation between the original live-crown ratio and the amount of change in the ratio after 11 growing seasons.

Smith (1963) noted a constant ratio between crown width and d.b.h. for a given density of stocking. This ratio increases with a decrease in stocking. He felt that control of crown development is the key to growing forest crops to meet any desired goal of quality or growth rate. He stated that stand density can be controlled to secure the necessary ratios of crown width to d.b.h. so as to obtain a desired growth rate, as well as to control the size and number of knots. Bennett (1955a) reported that 45-year-old slash pine with crowns averaging only 20 to 25 percent of the tree height were unable to respond to the release resulting from thinning.

Bennett (1960b) reported that the crown length of slash pine cannot be appreciably increased through additional height growth after age 30. For this reason the crown ratio cannot be increased by releasing older trees. He claimed that if the crown area could not be increased, diameter growth could be stimulated by thinning only through a reduction in the competition for moisture and nutrient elements. He concluded that trees should reach age 30 with the amount of crown deemed necessary for the desired diameter growth rate, since there will be little chance for trees to build longer crowns at more advanced ages.

Effects of Thinning on Quality

A number of papers have presented studies which have related tree quality to stand density. Some of these have already been mentioned.

Echols (1960) studied the influence of tree spacing on the specific gravity of loblolly pine growing in central Louisiana. He noted that fast growth is often associated with less dense wood. He found that young trees in understocked stands tend to grow more slowly as they grow older, so that rate of growth and age are confounded in their effect on specific gravity. He presented data from a 30-year-old plantation that was used for a combined thinning and spacing study. He could find no differences in specific gravity related to spacing during the first 20 years of growth, although there were differences in diameter growth and volumes. During the next ten years, changes in specific gravity reflected the effects on the different original spacing, but no effects due to subsequent thinning. Similar results were reported by Martin (1961) in a loblolly pine thinning study in southeastern Louisiana. Martin concluded that specific gravity was not affected by stocking levels ranging between 80 and 100 ft^2 of basal area per acre.

Paul and Smith (1950) reported that southern pines in fully stocked stands increase in specific gravity more rapidly from the pith to the bark than do trees growing under more open conditions. Wide spacing and fast growth result in a higher percentage of low density early wood. They did note that overcrowding will have the same effect, since the late-wood growth is reduced.

Paul (1958) noted that southern pines are found to respond readily to release both by enlarging their crowns and by increasing their diameter growth rate. In terms of specific gravity the response is not readily predictable. Often, as growth is accelerated, the wood increases in specific gravity for a few years and then decreases. Paul attributed these changes to varying proportions of earlywood and latewood in the annual ring.

On the other hand, Geyer and Gilmore (1965) found that the specific gravity and the percent summerwood were significantly greater in 14-year-old loblolly pine planted at wide spacings than those planted at closer spacings. These differences were only found in the juvenile wood. The wider spacings produced both larger juvenile wood and mature wood segments and the proportion of mature wood was greater than in the narrow spacings. They found that little of the variation in specific gravity could be attributed to the role of growth alone.

Hamilton and Matthews (1965) determined that the specific gravity of the 15-year-old shortleaf and loblolly pine in Georgia was significantly influenced by stand density. They reported that plantations planted at 5-ft spacing had a higher specific gravity than those planted in 4-ft, 6-ft, 7-ft, or 8-ft spacings. Crown class was also found to have an effect on specific gravity. The dominant and codominant trees had a significantly higher specific gravity than did the lower crown classes.

Effects of Thinning on Mortality

In general, stands are thinned to improve growth on the remaining trees. Trees that would ordinarily die are cut and salvaged in the thinning process. Li (1923) reported that thinning gives increased yields both by increasing the growth on the uncut trees and by salvaging mortality.

Williston (1950) presented data on mortality following the thinning of a 44-year-old shortleaf and loblolly pine stand. Four different thinning intensities were tried and compared with an unthinned control plot. Mortality was least on the most lightly thinned plot and greatest on the control plot. Ice and wind were found to be the chief cause of mortality, which explains why the mortality was so high on the more heavily thinned plots.

Chaiken (1941) found thinning loblolly pine resulted in an increase in the diameter increment of the released trees, but in high mortality among the smaller uncut trees. He felt that it would be best to remove the smaller trees and the defective trees in order to reduce the mortality. Lentz and Chapman (1941), however, believed that if Chaiken had not made such a heavy cut, the mortality might not have been so great.

Summary of Literature Findings

Only some of the many thinning studies have been presented here. However, these few point out most of the problems that face one who plans to make a thinning study or one who makes thinning recommendations to a forest owner.

A basic problem in thinning is the different reactions of tree growth and stand growth to changes in stand density. Apparently individual trees make faster growth with decreasing stand density up to the point where a tree can be classed as open-grown. If the number of these fast-growing trees is increased, the stand growth will also increase. But as the number of such trees increases, the rate of growth of the individual trees decreases, and if the number of trees continues to increase, this growth rate will decline until some trees will die. If there exists a maximum amount of wood of a certain species that can be grown on a given site, then apparently it would be best to grow this wood on the fewest trees possible. Because a tree probably has a maximum-growth peak, it is possible to reduce the number of trees below that number required to make the maximum stand growth. Most thinning studies have been concerned with finding how many trees and which trees can be removed and still reach this maximum stand growth.

The problem is a complicated one, since growth depends on many factors besides density. In addition, stand density is complicated by the question of how the trees are located within the stand and the relative sizes, ages, crown classes, crown ratios, and vigor classes of the trees within the stand.

The conclusions drawn from many of the studies mentioned here depend in part on the method of analyzing results. If only trees 8 inches and larger in diameter are considered, the conclusion is likely to be that heavy thinning early in the stand's life will give the greatest yield. If total basal area is the factor considered, then the treatment

that leaves the most trees is probably favored. If an economic analysis is made that includes the yield from intermediate thinnings, the conclusions may favor early thinning. This is especially true if the interest rate is high.

Most studies have not presented an objective description of the thinning method used. As previously explained, this is primarily because no measures exist that will always apply, even though numerous attempts have been made to develop objective measures of thinning treatments.

Many measures try to relate the stand in question to a hypothetical natural stand known as "normal," although an objective description of a normal stand does not exist. Such a measure is seldom applicable in studies involving plantations, because they are not developed under the same conditions as natural stands.

Others have used tree spacing or number of trees on the area as a means of describing a stand or a stand treatment. This measure does not consider the variation of tree sizes within this spacing and usually considers such spacing as regular. Plantations may be regularly spaced at first, but seldom will subsequent cutting or mortality allow such regular spacing to exist for long, especially since most thinning methods require the first consideration given to the condition of the tree and only second consideration to spacing.

Some thinning treatments have been described in terms of basal area. In some the percent of the original basal area that has been removed is listed. In others, the basal area of the residual stand is

shown. In still other studies, the basal area is related to the basal area of the normal stand. A deficiency with these measures of thinning treatment is that the sizes and the spatial distributions of the individual trees are not considered.

Perhaps the main objection to the thinning studies presented is the almost universal lack of statistical analysis (Wood 1963). This is especially true of studies initiated before 1950. Many of these studies had no replications of treatment; while average growth data were often presented, no mention was made of variation around these means. Most of the more recent studies have adequate statistical designs, but these studies are too recent to give any meaningful results. They indicate that the difficulty of objectively measuring and replicating the treatments continues to be a problem.

The reasons for lack of statistical designs are quite apparent. Thinning studies usually require a large amount of land. Perhaps this reason is becoming less important because now it is possible, through the use of electronic computers, to analyze large amounts of data from a few trees. Individual trees can now be used instead of stand totals as a means of determining results.

Objective measures of treatment are perhaps more essential in thinning studies than in any type of biological study, because the time involved over the length of the study is usually so great that those who initiate studies are seldom the ones who conclude them and publish the results. Everyone has his own idea of a dominant tree or a vigorous tree and his own definition of adequate stocking or proper spacing. But

these ideas are often modified as the years go by; when someone must decide what was meant 30 years ago by a "low" or "light" thinning, it becomes almost impossible to evaluate the results of a study.

In summary, this review has indicated the main problems in thinning research are the problems of adequately describing the stand before treatment, adequately describing the treatments themselves, and properly evaluating the results after long periods of time. These problems are all present in the study described in the following pages of this dissertation.

THE STUDY AREA

Location

This study was established in 1937 by A. D. Folweiler of the Louisiana State University Agricultural Experiment Station. The study plots, known as the Artesian Well Plots, were located in a slash pine plantation that had been planted with 1-year-old seedlings in the winter of 1924-1925. These plots are on land now owned by the Crown Zellerbach Corporation and are located approximately three miles north of Bogalusa in Washington Parish, Louisiana (Figures 1 and 2).

Ten 1/4-acre plots are included in this study. Five of the plots are designated as lying in the East block and are located on both sides of the boundary line between Sections 35 and 36, Township 2 South, Range 13 East. The other five plots, designated as the West block, are near the center of Section 35, Township 2 South, Range 13 East.

Soils

The soils on the plots are of three types. The Myatt fine sandy loam is found on the West Control, Low and Selection plots and on all plots of the East block. This soil is poorly drained with an acid, fine sandy loam to sandy loam A horizon to a depth of 18 inches and an acid, loam B horizon to a depth of 46 inches. According to Linnartz (1961), the average site index for Myatt soil in Southeastern Louisiana is 90.

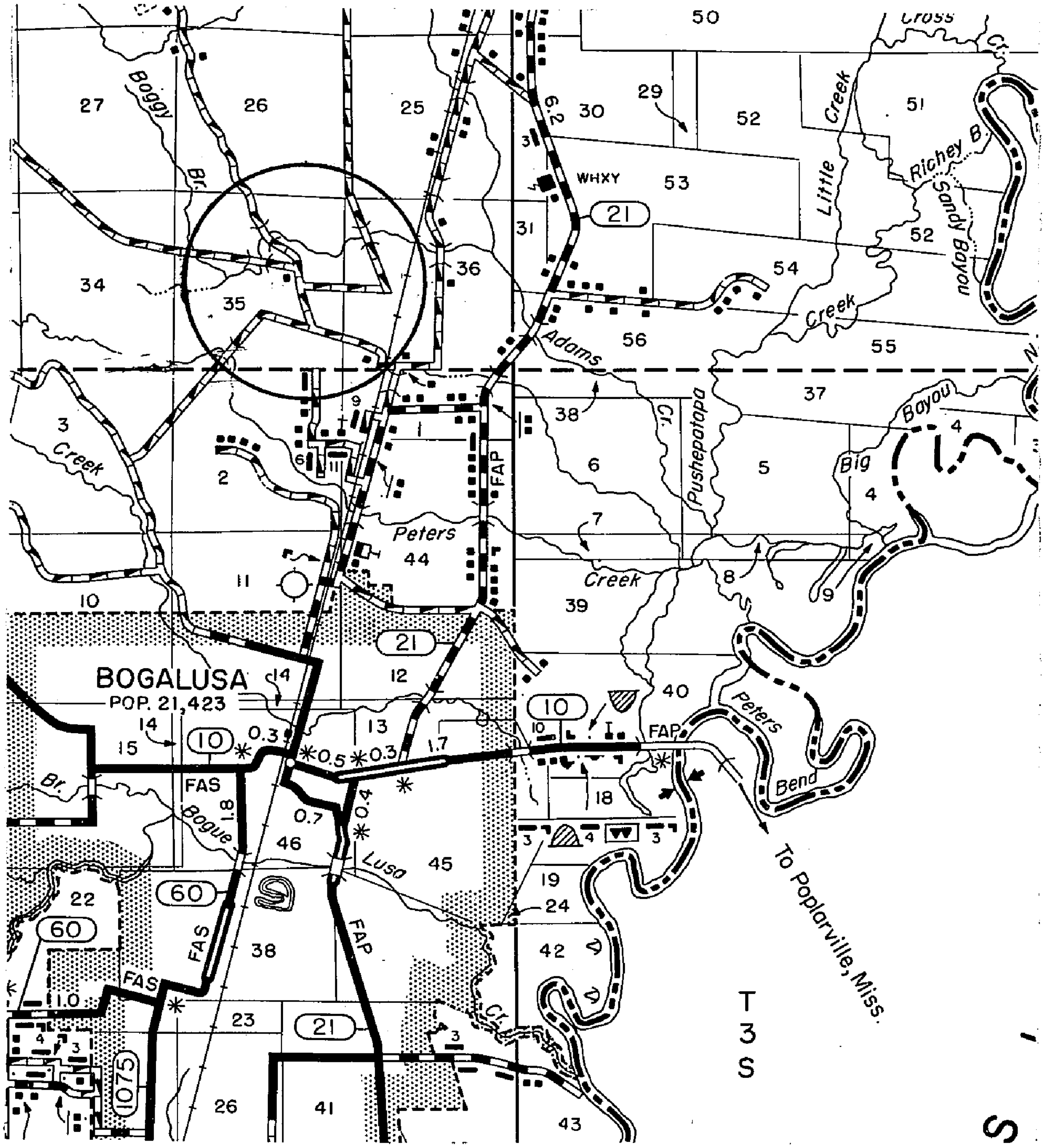
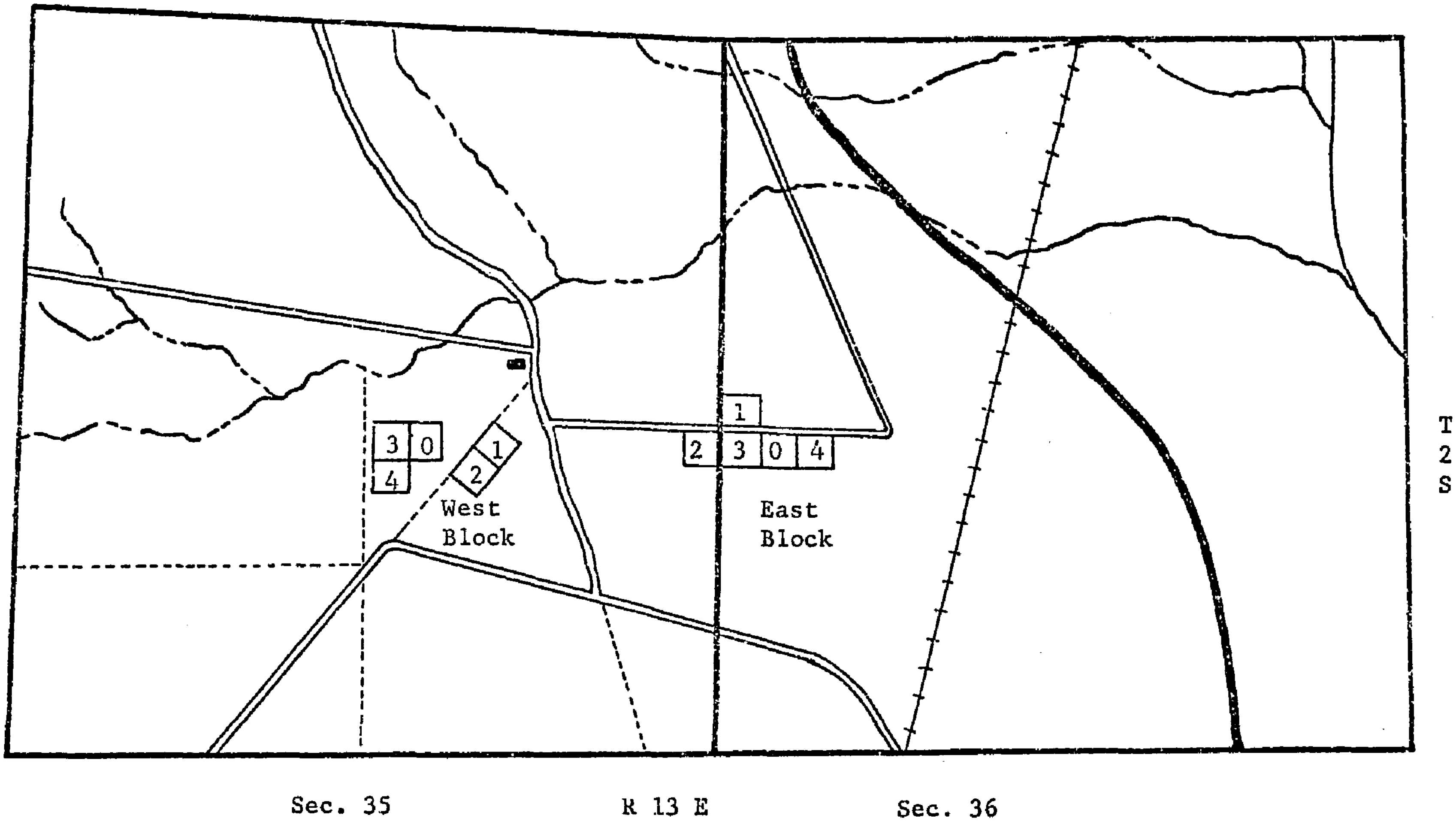


Figure 1. General study area (circled) near Bogalusa, Louisiana.
Scale: 1 in. = 1 mile.



Scale: 4 in. = 1 mile

PLOT TREATMENT KEY
0 = Control
1 = Low
2 = Light Crown
3 = Heavy Crown
4 = Selection

Figure 2. Location of study plots within the study area

The Stough fine sandy loam is found on the West Light Crown plot and is also found on the West Selection, West Low, West Heavy Crown, East Light Crown, East Heavy Crown, and East Selection plots. This soil is somewhat more poorly drained than the typical Stough soils, with an extremely acid, sandy loam to loam A horizon to a depth of 13 inches and an extremely acid, sandy loam B horizon to a depth of 40 inches. The average site index for slash pine on Stough soil is 100 (Linnartz 1961).

The Prentiss sandy loam, found on the West Heavy Crown plot, and on all plots of the East block except the Selection plot, is described as moderately well drained with an extremely acid, sandy loam to loam A horizon to a depth of 10 inches and an extremely acid, loam B horizon to a depth of 42 inches.

All soils have parent material described as local stream terrace, Coastal Plains sandy alluvium. Soil types on each plot are shown in Figures 3 and 4, and complete soil profile descriptions are presented in Appendix A. Soil descriptions were written by Warren Cockerham of the U. S. Department of Agriculture, Soil Conservation Service.

Climate

The climate in this area is typically warm and humid during the summer and mild during the winter. U. S. Weather Bureau records have been kept for Bogalusa since 1931 at a weather station less than three miles from the study area. These records indicate a mean annual temperature of 67.3^{o} Fahrenheit. July is the month of maximum temperature

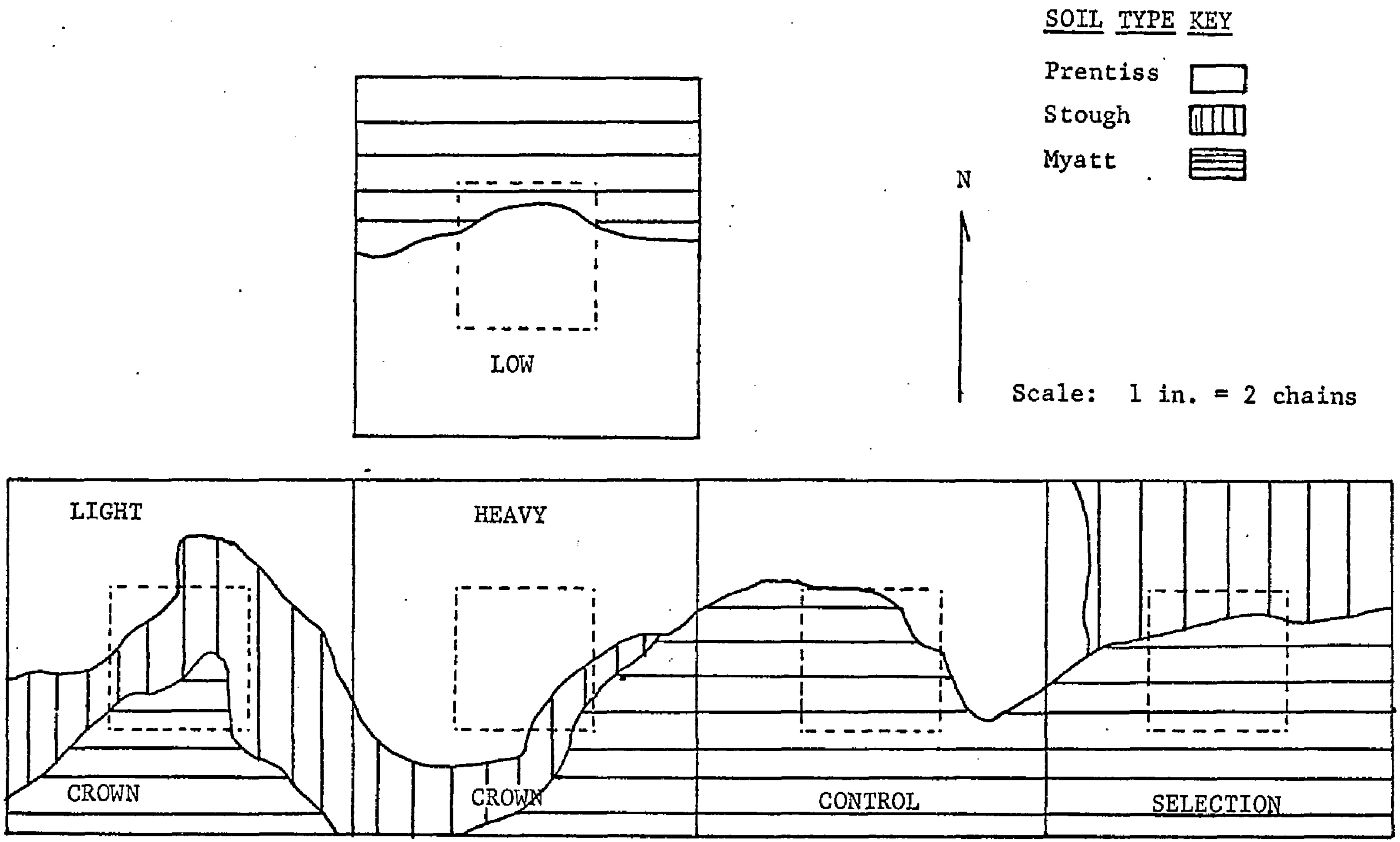


Figure 3. Soil map of plots in the East Block. Dashed lines show center plot used for study.

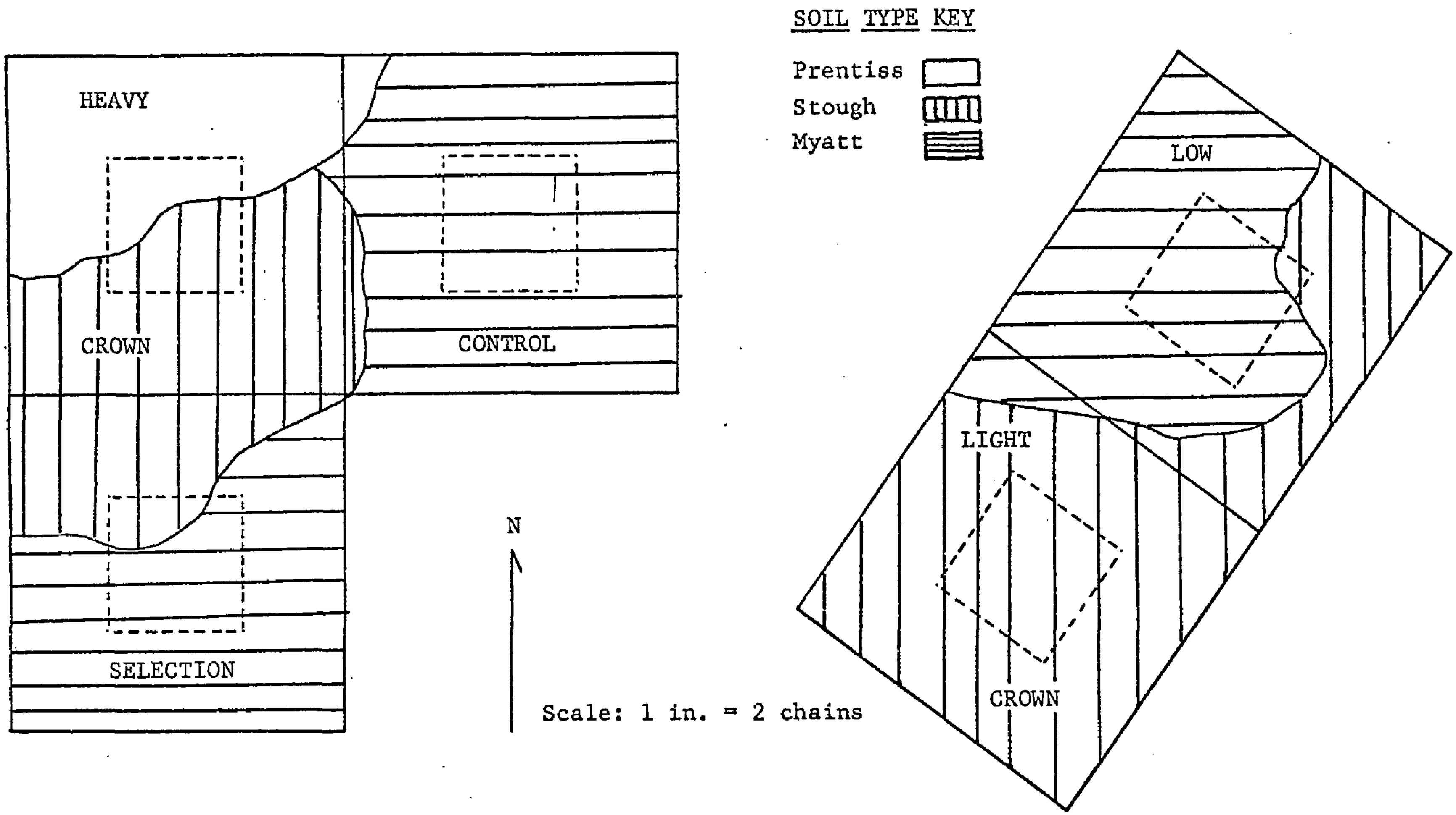


Figure 4. Soil map of plots in the West Block. Dashed lines show center plot used for study.

with a mean of 82.1°, while January is the coldest month with a mean of 52.8°. Precipitation for the station has averaged 59.2 inches per year since 1931. The driest year during the period was 1963, when 37.23 inches of rain were recorded. The most rainfall, 90.83 inches, fell in 1961. Rainfall is fairly well distributed throughout the year. The maximum rainfall generally occurs in March and July, while the driest month is October (see Figure 5). The average frost-free period is 250 days per year with the first frost not earlier than October 23, and the last not later than March 31.

Site Index

Site index (based on age 50) of the study area was computed by taking the average height in 1964 of the 10 tallest trees on each plot (Table 1) and inserting this value into an equation developed by Keister (1963):

$$\log_{10} \text{site index} = \log_{10} \text{ht.} + 4.7970 \ (1/\text{age} - 1/50)$$

This equation was developed from measurements taken from 165 dominant and co-dominant slash pine trees growing in Washington Parish, Louisiana, on several different sites and at several different ages.

The West block was found to have an average site index of 95.9 ft; the East block had an average site index of 98.9 ft. This difference was found to be not statistically significant when a paired comparison was made. Because there seemed to be no real difference in site between the blocks, it was assumed that the over-all site index based on age 50 is 97.4 ft, which is an excellent site quality for slash pine in the southern United States.

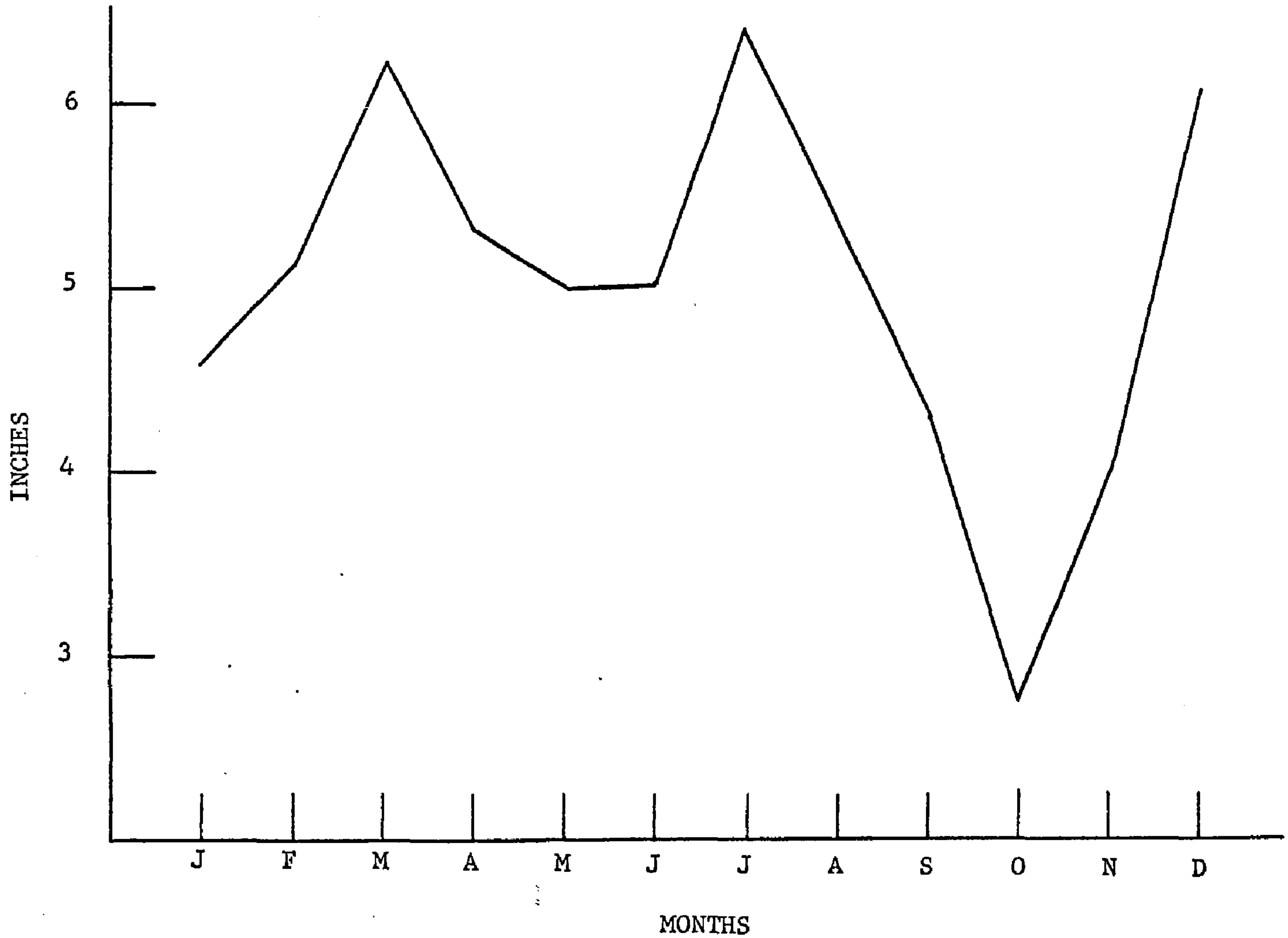


Figure 5. Average monthly rainfall, Bogalusa, Louisiana, 1931-1964.

