SIMULATED CROWN LIGHT INTERCEPTION AS AN INDEX TO COMPETITIVE ABILITY FOR UNEVEN-AGED MIXED HARDWOODS

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SIMULATED CROWN LIGHT INTERCEPTION
AS AN INDEX TO COMPETITIVE ABILITY
FOR UNEVEN-AGED MIXED HARDWOODS

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ABSTRACT

SIMULATED CROWN LIGHT INTERCEPTION
AS AN INDEX TO COMPETITIVE
ABILITY FOR UNEVEN-AGED
MIXED HARDWOODS

By

Michael Joseph Beauregard

An index of individual tree competitive ability based on simulated crown light interception was evaluated in this study. The basis for judging the relative merits of the index were (1) its ability to account for periodic basal area growth, and (2) its sensitivity to changes in competitive stress caused by partial release cutting. Data from a previously undisturbed oak-hickory stand in central Michigan were used for the investigation.

In developing this index (termed the crown view factor index), it was theorized that the competitive ability of a tree is directly related to the unobstructed area of its crown surface. To construct the competitive index, the three-dimensional spatial distribution of neighboring tree crowns, together with relative crown form and size were considered with respect to each study tree crown. Geometrically, the crown view factor index

respresents the view of the sky hemisphere from the centroid of the tree crown. The index value was set as the ratio of the crown view factor surface area for a tree to the maximum surface area expected under forest-grown conditions for a tree of the same size.

The determination of competing trees was designed to recognize that large trees receive competition primarily from immediate neighbors, whereas small trees may be affected by a large tree a greater distance away. To establish this relationship a conical influence space was established around each tree based on total tree height and crown form. Any tree crown intersecting this space was considered to be in a competitive relationship with the tree.

The regression model used to evaluate basal area growth included terms representing the initial d.b.h. for the growth period, indicator variables to distinguish between four species groups, the crown view factor competitive index, surface area of the crown view factor, the number of competitors, and a release factor represented by the change in the crown view factor surface area before and after partial cutting.

All variables relating to competitive ability were significant, with the exception of the number of competitors. The crown view factor index and related surface area and release factor terms accounted for a substantial amount of basal area growth variation. Significant first-order interaction terms were also observed between species groups and release factor, indicating a difference in response functions between species for trees influenced by release cutting. The crown view factor model, when compared to a competition circle model developed using the same data base, accounted for a greater percentage of growth variation. Most of the increase was attributed to a greater sensitivity in the competitive index measure used.

The crown view factor concept proved to be an effective measure of both competitive ability and release from competitive stress for individual trees in a mixed hardwood stand.

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A DISSERTATION

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CHAPTER I

INTRODUCTION

Silvicultural practices and recommendations have long been based on stand density as a measure of competitive stress for growing space within a forest stand. Measures commonly used to express this 'average' relationship include the number of trees or volume per unit area and expressions of tree crown area per unit ground area.

The inverse relationship existing between tree frequency and bole size, on any given unit area, is one of the cornerstones of silvicultural practice. The essence of this relation is that as trees increase in size they require a larger growing space. Therefore, it is assumed as axiomatic that competitive stress increases within a natural stand as average tree size increases. A corollary is that each individual tree also requires more growing space as it matures.

The importance of viewing a forest as a population of individuals, rather than as an average stand unit, lies in the fundamental contribution of each tree to the stand.

Managerial decisions, e.g., silvicultural treatments, can then be made on the basis of individual requirements rather than on average stand conditions. The drawback, of course, is the correspondingly higher cost for such treatments. Given current economic trends and resource shortages, however, increasingly intensive management will certainly be justified.

When considering silvicultural treatment on an individual tree basis the concept of stand density retains little meaning. Stand density is formulated on a macro-environmental basis, whereas the growth of any particular tree depends primarily on its specific micro-environment. Silvicultural treatment designed to increase growth will be effective only to the extent that it modifies the immediate environment of a tree in a beneficial manner.

Competition is considered the most important environmental factor influencing tree growth in that it can be controlled by silvicultural treatment. To most effectively apply treatments on a tree by tree basis, a predictive measure of competitive ability is necessary. A suitable measure of this nature has not as yet been developed for stands of mixed species composition.

Numerous factors and complex interactions are involved in the growth of a tree. Light interception, soil nutrients, soil moisture, slope, aspect, climate, and the number, size and location of neighbors are all important elements. A predictive measure including all such factors would have little practical application, however. A measure based on tree parameters which adequately account for the sources of growth variation would be preferable. The problem is to determine those parameters which provide the best estimates of competitive ability.