Table 1. Site indices based on average heights of ten tallest trees at age 40

Treatment	Average height		Site index		Block difference
	East block	West block	East block	West block	
	Feet	Feet	Feet	Feet	Feet
Control	93.4	86.3	98.7	91.2	7.5
Low	94.1	89.8	99.4	94.9	4.5
Light Crown	94.9	95.1	100.0	101.0	-1.0
Heavy Crown	95.5	91.8	100.0	97.0	3.0
Selection	91.2	90.4	96.4	95.6	0.9
Mean	93.8	90.7	98.9	95.9	3.0

OBJECTIVES, PAST HISTORY, AND TREATMENTS

The original objective of this study was to determine the relative rate of growth in stands of planted slash pine after they had been thinned by two methods and to determine which method is superior to the other, silviculturally and financially.

The two thinning methods originally tried in December 1937 were the French or Heavy Crown (designated H.C. in some tables - see Table 8) and the Borggreve or Selection (designated S in some tables - see Table 8) methods. Each method was applied to two 1.6-acre plots with a measured 1/4-acre plot in the center. Two additional 1.6 acre plots were designated as Control plots and were not thinned. The trees on the 1/4-acre center plots were measured and numbered so that individual tree records could be kept. The first treatments were applied when the planted trees had completed 13 growing seasons in the field.

In May 1938 two additional treatments were established on two additional pairs of 1.6-acre plots. These treatments have been designated as Low and Light Crown (designated L.C. in some tables - see Table 8) thinnings. Again, all trees in the 1/4-acre center were numbered and measured.

The entire study, then, was established on 10 plots. These plots were divided into two blocks with each of the four treatments and a control on each block. A diagram of the plot layout is shown in Figure 2 and a map showing the location of the study area in Figure 1. The original stocking and average sizes of the trees are listed in Table 2.

Table 2. Average tree characteristics at age 13, prior to first treatment

Block	Treatment	Average diameter	Average height	Average crown length	Average crown ratio	Total number trees
		Inches	Feet	Feet		
East	Control	5.43	36.1	14.7	.409	167
West	Control	5.33	32.9	14.5	.442	155
East	Low	5.46	40.8	16.3	.408	199
West	Low	5.67	37.0	18.4	.498	142
East	Light Crown	5.38	38.8	17.8	.458	167
West	Light Crown	5.89	38.7	18.8	.486	139
East	Heavy Crown	5.80	40.0	14.9	.372	151
West	Heavy Crown	5.91	37.2	14.5	.390	123
East	Selection	5.22	34.1	13.7	.401	172
West	Selection	5.40	34.7	14.8	.427	148

A brief description of the thinning methods follows: The Heavy Crown thinning removed co-dominant stems primarily, although small stems were cut if they were judged about to die. The Light Crown thinning was similar to the first, but less volume was cut. The Low thinning called for the removal of the more crowded and suppressed trees. The Selection method where large, rough dominant as well as suppressed trees were cut, and the better-formed intermediate and co-dominant trees were left to grow. A summary of the stocking and volume on the plots before thinning and the amount removed by thinning is shown in Tables 3, 4, and 5.

The Heavy Crown and Selection plots were thinned a second time in 1951 at age 26; the other two treatments (Low and Light Crown) were thinned a second time in 1949 at age 24 and a third time in 1954 at age 29. Intermediate results from this study have been presented elsewhere (Crow 1952, 1963) but are presented here as well (Tables 3, 4, and 5).

In 1955 the Selection, Heavy Crown, and Control plots on the East block were inadvertently thinned, thereby destroying one replication in each of these treatments. The thinning method used in 1955 was a relatively heavy low thinning which was done in accordance with marking guides used by the landowning corporation for its pine plantations in the Bogalusa area.

The measurements taken when the plots were established included diameter outside bark at breast height, total height, and clear height or height to lowest green limb. In addition, the crown class of each tree was recorded.

Table 3. Volumes before thinning cuts, cut in thinnings, and after thinnings

(In cubic feet per one-fourth acre)

Time of measurement	East block Control	Low	Light Crown	Heavy Crown	Selection	West block Control	Low	Light Crown	Heavy Crown	Selection
					Age 13					
Before cut	496	667	519	553	449	403	428	478	443	419
Cut	0	174	133	242	268	0	47	98	158	220
After cut	496	493	386	311	181	403	381	380	285	199
					Age 24					
Before cut	861	1094	982	--	--	1036	966	971	--	--
Cut	0	275	252	0	0	0	201	237	0	0
After cut	861	819	730	--	--	1036	765	734	--	--
					Age 26					
Before cut	1147	--	--	903	757	1070	--	--	824	744
Cut	0	0	0	325	241	0	0	0	291	243
After cut	1147	--	--	578	516	1070	--	--	533	501
					Age 29					
Before cut	1252	1009	938	736	648	1203	957	1099	741	596
Cut	591	206	191	160	190	0	199	260	0	0
After cut	661	803	747	576	458	1203	758	839	741	596
					Age 40					
Uncut	1056	1474	1319	973	888	1407	1209	1293	1096	1034

Table 4. Number of trees before thinning cuts, cut in thinnings, and after thinnings

Time of measurement	East block					West block				
	Control	Low	Light Crown	Heavy Crown	Selection	Control	Low	Light Crown	Heavy Crown	Selection
					<u>Age 13</u>					
Before cut	167	199	167	151	172	155	142	139	123	148
Cut	0	72	52	76	93	0	29	39	54	69
After cut	167	127	115	75	79	155	113	100	69	79
					<u>Age 24</u>					
Before cut	142	120	109	--	--	139	113	96	--	--
Cut	0	39	34	0	0	0	36	25	0	0
After cut	142	81	75	--	--	139	77	71	--	--
					<u>Age 26</u>					
Before cut	133	--	--	68	70	130	--	--	65	68
Cut	0	0	0	25	22	0	0	0	24	22
After cut	133	--	--	43	48	130	--	--	41	46
					<u>Age 29</u>					
Before cut	117	77	70	43	47	115	73	70	41	45
Cut	71	21	23	13	17	0	20	23	0	0
After cut	46	56	47	30	30	115	53	47	41	45
					<u>Age 40</u>					
Uncut	39	56	45	30	29	82	52	44	41	42

Table 5. Basal areas before thinning cuts, cut in thinnings, and after thinning

(In square feet per one-fourth acre)

Time of measurement	East block					West block				
	Control	Low	Light Crown	Heavy Crown	Selection	Control	Low	Light Crown	Heavy Crown	Selection
					Age 13					
Before cut	27.0	32.6	26.7	27.8	25.6	24.0	22.8	24.7	23.6	23.5
Cut	0	9.0	6.9	12.2	14.9	0	2.7	5.3	8.6	12.2
After cut	27.0	23.6	19.8	15.6	10.7	24.0	20.1	19.4	15.0	11.3
					Age 24					
Before cut	40.4	36.6	33.7	--	--	37.9	35.2	33.5	--	--
Cut	0	9.6	9.0	0	0	0	7.8	8.5	0	0
After cut	40.4	27.0	24.7	--	--	37.9	27.4	25.0	--	--
					Age 26					
Before cut	39.6	--	--	28.4	26.2	37.2	--	--	27.0	25.2
Cut	0	0	0	10.3	8.5	0	0	.0	9.9	8.3
After cut	39.6	--	--	18.1	17.7	37.2	--	--	17.1	16.9
					Age 29					
Before cut	39.7	30.4	28.2	20.5	20.5	38.3	29.7	29.7	19.8	18.9
Cut	20.4	6.5	6.2	4.7	6.3	0	6.4	7.1	0	0
After cut	19.3	23.9	22.0	15.8	14.2	38.3	23.3	22.6	19.8	18.0
					Age 40					
Uncut	25.4	32.6	30.9	22.4	21.8	37.6	30.7	30.7	27.4	26.1

All plots were remeasured periodically and additional information, such as incidence of disease, was also recorded. Diameter measurements were taken with a diameter tape or with calipers at d.b.h., a point 4.5 ft above the base of the tree. Heights were measured with an Abney level or a Haga altimeter. Crown class was estimated by the measuring crew, and the presence or absence of fusiform rust /Cronartium fusiforme (A. and K.) Hedgc. & Hunt/ was noted during the later measurements.

The first report of these plots (Crow 1952) presented their growth through age 24. The principal conclusion at that time was that no thinning at all will result in as much total wood volume as could be obtained by any of the thinning treatments. Mortality was low on all but the Control plots. In the Heavy Crown and Selection plots the basal area was still less than it had been before the thinning at age 13. The Low and Light Crown plots, however, surpassed their original basal area within five years.

As was expected, diameter growth varied inversely with the thinning intensity so that the Control had the smallest average diameter by age 24 and the Heavy Crown had the largest average diameter. Total height growth was not affected by the thinning treatments, but the live-crown ratio was reduced by age 24 on the Control, Low, and Light Crown plots. Volume growth (in cords) was greatest in the Control, Low, and Light Crown plots, although the Heavy Crown had by far the largest number of sawtimber-size trees (9.5 in. and larger).

A second report on this study area summarized some of the plot data through age 29 (Crow 1963), after all treated plots had been

thinned twice. At this time the Control plots had the largest volume (in cords) in standing trees, while the Heavy Crown and Selection plots had the least. The Light Crown plots had produced the most total volume (including thinning volume), but there was little difference in total volume produced by the Control, Low, and Light Crown plots. The Light Crown plots had made the greatest periodic growth (in cords) and had surpassed the Heavy Crown in producing sawtimber-size trees. Height growth still showed no effects from the treatments, but average diameters were somewhat inversely correlated with thinning intensity. Mortality increased with heavier stocking.

Two additional studies have been made on this area. One was an unpublished report by D. B. Sanders in 1954. Sanders studied the Girard form-class of the trees on these plots and could find no statistically significant differences in average form-class among the various treatments. The average form-class values at that time were: Control 77.2, Heavy Crown 78.4, Selection 78.4, Low 78.5, and Light Crown 79.0.

The second (Briscoe 1954) was a study to determine the effect of thinning treatment on tree quality. A tree-quality classification system was devised for this study based on the size and number of knots, the size of the tree, and the general form of the tree (i.e., sweep or crook). It was concluded that thinned plots yield a higher proportion of high-quality stems than do plots that are not thinned, although no differences were found among the thinning treatments.

The objective of this present study was to re-evaluate the past measurements along with new measurements in order to determine if any

treatment is financially and silviculturally superior. An additional goal was to devise an objective measure of stand density that would be correlated with individual tree growth as well as stand growth. This measure would allow an exact determination of the degree of thinning-intensity applied and would make it possible to describe precisely a thinning treatment so that such treatments could be re-applied at later times to the same stand or to different stands under different types of conditions.

Because the original design of this study was destroyed in 1955, it is impossible to compare statistically the effects of the treatments since that time. However, the individual tree records have been kept, so some analysis of tree development on these stands since 1955 was done.

PLOT DEVELOPMENT

For this phase of the study measurements obtained in the past were used. The available measurements included diameter at breast height, total height, clear-bole length, and the crown class of each tree on each plot. Measurements had been taken periodically by the Louisiana State University staff; in addition, student crews usually took measurements annually. The measurements used in this study are those taken by the staff because they correspond to the thinning schedule. All plots were measured in December 1937 (or in May 1938 in the case of the Low and Light Crown plots) and again in January 1943. The Low and Light Crown plots were measured again in March 1949; the other two treatments were remeasured in April 1951. All plots were remeasured in March 1954 and finally in December 1964. In this last measurement the crown widths were measured. This was done by measuring the width of the crown, projected on the ground, across the longest crown width and at right angles to this width and then recording the average of the two measurements.

The Control plots were measured whenever any of the treated plots were measured, although no height measurements were taken on either of the Control plots in 1951. Regression equations were prepared so that height could be estimated from diameter, and so that volume could be computed for this year on these plots.

The equation used was of the form:

$$Y = b_o + b_1x + b_2x^2$$

where Y = total height and x = diameter. The data used were the heights and diameters, at several ages, of those trees present on the plots in 1951. An additional variable (age) was used in the computation; however, this variable becomes a constant for any given age and the coefficient for intercept, b_o, was adjusted accordingly.

In 1954 no height measurements were taken on any of the plots at the time diameter measurements were made. Heights were taken later in the summer, and these measurements were used, even though the trees had experienced almost four extra months of height growth. This means that heights and, in turn, volumes are slightly higher than they should be for that year. This is true for all plots; therefore it should make little difference in comparisons of growth between treatments.

Volume Increment Between Age 13 and Age 29

Stand-volume increment was compared between several age periods. Because the treatments had been assigned within the blocks, the results were analyzed using a method of orthogonal comparisons from a randomized block design. Strictly considered, the four treatments should not be compared with each other, as their respective growth measurement periods did not coincide, and the locations of the Low and Light Crown plots were not random in relation to the other two treatments. (These two treatments were not established until one year after the Selection, Control, and Heavy Crown treatments had already been located). However,

these irregularities were not great enough to offset the advantages of the method of analysis used.

For purposes of analysis the cubic-foot volume of each tree was computed from an equation based on the breast-high, outside-bark diameter (d.b.h.) and the total height of the tree. The equation used was:

$$\text{volume, ft}^3 = 0.1 + 0.00258 \left[(\text{d.b.h.})^2 \ (\text{ht.}) \right]$$

This equation was prepared by Hubert O. Davis, at that time an employee of Crown Zellerbach Corporation, and presented at the Forest Management Control Conference at Purdue University in 1960. The equation gives the volume outside bark below a 4-inch, outside-bark, top diameter and is based on measurements of a large number of trees from the general area in which this study was made.

The first step in the analysis of the data was to compute the growth of the plots between the periodic measurements. The trees on each plot were sorted into 1-inch diameter classes based on diameter measurements at the beginning of the growth period. The basal area, cubic-foot volume and the number of trees in each class were computed for each plot at the start of each period. The volume, basal area, and number of trees that had died or had been cut were also determined. Growth, both in basal area and in cubic feet, was computed only on those trees in each diameter class that were still living at the end of the growth period. Growth was also computed on the basis of the crown class assigned to the trees at the commencement of the growth periods; however, the crown classes of the trees cut from Low and Light Crown plots were not recorded in 1937.

The net growth, including the growth on surviving trees plus the volume or basal area of the cut trees, was compared between treatments for each of the various time periods. The gross growth (which includes mortality) was also compared. All treatments were not compared over each time period because tree measurements were not taken on all treatments during the same years. All plots were measured in 1943; thus, all plots were compared over the time period between 1937 and 1943. Because all plots were again measured in 1954, yields were compared over the period from 1937 to 1954. The Low and Light Crown treatments and the Control were compared over the time periods from 1943 to 1949 and from 1949 to 1954. The Heavy Crown, Selection, and Control plots were compared over the periods 1943 to 1951 and 1951 to 1954. The experimental design used for these comparisons was a randomized block design with either three or five treatments in two blocks. When a significant difference (at .05 significance level) was found among treatments, the treatments were compared by the use of orthogonal coefficients. In the case where five treatments were used the order of comparison was Control vs. thinnings, Low and Light Crown vs. Heavy Crown and Selection, Low vs. Light Crown, and Heavy Crown vs. Selection. If only three treatments were used, the comparisons were unthinned vs. thinning and between two thinning treatments.

The growth in basal area and cubic feet for the time periods compared is shown in Tables 6 and 7. The results of the comparisons are listed in Tables 8 and 9. During the six years following the first application of the thinning treatments, the control plots made a net growth

Table 6. Gross growth, mortality, and net growth in volume by periods

(In cubic feet per one-fourth acre)

Type of measurement	East block					West block				
	Control	Low	Light Crown	Heavy Crown	Selec-	Control	Low	Light Crown	Heavy Crown	Selec- tion
					Between ages 13-19					
Gross growth	348	338	351	221	199	356	370	356	218	197
Mortality	17	5	2	7	1	3	0	0	7	5
Net growth	331	333	349	214	198	353	370	356	211	192
					Between ages 13-24					
Gross growth	671	631	618	--	--	674	585	619	--	--
Mortality	45	44	22	--	--	41	0	28	--	--
Net growth	626	587	596	--	--	633	585	591	--	--
					Between ages 13-26					
Gross growth	731	--	--	633	600	733	--	--	554	570
Mortality	80	--	--	41	24	66	--	--	15	25
Net growth	651	--	--	592	576	667	--	--	539	545
					Between ages 13-29					
Gross growth	945	891	838	791	818	925	809	988	769	676
Mortality	189	100	34	41	26	125	32	32	22	36
Net growth	756	791	804	750	792	800	777	956	747	640
					Between ages 13-40					
Gross growth	1389	1575	1437	1188	1165	1373	1285	1476	1124	1148
Mortality	238	113	61	41	27	369	57	66	22	70
Net growth	1151	1462	1376	1147	1138	1004	1228	1410	1102	1078

Table 7. Gross growth, mortality, and net growth in basal areas by periods

(In square feet per one-fourth acre)

Type of measurement	East block					West block				
	Control	Low	Light Crown	Heavy Crown	Selection	Control	Low	Light Crown	Heavy Crown	Selection
					Between ages 13-19					
Gross growth	7.8	8.3	8.8	5.6	6.5	7.8	9.6	8.9	5.2	5.8
Mortality	1.1	0.3	0.2	0.3	.0	0.2	.0	.0	0.4	0.3
Net growth	6.7	8.0	8.6	5.3	6.5	7.6	9.6	8.9	4.8	5.5
					Between ages 13-24					
Gross growth	15.8	14.3	14.8	--	--	15.7	15.1	15.2	--	--
Mortality	2.4	1.8	0.9	--	--	1.8	.0	1.1	--	--
Net growth	13.4	12.5	13.9	--	--	13.9	15.1	14.1	--	--
					Between ages 13-26					
Gross growth	16.5	--	--	14.5	16.7	16.2	--	--	12.7	15.2
Mortality	3.9	--	--	1.7	1.2	3.0	--	--	0.7	1.3
Net growth	12.6	--	--	12.8	15.5	13.2	--	--	12.0	13.9
					Between ages 13-29					
Gross growth	20.6	19.4	18.9	16.9	19.6	19.7	18.9	20.2	15.3	17.5
Mortality	7.9	3.7	1.5	1.7	1.3	5.4	1.6	1.3	1.0	1.7
Net growth	12.7	15.7	17.4	15.2	18.3	14.3	17.3	18.9	14.3	15.8
					Between ages 13-40					
Gross growth	28.4	29.2	28.6	23.5	27.2	27.3	27.0	29.3	23.2	25.9
Mortality	9.7	4.1	2.3	1.7	1.4	13.7	2.3	2.3	1.0	2.8
Net growth	18.7	25.1	26.3	21.8	25.8	13.6	24.7	27.0	22.2	23.1

Table 8. Analyses of variance of net growth by periods

Source	d.f.	Net cubic-foot growth: Sum squares	Mean square	F	Net basal-area growth: Sum squares	Mean square	F
		Ages 13-19 net growth (all plots)					
Total	9	51816.1			21.741		
Block	1	324.9			.320		
(Treatment)	4	50842.6	12710.65	78.388**	19.844	4.961	12.584**
Control vs thinning	1	6579.225	6579.225	40.57**	.014	.014	.035
Low, L.C. vs H.C.,S.	1	43956.12	43956.12	271.08**	18.942	18.942	48.047**
Low vs L.C.	1	1	1	1	.004	.004	.000
H.C. vs. S.	1	306.25	306.25	1.889	.884	.884	2.241
Error	4	648.6	162.15		1.577	.394	
		Ages 13-24 net growth (Control, Low and L.C. only)					
Total	5	2202			3.512		
Block	1	0			1.717		
(Treatment)	2	2163	1081.5	55.461*	.106	.053	.063
Control vs thinning	1	2100.75	2100.75	108.03**			
Low vs L.C.	1	56.25	56.25	2.885			
Error	2	39	19.5		1.689	.844	
		Ages 13-26 net growth (Control, H.C. and S. only)					
Total	5	16328.0			7.546		
Block	1	[illegible]			.637		
Treatment	2	12313.00	6156.50	9.911	5.602	2.801	4.286
Error	2	1242.33	621.165		1.307	.653	

Table 7. Gross growth, mortality, and net growth in basal areas by periods

(In square feet per one-fourth acre)

Type of measurement	East block					West block				
	Control	Low	Light Crown	Heavy Crown	Selec-tion	Control	Low	Light Crown	Heavy Crown	Selec-tion
					Between ages 13-19					
Gross growth	7.8	8.3	8.8	5.6	6.5	7.8	9.6	8.9	5.2	5.8
Mortality	1.1	0.3	0.2	0.3	.0	0.2	.0	.0	0.4	0.3
Net growth	6.7	8.0	8.6	5.3	6.5	7.6	9.6	8.9	4.8	5.5
					Between ages 13-24					
Gross growth	15.8	14.3	14.8	--	--	15.7	15.1	15.2	--	--
Mortality	2.4	1.8	0.9	--	--	1.8	.0	1.1	--	--
Net growth	13.4	12.5	13.9	--	--	13.9	15.1	14.1	--	--
					Between ages 13-26					
Gross growth	16.5	--	--	14.5	16.7	16.2	--	--	12.7	15.2
Mortality	3.9	--	--	1.7	1.2	3.0	--	--	0.7	1.3
Net growth	12.6	--	--	12.8	15.5	13.2	--	--	12.0	13.9
					Between ages 13-29					
Gross growth	20.6	19.4	18.9	16.9	19.6	19.7	18.9	20.2	15.3	17.5
Mortality	7.9	3.7	1.5	1.7	1.3	5.4	1.6	1.3	1.0	1.7
Net growth	12.7	15.7	17.4	15.2	18.3	14.3	17.3	18.9	14.3	15.8
					Between ages 13-40					
Gross growth	28.4	29.2	28.6	23.5	27.2	27.3	27.0	29.3	23.2	25.9
Mortality	9.7	4.1	2.3	1.7	1.4	13.7	2.3	2.3	1.0	2.8
Net growth	18.7	25.1	26.3	21.8	25.8	13.6	24.7	27.0	22.2	23.1

Table 8. Analyses of variance of net growth by periods

Source	d.f.	Net cubic-foot growth: Sum squares	Mean square	F	Net basal-area growth: Sum squares	Mean square	F
		Ages 13-19 net growth (all plots)					
Total	9	51816.1			21.741		
Block	1	324.9			.320		
(Treatment)	4	50842.6	12710.65	78.388**	19.844	4.961	12.584**
Control vs thinning	1	6579.225	6579.225	40.57**	.014	.014	.035
Low, L.C. vs H.C.,S.	1	43956.12	43956.12	271.08**	18.942	18.942	48.047**
Low vs L.C.	1	1	1	1	.004	.004	.000
H.C. vs. S.	1	306.25	306.25	1.889	.884	.884	2.241
Error	4	648.6	162.15		1.577	.394	
		Ages 13-24 net growth (Control, Low and L.C. only)					
Total	5	2202			3.512		
Block	1	0			1.717		
(Treatment)	2	2163	1081.5	55.461*	.106	.053	.063
Control vs thinning	1	2100.75	2100.75	108.03**			
Low vs L.C.	1	56.25	56.25	2.885			
Error	2	39	19.5		1.689	.844	
		Ages 13-26 net growth (Control, H.C. and S. only)					
Total	5	14326.0			7.346		
Block	1	770.67			.437		
Treatment	2	12313.00	6156.50	9.911	5.602	2.801	4.286
Error	2	1242.33	621.165		1.307	.653	

Table 8. Continued

Source	d.f.	Net cubic-foot growth Sum squares	Mean square	F	Net basal-area growth Sum squares	Mean square	F
			Ages 13-29 net growth (all plots)				
Total	9	54374.1			34.762		
Block	1	72.9			.217		
Treatment	4	30199.6	7549.9	1.253	27.705	6.926	4.051
Error	4	24101.6	6025.4		6.840	1.710	

Table 9. Analyses of variance of gross growth by time periods

Source	d.f.	Gross cubic-foot growth			Gross basal area growth		
		Sum squares	Mean square	F	Sum squares	Mean square	F
Ages 13-19 (all plots)							
Total	9	51084			21.3397		
Block	1	160			0.0008		
Treatment	4	50521	1263	125.4**	20.0984	5.0246	16.202**
Control vs thinned	1	8009		79.5**		0.2993	0.965
Low, L.C. vs H.C., S.	1	42050		417.4**		19.1581	61.774**
Low vs L.C.	1	<1		$F<1$		.0169	0.054
H.C. vs S.	1	462		4.6		.6241	2.012
Error	4	403	101		1.2405	.3101	
Ages 13-24 (Control, Low, L.C.)							
Total	5	5854			1.5121		
Block	1	294			0.1802		
Treatment	2	4791	2395	6.230	1.1461	.5731	6.169
Error	2	769	284		.1858	.0929	
Ages 13-26 (Control, H.C., S.)							
Total	5	30815			11.2603		
Block	1	1908			2.0416		
Treatment	2	27242	13621	16.368	8.5269	4.2635	12.326
Error	2	1665	832		.6918	.3459	

Table 9. Continued

Source	d.f.	Gross cubic-foot growth			Gross basal area growth		
		Sum squares	Mean square	F	Sum squares	Mean square	F
				Ages 13-29			
Total	9	78292			24.3048		
Block	1	1346			1.4137		
Treatment	4	53156	13289	2.234	19.7562	4.9391	6.302
Error	4	23790	5948		3.1349	.7837	

in cubic feet that was greater by 129 ft^3 than that made by the average of all thinned plots. This difference was statistically significant. The plots that were treated with the Low and Light Crown thinnings made a greater net growth in volume (by 593 ft^3) and in basal area (by 13 ft^2) than did those plots treated with Heavy Crown and Selection treatments. These differences were also significant. It is apparent that the lighter thinning treatments resulted in more growth than did the more severe thinning treatments, at least for the first six years after treatment application. The advantage of the light thinning over no thinning is not so clear-cut. The total net growth on the control plots in basal area and cubic feet was not so great as that of the lightly thinned plots. A valid statistical comparison between these treatments could not be made, and therefore it can only be assumed that if differences really exist between the unthinned and the lightly thinned treatments, they are probably quite small.

The analysis of the gross growth for this period (between age 13 and age 19) showed that, while the magnitude of the differences varied, the treatments showing the most net growth also made the most gross growth.

By age 24, or 11 years after the initial thinning, the unthinned plots had made a greater net growth in volume (by 159 ft^3) than had those receiving the lighter thinning treatments (Low and Light Crown). This difference was highly significant statistically. No such difference was found in net basal-area growth or in gross basal-area and cubic-foot growth. Apparently the additional height growth added to

the larger number of trees that were standing on the Control plots accounted for the difference in net volume growth, although there was no difference in the basal-area growth.

No statistically significant differences were found among the Control, the Heavy Crown, and the Selection treatments by age 26 (14 years after the initial thinning). Apparently the heavily thinned plots had grown fast enough to offset differences that had appeared at age 19.

The Low and Light Crown plots were thinned a second time at age 24, and the Heavy Crown and Selection plots were thinned a second time at age 26. Net and gross growth in both basal area and in cubic feet for the entire period between age 13 and age 29 was examined. There were no differences found among any of the plots that could be attributed to differences in treatment.

<u>Diameter Increment Between Age 13 and Age 29</u>

The periodic annual increment (P.A.I.) in diameter on the plots was examined and compared over the same time periods used previously (see Tables 10 and 11). During the period between age 13 and age 19, the P.A.I. on the Control plots (0.127 inch average) was .081 inch less than the average on all treatments (0.208 inch). This difference was highly significant statistically. The P.A.I. on the Selection plots (0.211 inch) was significantly greater than that on the Heavy Crown plots (0.172 inch). No other statistically significant differences were found during this period.

Table 10. Average annual diameter increment by periods

(Inches of diameter)

Period between	East block					West block				
	Control	Low	Light Crown	Heavy Crown	Selection	Control	Low	Light Crown	Heavy Crown	Selection
Ages 13-19	0.126	0.183	0.231	0.173	0.222	0.128	0.242	0.242	0.171	0.200
Ages 19-24	.115	.105	.111	--	--	.120	.095	.125	--	--
Ages 19-26	.097	--	--	.182	.211	.102	--	--	.162	.205
Ages 24-29	.077	.136	.120	--	--	.078	.111	.157	--	--
Ages 26-29	.106	--	--	.156	.214	.112	--	--	.209	.180
Ages 29-40	.178	.184	.189	.190	.227	.085	.145	.176	.161	.180

Table 11. Analyses of variance of diameter increment by periods

Source	d.f.	Sum squares	Mean square	F
		Between ages 13-19		
Total	9	0.01131		
Block	1	.00011		
Treatment	4	.01043	0.00261	13.589*
Cn vs Th	1		.00804	41.859**
L., L.C. vs H.C., S.	1		.00032	1.693
L. vs L.C.	1		.00055	2.875
H.C. vs. S.	1		.00152	7.922*
Error	4	.00078	.00019	
		Between ages 18-24		
Total	5	.00058		
Block	1	.00001		
Treatment	2	.00042	.00021	2.838
Error	2	.00016	.00007	
		Between ages 18-26		
Total	5	.01245		
Block	1	.00007		
Treatment	2	.01222	.00408	78.308*
Cn vs Th	1	.01092	.01092	140.0 **
H.C. vs S.	1	.00130	.00130	16.615
Error	2	.00016	.00008	
		Between ages 24-29		
Total	5	.00504		
Block	1	.00003		
Treatment	2	.00404	.00204	4.167
Error	2	.00097	.00049	
		Between ages 26-29		
Total	5	.01090		
Block	1	.00010		
Treatment	2	.00891	.00445	4.697
Error	2	.00190	.00095	

L - Low Cn - Control Th - Thinned

No statistically significant differences in P.A.I. were found between the Control plots and the Low or Light Crown plots during the period between age 19 and age 24. During the period between age 19 and age 26 the Control plots had a P.A.I. of 0.099 inch. This was significantly less statistically than the average of the Heavy Crown and Selection plots (0.190 inch). There were no statistically significant differences among any thinned plots and the unthinned plots during the period between the second thinnings and age 29.

Many of the differences among the various treatments, while not statistically significant, were quite large. If more replications had been available, the difference in P.A.I. between age 19 and age 26 of the Heavy Crown plots and the Selection plots would likely have been significant. The P.A.I. of the Selection plots is, in almost every case, higher than that of any other treatment. The only exception is the P.A.I. on the West Heavy Crown plot, which is greater than the P.A.I. of the West Selection plot between age 26 and age 29. It is apparent, from the results shown in Table 11, that thinning stimulated tree diameter growth, and that this increased growth rate was maintained longer on the more heavily thinned plots.

<u>Volume Increment Since Age 29</u>

It has already been explained that one replication (East block) of three of the treatments was cut in the fall of 1955. Between 1954 and 1964 the only measurements taken on the plots were those taken by students in forestry summer camp. The plots were carefully remeasured

in the fall of 1964; therefore all growth data used for this part of this study concern growth made between 1954 and 1964.

The actual volumes removed in 1955 from the Heavy Crown, Selection, and Control plots in the East block are not known. However, the tree number of each tree cut was noted, and the volume and basal area of the cut was computed on the basis of the 1954 measurement of these trees. Trees no longer present in 1964 and that were not known to be cut in 1955 were assumed to have died from natural causes. The volume and basal area of this mortality were also computed on the basis of the 1954 measurements.

As before, the growth, cut, and mortality were summarized on the plots by one-inch diameter classes. Comparison of net yield could not be made on the same basis as before, since only two of the treatments were still replicated. Instead, a covariance analysis of basal-area and volume increment of residual trees was made, considering each Control plot as a separate treatment, and the Low and Light Crown plots as four random treatments. Thus the thinned Control plot could be compared with the unthinned Control plot and the two Low plots could be compared with the two Light Crown plots. Analysis was based on growth added to the trees since 1954. Basal area and volume increment of each tree for the period were computed in order to get the dependent variables. The 1954 diameter of each tree was used as an independent variable. In this way increment could be compared on the basis of the adjusted 1954 diameter. By using individual tree growth it was possible

to obtain a treatment variance. However, it was necessary to assume completely random treatments. This assumption seems valid and reasonable in the case of the Control plots, since the thinned Control plot was apparently not deliberately picked to be thinned.

The assumption is not valid in the case of the Low and Light Crown plots, because they were not selected completely at random within blocks. If the analysis were made on the basis of growth per block, and growth per treatment, the numbers of blocks and treatments would have been too small to give a precise test. Individual trees cannot be used, since there are a different number of trees on each plot. Despite these objections to the assumption of randomness, the method of covariance in a completely randomized experiment was used (Snedecor 1956).

A summary of the comparisons of cubic-foot volume and basal-area increment for the period from age 29 (1954) to age 40 (1964) is shown in Table 12.

Highly significant differences in both volume and basal-area increment were found between the two Control plots. Based on a common age 29 diameter, residual trees on the thinned Control plot had increased 9.50 ft^3 in volume and 0.202 ft^2 in basal area by age 40 as compared with 6.36 ft^3 and 0.092 ft^2 on the unthinned Control plot. This indicates that slash pines do respond to release even if this release is deferred until age 29.

The Low and Light Crown plots received a scheduled third thinning treatment in 1954. No cutting has taken place since that time. The

Table 12. Covariance analysis of tree volume and basal area increment, ages 29-40

Source of variation	d.f.	Volume (cu. ft.) Sum squares	Volume (cu. ft.) Mean square	Volume (cu. ft.) F	Basal area (sq. ft.) Sum squares	Basal area (sq. ft.) Mean square	Basal area (sq. ft.) F
					Thinned vs unthinned Control plot		
Thinned	37	308.184			0.1210		
Unthinned	80	483.616			.2105		
Within	117	791.800	6.7675		.3315	0.00283	
Regression coef.	1		10.4723	1.547		.0049	1.709
Common	118	802.272	6.7989		.3364	.00285	
Adj. mean	1		237.331	34.907**		.0820	28.771**
Total	119	1039.603			.4184		
					Low and Light Crown Plots		
Low East	53	526.260			.2171		
L. C. East	43	446.340			.1800		
Low West	50	369.859			.1854		
L. C. West	42	654.475			.2681		
Within	188	1988.934	10.5784		.8506	.00453	
Regression coef.	3	70.355	23.4517	2.217	.0090	.00298	0.658
Common	191	2059.289	10.7816		.8596	.00450	
Adj. mean	3	79.236	26.4121	2.450	<0	<0	<0
Total	194	2138.525			.8478		

comparison between these two treatments revealed no statistical differences in either basal-area or volume increment since the last thinning.

These comparisons considered only the growth on trees that were still present in 1964. Mortality and volume removed by thinning were not considered here.

Discussion of Volume and Diameter Increment

Prior to age 29 no real differences were found among treatments as far as basal-area and cubic-foot growth are concerned. Between age 13 and age 19 the unthinned plots produced more increment than the thinned plots, especially those receiving heavy thinning. As the trees increased in size and age, however, the increased diameter growth of the fewer trees on the more heavily thinned plots offset the lesser growth on the larger number of trees on the unthinned plots.

Plot increment could not be compared by statistical analysis after age 29. However, a comparison of the individual tree increments revealed that the trees on the plot thinned for the first time after age 29 made considerably more growth than those on the unthinned plot.

Although the differences in gross and net growth among the plots could not be compared statistically after age 29, it is quite apparent that such differences actually did exist (Table 6). In terms of gross volume growth the Low and Light Crown plots seemed to be slightly better than the Control plots and considerably better than the Heavy Crown and Selection plots. In terms of net volume growth the results were similar to gross growth, with one notable exception; the unthinned Control plot produced less net growth than any other plot.

With the exception of the East Heavy Crown plot, those plots that received three thinnings since age 13 produced more net volume growth than did those that had received less than three. Frequent light thinnings appear to be a good treatment to apply to slash pine plantations on such sites as were present here.

No single thinning treatment had an outstanding silvicultural advantage over the control, or over any other thinning treatment, at least so far as cubic-foot growth was concerned. Growth of individual trees was greater on plots that were more heavily thinned, but the overall net growth of the stands was little affected by the various treatments.

It is possible to explain this lack of silvicultural superiority in two ways. First, since this was a planted rather than a natural stand, the competition between trees did not start as early as it does in a natural stand. Trees were relatively evenly spaced so that no tree started receiving competition long before another; consequently the more vigorous trees were growing at their full capacity even before the aplication of the thinning treatment at age 13. Even the less vigorous trees that remained after thinning were probably growing at nearly full capacity; release merely kept their growth from slowing. Stand development after thinning was probably more affected by the first 13 years of the stand life (before treatment) than by the various thinning treatments.

A second reason for the failure of any treatment to show a clear-cut growth superiority could be that the range of thinning intensity was

too narrow, even though the Heavy Crown and Selection treatments were originally considered rather heavy thinnings. The effects of release depend not only on the number of trees removed, but on the amount of competition that the trees have been undergoing and on the length of time this competition has been in effect. There were considerable differences in the stocking on the plots before the treatments were put into effect, and these differences could well have confounded the effects of the treatments. As has been mentioned, one of the major problems with any thinning study is measuring the original stand density.

At first it seemed unfortunate when some of the plots were inadvertently cut in 1955. However, the comparative development of the two Control plots after this cut proved to be quite interesting. Many foresters believe that thinning in slash pine should not be delayed. Yet the East Control plot was thinned for the first time at age 30, and the residual trees on the thinned plot showed a significant increase in both basal-area and cubic-foot increment. Apparently, at least in this case, age 29 or age 30 is still not too late to get response from thinning slash pine. In fact, such response to thinning could well be more spectacular at these later ages, since the planted trees do not begin mutual competition as early as trees growing in natural stands. Trees cannot respond to release unless they are being affected by competition.

The results of this study are similar to the findings of McMinn (1963) and Bennett (1963b), which indicated that thinning of slash pine did not greatly increase the merchantable wood production in cubic feet.

Height Growth

The average height of the trees on each plot at each measurement age is shown in Table 13. The average height of the trees on plots receiving the various treatments were compared for age 13 and again for age 29. The data were analyzed as in a randomized block design and the results of this comparison are shown in Table 14. The differences in average heights among the treatments were found to be not statistically significant at age 13, before the application of the first treatment. By age 29, however, significant differences were found among the treatments. The Control plots had an average height that was slightly less (5.3 ft) than the average for all thinning treatments. This difference was statistically significant at the .05 probability level. The average height of the trees on the Heavy Crown plots was 12.5 ft greater than that of those trees on the Selection plots. This difference was highly significant statistically. No other statistically significant differences were found, although if the Heavy Crown plots had been tested against all others, the conclusion might have been different, since these plots have the greatest average height of all.

The height growth of the dominant trees has seldom been found to be affected by treatment, and this study was no exception. The average height of all trees, however, was affected by treatment, in this study. This could be because of the height of the trees removed in thinnings rather than from any growth stimulation received by the residual trees. That is, if short trees were cut, the average height would rise; and if tall trees were cut, the average height would be lowered, even if the residual trees maintained their current height-growth rate.

Table 13. Average height of trees at given ages before thinning (In feet)

Block	Plot Treatment	Average height at age of --					
		13	19	24	26	29	40
East	Control	36.1	49.6	56.0	--	65.2	83.7
West	Control	32.9	47.6	55.0	--	63.8	76.0
East	Low	40.8	54.4	61.8	--	69.1	89.2
West	Low	37.0	51.6	56.4	--	67.1	82.1
East	Light Crown	38.8	52.8	59.0	--	67.7	89.0
West	Light Crown	38.7	53.6	59.5	--	74.1	86.4
East	Heavy Crown	40.0	51.8	--	65.6	75.6	90.3
West	Heavy Crown	37.2	51.4	--	62.7	77.1	82.2
East	Selection	34.1	44.3	--	58.8	63.8	84.4
West	Selection	34.7	45.9	--	60.0	63.9	81.3

Table 14. Analyses of variance of height at ages 13 and 29

Source	d.f.	Sum squares	Mean square	F
		Age 13		
Total	9	60.92		
Block	1	8.65		
Treatment	4	44.48	11.120	5.708
Error	4	7.79	1.948	
		Age 29		
Total	9	234.34		
Block	1	2.11		
Treatment	4	209.75	52.437	9.331*
Control vs Thinned	1		44.944	7.997*
Low, L.C. vs. H.C.,S.	1		0.720	0.128
Low vs L.C.	1		7.840	1.395
H.C. vs S.	1		156.250	27.802**
Error	4	22.48	5.620	

It was difficult to study the height growth of all residual trees. However, the growth of several sample trees was examined. These trees were randomly selected from among those trees on each plot that survived to age 40. Using the height of each tree at age 13 as the independent variable and the height growth added to these trees by age 40 as the dependent variable, the adjusted mean growths among the plots were compared. No statistical differences in the regression of growth on initial height by age 40 were found (i.e., the regression lines were parallel), but differences in the adjusted mean growth did occur.

Since most plots had received different treatments by age 40, the data were analyzed as a completely random study with 10 different treatments. Differences between individual adjusted plot means were compared by the sequential method of testing, and trees on the East Selection plot were found to have made more height growth than any other plot except the West Selection and East Heavy Crown plots. This method of testing is likely to find more statistically significant differences than are actually present. Apparently the height growth of individual trees differs among the plots, but it is not clear from these results which, if any, treatment favors height growth.

As a further test the heights of these same trees at age 29 were compared. Since the original block design was still intact at that age, the plots were combined into treatments. Again the height at age 13 was used as the independent variable, but this time the height at age 29 served as the dependent variable. There was a statistically significant difference among the adjusted treatment means. Individual comparisons

indicated that trees on the Heavy Crown plots had a significantly greater adjusted mean height (75.9 ft) than any other treatment, while trees on the Low plot had a significantly shorter adjusted mean height (66.1 ft) than any other plot. Differences in adjusted mean height between the Light Crown (72.3 ft), Control (70.6 ft) and Selection (68.9 ft) plots were not so evident, although the difference between the Light Crown and the Low was statistically significant.

The statistical testing method used here is not perfect, but it seems quite evident that the two crown thinning plots resulted in greater average height at least up to age 29.

The height growth of trees between age 13 and age 29 was also examined. The data were analyzed by treatment, using height at age 13 as the independent variable and growth between age 13 and age 29 as the dependent variable. Statistically significant differences were found in the slope of the regression of growth on initial height. Only the Control and the Low treatments had regressions that were statistically different from zero, but the differences between these two were significant. On the Control plots the growth increased with the initial height, but on the Low plots growth decreased with initial height. On the other treatments the height growth was apparently independent of initial height. These results are somewhat confusing, but it must be remembered that the trees involved here are some of those that survived to age 40. On the Low plots the shortest trees were cut. The taller trees on these plots no doubt reached the point of growth culmination earlier than would the shorter trees. On the Control plots

these shorter trees would have been somewhat suppressed throughout their lives and consequently would make slower height growth.

It is clear from the results that average height is affected by cutting treatment. It is not clear that the height growth is affected. The samples studied are small and only trees that survived to age 40 were studied. Differences in height growth between age 13 and age 40 could be caused by differences in the type and size of trees left on the plots, by differences in competition, or by small differences in the site quality among the plots.

Financial Comparison of Treatments

Financial gain is a common advantage ascribed to thinning. Joergensen (1951) stated that the essential value of thinning lies in the financial benefits obtained; Hiley (1956) wrote, "It is by thinning, more than any other operation, that a forester can control the destiny of a plantation and contribute to its financial success." One advantage to thinning is that capital investment is reduced and rotations are shortened (Hiley 1930, 1956). Fedkiw and Yoho (1960) believed thinning should be dominated more by economic considerations than by silvicultural considerations. Craib (1947a) noted that, while light thinnings might yield as much or more volume than heavy thinnings, heavy thinnings yield almost twice as much money value because of the greater value of the merchantable products.

A study of the yield in value was made on these plots. A stumpage value of seven cents was assigned to each cubic foot of volume. This value was based on the assumption of 75.3 cubic feet of rough wood per

cord (Messavage 1947) and a stumpage price of $5.27 per cord. A cost of five cents was assigned to each tree cut in the thinnings to cover the cost of marking trees for sale. A compound interest rate of 4.5 percent annually was used to determine the 1964 (age 40) values of past thinnings.

An additional analysis was made that was similar to the one just described except that all trees 9.6 inches and larger were evaluated in terms of their Doyle-rule board-foot volume. The stumpage value for sawtimber was set at $35/M.B.F. Trees larger than 9.5 inches d.b.h. in each cut were considered as sawtimber trees which could be sold for their board-foot value. A summary of the results of both analyses is shown in Table 15.

On the basis of the value of the total cubic-foot volume presently on the plots, the most lightly thinned and the unthinned plots are the most valuable. This is also true when the sawtimber value is considered. However, when compounded values of the thinnings as pulpwood are added, the East Low has the greatest value, followed in order by the East Heavy Crown and the East Light Crown. On this basis the unthinned plot has the lowest value. If sawtimber values are considered, the net 1964 value of the East Low plot is still the greatest. However, the West Light Crown is second and the East Heavy Crown plot is third in order of value. The unthinned plot still had the lowest value.

Possibly the East Low plot has the highest present net value merely because its value in 1937 was the greatest. In order to make a more realistic comparison between plots, the margins for profit between (1) the

Table 15. Financial analysis of thinning treatments

	Control		Low		Light Crown		Heavy Crown		Selection	
	East	West	East	West	East	West	East	West	East	West
1. Pulpwood only[1]										
1937 value	$ 34.72	$ 28.21	$ 46.69	$ 29.96	$ 36.33	$ 33.46	$ 38.71	$ 31.01	$ 31.43	$ 29.33
1964 values of										
1st cut	0	0	26.95	5.78	21.08	15.42	43.13	27.44	46.31	39.22
2nd cut	0	0	33.48	23.74	30.84	29.58	38.10	33.97	27.94	28.19
3rd cut	58.73	0	20.76	20.08	18.98	26.48	16.38	0	19.02	0
present stand	73.92	98.49	103.18	84.63	92.33	90.51	68.11	76.72	62.16	72.38
1964 plot value	132.65	98.49	184.37	134.23	163.23	162.09	165.72	138.13	155.43	139.79
Margin above interest	18.70	5.90	37.72	40.13	49.12	56.99	38.67	36.36	52.28	43.53
2. Sawtimber and pulpwood[2]										
1964 values of										
1st cut	0	0	26.95	5.78	21.08	15.42	43.13	27.44	46.31	39.22
2nd cut	0	0	33.88	23.74	30.84	30.50	41.87	36.13	29.36	31.23
3rd cut	60.74	0	20.76	20.08	19.24	27.72	17.58	0	31.88	0
present stand	105.03	112.35	136.92	109.44	131.14	135.48	102.20	109.86	94.50	101.25
1964 plot value	165.77	112.35	218.51	159.04	202.30	209.82	204.78	173.43	192.05	171.70
Margin above interest	51.82	19.76	71.86	64.94	88.19	104.72	77.73	71.66	88.90	75.44

1/ All trees considered as pulpwood valued at $5.27/cord of 75.3 cu. ft.

2/ Trees less than 9.6" d.b.h. valued as in 1. Trees 9.6" and up valued as sawtimber at $35.00/ M.B.F. Doyle rule.

1964 value of the stands (cash value of standing timber plus value of thinnings compounded at 4.5 percent interest to 1964) and (2) the value of the plots in 1937, compounded to the present at 4.5 percent interest, were computed (Table 15). On this basis the West Light Crown plot gave the greatest margin both as pulpwood-only ($56.99), and as pulpwood and sawtimber combined ($104.72). This was followed in order by the East Selection and the East Light Crown plots. Again the unthinned plot was lowest.

It should be noted that all plots thinned at age 29 yielded more in terms of margin than did the plots of similar prior treatment that were not thinned during that year. This seems to indicate that a thinning at age 29 is desirable.

In general this analysis indicates that thinning will yield a greater margin than will not thinning and that a light crown thinning will yield more than a light low thinning, especially if one of the desired products is sawtimber. In this study, at least, the Light Crown and Selection plots gave a consistently greater profit margin than any of the other plots. The Low plots may be slightly favored over the Heavy Crown plots in terms of pulpwood only, but the Heavy Crown plots are favored if sawtimber values are considered.

The comparison between the thinned and unthinned Control plots is especially noteworthy. The results indicate that the financial yields are better from a thinned stand than from an unthinned stand, even when the first thinning is deferred until age 29.

Crown Development

Thinning has been shown to influence the development of tree crowns, which in turn affects tree growth. Both live-crown ratio and crown width prior to thinning loblolly pine have been shown to be correlated with the increase in basal area after release (MacKinney 1933). A relationship among crown width, tree diameter, and stocking has been established in stands of Douglas fir, balsam fir, and white spruce (Smith 1963, Smith and Bailey 1964, Vezina 1962, 1963a). The variation in the live-crown ratio of northern red oak with changes in stand density has also been established (Ward 1964). Changes in the relationship between crown development and diameter have been used as expressions of stand density (Krajicek and Brinkman 1957). Deetlefs (1954) found that the growth in basal area in loblolly pine stands increases directly with the crown-surface area.

Bennett (1955a, b) found that the diameter growth of slash pine was reduced if the crown ratio was reduced to less than 50 percent. He reported that the crown ratio is highly correlated with the number of trees per acre (Bennett 1960a). Many others have described the influence of crown development on growth (Weck 1944, Warrack 1959, Bowen 1964, Badoux 1946, and others).

Stoeckeler and Olsen (1957) found that the diameter growth rate of jack pine was strongly correlated to the ratio of live-crown length to total height. Bowen (1964) found that the live-crown length and initial tree-d.b.h. were good indicators of the growth of red spruce (Picea rubens Sarg.).

Smith and Dubow (1960) found that crown length was better than live-crown ratio for predicting diameter growth of loblolly pine. They believed that the ratio of crown length to total height is not a satisfactory index.

Volume growth was compared with both live-crown ratio and live-crown length in this study. It was first assumed that such growth would depend, in part, on the diameter of the trees at the beginning of a growth period as well as on crown measurements. Therefore, volume increment was tested against initial diameter and the initial crown measurements.

As was expected, growth was strongly correlated with initial diameter; in fact, this correlation was so strong that it overshadowed most of the effect that might be due to variation in the crown parameters. It was decided that it would be necessary to drop the initial diameters from the data if the true effect of the crown parameters was to be found.

For this final analysis the linear and quadratic effects of both crown length and crown ratio on the cubic-foot volume growth between the application of thinning treatments were studied. Only those trees that survived from one treatment to the next were used in this analysis. Regression equations, using data from the Control plots, were computed for the growth periods between ages 13 and 19, 13 and 24, and 13 and 29. Equations, using data from the Low and Light Crown plots, were computed for the periods between ages 13 and 19, 13 and 24, 24 and 29, and 29 and 40. Equations, using data from the Heavy Crown and Selection plots, were computed for the periods between ages 13 and 19, 13 and 26, 26 and 29, and 29 and 40. Because one of the Control plots was cut after age 29,

the growth on each plot was analyzed separately for the period between ages 29 and 40. The results of these analyses are shown in Table 16.

A linear and a quadratic equation using either crown length or crown ratio as independent variables were computed for each combination of treatment and time period. However, in no case was the quadratic equation an improvement over the linear one, so only the linear equations are shown. Apparently both crown length and crown ratio have a linear relationship with volume increment.

An examination of the coefficients of determination (r^2 in Table 16) led to two conclusions. Quite clearly, first of all, more of the variation in volume growth can be explained by crown length than by crown ratio. In every case the higher r^2 value is for the equation that used crown length. In fact, the growth after age 29 on the Heavy Crown plots, and during most of the time periods on the Selection plots, showed no effect due to crown ratio.

The second conclusion was that in no case do the crown lengths show a great effect on volume growth. The best equation (Control plots, age 13 to 19) accounted for only 33 percent of the variation in volume increment although the regression coefficient was statistically highly significant in each case.

Even though little of the variation in volume increment was accounted for by the initial crown length, it was felt that further study of differences among the different treatments might be useful. Live-crown length accounted for more increment variation on the Control plots than on any of the thinned plots, although the differences were not

Table 16. Regression coefficients from the equations of volume increment as a function of crown length and crown ratio

Age	Treatment	Initial Mean crown length (Feet)	Initial Mean crown ratio	Mean increment (Cu. ft.)	Regression coefficient: Crown length	Regression coefficient: Crown ratio	Constant	r^2	Basis: number of trees
13-19	Control	14.93		2.308	0.22986**		-1.12407	0.331	305
13-19			0.427			6.74620**	-0.55140	.142	305
13-24	Control	15.20		4.709	.53106**		-3.36287	.298	281
13-24			.427			15.30871**	-1.82708	.136	281
13-29	Control	15.44		7.498	.92669**		-6.81332	.273	232
13-29			.430			25.53861**	-3.49416	.124	232
29-40	Uncut	16.67		5.460	.63337**		-5.09917	.353	82
29-40	Control		.253			39.80903**	-4.59595	.212	82
29-40	Cut	18.41		11.373	.40944**		3.83516	.282	39
29-40	Control		.251			28.18232**	4.30455	.187	39
13-19	Low	18.32		2.977	.10975**		0.96543	.094	238
13-19			.452			3.76563	1.27544	.060	238
13-24	Low	18.33		5.199	.19502**		1.62385	.087	233
13-24			.452			3.65344*	3.54567	.017	233
24-29	Low	17.01		3.021	.12189**		0.94841	.078	150
24-29			.277			6.21829**	1.29648	.045	150
29-40	Low	18.46		10.883	.67521**		-1.62960	.292	107
29-40			.267			38.64153**	0.52245	.156	107

Table 16. Continued

Age	Treatment	Initial: Mean crown length	Initial: Mean crown ratio	Mean increment	Regression coefficient: Crown length	Regression coefficient: Crown ratio	Constant	r^2	Basis: number of trees
		Feet		Cu. ft.					
13-19	Light Crown	19.24		3.336	0.22500**		-0.99354	0.323	212
13-19			0.481			7.30946**	-0.17686	.139	212
13-24	Light Crown	19.22		5.935	.46248**		-2.95570	.317	205
13-24			.480			14.80411**	-1.17592	.129	205
24-29	Light Crown	18.46		4.209	.31821**		-1.66427	.203	140
24-29			.301			17.76155**	-1.13245	.120	140
29-40	Light Crown	21.97		12.218	.51232**		0.96450	.204	89
29-40			.296			48.47172**	-2.11216	.156	89
13-19	Heavy Crown	15.88		3.138	.18207**		0.24656	.245	140
13-19			.399			5.50636**	0.94162	.104	140
13-26	Heavy Crown	15.94		8.790	.46336**		1.40427	.194	133
13-26			.400			11.35567**	4.24856	.055	133
26-29	Heavy Crown	19.96		4.361	.18974**		0.57275	.181	84
26-29			.306			10.04610**	1.28537	.092	84
29-40	Heavy Crown	25.13		10.595	.36737**		1.36458	.093	71
29-40			.324			14.91434^ns	5.76543	.017	71

Table 16. Continued

Age	Treatment	Initial: Mean crown length	Initial: Mean crown ratio	Mean increment	Regression coefficient: Crown length	Regression coefficient: Crown ratio	Constant	r^2	Basis: number of trees
		Feet		Cu. ft.					
13-19	Selection	14.18		2.624	0.16816**		0.23961	0.197	151
13-19			0.416			1.34649**	2.06377	.007	151
13-26	Selection	14.24		8.312	.53717**		0.66282	.237	138
13-26			.414			7.75375^{ns}	5.10522	.026	138
26-29	Selection	20.35		2.612	.18136**		-1.07794	.303	92
26-29			.337			10.74184**	-1.01243	.163	92
29-40	Selection	18.61		12.727	.25254**		8.02864	.108	71
29-40			.281			11.53837^{ns}	9.48360	.045	71

ns - Not significant

great. Crown lengths of the trees on the Low plots accounted for almost none of the variation in growth until after age 29. On the Light Crown plots the crown lengths were relatively important at all age periods, although the greatest effect was following the first thinning at age 13. On the Heavy Crown plots the initial crown length decreased in importance as the age increased. There seem to be no clear relationships between the effects of crown length and the treatment applied. This is not surprising when one considers that the best regression found between growth and crown length only accounted for 33 percent of the variation in growth. It can only be concluded that, at least for this study, initial crown length has little effect on subsequent growth.

Only those trees that survived from the start of a growth period to the end of that period were considered in the foregoing analysis. It will be shown in the section on mortality that trees whose crown length and crown ratios are considerably below the average for the stand are the trees that do not survive. Apparently, the length of crown might be more useful for predicting potential mortality than for predicting future growth.

A comparison of crown development between treatments was also made. Covariance analysis was used to see if any of the difference in crown ratio, or crown length, could be attributed to differences in plot treatment. For purpose of this analysis the original crown length or crown ratio was used as the independent variable, and the crown length or crown ratio by the time of the next thinning was used for the dependent variable. In this way changes in crown could be compared to an adjusted-mean-crown measurement common to all plots. Plots of the Control, Low,

and Light Crown treatments were compared over the period from before the first thinning at age 13 to just before the second thinning at age 24, and over the period from age 24 to the time of the third thinning at age 29. The Low and Light Crown plots were compared over the period from age 29 to age 40. The Heavy Crown and Selection plots were compared over the period from age 13 to age 26, and from age 26 to age 29.

Statistical comparisons between the crown lengths and crown ratios on the various plots are shown in Tables 17, 18, and 19, and average crown lengths and ratios are shown in Table 20. No differences were found in the crown ratios on the Control, Low, or Light Crown plots during the period between age 13 and age 24, but all ratios were reduced by age 24. Crown lengths were also reduced on these plots during this period, although on the Control plots the crowns that were longer than 16 ft were reduced less than similar lengths on either of the thinned plots (Table 20). The lengths on the Low plots showed the most reduction.

Crown ratios on the Heavy Crown and Selection plots were reduced between age 13 and age 26 if the age 13 crown ratio was greater than 0.30; the Heavy Crown showed more reduction than the Selection plots. For ratios less than 0.30 both treatments showed an increase by age 26, with the Selection plots showing more increase than the Heavy Crown. There were no statistically significant differences in crown length between these treatments and all lengths had increased by age 26.

Following the second thinning at age 24, the crown ratio on the Control plots continued to decrease as before, and by age 29 the crown ratios on these plots were smaller than on any of the others. There was

Table 17. Covariance analyses of crown ratios by periods, ages 13-29

Treatment	d.f.	Sum squares	Mean square	F	Reg. coef.
			Ages 13-24		
Control	303	2.549			
Low	236	2.116			
Light Crown	210	1.309			
Within	749	5.974	.00798		
Reg. coef.	2	0.013	.00624	0.782	
Common	751	5.986	.00797		
Adj. mean	2	.014	.00722	.905	0.29599
Total	753	6.000			
			Ages 13-26		
Heavy Crown	138	1.203			.20986
Selection	149	2.354			-.07966
Within	287	3.558	.01240		
Reg. coef.	1		.03601	2.905*	
Common	288	3.594			
			Ages 24-29		
Control	147	3.907			
Low	138	.302			
Light Crown	230	.357			
Within	515	4.566	.00887		
Reg. coef.	2	.016	.00815	.036	.37360
Common	517	4.582	.00886		
Adj. mean	2	.458	.22841	25.770**	
Total	519	5.040			
			Ages 26-29		
Heavy Crown	81	.168			
Selection	90	.733			
Within	171	.901	.00527		
Reg. coef.	1		.00718	1.362	.436244
Common	172	.908	.00528		
Adj. mean	1		.09425	17.848**	
Total	173	1.003			

Table 18. Covariance analyses of crown lengths by periods, ages 13-29

Treatment	d.f.	Sum squares	Mean square	F	Reg. coef.
			Ages 13-24		
Control	303	8650.755			0.93824
Low	236	5169.648			.23524
Light Crown	210	4600.081			.48332
Within	749	18420.484	24.593		
Reg. coef.	2	771.584	385.792	15.686**	
Common	751	19192.068			
			Ages 13-26		
Heavy Crown	138	5768.675			
Selection	140	8165.115			
Within	287	13933.790	48.549		
Reg. coef.	1	.226	.226	0.005	
Common	288	13934.016	48.382		
Adj. mean	1		60.569	1.252	
Total	289	13994.585			.52851
			Ages 24-29		
Control	230	15471.888			.84366
Low	147	1713.309			.37866
Light Crown	138	3237.069			.65671
Within	515	20422.266	39.655		
Reg. coef.	2	283.921	141.961	3.580*	
Common	517	20706.187			
			Ages 26-29		
Heavy Crown	81	1577.559			
Selection	90	3138.006			
Within	171	4715.565	27.576		
Reg. coef.	1		69.696	2.527	.61246
Common	172	4785.261	27.821		—
Adj. mean	1		1743.679	62.675**	
Total	173	6528.940			

Table 19. Covariance analyses of crown lengths and ratios, ages 29-40

Treatment	d.f.	Sum squares	Mean square	F	Reg. coef.
			Crown length		
Low	105	1594.000			
Light Crown	87	1424.382			
Within	192	3018.382	15.720		
Reg. coef.	1	7.413	7.413	0.470	
Common	193	3025.795	15.677		
Adj. mean	1		1.641	.104	0.632428
Total	194	3028.436			
Cut Control	37	711.655			.37462
Uncut Control	80	1800.975			.72285
Within	117	2512.630	21.475		
Reg. coef.	1		110.793	5.159*	
Common	118	2623.423			
			Crown ratio		
Low	105	.16629			
Light Crown	87	.13794			
Within	192	.30423	.00158		
Reg. coef.	1	.00002	.00002	.026	
Common	193	.30425	.00158		
Adj. mean	1	.00001	.00001	.006	
Total	194	.30425			.42216
Cut Control	37	.06887			
Uncut Control	80	.23162			
Within	117	.30049	.00257		
Reg. coef.	1		.00685	2.665	.32882
Common	118	.30733	.00260		
Adj. mean	1		.04949	19.006**	
Total	119	.35683			

Table 20. Average crown length and crown ratio by treatment and periods

Treatment	Age 13 crown Length Feet	Age 13 crown Ratio	Age 24 crown Length Feet	Age 24 crown Ratio	Age 26 crown Length Feet	Age 26 crown Ratio	Age 29 crown Length Feet	Age 29 crown Ratio	Age 40 crown Length Feet	Age 40 crown Ratio
Uncut Control										
Before cut 1/	14.60	0.423	14.71	0.262	--	--	14.19	0.212	16.60	0.215
After cut 2/	14.93	.424	16.79	.291	--	--	16.67	.253		
Low										
Before cut 1/	17.18	.440	15.59	.265	--	--	17.87	.262	21.94	.255
After cut 2/	18.32	.452	16.96	.277	--	--	18.46	.267		
Light Crown										
Before cut 1/	18.22	.471	17.05	.285	--	--	20.10	.279	23.58	.267
After cut 2/	19.24	.481	18.46	.301	--	--	21.97	.296		
Heavy Crown										
Before cut 1/	14.72	.379	--	--	18.62	0.288	24.27	.316	23.96	.278
After cut 2/	15.88	.399	--	--	19.96	.305	25.13	.324		
Selection										
Before cut 1/	14.20	.413	--	--	18.61	.313	18.17	.282	25.35	.306
After cut 2/	14.18	.416	--	--	20.35	.337	18.61	.281		
Cut Control										
Before cut 1/	--	--	--	--	--	--	14.19	.212	22.29	.257
After cut 2/	--	--	--	--	--	--	18.41	.251		

1/ Measurement of all trees present at measurement time

2/ Measurement of trees that survived to next measurement

little difference found between the Low and Light Crown plots in the way in which the ratios changed over this period. Ratios greater than 0.25 at age 24 had decreased by age 29, although the decrease was not as great as that on the Control plots. Crown lengths that were less than 19 ft on the Low and less than 22 ft on the Light Crown at age 24 had increased by age 29, with the Light Crown plots having the longest crowns at age 29.

By age 29 the crown lengths of the Heavy Crown plots were greater than on any other treatment. All crown lengths increased on these plots after thinning at age 26. During this same period crowns on the Selection plots were reduced in length. Crown ratios on the Heavy Crown plots decreased slightly if the age 26 ratio was greater than 0.3. Crown ratios greater than 0.24 on the Selection plots had decreased by age 29, so that there was little difference between the ratios on this treatment and those of the Low and Light Crown treatments.

Clearly, differences in treatment resulted in differences in crown development. Unthinned plots consistently showed decreasing crown lengths and ratios. Trees on the Heavy Crown plots actually increased in crown length, although the crown ratios decreased slightly. In general thinning resulted in larger crowns, although the Heavy Crown thinning was the only method tried that developed significantly larger crowns. Smaller crowns were more affected by release than large ones, and most trees that had crown ratios greater than 0.3 at time of thinning showed little effect from this release.

Czarnowski (1961) used the live-crown ratio as an index of crowding in loblolly pine. He found that the value of this ratio was between 0.30 and 0.35, or about 1/3, for fully stocked stands having a "normal" number of trees. Ratios greater than about 1/3 would indicate understocking (in terms of number of trees) and ratios less than 1/3 would indicate overstocking. This ratio of 1/3 is very close to the value of 0.3 that was found to be significant in this study. This seems to indicate that ratios greater than 0.3 indicate understocked stands with a minimum amount of competition, while ratios less than 0.3 indicate considerable amounts of competition within the stands.

The increment equations (Table 16) indicated that neither initial crown length nor crown ratio had an appreciable effect on subsequent growth of the trees. Yet crown length, crown ratio, and growth were affected by treatment. It was concluded, therefore, that most of the crowns on most of the trees were large enough to survive and to respond to treatment. When the trees were released they responded by increasing in diameter and in height. Crown lengths responded by either increasing or decreasing as room permitted. By age 40 there was little difference in the average lengths of the crowns on any of the thinned plots. Only on the unthinned Control were the crowns much shorter. It seems likely that subsequent growth of the trees that survive on this plot will be little affected by their present crown length. Mortality will be higher on this plot, however, since more of the crowns must be approaching the minimum length that allows for survival. Unfortunately, as will be shown, just what this minimum length may be is not known.

In conclusion, there seems little reason for choosing to leave rather than cut a tree on the basis of its crown length or ratio unless the crown is so small that survival is unlikely. Crown lengths tend to increase with age and so the minimum length for survival must also increase with age. Judging from the results on the Control plots, trees whose crowns are less than 16 feet long by age 29 are unlikely to live until age 40. The growth of those trees that do survive seems to depend far more on factors other than the size of their crown.

Although growth was only slightly affected by crown length or crown ratio, the regressions, where significant, were positive. That is, trees with longer crowns made slightly more growth. However, the fact that crown length was more important to growth than was crown ratio indicates that the longer crowns were on taller trees (i.e., total height increased as crown length increased). Since height is strongly correlated with diameter, and since growth in both diameter and volume is correlated with initial diameter, all that is really shown by the crown-length effects is that larger trees at a given age tend to grow more than small trees at that same age.

Mortality

Only an incomplete record of mortality causes was available. The number of trees lost to mortality on each plot had been recorded, and a test was made to see if mortality was significantly different on plots receiving different treatments.

The hypothesis that mortality was independent of thinning treatment was tested using a chi-square test. Chi-square was computed by a method described by Snedecor (1956) where:

$$\chi^2 = (\sum p_i\ x_i - \bar{p} \sum x_i) / \bar{p}\bar{q}$$

p_i = proportion of total trees on the i^{th} plot that died (and were not salvaged) by 1954

x_i = number of trees that died in the i^{th} plot

$\bar{p}$ = $\sum x_i / n$

$\bar{q}$ = $1 - \bar{p}$

n = total number of trees on all treatments in 1937-38.

A summary of the mortality is shown in Table 21, and the computed chi-square values for each comparison are shown in Table 22. The unthinned plots had significantly higher mortality than any of the thinned plots. No real differences were found among the thinned plots that could be attributed to differences between the thinning treatments. Apparently most of the prospective mortality was salvaged by even the lightest of the thinning treatments.

The principal cause of mortality has no doubt been fusiform rust. This is especially true on the thinned plots. The East Low plot also suffered some mortality from a lightning strike in 1953. Only on the Control plots has there been much mortality due only to suppression. It is difficult to tell if the prevalence of fusiform rust is worse for any of the various treatments, since many of the trees removed in the

Table 21. Number of dead trees by periods

	Control		Low		Light Crown		Heavy Crown		Selection	
	East	West	East	West	East	West	East	West	East	West
Age 13-19										
Total trees	167	155	199	142	167	139	151	123	172	148
Dead trees	14	3	2	0	3	0	2	2	1	6
Treatment total	322		341		306		274		320	
Treatment dead	17		2		3		4		7	
Age 19-24										
Total trees	153	152	125	113	112	100	--	--	--	--
Dead trees	11	13	6	0	3	4	--	--	--	--
Treatment total	305		238		212		--		--	
Treatment dead	24		6		7		--		--	
Age 19-26										
Total trees	153	152	--	--	--	--	73	67	78	73
Dead trees	20	22	--	--	--	--	5	2	8	5
Treatment total	305		--		--		140		151	
Treatment dead	42		--		--		7		13	
Age 24-29										
Total trees	142	139	120	113	109	96	--	--	--	--
Dead trees	25	24	5	4	5	1	--	--	--	--
Treatment total	281		233		205		--		--	
Treatment dead	49		9		6		--		--	

Table 21. Continued

	Control		Low		Light Crown		Heavy Crown		Selection	
	East	West	East	West	East	West	East	West	East	West
					Age 26-29					
Total trees	133	130	--	--	--	--	68	65	70	68
Dead trees	16	15	--	--	--	--	0	1	1	1
Treatment total	265		--		--		133		138	
Treatment dead	31		--		--		1		2	
					Age 13-29					
Total trees	167	155	199	142	167	139	151	123	172	148
Dead trees	50	40	13	4	11	5	7	5	10	12
Treatment total	322		341		306		274		320	
Treatment dead	90		17		16		12		22	

Table 22. Statistical analysis of mortality, age 13-29

Item	Control		Low		Light Crown		Heavy Crown		Selection	
	East	West	East	West	East	West	East	West	East	West
Number dead trees[1]	50	40	13	4	11	5	7	5	10	12
Total number trees[2]	167	155	199	142	167	139	151	123	172	148
Mortality ratio	.2994	.2581	.0653	.0282	.0659	.0360	.0464	.0407	.0581	.0811

Comparison	Degrees of freedom	Chi-square
Among plots	9	149.251**
Thinned vs. unthinned	1	144.046**
Low and Light Crown vs. Heavy Crown and Selection	1	0.192
Low vs. Light Crown	1	0.043
Heavy Crown vs. Selection	1	1.75
Control vs. Low and Light Crown ages 13-24	1	37.184**
Control vs. Heavy Crown and Selection ages 13-26	1	40.517**
Low vs. Light Crown ages 13-24	1	0.54
Heavy Crown vs. Selection ages 13-26	1	1.473

1/ Number of trees that died and were not salvaged

2/ Total number of trees at age 13

various thinnings were infected at the time they were cut. Plate 1 shows an example of mortality caused by fusiform rust.

An attempt was made to determine the characteristics of the trees that died from causes other than fusiform rust, wind, and lightning. Only the unthinned plots were considered for this phase of the study since only these plots had significant amounts of mortality. The records of all trees that died and were not salvaged on these plots were examined and divided into causal classes. The diameter, height, and clear length of these trees at the time of their last living measurement were noted. The averages of these measurements for the trees whose mortality cause was neither disease, wind, or lightning are listed by time period in Table 23.

In every case the average diameter, height, and live-crown ratio of these trees are considerably less than the average for all trees on these plots. No statistical test is necessary here to point out these differences. It is apparent that trees much smaller than average in height, diameter, or live-crown ratio are poor risks to leave. Nearly all such trees were removed in the treatments of the thinned plots, and consequently the mortality on the treated plots was less than that of the controls.

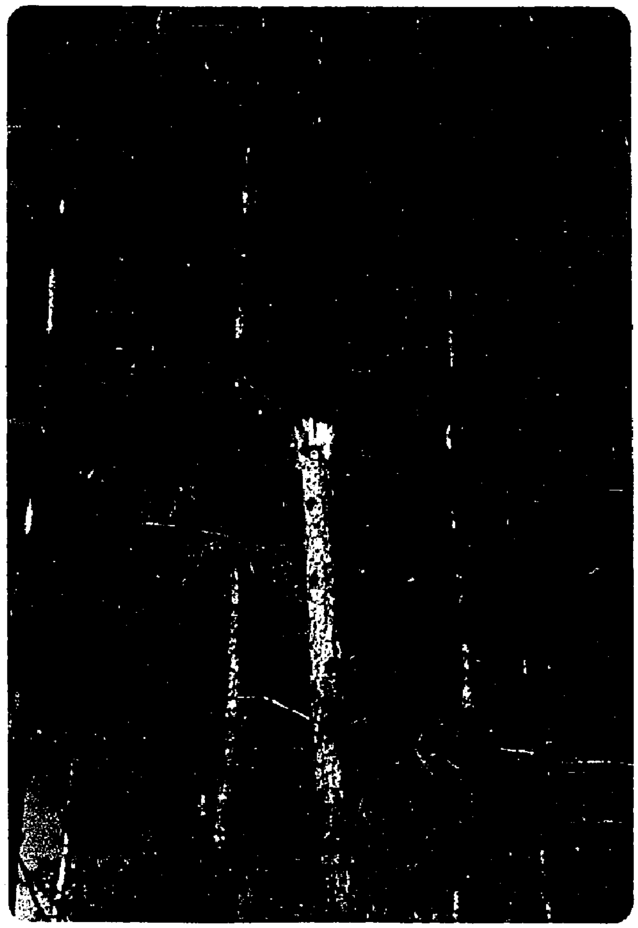


Plate 1. An example of mortality indirectly caused by fusiform rust on a 40-year old slash pine. The tree broke off at the rust canker during a wind storm.

Table 23. Characteristics of trees which died from unknown causes on the unthinned plots

	Diameter	Total height	Live-crown length	Live-crown ratio
	Inches	Feet	Feet	
		Age 13		
Plot average	5.38	34.6	14.6	0.423
Mortality avg.	2.52	21.8	8.4	.385
		Age 19		
Plot avg.	6.27	48.6	15.7	.323
Mortality avg.	4.15	38.3	9.2	.240
		Age 24		
Plot avg.	7.14	55.5	16.0	.288
Mortality avg.	4.92	43.2	9.4	.218
		Age 29		
Plot avg.	7.67	63.8	15.8	.247
Mortality avg.	5.88	56.6	10.8	.191

DEVELOPING A COMPETITION INDEX

One of the greatest impediments to thinning research is the large area which must be provided for the various treatments. For this reason most thinning studies have an inadequate number of replications with which to compare treatments. Another impediment is the difficulty of defining a range of thinning regimes by mathematical functions suitable for statistical analyses (Dawkins 1960). Osborne (1939) has suggested that the first impediment may be overcome by using individual trees rather than stands as units of study. Regression techniques may be used to compare the development of individual trees that have received particular amounts of release by thinning. If individual tree measurements are used rather than stand measurements, much more information can be learned with less involvement of stands and land area. Thinning studies are usually more concerned with differences in degree of thinning rather than in kind of thinning, and individual tree measurements lend themselves to this type of study (Smith 1959).

Defining the Degree of Thinning

Probably the main reason that thinning studies have more often been concerned with stands than with single trees is the difficulty, already mentioned, of defining the degree of thinning. Wicht (1948) felt that thinning degree could be expressed in terms of stems per acre. Hummel replied in this same article that experience in Great Britain has shown that the number of stems per acre is a suitable variable for

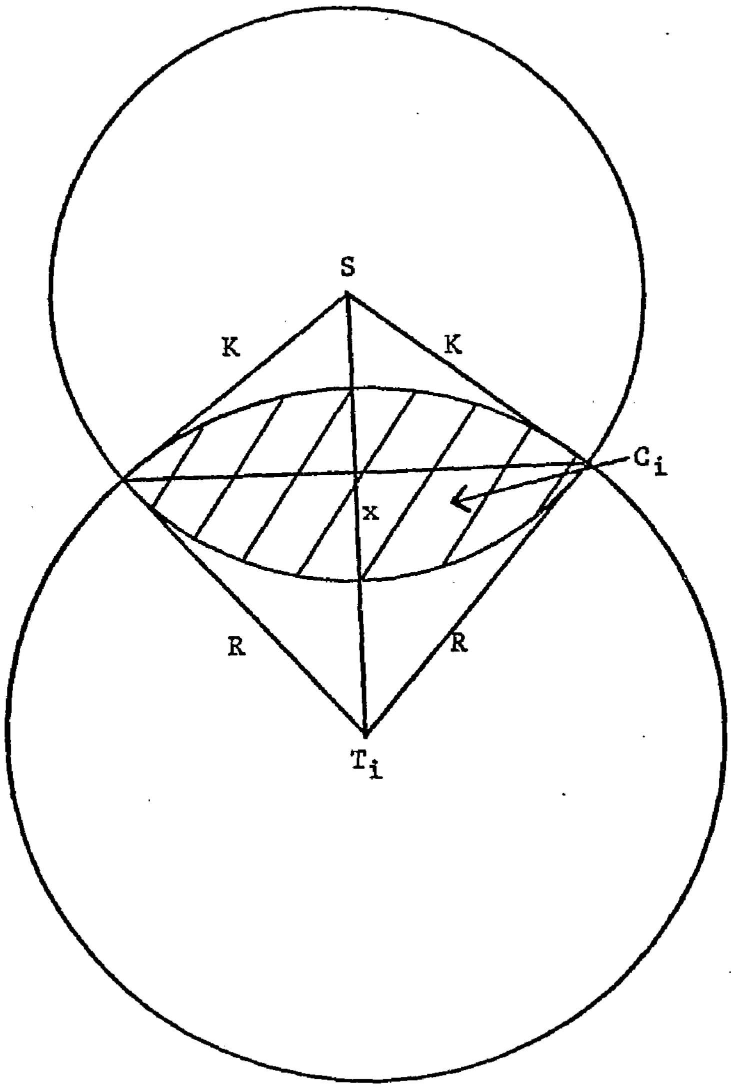
experiments designed to find the most suitable height or age at which to start thinning. However, in experiments where thinning is started on all plots at the same age and differs only in severity, such a measure is not as good as an index of stand density which considers mean basal area and height as well as the number of stems. Worthington et al. (1962) tried to measure thinning intensity with a specified stand-density index but found this was not satisfactory since cutting was not uniformly distributed over the entire range of tree diameters. Johnston and Waters (1961) stated that it is impossible to give a definition of a thinning grade which can be widely applied both qualitatively and quantitatively. Wicht (1936) and Vezina (1962) have both mentioned the need for research to find a measure of stand density.

A major part of this study was concerned with finding some measure of stand density, or of thinning intensity, that could be objectively applied to individual trees within a stand. It was felt that if the competition an individual tree was receiving from surrounding trees could be objectively measured, then the degree of thinning could be measured by determining the reduction in this competition following the thinning. Such a measure of competition would be a measure of stand density if it could describe the degree of crowding of individual trees within the portion of the area actually stocked with trees (Smith and Bailey 1964).

surrounds it. That is, its crown shades a certain area and its roots occupy a certain area. The combined area influenced by a tree can be called its "circle of influence" (Zinke 1962). It seems reasonable to assume that this area approximates a circle, since both roots and limbs if not impeded tend to grow away from the tree at nearly an even rate in all directions. The circular area might be more elliptical where the ground slopes considerably, and the area might take an entirely different shape where there are abrupt and significant changes in soil, site, or climate.

Development of an Equation for a Competition Index

Where the site has little slope and there is no great variability in soil conditions, it is assumed that each tree has influence over a circular area. The radius of this circular area varies in size according to the over-all size of the tree. A zone of competition exists wherever two of these areas overlap, and the effect of this competition on either of the trees, at the center of the influence circles, is theoretically proportional to the ratio of the area of the competition zone to the area of either circle of influence (Figure 6). The amount of competition received by any one tree from a single neighbor depends on the size of the individual (which determines the size of its circle of influence) and on the portion of this area that is overlapped by the neighbor's circle of influence. If the individual's entire circle is overlapped, then the competition received will be unity. If no overlapping takes place, the amount of competition received will be defined as zero. The



C_i = Zone of Competition

S = Sample Tree

T_i = i^{th} competing Tree

K = Radius of Circle of Influence for S

R = Radius of Circle of Influence for T_i

x = Distance between S and T_i

Figure 6. The zone of competition between two trees.

size of the competition zone will vary according to the relative sizes of the two overlapping circles and the horizontal distance between their axes.

If a tree has its circle of influence overlapped by the circles of several other trees, then the amount of competition it receives will be equal to the sum of the ratios of the areas of all the competition zones to the area of the circle of influence of that individual tree. This total competition or competition index may be defined as:

$$I = \sum_{i=1}^{n} C_i / K^2 \pi$$

where:

I = the competition index

K = the radius of the influence circle of the sample tree that receives the competition

C_i = the area of the zone of competition caused by the overlap with the i^{th} competing tree's influence circle.

The area of each C_i can be computed by using the equation:

$$C_i = K^2 \arctan [U/(x_i^2 + B)] + R_i^2 \arctan [U/(x_i^2 - B)] - U/2$$

where:

R_i = the radius of the influence circle of the i^{th} tree providing the competition,

x_i = the horizontal distance between the sample tree and the i^{th} competing tree,

$B = K^2 - R_i^2$

$U = [x^2 (2A - x^2) - B^2]^{\frac{1}{2}}$

$A = K^2 + R_i^2$, and

$i = 1, 2, 3, \ldots n$

Competition Exerted Upon a Forest Tree

The growth rate of a single tree is greatly influenced by the amount of space available to the tree. Maximum diameter growth occurs when crowns and roots are not confined (Gingrich 1965). This fact formed the basis for the "competition index" developed in this study. Two basic premises were proposed. The first was that the growth made by an individual tree in a pure, even-aged stand depends on size of the individual tree relative to the sizes of the trees surrounding that individual. In other words, large trees in such stands would likely grow more and receive less competition than small trees. The second premise was that the growth rate of a given individual tree will vary directly with the horizontal distances between the individual tree and its neighbors. Presumably each tree neighboring any individual tree would have a certain effect on the growth and development of that individual tree. If an open-grown tree of a given species on a given site has a particular pattern of growth that can be defined by some curve of growth plotted over time, then this curve will be modified by the proximity of other trees. The purpose of thinning is to control this modification in the growth of trees by making adjustments in the number of adjacent or competing trees.

The Circle of Influence of a Tree

This modification in growth is the result of competition forces exerted by adjacent trees in their mutual struggle for water, light, and nutrients. Each tree influences a certain amount of the area that

The derivation of the equation for C_i is given in Appendix C along with an example for calculating a particular index value.

Newnham's Study of Competition in Douglas-fir

This method of measuring competition is similar to one developed by Newnham (1964). Newnham used the horizontal projection of the crown to determine an area that corresponds to the "circle of influence" described above. When the crown area of a competing tree overlapped that of the sample tree, he measured competition by determining the length along the circumference of the sample tree crown that was overlapped. In this way the measure of overlap was weighted by the ratio of the crown width of the competing tree to the crown width of the sample tree. Crown width was related to d.b.h. of the tree.

Importance of Root Competition

Newnham's method seems to work quite well with Douglas-fir. In the slash pine stands dealt with in this study, some other method seems to be needed. There is little overlapping of crowns in these stands (see Appendix D), and in many cases the crowns of adjacent trees do not even touch. Yet differences in diameter growth suggest the presence of competition between individuals. It was decided that a tree some distance from the sample tree could still be actively competing with that tree, even though the crowns of the two trees did not touch. Since light is only one of the necessary requirements for growth, it was assumed that root competition might be even more important than competition for light in these stands.

One of the earliest studies of the effect of competition on growth of individual southern pine trees was carried out by MacKinney (1933). MacKinney found no satisfactory method for measuring the effects of different degrees of release on the growth of loblolly pine trees having the same characteristics of size and crown development. He noted the number and size of competing trees in 10-ft zones out to 30 ft from his sample trees. Much to his surprise he discovered that competing trees in the outer zones had more effect on the basal-area growth of sample trees than those within 10 ft of the sample trees. He also found that the removal of competing trees from the 20-ft zone had more effect on growth than did the removal of trees from either the 10-ft or 30-ft zone. These results certainly suggest the presence of competition other than that from the crowns of adjacent trees. MacKinney ignored these results and concluded: (1) important variables were not considered, (2) the relationships were curvilinear, (3) there was a joint relationship, or (4) the relationship was both joint and curvilinear.

Recent work with radioactive isotopes has given new insight into the horizontal distance tree roots extend (Hough et al. 1965; Pritchett and Robertson 1960; Curtis 1964).

Many articles have indicated the importance of soil water to growing trees. Moyle and Zahner (1954) concluded that lack of soil moisture, which occurs nearly every year in southern Arkansas, undoubtedly limits tree growth. Korstian and Coile (1938) showed that competition for soil moisture between individual components of a stand

is a highly significant factor in the growth, development, and regeneration of trees in the Piedmont Plateau. Chapman and Bulchis (1940) stated that the distance longleaf pine roots could spread from the tree's bole is the factor that finally limits increases in growth rate. Bassett (1964) suggested that increased growth following thinning in stands of loblolly pine resulted from water reserves left in the soil when trees with large root systems had been cut. Larson (1957) and Smith and Wilsie (1961) found that availability of soil moisture was indicated by changes in structure of slash- and loblolly-pine wood.

Bennett (1960b) reported that the response of slash-pine crowns to thinning after the trees had reached the age of 30 is negligible; since crown development could not be stimulated beyond this age, diameter growth could be stimulated by thinning only through a reduction in competition for moisture and nutritive elements and/or through increased photosynthetic activity as a result of added light.

Harms (1962) found that diameter growth of slash pine was significantly correlated with available soil moisture, maximum air temperature, evaporation, and number of elapsed days since January 1. None of these factors explained the difference in diameter growth of 6-year-old trees planted at three different spacings, and he concluded that the photosynthetic surface of the crown, which increased with spacing, accounted for differences in growth. Reukema (1964), on the other hand, concluded the crown build-up was not a major contributing factor in the stem-growth response in released trees of Douglas-fir.

It appears, from reading the above references, that competition cannot be determined from the measurement of only one factor. Probably certain factors will be more important than others under conditions where these certain factors are limiting. When trees are young and growing close together, competition for the same light may have the most effect on growth. Later, and in more open stands, the most active competition may occur some distance from the trees, at the point where roots are actively competing for food and water. The zone of maximum competition will change with changes in the size and distribution of trees in the stand. Conceivably, for a given species and site, the zone of maximum competition may move away from the trees with increasing age. On the basis of the "circle of influence" theory, as the circle increases in radius, the trees offering competition will be located at increasing distances from the sample tree. If this is true, then the "circle of influence" must soon extend beyond the radius of the crown. If it is not true, trees whose crowns do not touch, or overlap, do not compete.

Determination of the Radius of the Circle of Influence

The major problem in the development of the competition index in this study was the determination of the proper radius for the circle of influence. In most stands there is a relationship between the stem diameter and the total height (Curtin 1964, Czarnowski 1961), but this relationship is modified by stand density. Equations for predicting height from diameter were prepared for each of the plots in this study. The heights and diameters of those trees present on the area in 1964

were used to calculate regression equations. The dependent variables used were the heights of these same trees at several different ages, and the independent variables were the diameter and the squared diameter at each age in question and the interaction between diameter and age.

The equation used for each plot was in the form:

$$h = b_o + b_1 x + b_2 x^2 + b_3 Ax$$

where:

A = age of the stand or the tree (age used was 40),

h = the average height for a given diameter (d.b.h.),

x = the d.b.h. of the tree, and

b_o, b_1, b_2, and b_3 are constants.

If b_4 is said to equal $(b_1 + A\ b_3)$ the equation for predicting height from a given diameter at the present age can be reduced to:

$$h = b_o + b_4 x + b_2 x^2$$

which is in a form recommended by Ker and Smith (1957). The equations computed for each plot are listed in Appendix E.

Since the height-diameter relationship is affected by thinning treatment, or by stand density, and since several thinnings had been carried out on these plots, individual height-diameter equations were computed for each plot. A simple mean height-over-diameter curve derived from stands given a particular thinning treatment will not adequately reflect this relationship in stands otherwise thinned (Marsh 1957).

It was theorized that the circle of influence of a tree of a given diameter would have a radius that was proportional to the average

height of trees in the stand of that same diameter. Trees of the same diameter on a given plot should all have circles of influence that are the same size. Large trees would have larger circles than small trees, but the increase of circle radius with increasing diameter would be curvilinear. In this way both diameter and height of the tree are considered in computing the size of the circle of influence.

Height was used in the expression, since as the tree grows older, the rate of height increment decreases much faster than does the rate of diameter increment, and most likely the circle of influence, like height, crown width, and many other measures of tree parameters, will increase at a decreasing rate as the tree matures. Height is also more constant for a given even-aged stand condition than is diameter, so that variations in the height-diameter curve for a given stand will reveal more about variations in competition than will be revealed by merely comparing differences in diameter.

In theory the competition received by a sample tree should be a constantly changing value. If the sample tree is growing at a faster rate than the competing trees, the value of the competition received, or the competition index, should be decreasing. This would be true of dominant trees. A suppressed tree, or one growing slower than the surrounding trees, will have an increasing index value. This would be especially apparent if the number of competing trees were held constant. A stand that is thinned to a point where no circles are overlapping (i.e., the index value is 0) will have circles that increase with growth until the index values will be greater than zero. Index values for all trees

will increase with time, but the increase will be much faster for trees growing at the slowest rate. As the competition increases some trees will die from suppression. The removal of these trees from the stand will cause index values to drop on all trees that have been competing with them. The largest trees have the largest circles, so more of these large trees would have been actively competing with those trees that died, and consequently the competition indices would decrease most on the largest and fastest growing trees.

The size of the trees at the present time is at least partly the result of the competition in the past. In thinned stands the most significant competition indices should have been those immediately following the thinning. The present competition-index values result from the relative rates of growth of the trees in the past. In other words, the present index is the result of past growth, but future growth will depend on the present index.

Field Procedure

A number of trees were randomly selected from each plot to be used for this phase of the study. The number selected from each plot varied with the total number of trees on the plot at age 40. Approximately 1/3 of the trees on each plot were selected for a total of 158 trees. Additional measurements taken from the sample trees included the inside-bark-diameter measurement (subtracting double-bark thickness from the outside-bark diameter) 17.5 ft above the ground, and the number and size of knots on the lower 17.5 ft of the bole (see

section on quality). A core of wood, including at least the last 10 growth rings, was extracted from a point 4.5 ft above the mean ground line with a 12-mm increment borer. The diameter of each tree within a 50-ft radius of each sample tree was recorded, along with the horizontal distance (to the nearest 0.1 ft) from each tree center to the sample tree center. Trees that fell outside the plot boundary but within 50 ft of the sample trees were included for these measurements. A list of the selected sample trees and their measurements are given in Appendix B.

Computational Procedure

The 158 sample trees, along with the diameter measurements of trees within 50 feet of each sample tree, were used to provide a means of testing the theory that the present index is dependent on past growth. It was thought that a radius of 50 feet would be sufficient to include all trees which were competing with the sample tree. The past growth of these trees was also used to determine the proper radius for the circle of influence of each tree (Plates 2 and 3).

The first step was to compute the proper equation for estimating height from diameter. This method has already been described. Next, a "Fortran" program for computing this index was written by Mr. Peter Fogg of the L.S.U. School of Forestry and Wildlife Management. The program is shown in Appendix F. The principal problem was to determine the proper radius for the circle of influence of each tree, since these radii are necessary for computing the index. As has been stated, this radius was assumed to be proportional to the height estimated from the diameter of each tree.

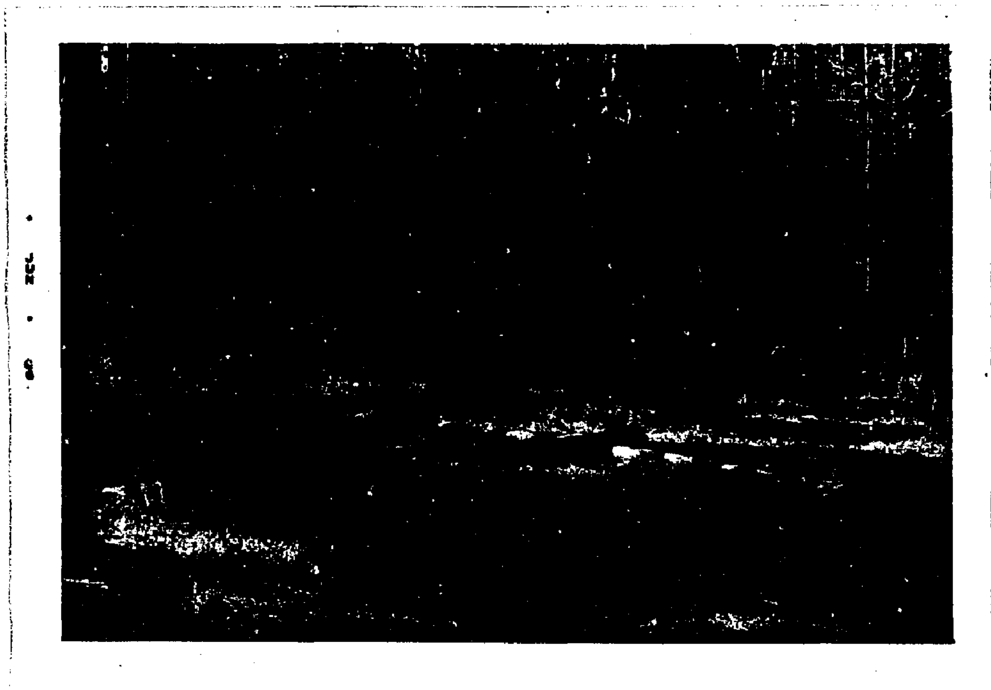


Plate 2. Sample tree #839 (white bands) on the East Light Crown Plot at age 40. Sample tree d.b.h. 11.9 inches, height 93 ft, competition index ≒ 23.88. Trees with orange bands are within 50 ft of sample tree.

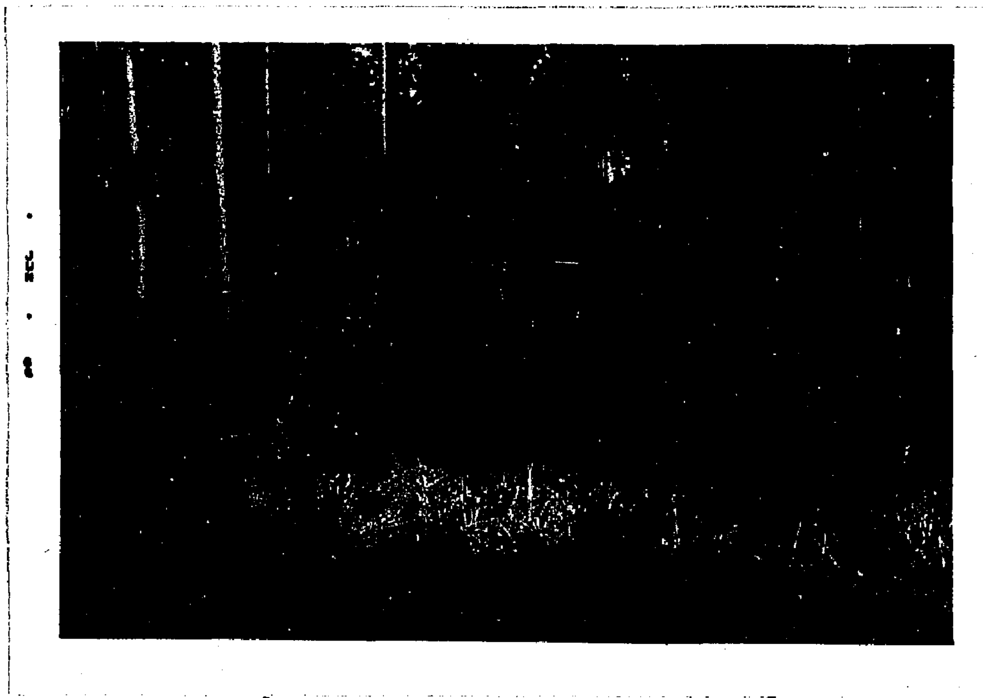


Plate 3. Sample tree #85 (white bands) on the East Selection Plot at age 40. Sample tree d.b.h. 11.2 inches, height 83 ft, competition index = 12.12. Trees with orange bands are within 50 ft of sample tree.

The radius of any tree's circle is defined as T = Zh, where T is the radius of the circle, Z is the proportionality constant, and h is the average height of trees having the same diameter as the tree in question. The value for h is estimated by inserting the tree diameter expression from the equation developed on page 133. In other words:

$$T = Zh = Z(b_o + b_4 x + b_2 x^2)$$

where x = tree diameter. The proper value for Z then remained to be determined.

Different values for Z were tried, on different runs of the data, and the resulting index values were tested as to their correlation with the sample-tree diameter growth for the last 10 years. The values for Z that were tried ranged from 0.333 to 1.2. The correlation coefficients resulting from each of the various Z factors on each plot are shown in Table 24. On each plot the correlation coefficients increased with increasing values for Z up to a maximum, after which they either leveled off or declined.

The Z factor that gave the best correlation between the competition index and the diameter growth differed from plot to plot. At first it was thought that one Z should be best for all plots. However, each plot had a different curve of diameter over height, and most of the plots had been treated differently during their lifetime, so probably each plot should have a unique Z factor depending on past stand treatment.

Table 24. Correlation coefficients of diameter growth with competition index using various values for Z

Plot	Values for Z								
	0.333	0.5	0.6	0.7	0.8	0.9	1.0	1.1	1.2
East Control	---	-.217	-.284	-.324	-.349	-.364	-.376	-.354	---
East Low	-.455	-.596	-.612	-.618	-.618	-.618	-.618	-.618	---
East Light Crown	-.246	-.543	-.560	-.566	-.571	-.572	-.574	-.574	---
East Heavy Crown	-.764	-.890	-.864	-.844	-.819	-.810	-.802	---	---
East Selection	-.345	-.573	-.577	-.573	---	---	---	---	---
West Control	-.352	-.683	-.734	-.749	-.753	-.762	-.766	-.747	---
West Low	-.034	-.478	-.526	-.539	-.545	-.547	-.548	-.561	-.561
West Light Crown	+.162	-.578	-.634	-.656	-.670	-.676	-.679	-.680	-.680
West Heavy Crown	+.113	-.481	-.590	-.631	-.650	-.661	-.665	-.666	-.669
West Selection	-.706	-.932	-.948	-.952	-.953	-.954	-.953	-.953	-.917

The Z factors finally chosen for each plot (i.e., those most closely correlated with diameter growth) are shown in Table 25. The radii for the influence circles of the largest and the smallest sample trees, along with the radius of the influence circle for the sample tree of average diameter on each plot, are also presented in Table 25. Apparently it was not sufficient to measure just those trees within 50 ft of the sample trees. There are trees beyond this 50 ft whose influence circles no doubt overlap the circles of the sample trees, and these trees also should influence the growth of the sample trees. Perhaps, if the competition zones of these trees had been considered in computing the index values, a better correlation with growth would have been found.

The competition was computed for several of the plots using only those competing trees within certain distance zones from the sample trees. This was done in order to better understand how the values for Z might change. The index values from trees within 25-ft, 35-ft, and 45-ft zones were computed using the various Z values already mentioned. It was hoped that some trend might be found that would give some indication as to the ideal distance from which to measure competition. No such trend was found. The values for Z that gave the best correlation with past growth were either the same for all zones, or else increased slightly as more competing trees were included. The correlation with past growth generally improved as more competing trees were included. However, the East Low and the West Heavy Crown plots gave the best correlation when only trees within 35

Table 25. Z values, average sample tree diameters, and radii of influence circles

Plot	Z	Average sample tree		Smallest sample tree		Largest sample tree	
		Diameter	Circle radius	Diameter	Circle radius	Diameter	Circle radius
		Inches	Feet	Inches	Feet	Inches	Feet
East Control	1.0	10.41	76.13	8.8	67.32	12.9	86.94
East Low	1.1	10.39	88.68	7.8	69.86	13.3	97.22
East Light Crown	1.1	11.15	89.16	7.7	65.84	15.7	102.37
East Heavy Crown	0.5	11.57	42.37	8.2	30.31	13.5	49.17
East Selection	0.6	12.03	51.82	10.3	43.66	14.4	63.95
West Control	1.0	9.56	71.07	6.2	49.68	16.2	88.50
West Low	1.1	9.97	81.25	7.9	65.38	12.2	92.50
West Light Crown	1.1	11.82	94.74	7.7	66.30	15.4	110.19
West Heavy Crown	1.2	10.73	91.13	6.5	56.65	12.6	103.88
West Selection	0.9	10.43	53.28	4.4	19.73	13.8	70.78

ft from the sample trees were included, and the East Light Crown and the West Control plots gave the best correlation when only trees within 45 ft from the sample trees were included.

These results are quite inconclusive, probably because the past growth was compared with the present competition index. If the index values at age 29 could have been computed and then compared with the next 10-years' diameter growth, much better results probably would have been found. The fact that the correlations with growth were quite good indicates only a strong relationship between tree growth and the competition index, even when that growth was made in the past.

It is not possible to ascertain the best value for Z without further testing. If young stands had been used, the distance of 50 ft might have been adequate. Trees within a distance from the sample trees at least equal to twice Z times the height of the tallest sample tree should be considered as possible competing trees and should be measured. According to the theory, all trees are competing when the distances between them are less than the sums of the radii of the influence circles.

If the plots had not been thinned previously, one Z probably could have been used for all plots. In that case the competition index among the plots could have been compared statistically. Since a common Z was not used such a comparison could not be made.

Possibly the Z factor changes with age. Data were not available to test this hypothesis. The effect of distance between trees might not be linear. That is, trees of the same size might have a maximum

effect on sample tree growth at a certain distance from the sample tree. This effect would decrease at either greater or lesser distances. Again, it was not possible to test this hypothesis from the data on hand. If competing trees are separated into distance zones, a regression equation that used future diameter growth as a dependent variable, and the competition index values for each of the distance zones as independent variables, could be used to compare the relative value of the competition from each of these zones. Such a study should be done in the future.

Crown Width as Related to Competition Index

It was assumed that the crown width of the trees should be correlated with the competition index, and this assumption was tested using the best Z value on each plot. Crown width has been proposed by several researchers as an index of crowding (Vezina 1962, 1963a, b; Briegleb 1952; and others).

The coefficients of correlation between crown width and diameter growth are shown in Table 26, along with correlations of several other tree parameters that will be explained later. There is a highly significant positive correlation on most of the plots between crown width and diameter growth. This correlation is one that has often been reported in the literature (Arnold 1949; Krajicek and Brinkman 1957; Krajicek *et al*. 1961; Curtin 1964). Crown width is also well correlated negatively with the competition index. Crown widths have been used as measures of competition. There is no immediate change in crown development on the residual trees when a stand is thinned, so

Table 26. Correlation coefficients for the competition index and various other tree parameters

Plot	X_1X_2	X_1X_3	X_1X_4	X_1X_5	X_1X_6	X_2X_3	X_2X_4	X_2X_5	X_2X_6	X_3X_4
East Control	-.376	-.306	.084	.189	.353	.756**	.316	.554	.109	.497
East Low	-.618**	-.787**	-.417	-.069	-.013	.737**	.357	.051	.264	.319
East Light Crown	-.574**	-.625**	-.392	-.482	-.041	.857**	.714**	.185	.396	.732**
East Heavy Crown	-.890**	-.895**	-.088	-.383	.304	.891**	.188	.426	-.459	.093
East Selection	-.577	-.765**	-.775**	-.614*	-.608*	.317	.466	.026	.726**	.698**
West Control	-.766**	-.879**	-.392*	.187	-.006	.860**	.462*	-.404	-.129	.482**
West Low	-.561	-.875**	-.224	-.071	-.108	.351	.062	.018	.231	.161
West Light Crown	-.680**	-.833**	-.549*	-.399	-.098	.636**	.646	.088	.222	.512*
West Heavy Crown	-.669*	-.829**	-.209	-.112	-.506	.868**	.506	-.122	.410	.490
West Selection	-.954**	-.865**	-.556*	-.420	.632**	.819**	.515*	.294	-.596*	.545*

X_1 = Competition index

X_2 = 10-yr. diameter growth

X_3 = Crown width

X_4 = Form class

X_5 = "K" factor

X_6 = Specific gravity

crowns cannot be used as a measure of thinning intensity. The competition index developed here is closely correlated with both growth and crown width.

Advantages of the New Competition Index

The competition index, as described, should make it possible to obtain objective measures of thinning intensity, because the degree of release received by an individual tree can be measured. Thinning intensity can be defined as the difference between the before- and after-thinning indices. Stand-wide thinning intensity can be computed from the mean of several sample trees, and the degree of the accuracy of this estimate can be asertained. Furthermore, if the theory is true, estimates of future growth, based on present competition, can be made. Crown class or vigor class may be measured as a continuous, rather than as a discrete variable, since dominant trees should show a decrease in index values, suppressed trees should shown an increase, while codominant and intermediate trees will show little change.

Many different methods of measuring stand density have been proposed by other researchers and have been reviewed in the literature review section of this dissertation. Some of the methods that have been mentioned are not entirely suitable for use with plantations, since they compare natural stands to some standard (i.e., a normal stand). Methods that use the number of trees, the basal area cut, the residual basal area, or the average spacing are most often applied to plantations. Other common measures are the $(D + x)^2$

method (Mitchell 1952) or an expression of spacing as a percentage of height (Wilson 1946, 1951).

It is felt that the competition index developed above is a better expression of stand density than most other methods that have been proposed. First, a measure of the variation in the competition index can be computed so that statistical comparisons can be made between the mean indices of several stands. In order to make such comparisons it is necessary to assume that the population of competition indices is normally distributed. The index values for each plot in this study show a dispersion clustered around the mean and with the proper proportion for a normal distribution within one and two standard deviations from the mean. As a further test, the amounts of skewness (the g_1 statistic) and kurtosis (the g_2 statistic) were tested on the plot with the largest number of sample trees (the West Control plot). Using the method proposed by Snedecor (1956), no significant departure from normality was found. Although only small samples are used here, the assumption of a normal population appears to be valid. Therefore, it is possible to make the usual comparisons that can be made with populations that are normally distributed. When total basal areas or numbers of trees are used to express density, no measure of variation is possible and so no such comparison can be made.

This new competition index considers the actual spacing of the trees rather than assuming an even spacing between the trees, and it considers relative sizes of the various trees rather than an over-all average. Finally, it makes possible the use of individual trees

rather than plots for thinning studies. Individual trees can be released by different degrees, and the study of their subsequent development can be made without the involvement of large plot areas. Thinning intensity can be measured along a continuous scale rather than by discrete classes.

Difficulties in Using the New Competition Index

There are several disadvantages to the use of the competition index. Probably the most serious disadvantage to its use is the large number of measurements that must be taken. Sample heights and diameters must be measured in order to determine the curve of average height for a given diameter. All possible competing trees surrounding a sample tree should be measured and the horizontal distance between trees must also be measured. In older stands the number of competing trees will be large, since theoretically any tree within a distance at least equal to twice Z times the height of the tallest sample tree must be considered a competing tree.

Another serious disadvantage to this method is the complication of computing the index. This can be easily done with an electronic computer but will be most difficult to compute without such equipment.

Finally, the true value for Z may be hard to determine. Conceivably the value for this factor might change with site, age, or species. Mixed stands, especially those with hardwood competition, will add still more complications.

In spite of these disadvantages, this index can probably be used successfully in thinning studies, both to compare thinning intensity

and to predict future growth of the stand. With further study the Z factor should become more clearly understood, and it will be possible to determine a Z factor that is suitable for any even-aged stand. Quite possibly Z does not change with age or even site but depends solely on the diameter-height relationships between the trees, in which case the competition index will apply to both even- and all-aged stands of a single species.

Comparison of Competition Index to Other Stand Density Indices

Table 27 shows a comparison between the competition index and several common methods of measuring stand density. The methods of Wilson (1946, 1951) and Mitchell (1952), along with basal area per acre, average square-spacing, and number of trees per acre, were considered for this comparison, since none of these methods make comparison with "normal" or fully stocked stands. Measures that make such comparisons are not suitable for use in planted stands, since planted stands are relatively free of competition during the early years. The effects of the early growth are never really lost, no matter how severe the competition becomes during later years. Planted stands should have larger average diameters for a given age, and less variation in diameter, than will natural fully-stocked stands.

Table 27 shows that the West Control plot is the most dense and that the East Selection and East Heavy Crown are the least dense by all the stand density measures used. There is considerable disagreement as to the proper order of density for the rest of the plots. In general,

Table 27. Indices of stand density at age 40, computed by several methods

	East					West				
	Control	Low	Light Crown	Heavy Crown	Selec- tion	Control	Low	Light Crown	Heavy Crown	Selec- tion
No. trees/acre	156	224	180	120	116	328	208	176	164	168
Basal area/acre, sq. ft.	101.7	130.4	123.5	89.5	87.4	150.3	122.9	122.6	109.5	104.6
Avg. sq. spacing, ft.	16.7	13.9	15.6	19.1	19.4	11.5	14.5	15.7	16.3	16.1
Nearest tree 1/, ft.	11.0	11.0	11.8	11.9	12.1	7.1	9.8	11.1	10.5	11.5
Wilson 2/	19	16	17.5	21	23	15	17.5	18	19	20
Mitchell 3/	D+6.0	D+3.1	D+4.5	D+7.5	D+7.7	D+2.5	D+4.1	D+4.6	D+5.4	D+5.6
Competition index 4/	17.71	28.27	24.32	11.69	10.67	37.98	28.78	23.13	23.61	21.76
Avg. diam. increment 5/, in.	1.78	1.84	1.89	1.90	2.27	0.85	1.45	1.76	1.61	1.80
Avg. height, ft.	85.9	89.2	89.0	90.3	84.4	76.0	82.1	86.5	82.2	81.3
Avg. diameter, in.	10.76	10.81	11.10	11.56	11.67	8.94	10.33	11.11	10.90	10.48

1/ Based on sample trees - the average distance from sample trees to nearest competing tree (used by ecologists).

2/ Spacing as percent of average tree height.

3/ D+2 is equal to a fully stocked stand.

4/ Using best value for Z on each plot.

5/ Increment for past 10 years.

the Low thinned plots are either second or third in order of stand density, while the East Control (cut heavily in 1955) is eighth in order of stand density. The number of trees per acre, the average square-spacing, and Mitchell's D + x spacing are in close agreement as to the order of density, and with the exception of the West Selection plot, so is the method proposed by Wilson. With the exception of the most and the least dense plots, there is little correlation between average diameter increment and the various measures of stand density.

The order of plot density, according to the competition index values, differs somewhat from other measures of stand density shown here. This index is highly correlated with past diameter growth. Since the index considers variations in tree size (both in diameter and height) and variation in spacing between the trees, it therefore is able to give a good picture of the stand density. An even better indication of stand density would have been possible if trees a distance equal to twice Z times the height of the tallest trees had been used. However, on some plots this would have required the measurement of all trees within about 200 ft of the sample trees (across a road in the East block).

The Low and Light Crown plots have a common Z factor, and so the mean index values for these plots were compared statistically, using the t test. No significant differences were found between the mean index values on either of the Low plots or on either of the Light Crown plots. The Low plots were found to have a higher mean index value

(28.5) than the Light Crown plots (23.7), and this difference of 4.8 was statistically highly significant.

QUALITY

There has been much discussion among foresters about the effects of thinning on the quality of the wood cut from the trees. It is necessary to define "quality" before any discussion can be made about the relative quality of a given tree. There have been a great many different definitions of the characteristics of a "high-quality" or "quality" tree. Each definition depends on the desired end-product for which the tree will be used. With coniferous trees, such as slash pine, there are certain criteria of quality which apply for nearly every use. A "quality" tree has been defined as one that is straight, single-stemmed, rot- and pest-free, and that has cylindrical bole form, good knot characteristics (few, small, widely separated, sound knots), even grain, strong fibers, and high density (Crow 1962; Anderson 1958; Penistan 1956). Density, expressed as specific gravity, has often been found to be the most useful index of quality (Hall 1955; Aldridge and Hudson 1955; Mitchell 1954, 1962).

The features of quality can be divided into two broad categories. The knot characteristics, bole form, and straightness can all be called external features of quality since they are visible while the tree is standing in the forest. The other features are all internal features since they are only apparent after wood is cut from the tree. There is

considerable argument as to whether any of these features of quality can be controlled by thinning practices.

Several workers have only considered the external features of quality. Briscoe (1954) concluded that a light thinning improved the quality of the stand. Foster (1953) found that high stocking density is essential in order to secure high-quality trees, and Grah (1961) noted that the number and size of knots in the butt log is affected by the distance between trees. Paul (1952) stated that decreased growing space improves log quality in the same way as pruning. Hopkins (1958) and Guilkey and Nelson (1963) found age to be the most significant factor in determining external quality of unpruned loblolly pine. Hopkins also noted a curvilinear relationship between external quality and the percent of total stand basal area in subdominant hardwoods.

There is more disagreement when the internal features of quality are considered. Strength properties have been shown to be closely correlated with wood density. Many workers have reported that the fast growth resulting from relatively open-grown trees in thinned stands causes considerable reduction in wood density (Bray and Paul 1930, 1934; Hagglund 1944; Harris 1958; Kano 1957; Lutz 1964; and many others). On the other hand, Turnbull (1947) and Paul (1958) found that thinning either has no effect or increases the density of the wood. Huang and Liu (1959) could find no difference in strength of fast-grown and slow-grown trees. Klem (1952) found that the difference between specific gravity in wood from trees planted at different spacings tended to decrease as age increased. Zobel and Rhodes (1955) concluded that growth

rate of loblolly pine has little effect on wood density if juvenile wood near the center of the tree is ignored. (See also Zobel and McElwee 1958.) Rendle and Philips (1957) have shown that wood formed early in the life of a coniferous tree is always less dense than wood formed later, regardless of the ring width or growth rate, so that after a certain age, rapid growth can produce wood of reasonably high density. Spurr and Hsuing (1954) recommended that, in general, conifers should be grown at the fastest rate commensurable with good form, small knot size, natural pruning, and other silvicultural considerations.

An attempt was made with this study to see if past treatment had had any effect on the external and internal quality of the trees. A core of wood was removed from each of the random samples of trees. The visible knots were counted on each of these trees.

Knots were designated as overgrown or exposed. When the only indication of a knot was on the outer bark, the knot was classified as overgrown (Plate 4). Exposed knots were those that were visible in the outer layer of living wood (Plate 5). Such knots were further classified as sound or unsound, and the diameter of the knot was recorded. In addition, a notation was made for every tree on all plots as to whether it was a potential pole or piling tree. Potential pole or piling trees were those that contained no crook or fork and that had sweep no greater than one inch per five linear feet.

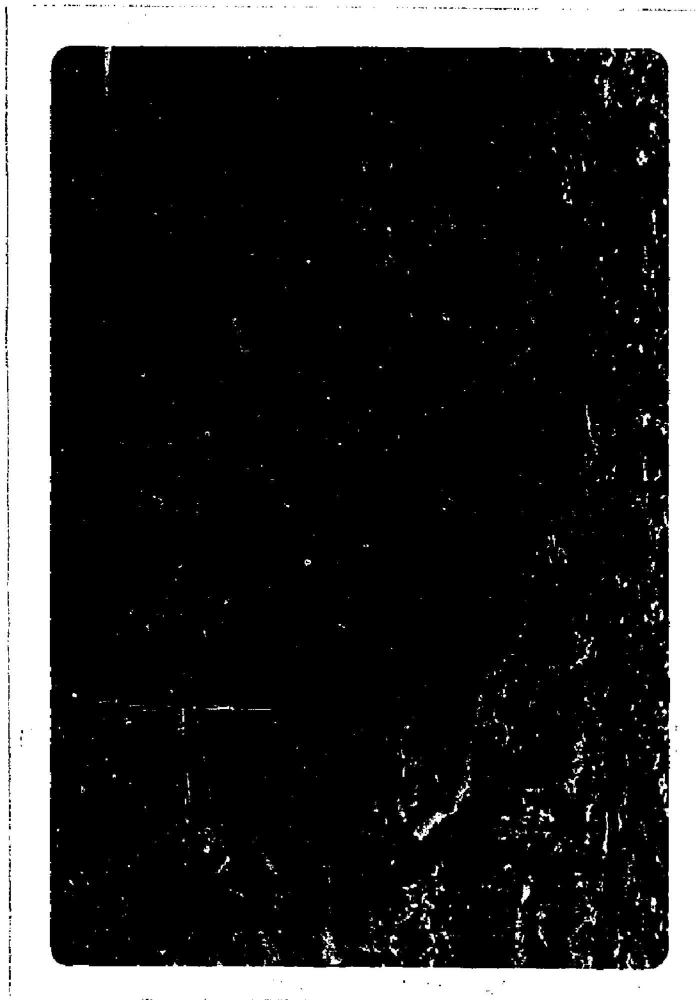


Plate 4. An example of an overgrown knot.

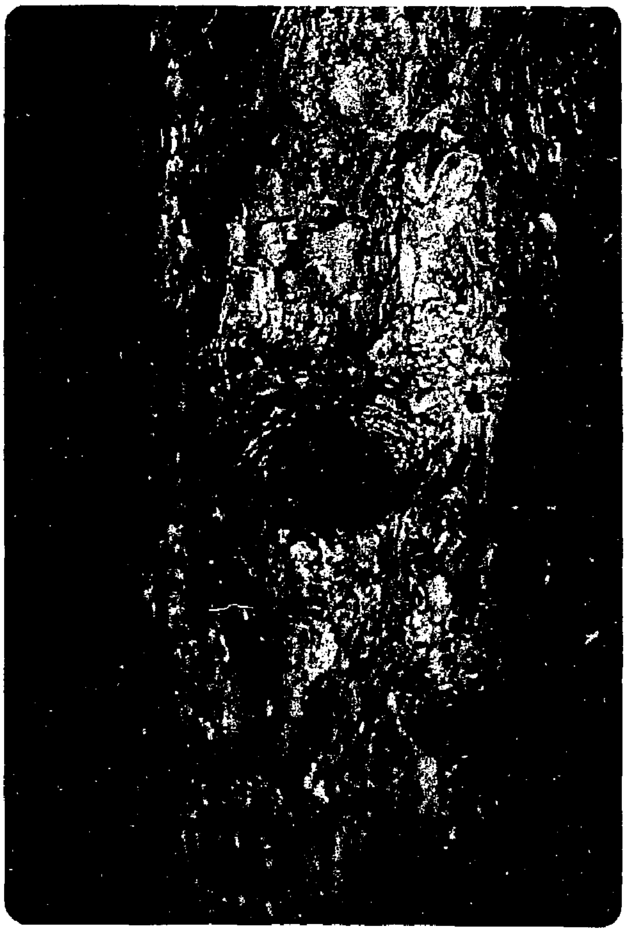


Plate 5. An example of an exposed knot.

a. Pole and Piling Trees

A chi-square test was made to see if the proportion of pole and piling trees on the plots was affected by the kind of treatment the plots had received. For purposes of this test each plot was considered as receiving a different treatment. In this way 10 treatments were considered. The hypothesis that the ratio of pole and piling trees is independent of treatment was tested.

The results of this phase of study are shown in Table 28. No statistically significant differences in the proportion of trees suitable for poles or piling were found among plots or between thinned and non-thinned plots. The conclusions must be that the thinning applied here had no real effect on the proportion of the total number of trees in a stand that would be suitable for poles or piling.

Exterior Quality

An attempt was made to compare the exterior quality of the butt-log of trees on these plots. A factor K, similar to that used by Guilkey and Nelson (1963) and Hopkins (1958), was developed that considered both the number and size of knots on the butt log. For this study the "K" factor for each sample tree was computed as follows:

$$K = N + \sum ds_i + 2 \sum du_i$$

where

N = the total number of overgrown and exposed knots on the butt log,

ds_i = diameter of the i^{th} sound exposed knot in inches, and

du_i = diameter of the i^{th} unsound exposed knot in inches.

Table 28. Statistical analysis of pole-and-piling trees at age 40

Item	Control		Low		Light Crown		Heavy Crown		Selection	
	East	West	East	West	East	West	East	West	East	West
P & P trees (X)	12	13	17	8	8	10	12	9	9	10
Total trees (T)	39	82	56	52	45	44	30	41	29	42
Proportion (X/T = P)	.308	.159	.304	.154	.178	.227	.400	.220	.310	.238

Chi-square test for pole-and-piling proportions (P)

Source	Degree freedom	chi-square	$\text{chi-square}_{.05}$
Among	9	13.8515	16.9190
Control vs. Thinning	1	3.1387	3.8415
Low vs. L. Crown	1	.2356	3.8415

The "K" value of each tree was tested for the degree of correlation with the last 10-years' growth and with the competition index of each tree.

The hypothesis that the average "K" value for each plot is independent of the treatment the plot received was tested. Again, each plot was considered as a treatment, giving 10 treatments in all. The data were analyzed as a completely randomized experiment with unequal numbers in each of the 10 treatments. Comparisons among all plot combinations were made using the sequential method of testing as outlined by Snedecor (1956).

The correlation coefficients for "K" with competition index and with the past 10-years' diameter increment are shown in Table 26. Most of these correlations are not statistically significant. There is little consistency in the direction of the correlation, and in general it can be concluded that no definite relationship between the "K" value and either the degree of competition or the rate of growth has been established.

However, in the statistical comparison of the "K" values between the plots, the West Control plot, which was never thinned, had a significantly higher average "K" value than all the other plots (Table 29). The East Low thinning plot had a significantly higher "K" value than the East Light Crown and Selection plots and the West Heavy Crown and Selection plots. The West Low plot had a significantly greater "K" value than the West Selection. This type of testing does have certain faults, since the exact probability of rejecting a true hypothesis

Table 29. Statistical analyses of "K" values at age 40

Plot	K	$\bar{K}$-24.06	$\bar{K}$-26.73	$\bar{K}$-26.90	$\bar{K}$-28.75	$\bar{K}$-30.13	$\bar{K}$-30.23	$\bar{K}$-30.84	$\bar{K}$-33.49	$\bar{K}$-35.90
West Control	42.14	18.08*	15.41*	15.24*	13.39*	12.01*	11.91*	11.30*	8.65*	6.25*
East Low	35.90	11.83*	9.17*	9.00*	7.15*	5.77	5.67	5.06	2.41	
West Low	33.49	9.43*	6.76	6.59	4.74	3.36	3.26	2.65		
East Control	30.84	6.78	4.11	3.95	2.10	.71	.62			
East H. Crown	30.23	6.16	3.50	3.33	1.48	.10				
West L. Crown	30.13	6.07	3.40	3.23	1.38					
East L. Crown	28.75	4.68	2.01	1.85						
East Selection	26.90	2.83	.16							
West H. Crown	26.73	2.67								
West Selection	24.06									

a	D 1/	Qa 2/
2	4.609	2.77
3	5.524	3.32
4	6.040	3.63
5	6.423	3.86
6	6.706	4.03
7	6.939	4.17
8	7.139	4.29
9	7.305	4.39
10	7.438	4.47

Analysis of variance of "K" values

Source	d.f.	Sum sq.	Mean sq.	F
Total	157	11113.9266		
Treatment	9	4937.5585	548.6176	13.146**
Error	148	6176.3681	41.7322	

$N_o = 1/9(158-2696/158) = 15.6596$

$S_{\bar{x}} = (S^2/N_o)^{\frac{1}{2}} = (41.7322/15.6596)^{\frac{1}{2}} = 1.664$

1/ $D = S_{\bar{x}}\, Q_a$, where a = number of ranks apart

2/ From Table 10.6.1 on page 252 in Snedecor (1956)

cannot be ascertained. Nevertheless, it appears rather certain that the more lightly thinned and the unthinned plots will have larger "K" values (*i.e.*, more exposed knots) than will the more heavily thinned plots. This conclusion is different than the one that was expected. It is often thought that close spacing and high competition causes early pruning and hence more clear wood. However, the competition that causes early natural pruning also causes slower growth, and the slower growing trees are slow to cover over the knots or dead limbs. It should be noted that the only significant correlation between the "K" value and the 10-year diameter increment was the one on the unthinned plot (see Table 26). The correlation was negative, which means that faster growing trees have lower "K" values (fewer exposed knots).

Specific Gravity

The specific gravities of the wood cores taken from the trees were calculated. There has been much controversy as to whether specific gravity variation is caused by age, distance from pith, or rate of growth (see references cited previously). There is rather general agreement, however, that the center core of the stem is not a reliable indicator of the over-all specific gravity of the tree. The purpose of this phase of the study was to find what effect thinning had on wood density. In order to test the hypothesis that the rate of growth is correlated with wood density, only the wood laid on during the last 10 years was considered. In this way no wood from the center of the tree was considered and all wood was the same age, although at different distances

from the pith. The last 10 years of growth were used, since there has been little cutting in the stands during that time. The tree distribution in the stands has remained rather constant, at least since 1956.

The increment core from each sample tree was cut so as to remove the bark and all wood closer to the pith than the earlywood laid on at the start of the 1955 growing season. The total green length of each segment was measured, and the proportion of latewood in the segment was measured as closely as possible under three-power magnification. The latewood of slash pine is quite distinct from the earlywood, and most likely the proportions, calculated in this way, are fairly accurate.

The specific gravity of the wood segments was determined by using the maximum-moisture-content method as described by Smith (1954). The mean specific gravities of the plots (Table 30) were compared. Since the treatments were no longer replicated, the study was considered a completely random design with 10 treatments. This is not a strictly valid way to test these data, but the probability of committing a type II error (failing to reject a hypothesis that is not true) is lower than if the original randomized block design had been used. Of course, the probability of committing an error of the first type is increased by some unknown amount.

The correlation between diameter growth and specific gravity for 10 years was studied in order to test the hypothesis that fast growth causes lower wood density. The correlation between wood density and the competition index was studied in order to test the hypothesis that wide spacing and low competition would cause reduction in wood density.

Table 30. Average specific gravity of last ten years' growth of wood at age 40

Block	Treatment				
	Control	Low	Light Crown	Heavy Crown	Selection
East	.604	.579	.574	.597	.555
West	.578	.563	.562	.571	.584

No statistically significant differences were found among the average specific gravities of the sample trees on any of the plots. This indicates that the variation between trees on the same plots is greater than that of the average specific gravity among the plots, and leads to the conclusion that the different growing conditions on the plots since 1954 have had no effect on the specific gravity of the trees (or at least on the wood formed 4.5 ft above the ground).

The correlations between 10-year diameter growth and specific gravity are shown in Table 26. Only two plots showed any statistically significant correlations, and these two correlations have opposite arithmetic signs. Apparently the amount of growth (i.e., the growth rate) has little relationship with specific gravity.

The correlations between specific gravity, crown width, and the competition index are also shown in Table 26. Again little relationship is indicated between specific gravity and either crown width or the competition index. The only conclusion that can be reached from a study of these data is that little if any of the variation in specific gravity can be explained by the different growing conditions of the individual trees.

The ratio of earlywood to latewood was tested as to its correlation with rate of diameter growth. Only three of the plots had correlations that were statistically significant. Several of the correlation coefficients were rather high, but the samples were so small that no significance was found. Two of the significant correlations were significant at the .01 probability level, and so a relationship probably exists between growth rate and the earlywood-latewood ratio. This

relationship must not be very strong, however, since seven of the plots showed no significant correlation. All three of the significant correlations were negative, indicating that as growth rate increases the amount of latewood increases faster than the earlywood. Under such conditions, fast growth should increase the density of the wood. The fact that specific gravity showed no correlation with growth rate is further indication that these relationships, if they exist at all, are either trivial or extremely complex.

Tree Form

A study of the form class of the trees on these plots was made by D. B. Sanders in 1954. This report has already been mentioned. The present form class (actually form "quotient") for each of the sample trees was computed from the current measurements. Form class was computed as follows:

$$FC = d/D$$

where:

d = the inside-bark diameter of the tree at a point 17.5 ft above the ground, and

D = the outside-bark diameter of the tree 4.5 ft above the ground.

This ratio gives an indication of tree taper; the ratio varies inversely with the degree of taper.

The form class values were tested as to their degree of correlation with the past 10 years' diameter growth, the competition index, and the crown width of each tree (Table 26). The hypothesis that the average

form class on each plot is independent of the plot treatment was tested; each plot was considered as a separate treatment, and statistical methods already described were used.

Statistically significant differences in form class were found among the various plots (see Table 31). The sequential method of testing was used to compare individual plots. The West Light Crown plot had the greatest form class of all the plots. However, this average form class was significantly (at .05 probability) greater than only those of the East Control (that had been thinned), the West Control, and the West Heavy Crown plot. No clear-cut trend is apparent in average form class, and it seems likely that the differences in form class are caused by something other than differences in treatment.

It is usually thought that trees in understocked stands will have more taper, since the trees grow more wood on the lower portion of the bole in such stands (Wilson 1955). Such trees, therefore, have a low form class. Myers (1963) found that the annual layer of radial growth on unthinned ponderosa pine was widest at a point about 80 percent of the total height and the narrowest at about 20 percent of total height. After thinning the widest point in the annual growth layer was at the base of the tree; the narrowest was about 70 percent of the tree height. This change resulted in greatly increased taper on the thinned trees. The greatest change in points of wide and narrow growth rings came after releasing trees that had been greatly suppressed. Horn (1961) noted that taper increased when red pine were released. Lohrey (1961), however, found little difference in form

Table 31. Statistical analysis of form classes at age 40

Plot	Mean ($\bar{x}$)	Sequential test								
		$\bar{x}$-.777	$\bar{x}$-.782	$\bar{x}$-.785	$\bar{x}$-.795	$\bar{x}$-.796	$\bar{x}$-.797	$\bar{x}$-.798	$\bar{x}$-.801	$\bar{x}$-.803
West L. Crown	.825	.048*	.043*	.040*	.030	.029	.028	.027	.024	.023
West Low	.803	.026	.021	.018	.008	.007	.006	.005	.002	
East L. Crown	.801	.024	.019	.016	.006	.005	.004	.003		
East Low	.798	.021	.016	.013	.003	.002	.001			
East Selection	.797	.020	.015	.012	.002	.001				
East H. Crown	.796	.019	.014	.011	.001					
West Selection	.795	.018	.013	.010						
East Control	.785	.008	.003							
West H. Crown	.782	.005								
West Control	.777									

a	D 1/	Qa 2/
2	.024	2.77
3	.029	3.32
4	.031	3.63
5	.033	3.86
6	.035	4.03
7	.036	4.17
8	.037	4.29
9	.038	4.39
10	.039	4.47

Analysis of variance of form class

Source	d.f.	Sum sq.	Mean sq.	F
Total	157	.20075		
Treatment	9	.02770	.003078	2.632**
Error	148	.17305	.001169	

$N_o = 1/9\ (158-2696/158) = 15.6596$

$S_{\bar{x}} = (S^2/N_o)^{\frac{1}{2}} = (0.001169/15.6596)^{\frac{1}{2}} = .00864$

1/ $D = S_{\bar{x}}\, Q_a$ where a = number of ranks apart

2/ From Table 10.6.1 on page 252 in Snedecor (1956)

of red pine growing over a wide range of stand densities, and Yerkes (1960) found no statistically significant differences between released and unreleased Douglas-fir trees.

In this study the effects of thinning are not reflected by any definite increase or decrease in taper. Indeed, the plot that was never thinned had the greatest taper, whereas the most recently thinned plots had the least amount of taper.

Discussion of Quality

Nothing in this study indicated that the quality of the trees produced on thinned plots is inferior to that of trees produced in unthinned stands. It was established as early as 1954 that tree quality was improved in these plots by thinning (Briscoe 1954). The most valuable trees that can be cut from southern pine forests are those suitable for poles or piling. Nothing in this study indicated that any of the various treatments had any effect on the proportion of such trees present in the stand.

Another measure of quality is the number and size of knots on the trees. A sample of the trees from each of the various plots revealed that the heaviest thinning treatments had no adverse effect on the number and size of knots on the butt log of the trees. Indeed, just the opposite seemed to be true, since trees from the unthinned plot were shown to have significantly more knots than those on any of the thinned plots.

Probably the most important single measure of quality in southern pine is the specific gravity of the wood produced. Here again no adverse effect was found to result from thinning. No differences in specific gravity were found between the averages for trees from any of the plots. Differences in average growth rate were found among plots, although there seemed to be no correlation between growth rate and specific gravity.

It is sometimes thought that trees growing under rather heavy competition will have less taper than trees that have had little competition. The Girard form class was measured on several sample trees on each plot. Differences in Girard form class were found among the plots. However, there seemed to be no association between these differences and the different treatments received by the plots. Plots that had been thinned the most recently had the highest form class (*i.e.*, the least taper), which would indicate that thinning improves the form. It is more likely, however, that the trees of poorer form were removed in the thinnings, thereby upgrading the average form class for the stand.

SUMMARY AND CONCLUSIONS

A study of the effects of different methods of thinning was begun in 1937 in a 13-year-old slash pine plantation near Bogalusa, Louisiana. The four thinning methods tried were designated as Low, Light Crown, Heavy Crown, and the Selection or Borggreve methods. Ten 1/4-acre plots were used so that each treatment was replicated twice, and two plots were left for unthinned controls. The first treatment on the Heavy Crown and Selection plots was applied in December 1937, and on the Low and Light Crown plots in March 1938. Treatments were applied a second time to the Low and Light Crown plots at age 24 and again at age 29. Treatments were applied a second time to the Heavy Crown and Selection plots at age 26. The diameter, clear height, and total height of each tree on each plot was measured at the time of the treatments and recorded, and records of cuts and mortality were also kept.

In 1955 one replication of the Heavy Crown and Selection treatments and one of the Control plots were inadvertently thinned. Because of this unscheduled cutting, the effects of treatment on increment were statistically analyzed as in a randomized block design before age 29, but as a completely random design after age 29.

The net growth and gross growth in both basal area and cubic feet were compared among the various treatments for the periods between

treatment applications and between age 13 and age 29. The periodic-annual-diameter increment (P.A.I.) was examined for these same periods. The method of orthogonal comparisons was used to compare differences among individual treatments.

Tree basal-area and volume increments between age 29 and age 40 on certain plots were compared by covariance analyses, using increment as the dependent variable and the diameter measurement at age 29 as the independent variable. The thinned Control was compared with the unthinned Control, and the two Low plots were compared with the two Light Crown plots.

The average heights at different ages and the average height-growth differences between the various ages were studied; height-growth studies were confined to the growth on trees that were randomly selected from those trees still living at age 40.

A study of the financial gain from the plots was made by comparing the profit margins among the various plots.

The effects of live-crown length and live-crown ratio on cubic-foot increment were studied by regression analysis. A study of the mortality was made in order to determine if the number of trees that died was independent of treatment, and to find out some of the characteristics of those trees that died.

In addition to the general plot analysis, a study was made of 158 individual sample trees selected at random from trees standing on the plots in 1964. Form classes, degrees of crook, and the numbers of

exposed and overgrown knots were determined. A core of wood was removed from each tree; specific gravity and the earlywood-latewood ratio were computed for the wood grown during the last 10 years on each tree. The horizontal distance between each sample tree and every competing tree growing within 50 ft of the sample tree, and the d.b.h. of each competing tree were measured.

The sizes of the sample trees relative to the sizes of the surrounding trees and the distances between the sample trees and the surrounding trees were used to develop a competition index that can be used to measure the competition received by an individual tree.

Finally, both internal and external quality characteristics of these sample trees were studied in order to determine what effects variation in growing conditions have on the features that are often used to classify trees as having good quality.

The results of this study have led to the following conclusions:

1. There were no statistically significant differences in either the net or the gross cubic-foot or basal-area growth among the treatments by age 29. Prior to age 29 the thinnings of the lowest intensity gave a slightly higher yield, but as the trees increased in age and size, the faster growth on individual trees of the more heavily thinned plots allowed these plots to overcome the early disadvantage. The plots that had been thinned three times by age 40 produced more, in terms of net volume growth, than did plots that had less than three treatments. Although differences in net or gross growth were not compared statistically after age 29, it nevertheless appears that frequent light thinnings might produce more net volume than no thinning at all. The most

heavily thinned plots had made the least growth, in terms of gross volume, by age 40.

2. Diameter growth on individual trees can be increased by thinning. The P.A.I. on the unthinned plots was consistently less than the P.A.I. on thinned plots. Slash pine trees released for the first time at age 30 can still show a considerable increase in increment.

3. The average height of the trees showed the effects of the treatments. This change in height probably resulted from the artificial effect of removing short trees on one plot and tall trees from another, rather than from any stimulation in height growth after thinning.

4. There is a definite financial advantage to thinning over not thinning. On the basis of either pulpwood yields only or both pulpwood and sawtimber yields, the Light Crown and Selection plots had the greatest profit margin, while the unthinned Control plot had a profit margin far less than any other plot. The Low plots gave a slightly higher profit margin than the Heavy Crown if pulpwood was the only product, but the reverse was true on the basis of pulpwood and sawtimber. Even when the first thinning was not applied until age 29, the thinning yielded greater margin of profit.

5. The initial crown length is better for predicting subsequent volume increment than is the initial crown ratio, but neither parameter accounted for much of the variation in increment. However, cubic-foot increment was positively correlated with both live-crown

length and live-crown ratio. The crowns of the trees that survived from one treatment to the next all seemed to have been long enough to allow the trees to respond to treatment. There seems little reason for choosing to leave rather than cut a tree on the basis of its crown length or crown ratio unless the crown is so short that survival is unlikely (less than 16 ft at age 29). The growth of trees that survive seems to depend far more on factors other than the length of their crown.

6. Even the lightest of the thinning treatments applied salvaged the potential mortality from suppression and competition. Trees that died from these causes were, for the most part, much smaller in diameter, height, crown length, and crown ratio than the average for the stand.

7. Thinning had no adverse effects on either the internal or external quality of the trees, although there was some indication that the external quality of the trees was slightly improved by thinning. Tree form and wood specific gravity were apparently unaffected by differences in growing conditions of the trees examined.

8. A method for determining the amount of competition a tree is undergoing was developed and tested. The competition-index value of an individual tree is correlated inversely with the past growth and with crown width. It is suspected but not proved that the present index value of a tree can be used to predict the future growth of the tree. The index values of all the trees on a stand apparently are normally distributed, so that the index values of a random sample of the trees in a stand can be used to estimate an average index value for the entire stand. The averages of different stands can be compared to

determine differences in stand density among stands. Thinning intensity can be objectively measured by comparing the before-thinning and after-thinning index values.

The author feels that the major accomplishment from this study is the development of this competition index. There has been a need for objective measures of tree density and of thinning intensity and this index is a step forward toward filling that need. The index also offers a way to use individual trees rather than stands for thinning studies so that regression techniques can be used to study the effects of thinning. However, more work is needed before the index can be widely used. The effects of the present index value on future growth have not been studied, and the radius for a tree's circle of influence is not known with certainty. This radius appears to vary from about half the tree's height to a little more than the tree's height, possibly varying with site and tree age. The competition index does not begin to answer all the questions about how trees react to the competition from other trees, but it does offer a means of measuring this reaction.

The other results from this study in general confirm the findings in other thinning experiments, with the exception of the fact that slash pine can respond to release even at more advanced ages than has heretofore been believed. Results of this study indicate that, at least on sites such as those studied here, 30-year-old slash pines are still quite capable of responding to release.

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APPENDIX A - DESCRIPTION OF SOILS FOUND ON THE ARTESIAN WELL PLOTS

PRENTISS LOAM

Location: Washington Parish, Louisiana, on Artesian Well Plots - Crown Zellerbach - Heavy Crown Plots, Section 36.

Vegetation: Slash pine plantation.

Slope and Land Form: Nearly level; very slightly elevated.

Drainage and Permeability: Moderately well drained. Permeability is moderate in the upper part of the solum and slow in the lower part.

Parent Material: Coastal Plains, sandy alluvium. Local stream terrace.

Profile Described By: Warren Cockerham, Dr. Norwin Linnartz, Bradley Spicer, and Harvey Kennedy, August 25, 1965.

HORIZON	DEPTH	DESCRIPTION
A1	0-6"	Dark gray (10YR 4/1) sandy loam; weak medium subangular blocky to weak fine granular structure; very friable; very strongly acid; clear wavy boundary.
A2	6-10"	Yellowish brown (10YR 5/6) loam; weak coarse subangular blocky to massive; friable; few worm casts and pores; extremely acid; diffuse wavy boundary.
B21t	10-18"	Yellowish brown (10YR 5/6) loam; weak coarse subangular blocky structure to massive; friable; a few clay films in common pores; slightly heavier than A2; a few large soft brown and red aggregates; extremely acid; diffuse wavy boundary.
B22t	18-27"	Yellowish brown (10YR 5/4 and 5/8) loam; weak coarse subangular blocky structure to massive; firm; small pockets of uncoated sand grains; fine charcoal; a few chert gravel; a few soft brown and red aggregates; extremely acid; diffuse wavy boundary.

Prentiss Loam

Btx	27-42"	Light brownish gray (10YR 6/2) sandy loam in about equal proportions with yellowish brown (10YR 5/6); platy structure; very firm; gray (10YR 6/1) sandy loam in polygonal cracks; small patches of uncoated sand grains; many pores; a few medium to coarse soft brown and red aggregates; extremely acid.

REMARKS:

Colors given for moist soil.

Profile described from pit.

Reaction and textural analysis made by LSU Soils Laboratory.

HORIZON	DEPTH	pH	TEXTURE	TEXTURAL FRACTIONS Sand	Silt	Clay
A1	0-6"	4.8	sandy loam	58	37	5
A2	6-10"	4.4	loam	50	40	10
B21t	10-18"	4.4	loam	48	40	12
B22t	18-27"	4.4	loam	48	40	12
Btx	27-42"	4.4	sandy loam	60	30	10

MYATT VERY FINE SANDY LOAM

Location: Washington Parish, Louisiana, on Artesian well plots, Crown Zellerbach, Selection Plot - section 35.

Vegetation: Slash pine plantation.

Slope and Land Form: Level to slightly depressed areas. Low local elevation between local stream floodplains and the uplands.

Drainage and Permeability: Poorly drained. Surface runoff and internal drainage very slow to slow. Permeability slow.

Parent Material: Coastal Plains, sandy alluvium; local stream terrace.

Profile Described By: Dr. N. Linnartz, W. Cockerham, B. Spicer, and H. Kennedy, August 25, 1965.

HORIZON	DEPTH	DESCRIPTION
Ao	0-1"	Partially decomposed forest litter mixed with brown mineral soil.
A1	1-8"	Gray (10YR 5/1) sandy loam with yellowish brown (10YR 5/8) mottles mainly in root channels and pores; massive; friable; many fine roots and worm casts; very strongly acid.
A2	8-18"	Gray (10YR 6/1) sandy loam with many coarse distinct yellowish brown (10YR 5/6) mottles; massive; friable; few medium dark brown concretions; exidized root channels and pores; extremely acid.
B21t	18-27"	Gray (10YR 5/1) loam with many coarse distinct yellowish brown (10YR 5/4) mottles; weak medium subangular blocky structure; friable; clay films in pores and on cleavage planes; extremely acid.
B22t	27-31"	Gray (10YR 6/1) loam with many coarse distinct yellowish brown (10YR 5/4) mottles; weak coarse subangular blocky structure; firm; slightly heavier than B21t; common coarse aggregates with gray (10YR 6/1) exterior and yellowish brown (10YR 5/8) fine sand loam interior; many clay films in pores and on cleavage planes; extremely acid.

Myatt Very Fine Sandy Loam

B3t	31-46"	Gray (10YR 5/1) loam with many medium distinct yellowish brown (10YR 5/6) mottles; moderate coarse subangular blocky structure; nearly continuous clay films on ped surfaces; few medium reddish brown concretions; few pores; large very firm cemented areas with yellowish brown (10YR 5/8) interior; extremely acid.
C	46+"	Gray (10YR 6/1) and yellowish brown (10YR 5/6) very fine sandy loam in about equal proportions; massive; friable; few clay films in pores; few small patches of charcoal; extremely acid.

REMARKS:

Colors given for moist soil.

Profile described from pit.

Reaction and textural analysis made by LSU Soils Laboratory.

				TEXTURAL FRACTIONS		
HORIZON	DEPTH	pH	TEXTURE	Sand	Silt	Clay
A1	0-8"	4.6	sandy loam	48	47	5
A2	8-18"	4.4	sandy loam	45	47	8
B21t	18-27"	4.0	loam	44	45	11
B22t	27-31"	4.0	loam	40	45	15
C	31-46"	4.2	loam	43	47	10

STOUGH VERY FINE SANDY LOAM*

Location: Washington Parish, Louisiana, Artesian well plots - Crown Zellerbach - Heavy Crown Plots, Section 36.

Vegetation: Slash pine plantation.

Slope and Land Form: Level.

Drainage and Permeability: Somewhat poorly drained. Surface runoff and internal drainage slow. Permeability is moderate in the upper part of the solum but slow in the fragipan.

Parent Material: Coastal Plains, sandy alluvium. Local stream terrace.

Profile Described By: Warren Cockerham, Dr. Norwin Linnartz, Bradley Spicer, Harvey Kennedy, August 25, 1965.

HORIZON	DEPTH	DESCRIPTION
A1	0-4"	Grayish brown (10YR 5/2) sandy loam; weak medium subangular blocky structure; friable; common worm casts; extremely acid; diffuse wavy boundary.
A2	4-13"	Grayish brown (10YR 5/2) loam with few fine distinct yellowish brown (10YR 5/6) mottles; massive; friable; many pores and worm casts; few small brown concretions; extremely acid; diffuse wavy boundary.
B21x	13-26"	Light brownish gray (10YR 6/2) loam with common coarse distinct yellowish brown (10YR 5/6) mottles; massive; firm; brittle; many pores; few fine dark reddish brown concretions; extremely acid; diffuse wavy boundary.
B22tx	26-40"	Gray (10YR 6/1) sandy loam with many coarse distinct strong brown (10YR 5/6) mottles; massive; very firm; brittle; discontinuous clay films; many pores; few soft dark brown aggregates; scattered charcoal; many plinthite aggregates; extremely acid; diffuse boundary.
C	40+"	Gray (10YR 6/1) very fine sandy loam with many coarse distinct yellowish brown (10YR 5/6) mottles; massive; friable; extremely acid.

Stough Very Fine Sandy Loam*

REMARKS:

Colors given for moist soil.

Profile described from pit.

Reaction and textural analysis made by LSU soils laboratory.

HORIZON	DEPTH	pH	TEXTURE	TEXTURAL FRACTIONS Sand	Silt	Clay
A1	0-4"	4.4	sandy loam	53	42	5
A2	4-13"	4.2	loam	50	40	10
B21x	13-26"	4.2	loam	48	37	15
B22tx	26-40"	4.0	sandy loam	53	30	17

*This soil is more poorly drained than typical Stough soils.

Classification: Typic Fragiaqualts, coarse loamy, siliceous thermic.

APPENDIX B. SUMMARY OF SAMPLE-TREE MEASUREMENTS

Table 32. Sample-tree data at age 40

Tree	Diameter	Height	Crown width	Competition index	Past 10 yr Specific gravity	Past 10 yr Diameter growth	Girard form class
	Inches	Feet	Feet			Inches	
				East Control			
240	10.5	88	11.0	17.19	.604	1.5	.781
244	12.9	93	17.0	17.51	.637	2.4	.798
269	10.2	83	9.0	19.06	.600	0.9	.765
270	11.0	88	11.0	19.64	.612	2.0	.809
282	8.8	83	9.0	20.31	.627	0.4	.784
293	9.2	78	10.0	19.71	.616	1.3	.750
319	10.9	92	12.0	15.64	.614	1.6	.789
339	10.8	88	13.5	17.46	.603	1.6	.769
345	10.6	83	10.0	15.94	.568	1.5	.774
356	10.2	83	13.5	16.43	.617	1.3	.765
357	11.5	84	17.5	16.80	.598	2.6	.809
392	9.3	80	14.0	18.85	.578	1.1	.839
394	9.5	81	10.5	15.71	.581	1.3	.779
				West Control			
1009	12.7	83	13.5	32.31	.568	2.7	.787
1015	9.3	78	8.0	39.45	.626	1.0	.753
1262	7.2	73	6.0	44.53	.506	0.4	.750
1263	16.2	93	19.0	31.01	.468	2.9	.815
1266	10.9	83	12.0	35.70	.549	1.9	.798
1267	7.4	75	6.5	45.08	.583	0.3	.784
1284	6.9	73	6.5	43.91	.577	0.2	.754
1291	9.9	80	10.5	35.13	.477	1.2	.788
1305	6.5	73	5.0	45.09	.616	0.1	.708
1313	8.9	83	12.0	37.80	.618	1.0	.820
1322	11.0	83	11.5	33.12	.672	1.0	.718
1328	8.5	78	7.0	38.19	.536	0.7	.742
1339	6.2	78	4.5	48.99	.633	0.1	.823
1340	9.0	78	6.5	40.27	.577	0.6	.800
1342	10.1	78	11.0	36.17	.499	1.3	.772
1349	8.2	74	7.5	38.98	.525	0.1	.744
1351	8.4	75	5.5	39.66	.607	0.5	.726
1352	10.4	83	10.0	34.99	.661	1.4	.865
1360	10.0	84	7.5	37.88	.656	1.3	.760
1363	7.1	63	4.5	43.36	.472	0.1	.704
1367	9.7	62	8.0	37.36	.549	1.2	.825
1369	9.5	58	9.5	33.87	.639	0.1	.800

Table 32. Cont'd

Tree	Diameter	Height	Crown width	Competition index	Past 10 yr Specific gravity	Past 10 yr Diameter growth	Girard form class
	Inches	Feet	Feet			Inches	
			West Control (cont'd)				
1372	11.9	63	12.5	33.49	.598	2.0	.748
1374	10.3	81	11.0	32.70	.581	1.5	.806
1384	6.7	77	5.0	45.42	.601	0.4	.731
1385	12.6	86	13.0	32.89	.587	2.3	.841
1392	12.7	83	16.5	28.19	.614	1.6	.811
			West Low				
89	7.9	75	8.0	32.24	.549	0.9	.797
102	9.7	82	8.0	30.29	.661	0.8	.814
103	12.2	85	15.5	25.66	.534	1.4	.754
109	9.4	82	9.0	29.32	.529	1.0	.819
110	8.8	82	7.0	31.71	.585	1.4	.830
118	11.5	87	12.5	24.58	.590	1.9	.817
125	10.7	88	10.0	27.81	.575	1.5	.822
126	10.7	92	11.5	27.59	.626	1.8	.804
128	9.1	78	10.0	29.45	.531	0.6	.824
129	9.2	78	9.5	30.62	.567	0.9	.750
137	10.3	83	11.0	28.54	.500	1.2	.854
139	10.5	81	11.5	27.28	.581	1.2	.838
142	8.5	78	7.5	32.49	.536	1.0	.741
149	10.6	78	12.5	28.14	.540	1.1	.840
163	10.7	83	11.0	26.51	.542	1.4	.776
170	11.6	85	13.0	26.69	.606	0.8	.828
178	9.4	78	8.5	29.68	.505	0.8	.777
181	8.6	78	7.5	29.41	.570	1.2	.767
			West Light Crown				
7	12.3	96	14.5	22.64	.609	2.8	.846
9	13.6	98	14.0	21.02	.561	2.5	.846
29	14.0	86	19.0	20.66	.519	1.8	.843
32	15.4	93	18.5	19.24	.541	2.7	.870
34	11.8	88	11.5	20.62	.587	1.6	.864
49	7.8	73	8.0	28.91	.612	1.1	.756
55	13.9	93	17.5	20.59	.571	1.5	.806
56	12.1	92	14.5	22.59	.644	2.0	.785
64	11.6	93	11.5	25.97	.581	2.3	.879

Table 32. Cont'd

Tree	Diameter	Height	Crown width	Competition index	Past 10 yr Specific gravity	Past 10 yr Diameter growth	Girard form class
	Inches	Feet	Feet			Inches	
			West Light Crown (cont'd)				
66	12.5	88	13.5	20.31	.561	2.0	.800
71	13.8	95	17.0	19.48	.543	3.1	.884
73	12.4	88	12.0	21.37	.518	1.6	.823
81	7.7	76	10.0	28.90	.555	0.6	.818
721	10.4	86	12.0	24.73	.569	1.9	.779
789	8.0	73	7.5	29.92	.455	0.9	.775
			East Low				
93	9.9	89	10.0	28.97	.624	1.4	.808
190	8.7	84	6.0	31.73	.536	0.3	.782
192	11.2	89	10.0	27.57	.544	2.0	.804
199	8.5	84	8.0	30.04	.591	1.0	.741
1158	11.0	90	18.0	24.69	.553	2.0	.818
1169	11.7	87	14.0	23.03	.534	1.5	.855
1174	12.2	97	15.0	26.90	.543	2.5	.844
1178	9.5	83	9.0	30.16	.618	1.3	.758
1182	12.4	93	17.0	26.05	.605	1.5	.774
1185	13.3	89	14.0	24.80	.599	1.8	.774
1194	11.8	95	17.0	27.24	.640	2.2	.822
1201	7.8	84	9.0	32.67	.534	0.6	.795
1204	8.8	84	9.0	31.88	.604	1.2	.807
1209	9.2	89	11.0	29.79	.523	0.7	.783
1216	9.8	84	14.0	27.60	.645	1.8	.735
1219	8.9	84	10.0	29.38	.589	1.1	.820
1234	10.8	89	14.0	27.92	.563	1.6	.815
1239	11.5	94	14.0	28.20	.557	2.3	.783
1241	10.4	89	14.0	28.43	.608	2.4	.837
			East Light Crown				
803	9.4	81	12.0	26.06	.464	1.0	.809
813	11.7	93	16.0	24.28	.577	2.1	.812
814	10.5	89	11.0	25.23	.539	1.5	.790
837	10.5	84	10.0	22.51	.511	0.6	.762
839	11.9	93	14.0	23.88	.546	1.8	.782
843	7.7	84	8.0	30.55	.605	0.5	.753
851	11.4	89	12.0	22.18	.611	1.7	.781

Table 32. Cont'd

Tree	Diameter	Height	Crown width	Competition index	Past 10 yr Specific gravity	Past 10 yr Diameter growth	Girard form class
	Inches	Feet	Feet			Inches	
				East Light Crown (cont'd)			
855	10.3	89	10.0	26.34	.614	1.8	.786
869	9.9	90	14.0	26.26	.641	1.9	.818
878	10.2	89	13.0	23.49	.623	1.8	.833
888	10.2	89	12.0	23.80	.601	1.2	.775
897	15.0	99	22.0	19.92	.591	2.5	.833
908	15.7	99	23.0	21.93	.615	3.1	.828
915	11.5	87	16.0	25.78	.496	1.6	.835
921	11.4	90	14.0	22.59	.552	2.0	.825
				West Heavy Crown			
176	11.8	88	11.5	24.61	.636	1.6	.822
179	12.6	88	12.0	21.76	.602	1.9	.762
190	8.0	73	7.5	29.02	.546	0.3	.738
192	12.5	92	14.0	22.30	.555	2.3	.800
193	11.4	88	10.0	21.86	.621	1.2	.807
201	12.3	83	14.5	19.64	.648	1.4	.813
206	8.4	66	9.0	25.90	.496	0.8	.762
218	6.5	58	8.5	27.85	.531	0.6	.754
224	12.5	81	12.0	19.12	.555	1.2	.736
225	11.9	81	14.0	22.04	.584	2.0	.815
235	8.9	78	9.0	27.44	.476	1.0	.787
236	12.2	88	13.0	20.60	.553	2.0	.762
238	10.5	83	11.5	24.74	.621	1.6	.810
				East Heavy Crown			
18	12.4	89	18.0	9.59	.600	2.5	.766
27	11.2	67	12.5	11.94	.631	1.6	.786
38	13.5	102	15.0	10.31	.575	2.1	.867
40	11.0	69	12.0	12.56	.581	2.0	.855
48	11.5	95	11.5	12.28	.653	1.6	.800
50	11.9	89	11.0	11.33	.639	1.7	.790
51	11.9	89	12.0	11.97	.533	1.8	.815
55	13.3	92	13.5	11.42	.623	1.9	.752
56	9.3	84	7.0	13.49	.668	1.4	.763
60	12.4	93	13.0	11.15	.584	2.0	.782
65	11.2	85	12.0	12.82	.572	1.6	.786
66	8.5	79	10.5	13.05	.571	1.4	.788
72	12.4	91	15.5	10.12	.530	2.4	.798

Table 32. Cont'd

Tree	Diameter	Height	Crown width	Competition index	Past 10 yr Specific gravity	Past 10 yr Diameter growth	Girard form class
	Inches	Feet	Feet			Inches	
				East Selection			
76	14.4	102	19.0	8.88	.589	2.3	.826
85	11.2	83	13.5	12.12	.523	1.7	.759
90	11.7	88	15.0	11.20	.538	2.3	.812
107	11.7	88	13.0	10.79	.617	2.6	.795
114	12.5	88	15.0	8.44	.575	2.4	.808
120	10.8	76	13.5	11.33	.558	2.3	.787
121	12.7	89	13.5	10.65	.553	2.8	.803
122	11.3	83	11.0	12.27	.516	1.6	.788
131	13.7	85	17.0	9.51	.549	2.3	.819
140	10.3	78	14.0	11.50	.539	2.0	.777
				West Selection			
409	8.8	83	9.0	24.51	.600	1.3	.841
419	11.7	86	16.5	18.41	.584	2.0	.812
434	8.5	79	6.0	26.63	.526	0.8	.741
437	12.0	88	13.0	19.05	.578	1.9	.812
444	13.3	88	14.0	17.30	.565	2.3	.797
446	11.2	88	10.0	20.65	.598	1.8	.795
448	4.4	53	5.5	33.01	.651	0.1	.773
451	13.8	93	19.0	17.35	.538	2.2	.790
456	7.8	75	6.5	25.57	.636	1.4	.718
457	8.8	78	10.0	25.85	.612	1.2	.784
467	13.5	83	15.0	16.87	.532	2.4	.815
472	11.6	83	12.5	17.71	.583	1.8	.836
473	11.8	88	12.5	18.88	.550	2.5	.831
475	8.9	74	9.5	23.69	.616	1.3	.753
485	10.3	78	13.0	20.95	.592	1.8	.816

APPENDIX C - DEVELOPING THE EQUATION FOR DETERMINING THE AREA OF OVERLAP BETWEEN TWO CIRCLES OF INFLUENCE

A diagram of this problem is shown in Figure 7. It can be seen in the diagram that if C_i is the area of overlap, then this area can be computed as follows:

C_i = Area of the circle sector ESF + Area of the circle sector ETF - Area of triangle ESF - Area of triangle ETF

where the area of:

Circle sector ESF $= 2\int_0^{\alpha} 1/2\ K^2\ d\alpha = K^2\alpha$

Circle sector ETF $= 2\int_0^{\beta} 1/2\ R^2\ d\beta = R^2\beta$

Triangle ESF = ay

Triangle ETF = by

therefore: $C_i = K^2\alpha + R^2\beta - y(a + b)$, but $x = a + b$, so:

Equation 1. $C_i = K^2\alpha + R^2\beta - xy$

Now $\alpha = \arctan(y/a)$ and $\beta = \arctan(y/b)$, so:

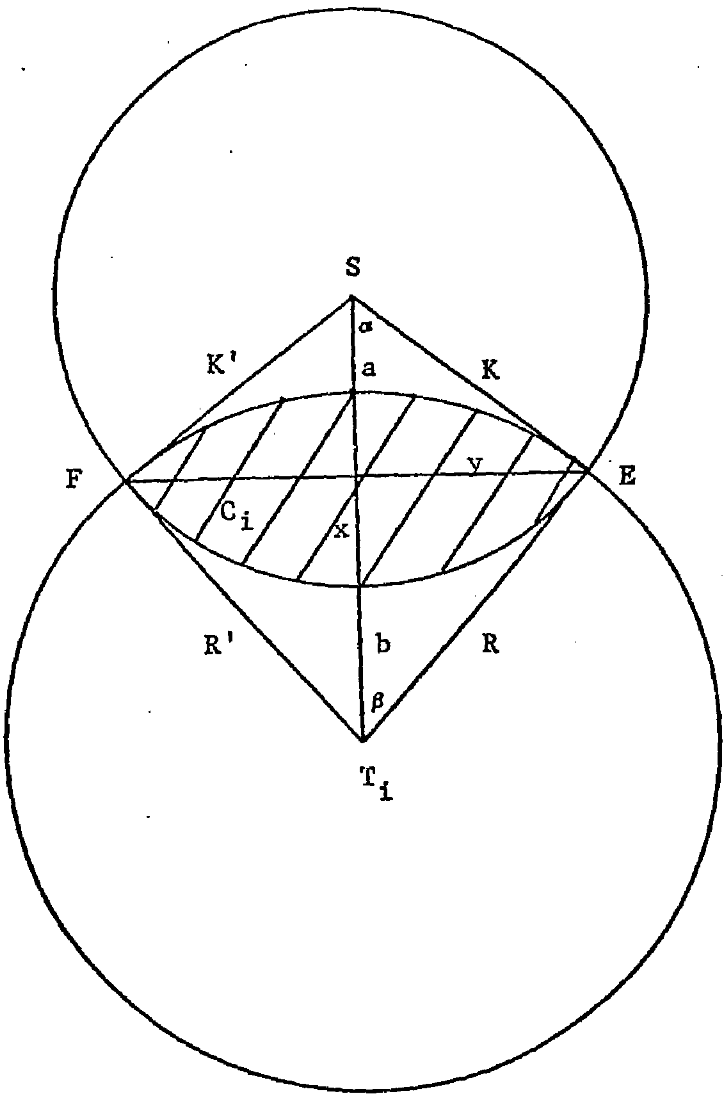
Equation 2. $C_i = K^2 \arctan(y/a) + R^2 \arctan(y/b) - xy$

To solve for a, b, and y:

$K^2 = a^2 + y^2$ and $R^2 = b^2 + y^2$; so $K^2 - R^2 = a^2 - b^2$; $a^2 = K^2 - R^2 + b^2$
or
$b^2 = R^2 - K^2 + a^2$, but $a = x - b$, and $b = x - a$; so $(x-b)^2 = K^2 - R^2 + b^2$, and $(x-a)^2 = R^2 - K^2 + a^2$. Expanding the left terms these become

$x^2 - 2xb + b^2 = K^2 - R^2 + b^2$, and $x^2 - 2ax + a^2 = R^2 - K^2 + a^2$

so $x^2 - 2bx = K^2 - R^2$, and $x^2 - 2ax = R^2 - K^2$.



S = Sample Tree

T_i = i^{th} competing tree

C_i = Area of Competition (diagonal lines)

x = a + b

Figure 7. Computing the area for C_i.

Therefore $b = [x^2 - (K^2 - R^2)]/2x$, and $a = [x^2 + (K^2 - R^2)]/2x$.

Now since $K^2 = a^2 + y^2$, then $y^2 = K^2 - a^2$, and $y = (K^2 - a^2)^{\frac{1}{2}}$

or $y = \left(K^2 - [(x^2 - R^2 + K^2)/2x]^2\right)^{\frac{1}{2}} = \left(x^2\,(2[K^2 + R^2] - x^2) - (K^2 - R^2)^2\right)^{\frac{1}{2}}/2x.$

Let $A = K^2 + R^2$, $B = K^2 - R^2$, and $U = [x^2\,(2A - x^2) - B^2]^{\frac{1}{2}}$

Then substituting in equation 2 gives:

Equation 3. $C_i = K^2 \arctan [U/(x^2 + B)] + R^2 \arctan [U/x^2 - B)] - U/2$

For computing the competition zone this equation is subject to the following restrictions tested in sequence:

1. $0 \leq C_i \leq$ the smallest of πR^2 or πK^2
2. If $x \geq K + R$ then $C_i = 0$
3. If $K \geq x + R$ then $C_i = \pi R^2$
4. If $R \geq x + K$ then $C_i = \pi K^2$
5. If $x^2 + B = 0$ then $\arctan [U/(X^2 + B)] = \pi/2$
6. If $x^2 - B = 0$ then $\arctan (U/(X^2 - B)] = \pi/2$
7. If $x^2 < R^2 - K^2$ then $\alpha = \pi - \left|\arctan [U/(X^2 - B)]\right|$
8. If $x^2 < K^2 - R^2$ then $\beta = \pi - \left|\arctan [U/(X^2 - B)]\right|$

An example is given below where the competition index is computed for a sample tree with two competing trees.

Given: $K = 15$ ft. $R_1 = 12$ ft. $R_2 = 18$ ft. $x_1 = 20$ ft.

$x_2 = 10$ ft.

$$C_1 = \left(15^2 \arctan \left[(20^2\,[2(15^2 + 12^2) - 20^2] - (15^2 - 12^2)^2\right]^{\frac{1}{2}}/[20^2 + (15^2 - 12^2)]\right) + \left(12^2 \arctan \; (20^2\,[2(15^2 + 12^2) - 20^2] - (15^2 - 12^2)^2\,)^{\frac{1}{2}}/[20^2 - (15^2 - 12^2)]\right) - \left((20^2[2(15^2 + 12^2) - 20^2] - (15^2 - 12^2)^2)^{\frac{1}{2}}/2\right)$$

$$= 225 \arctan [(128639)^{\frac{1}{2}}/481] + 144 \arctan [(128639)^{\frac{1}{2}}/319] - (128639)^{\frac{1}{2}}/2 = 86.369 \text{ sq. ft.}$$

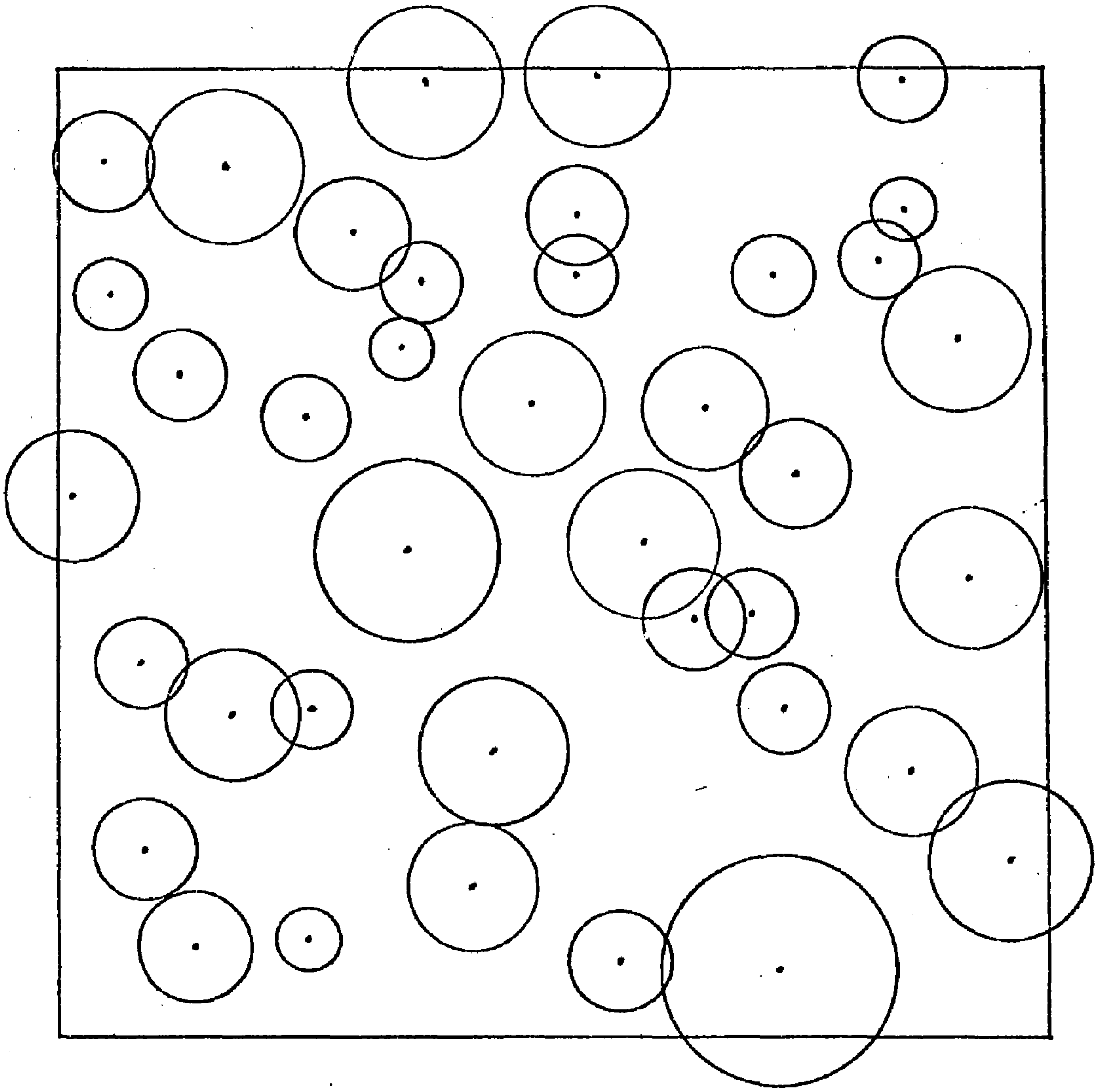
$$C_2 = 225 \arctan [948.676)/1] + 324 \arctan [(948.676/19] - 948.676/2$$

$$= 320.840 \text{ sq. ft.}$$

$$I = \sum_{i=1}^{2} C_i/\pi K^2 = (86.369 + 320.840)/\pi 225 = 407.209/706.858 = .5761$$

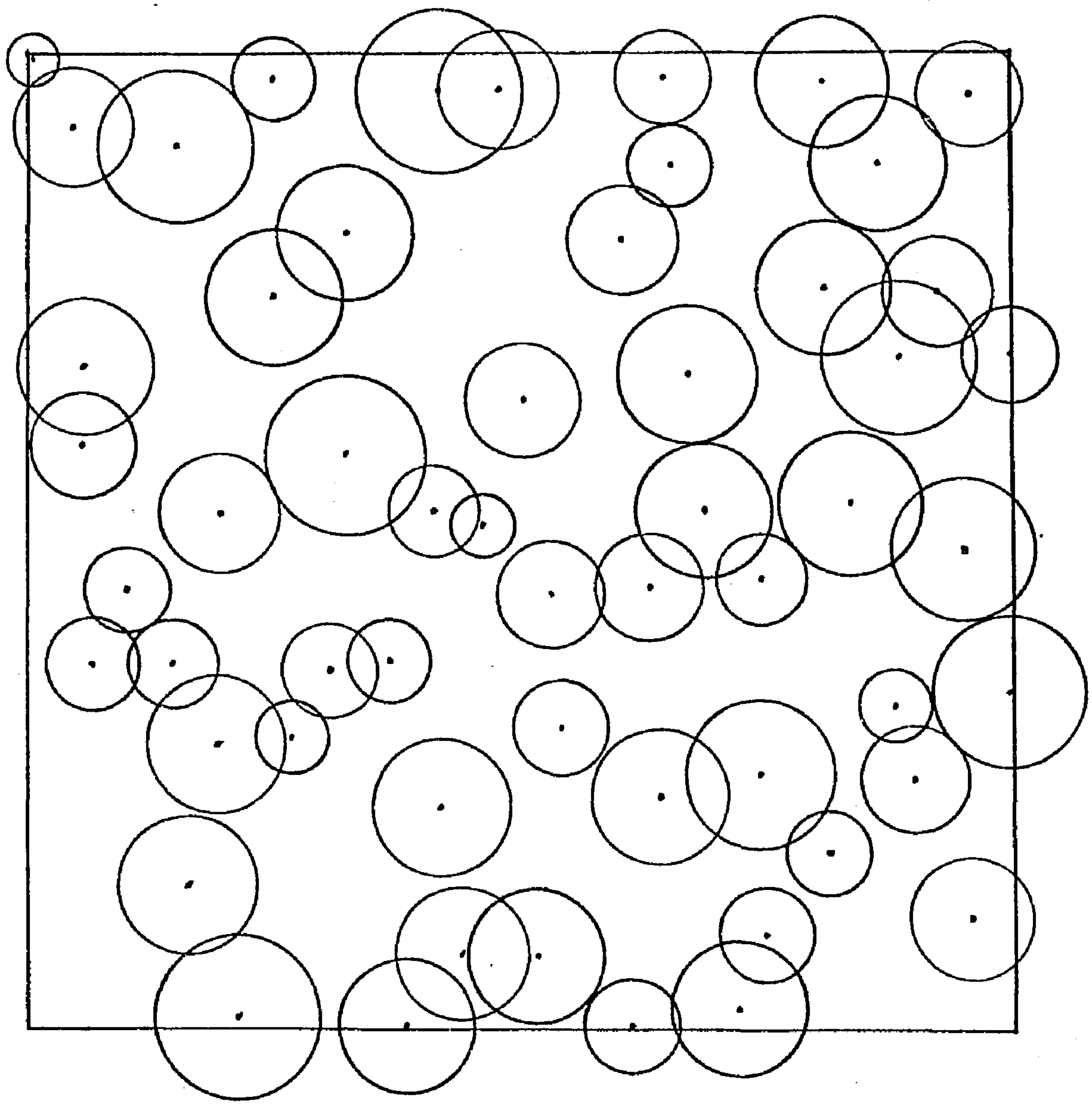
APPENDIX D

DIAGRAMS SHOWING TREE DISTRIBUTION AND CROWN WIDTHS IN 1964 AT AGE 40



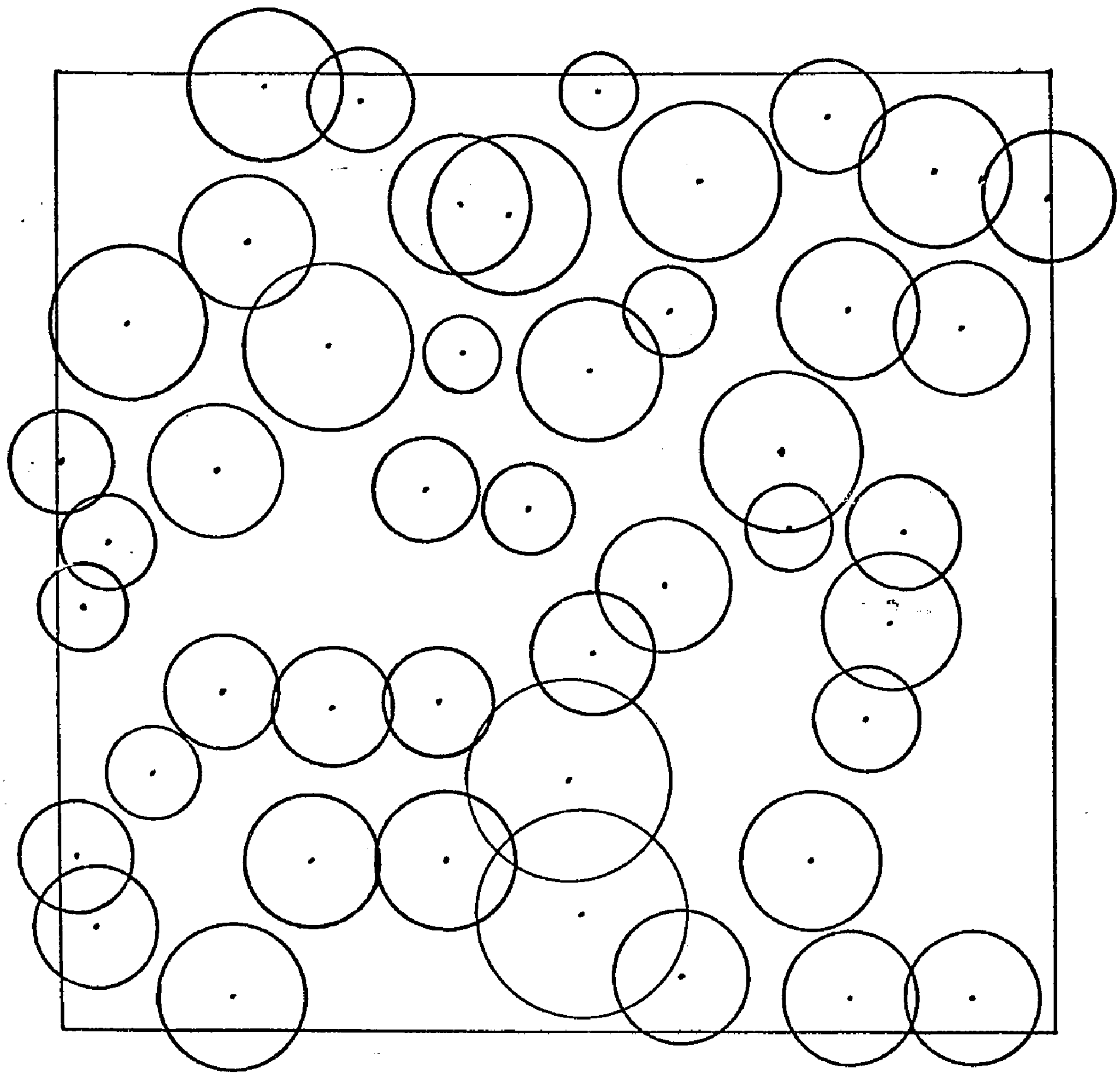
Scale: 1 in. = 20 feet

Figure 8. East Control plot showing tree distribution and crown widths.



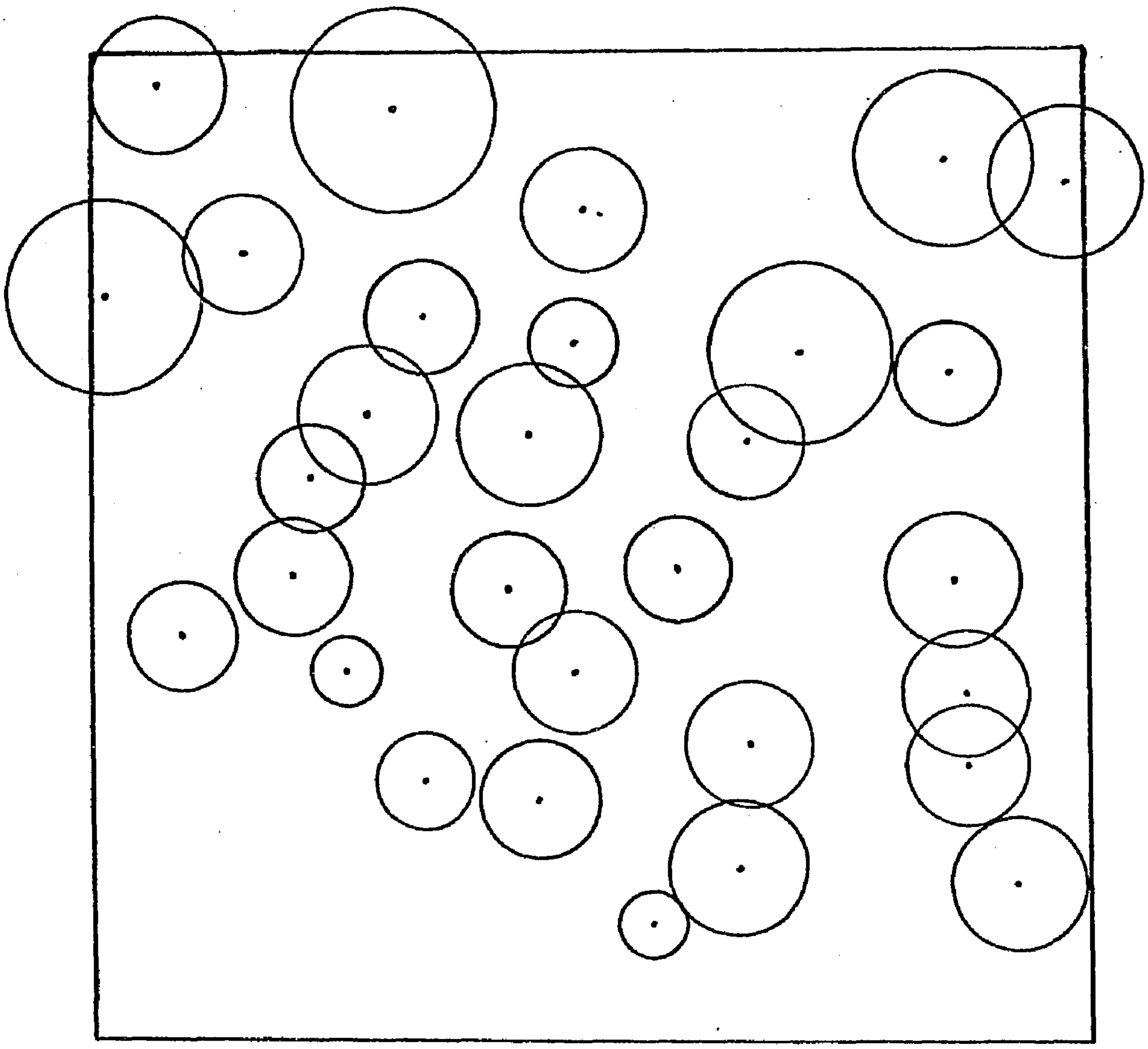
Scale: 1 in. = 20 feet

Figure 9. East Low plot showing tree distribution and crown widths.



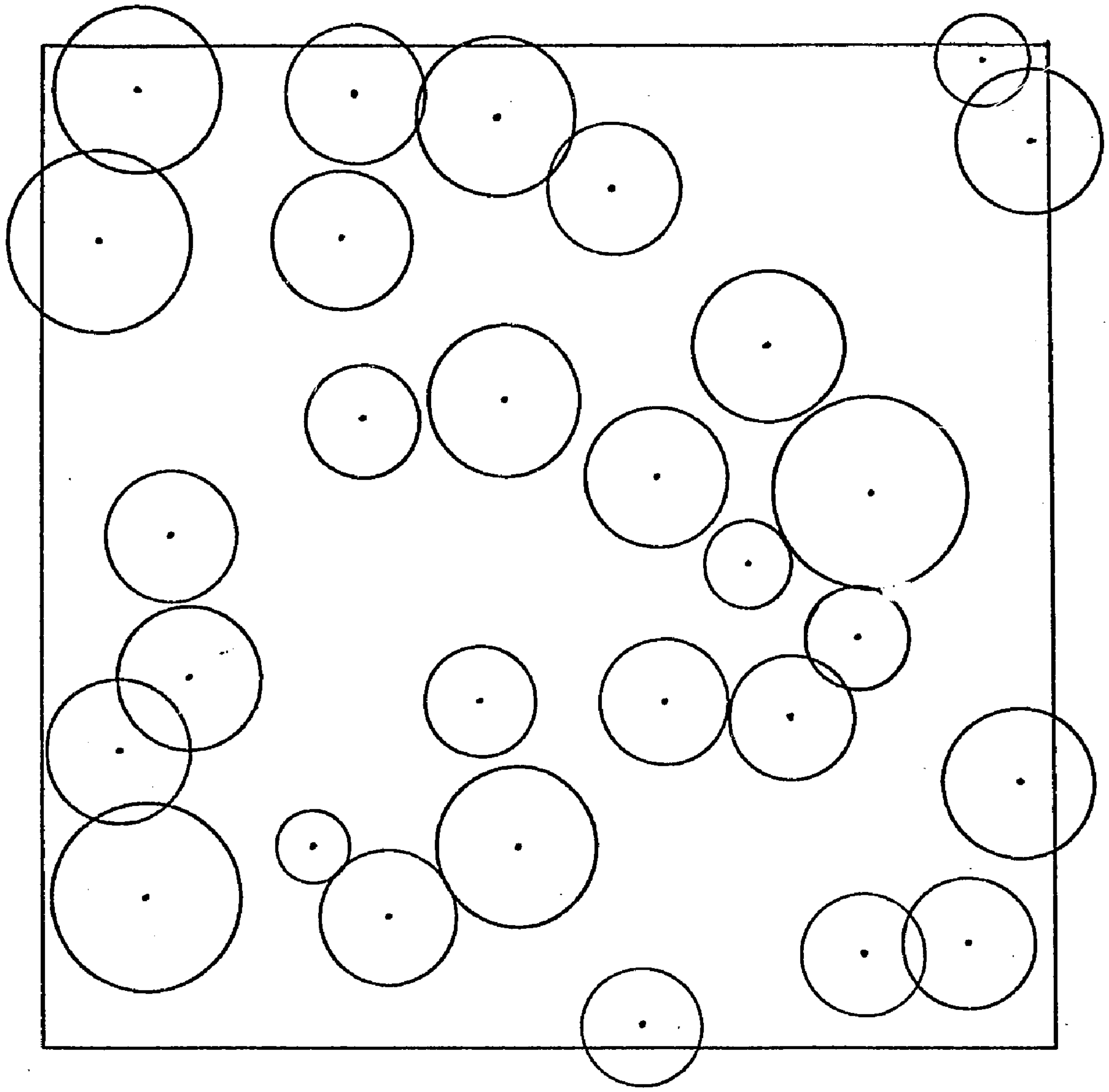
Scale: 1 in. = 20 feet

Figure 10. East Light Crown plot showing tree distribution and crown widths.



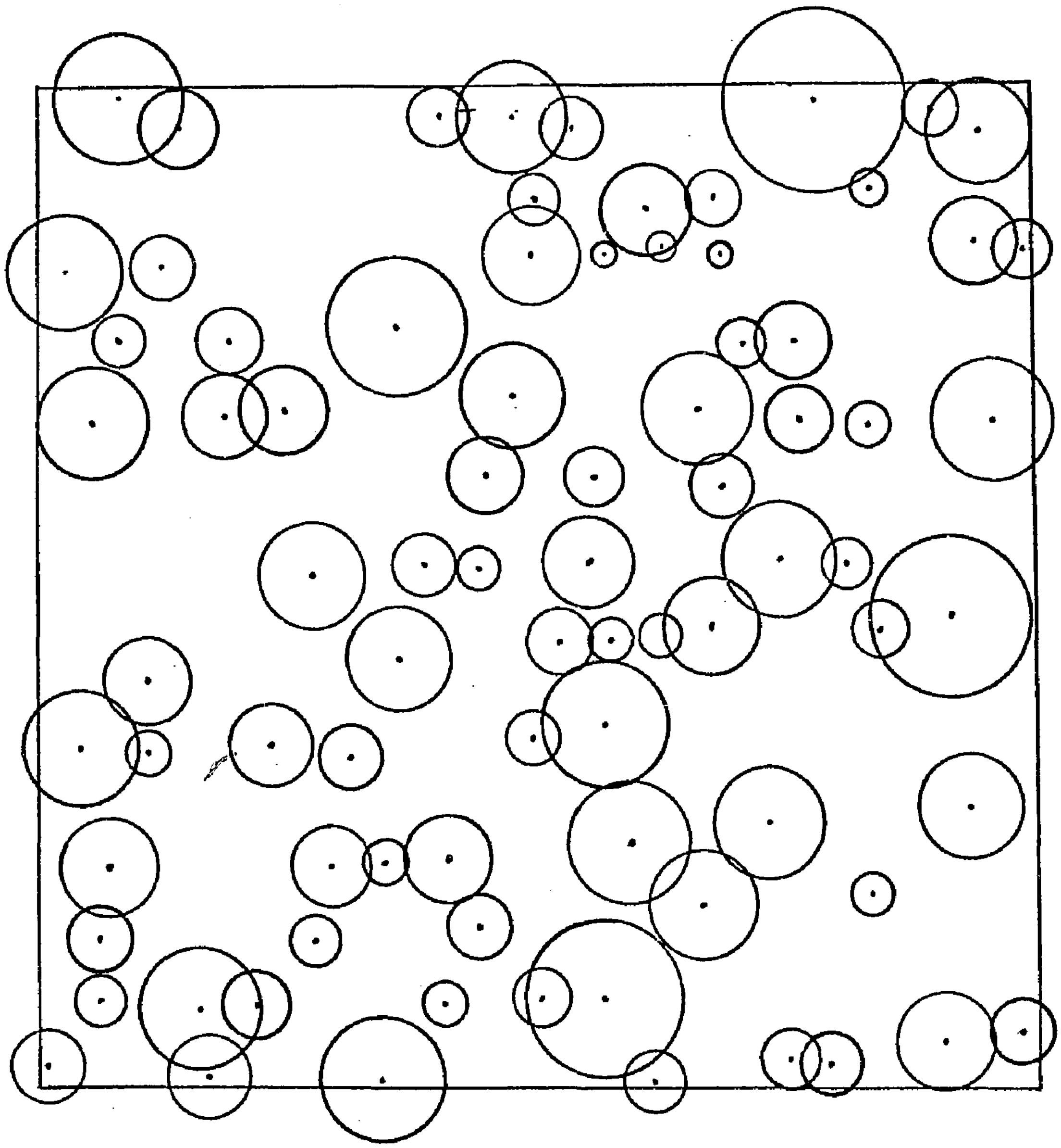
Scale: 1 in. = 20 feet

Figure 11. East Heavy Crown plot showing tree distribution and crown widths.



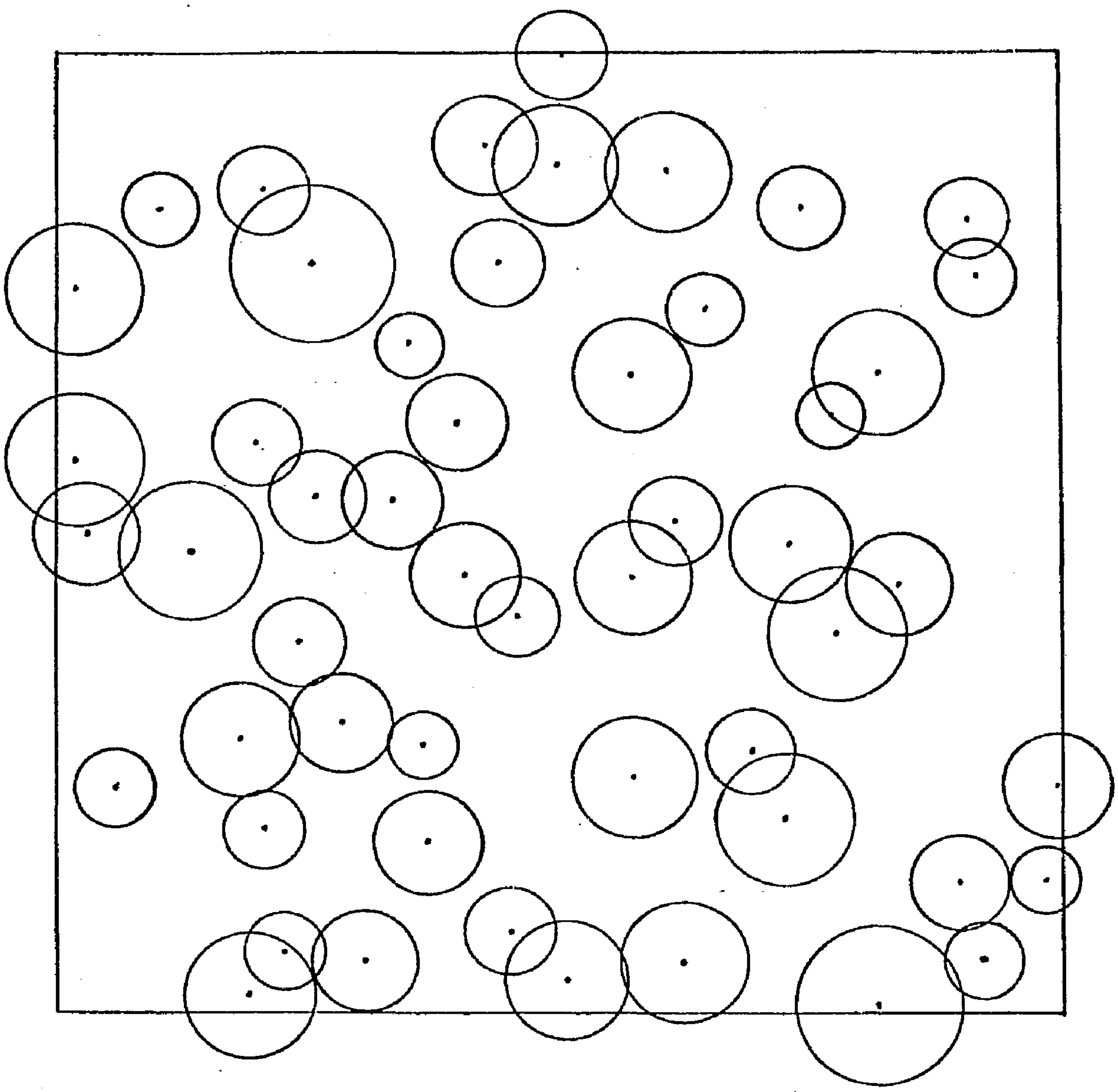
Scale: 1 in. = 20 feet

Figure 12. East Selection plot showing tree distribution and crown widths.



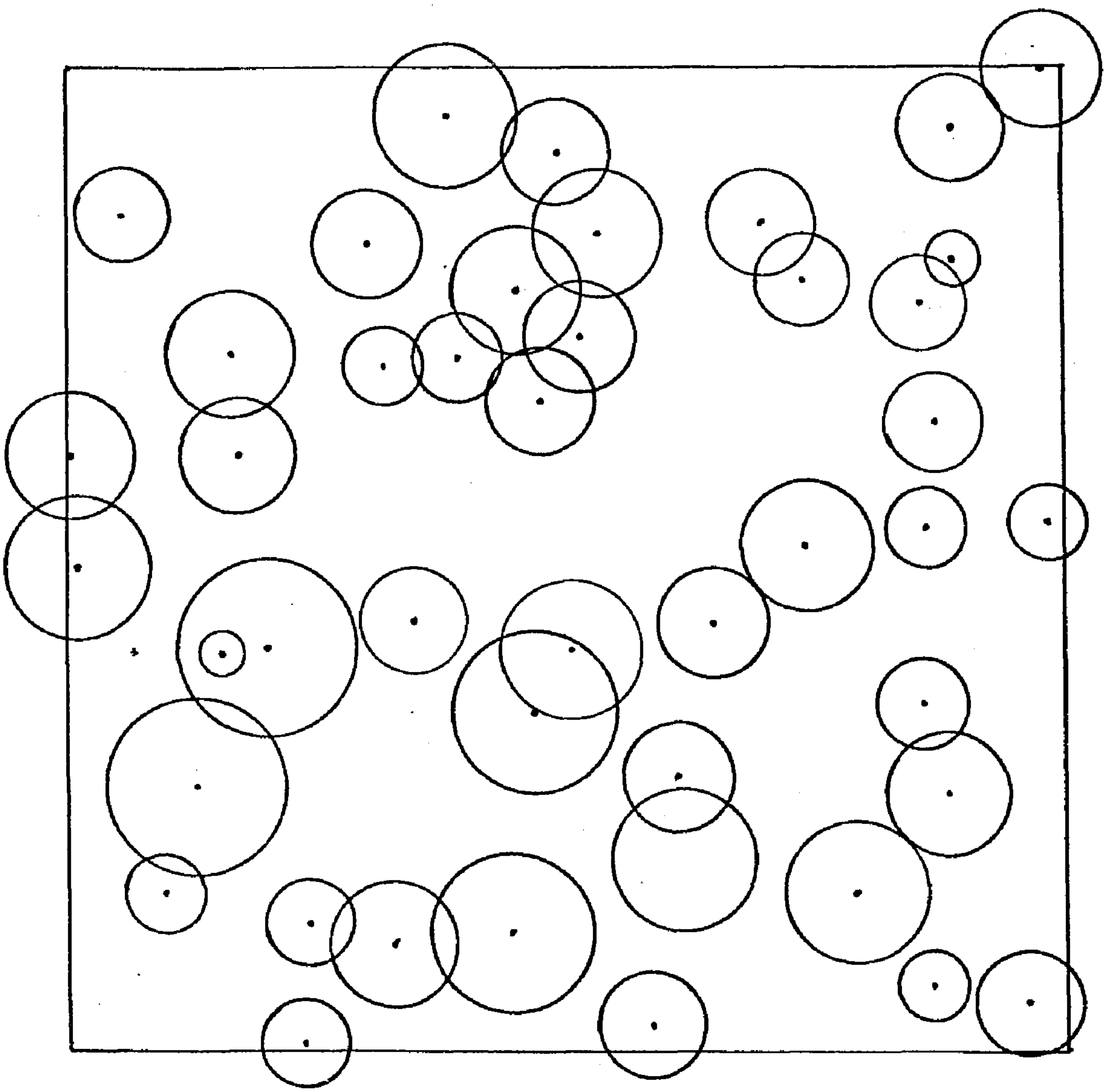
Scale: 1 in. = 20 feet

Figure 13. West Control plot showing tree distribution and crown widths.



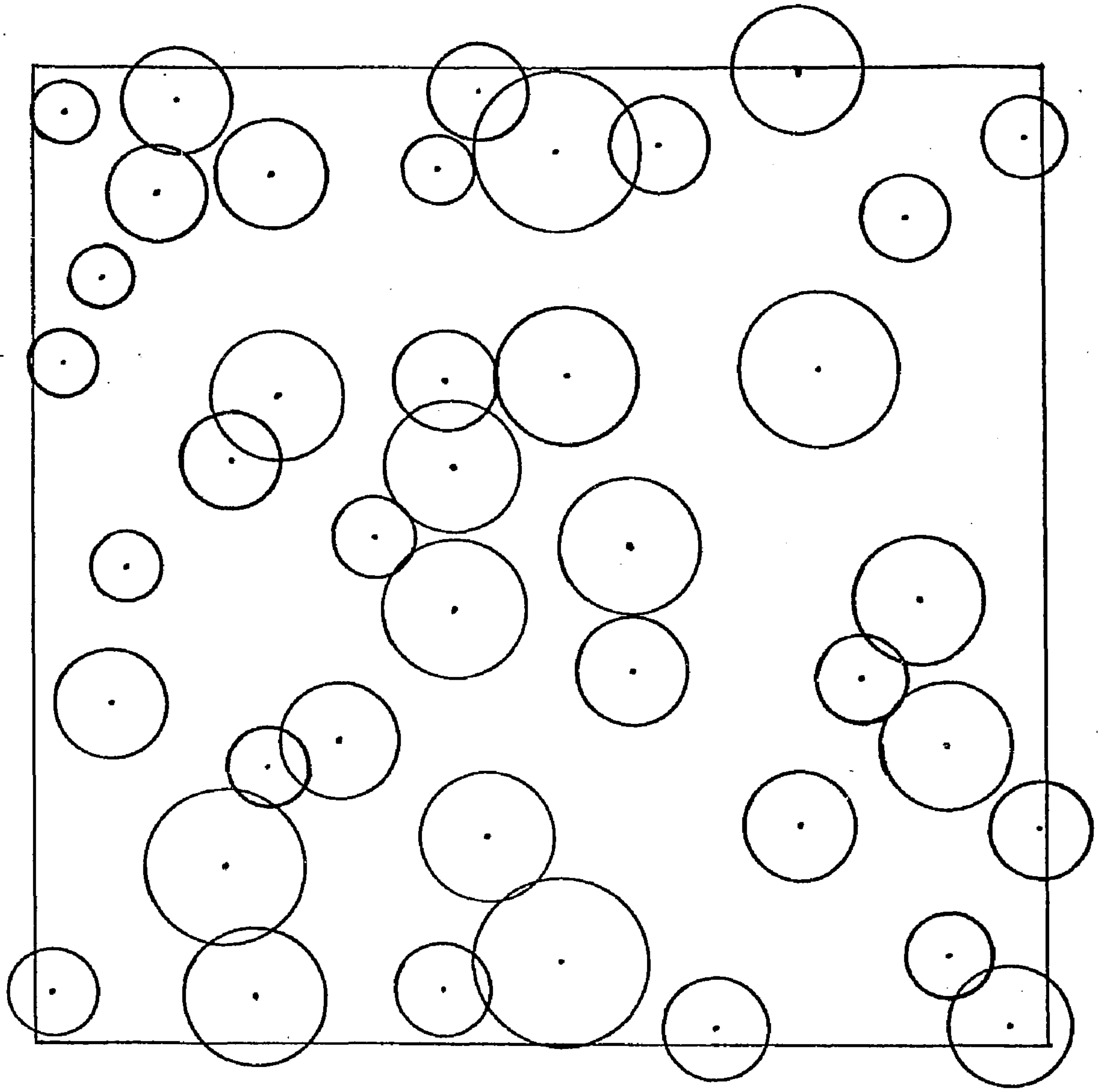
Scale: 1 in. = 20 feet

Figure 14. West Low plot showing tree distribution and crown widths.



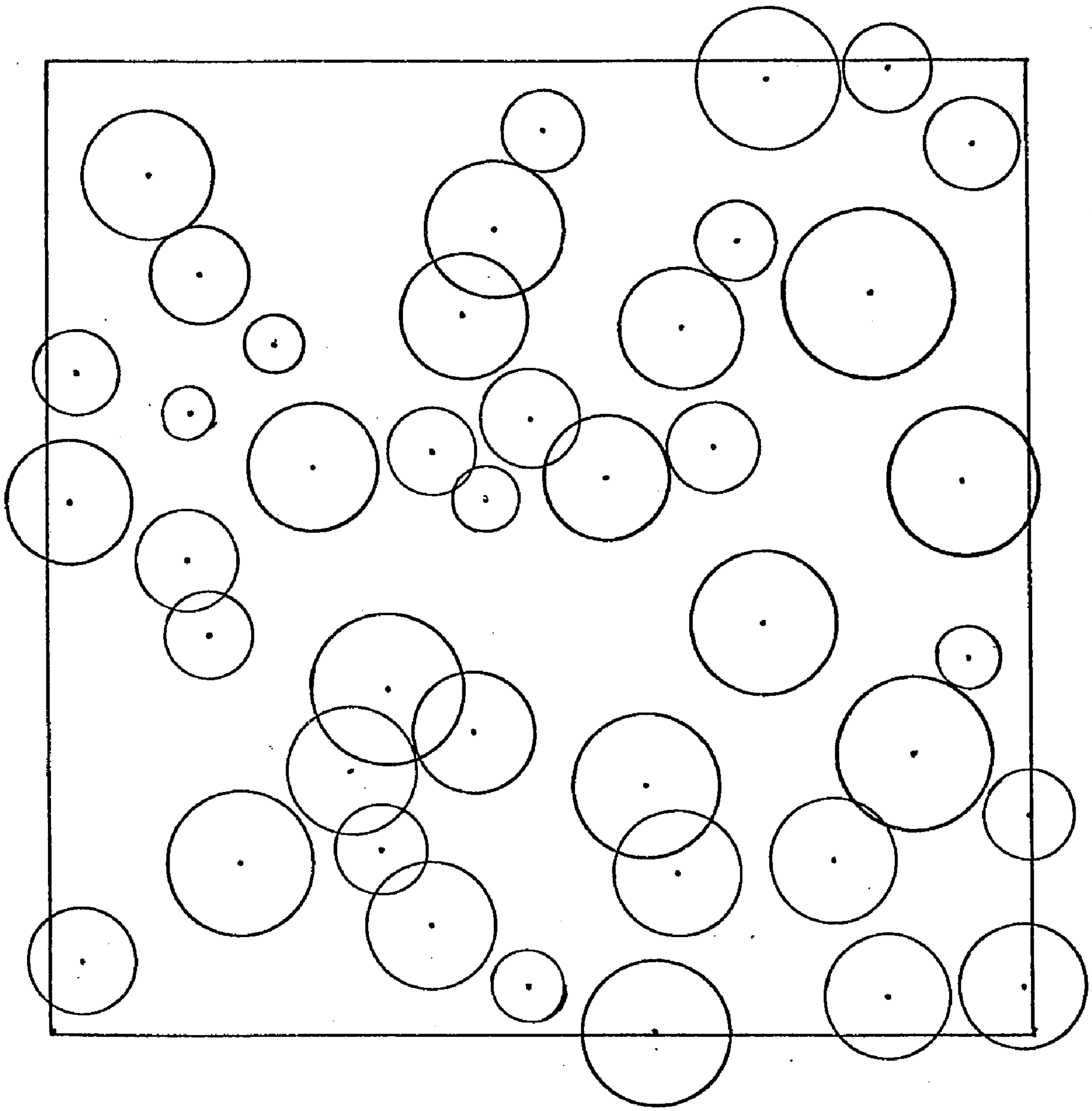
Scale: 1 in. = 20 feet

Figure 15. West Light Crown plot showing tree distribution and crown widths.



Scale: 1 in. = 20 feet

Figure 16. West Heavy Crown plot showing tree distribution and crown widths.



Scale: 1 in. = 20 feet

Figure 17. West Selection plot showing tree distribution and crown widths.

APPENDIX E - REGRESSION EQUATIONS FOR PREDICTING THE HEIGHT OF TREES ON EACH PLOT FROM THE DIAMETER (D.B.H.) AT AGE 40

Plot	Regression equation
East Control	$h = -6.0650 + 10.7638X - .2755X^2$
East Low	$h = -46.0725 + 19.6372X - .7164X^2$
East Light Crown	$h = -25.1040 + 14.4091X - .4384X^2$
East Heavy Crown	$h = -.1244 + 7.5814X - .0213X^2$
East Selection	$h = 12.5212 + 4.1357X + .1664X^2$
West Control	$h = -11.9926 + 12.2682X - .3744X^2$
West Low	$h = -39.2127 + 16.8606X - .5536X^2$
West Light Crown	$h = -15.8495 + 12.2383X - .3055X^2$
West Heavy Crown	$h = -9.6148 + 9.9218X - .1816X^2$
West Selection	$h = 7.2930 + 6.8328X - .0439X^2$

h = height X = diameter

APPENDIX F. A DESCRIPTION OF THE FORTRAN PROGRAM FOR COMPETITION INDEX

1. A list of the more important variables in the program with their meanings.

AI	The b_o coefficient from the height-diameter regression developed on page 133.
BI	The b_4 coefficient from the height-diameter regression developed on page 133.
CI	The b_2 coefficient from the height-diameter regression developed on page 133.
COMP	The area in sq. ft. of the zone of overlap of two circles of influence (the value C_i in equation on page 128).
CONS	The radius of the sample tree's circle of influence (K in equation on page 128).
DC	Diameter in inches of a competing tree.
DS	Diameter in inches of a sample tree.
E4(I)	Index for zone I in all quadrants. I = 1, 2, ...n. Zones were 15, 25, 35, 45, and 55 ft. from sample tree in this study. There were four quadrants; northeast, southeast, southwest, and northwest.
EF(I)	Index for Zone I within the quadrant J. I = 1, 2, ...n; J = 1, 2, 3, 4.
N4(I)	Number of trees in Zone I for all quadrants.
NS(I)	Number of trees in Zone I; quadrant J.
QUAD	Quadrant number. Northeast = 1, Northwest = 4, Southeast = 2, Southwest = 3.
R	Radius of a competing tree's circle of influence (R in equation on page 128).
S4(I)	Sum of the COMP in Zone I, all quadrants.
STREE	Sample tree number.

SUM(I) — Sum of all COMP in Zone I within quadrant J.

X — Distance in feet between a sample tree and the i th competing tree (X in equation on page 128).

Z — Proportionality constant as developed on page 139.

2. Arrangement of cards for input data

Card	
1	Card with a value for Z, the proportionality constant that will be used.
2	Sample tree card - contains the tree number and diameter as well as the b_o, b_1, and b_2 constants from the height-diameter regression. (AI, BI, and CI in program.)
3	Quadrant number = card following sample tree card must always equal 1.
4···n	Competing tree cards. Contains tree diameter and distance to the sample tree.
n + 1	A 999 card. 999 is placed in columns reserved for diameter to indicate end of Quadrant.
n + 2	Quadrant number (2 in this case)
n + 3···m	Competing tree cards
m + 1	A 999 card
m + 2	Quadrant number (3)
m + 3···o	Competing tree cards
o + 1	A 999 card
o + 2	Quadrant number (4)
o + 3···p	Competing tree cards
p + 1	A 999 card
p + 2	Next sample tree card and continues as from card 2. If there are no more sample trees an 888 card (instead of 999) is inserted to indicate last card.

3. Description of the FORTRAN program.

Line No.	Operation No.	
1 - 17		Input section. The basic data are read into the machine with print out headings for output data.
22 - 24	31	Checks for last tree and goes to operation 41 if not the last tree and to operation 42 if last tree and end of program.
25 - 26	41	Computes CONS
34 - 36	20	Tests for competing tree. If not a 999 card go to operation 12. If a 999 card go to next card.
37 - 40	12	Compute R and values A and B from equation on page 128.
41 - 65		Computes value for COMP taking into consideration the various restrictions listed in Appendix C.
66 - 89		Sort into competition by zones and quadrants and total.
90 - 103		Computes index and sums by zone, quadrant, and total
104 - 109		Print total tree competition.

4. The FORTRAN Program

Source Statement

```
$IBETC    COMP IB
          DIMENSION SUM(6),NS(6),S4(6),N4(6),EF(6),E4(6)
     6    FORMAT (F6.2,F5.1,3F9.4)
     7    FORMAT (22H SAMPLE QUADRANT NO OF)
     8    FORMAT (30H TREE NO          COMP          I)
     9    FORMAT (22H                 TREES)
    10    FORMAT (F2.0)
    11    FORMAT (F5.1, F4.1)
    17    FORMAT (2X.F8.2,1X,I2,5X,I3,2X,E14.4)
    22    FORMAT (2X,I2,2X,E14.4,3X,I2,2X,E14.4,3X,I2,2X,E14.4)
    24    FORMAT (2X,I2,2X,E14.4,3X,I2,2X,E14.4)
    27    FORMAT (2X,F7.2,4H ALL,5X,I3,2X,E14.4)
    75    FORMAT (2X,F10.5)
     5    FORMAT (F3.2)
          PRINT 7
          PRINT 8
          PRINT 9
          READ5,Z
    25    COUNT=0.0
          DO31I=1,6
          S4(I)=0.0
    31    N4(I)=0
          READ6,STREE,DS,AI,BI,CI
          NOS=STREE
          IF(NOS-8)41,42,41
    41    CONS=Z*(AI+BI*DS+CI*(DS**2))
          PRINT75,CONS
    21    QNO=0.0
    29    SCOR=0.0
          DO30I-1.6
          SUM(I)=0.0
    30    NS(I)=0
          READ10,QUAD
          QNO=QNO+1.
    20    READ11,DC,X
          NC=DC
          IF(NC-99)12,18,12
    12    SCOR=SCOR+1.
          R=Z*(AI+BI*DC+CI*(DC**2))
          A=CONS**2+R**2
          B=CONS**2-R**2
          IF(X-(CONS+R))51,48,48
    51    IF(X+R-CONS)54,54,53
```

```
48    COMP=0.
      GOTO49
54    COMP=3.1416*R**2
      GOTO49
53    IF(X+CONS-R)55,55,4
55    COMP=3.1416*CONS**2
      GOTO49
 4    UNITA=SQRT(X**2*(2.*A-X**2)-B**2)
      IVAR=X**2+B
      IVAR2=X**2-B
      IF(IVAR)56,57,58
56    UNITI=3.1416-ATAN(UNITA/(-(X**2+B))
      GOTO59
57    UNITI=1.5708
      GOTO59
58    UNIT1=ATAN(UNITA/(X**2+B))
59    IF(IVAR2)60,61,62
60    UNIT2=3.1416-ATAN(UNITA/(-(X**2-B))
      GOTO63
61    UNIT2=1.5708
      GOTO63
62    UNIT2=ATAN(UNITA/(X**2-B))
63    COMP=UNIT1*(CONS**2)+UNIT2*(R**2)-UNITA/2.
49    NX=X
      IF(NX-15)81,83,80
81    SUM(1)=SUM( 1)+COMP
      NS(1)=NS(1)+1
      GOTO50
80    IF(NX-25)83,85,82
83    SUM(2)=SUM(2)+COMP
      NS(2)=NS(2)+1
      GOTO50
82    IF(NX-35)85,87,84
85    SUM(3)=SUM(3)+COMP
      NS(3)=NS(3)+1
      GOTO50
84    IF(NX-45)87,86,86
87    SUM(4)=SUM(4)+COMP
      NS(4)=NS(4)+1
      GOTO50
86    SUM(5)=SUM(5)+COMP
      NS(5)=NS(5)+1
50    SUM(6)=SUM(6)+COMP
      GOTO20
18    NTREE=STREE
      NOQ=QNO
      NSCOR=SCOR
23    BVAR=1./((CONS**2)*(3.1416))
      DO321=1,6
32    EF(I)=BVAR*SUM(I)
```

```
      PRINT17,STREE,NOQ,NSCOR,EF(6)
      PRINT22,NS(1),EF(1),NS(2),EF(2),NS(3),EF(3)
      PRINT24,NS(4),EF(4),NS(5),EF(5)
      DO33I=1,6
      S4(I)=S4(I)+SUM(I)
33    N4(I)=N4(I)+NS(I)
      COUNT=COUNT+SCOR
      IF(NOQ-4)29,19,29
19    DO34I=1,6
34    E4(I)=BVAR*S4(I)
      NCOUN=COUNT
      PRINT27,STREE,NCOUN,E4(6)
      PRINT22,N4(1),E4(1),N4(2),E4(2),N4(3),E4(3)
      PRINT24,N4(4),E4(4),N4(5),E4(5)
      GOTO25
42    STOP
      END
```

VITA

Thomas D. Keister was born May 1, 1927, at Neligh, Nebraska. He was the second of two children born to Baird V. and Emma Keister.

He attended Arkansas State College from September 1944 until July 1945 and from January 1947 until August 1947.

He entered Iowa State University in September 1947 where he majored in Forestry. He received a Bachelor of Science degree from this school in June 1950.

In 1956 he entered Louisiana State University where he majored in forestry and received a Master of Science degree in August 1963. He is currently seeking a Doctor of Philosophy degree from Louisiana State University.

He was employed by the International Paper Company as a forest technician at Springhill, Louisiana, from July 1950 until October 1951.

He was employed by Gaylord Container Corporation (now Crown Zellerbach Corporation) as an area forester from October 1951 until July 1959 and as a forest statistician from July 1959 until June 1964.

Since June 1964 he has been employed as an Instructor in the School of Forestry and Wildlife Management at Louisiana State University, Baton Rouge, Louisiana.

Mr. Keister served in the United States Army Reserve and was on active duty from July 1945 until January 1947. Most of this time was spent in Vienna, Austria.

He is married and is the father of two sons, aged 11 and 13.

EXAMINATION AND THESIS REPORT

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Title of Thesis: Thinning methods in slash pine plantations

Approved:

Paul Y. Burns
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Date of Examination:

May 27, 1966