The growing space of a tree is a critical environmental factor, and may be defined as the aerial and terrestrial region from which the tree extracts its food supply. Required growing space varies with the individual tree by species, age, and genotypic characteristics. Available growing space is determined by the environmental factors influencing the tree and by the frequency and proximity of its neighbors. The environmental factors affect tree growth and quality directly through the tree crown and roots. Therefore, the physical crown and root characteristics are of primary importance in determining growth.

From a forestry standpoint, tree bole or stem increment is the most important aspect of tree growth. Bole growth is a reflection of the physiological activities of the tree crown and roots, under specific competitive status. Given the relative inaccessibility of root measurement, the tree crown is the most logical characteristic to use for estimating individual tree competitive ability. The tree crown in this respect was acknowledged by Mitchell (1969) as often being the main competitive factor limiting survival.

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The importance of tree crowns as indicators of growth and competition is evident in the use of crown size and position in developing silvicultural crown class categories. Tree crowns have also been recognized as a measure of stand density, wherein the area available to the average tree in a stand is determined in relation to the maximum area it could use if open-grown (Krajicek et al., 1961).

Very little investigative effort has been made to evaluate the importance of aerial crown dimensions and spatial position in relation to individual tree competition and growth, particularly in mixed species stands. A notable exception is the work of Horn (1971) in developing a model for light interception and forest succession. Thorough analysis of such spatial relationships should provide a good measure of competitive light interception ability. It should also serve as a general index of competitive ability, since light is a primary limiting factor in tree growth.

The purpose of this study is to develop and evaluate an index of simulated crown light interception ability for individual trees in a mixed hardwood stand. The model proposed represents a new approach to measuring competitive ability in that vertical and horizontal spatial distributions, as well as relative crown form and size, are considered in a three-dimensional relationship. Basal area growth will be utilized for response evaluation in the model, since the growth of individual trees varies directly in relation to respective competitive ability.

CHAPTER II

MEASURES OF INDIVIDUAL TREE COMPETITION

Active interest in evaluating individual tree competition is relatively recent and corresponds quite closely with the development of high-speed digital computing capabilities. This is not totally coincidental since most of the measures proposed involve fairly elaborate mathematical operations. Problems of this type are ready made for the ever increasing computational and memory storage abilities of modern digital computers.

Measures of individual tree competition proposed to date are variations of three or four basic concepts. These are summarized below according to the underlying developmental procedure.

Angular Functions

Various expressions of basal area angle count were the first measures developed for the determination of competition for individual trees. Among such measures were angle count (Lemmon and Schumacher, 1962), angle summation (Steneker and Jarvis, 1963), and point density

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(Spurr, 1962). An unsatisfactory aspect of these measures in defining competitive stress was the failure to adequately define competing neighbors with respect to distance and size.

Area Potentially Available

Brown (1965) introduced the concept of area potentially available (APA) as an index of point density. Trees were partitioned into a closed network of polygons, each encompassing a single tree, on the premise that each tree has potentially available to it one-half of the distance to each of its neighbors. This procedure assigns equal weight to all trees in determining growing space. Moore et al. (1973) modified the APA concept by dividing the distance between neighbors in proportion to relative tree size. This provided a more meaningful measure of competitive ability. A disadvantage of both APA models is that the area polygons may assume unrealistic shapes and sizes, bearing little relationship to actual areas of biological influence.

Competition Circle Functions

Several researchers have developed competition models based on the concept of tree competition circles or influence zones. The competition circle is considered to represent the area over which a tree competes. Only those trees whose circles overlap are considered competitors. The circle radius is generally established as some function of tree diameter or crown width. Competition is expressed as the overlap of circles of adjacent trees. Competition circles may be considered measures of crowding, as opposed to available area determined in the APA models.

Staebler (1951) first developed a competition index based on competition circles. He established circle radius as a function of tree diameter. Competition was measured as the amount of linear overlap of intersecting circles. Newnham (1966) set circle radius as both a function of crown radius of open-grown trees of equal size and as a diameter expansion factor. He expressed competition as the proportion of the circumference of the competition circle overlapped by competitors.

Opie (1968) used the circular influence zone concept and based the radius value on both tree diameter and site conditions. He measured competition as the actual area of overlap, expressed in terms of basal area per acre. Gerrard (1969) also measured the area of overlap in determining a competition quotient index. He based the competition circle radius on a diameter expansion factor selected as optimal from a series of trial factors. Gerrard compared the competition quotient index with Newnham's competition index, Spurr's measure of point density, and a modified version of Spurr's point density index. The competition quotient index provided the strongest correlations with basal area growth.

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Bella (1971) proposed a competitive influence-zone overlap index of competition which recognized that trees of different sizes do not affect each other equally in competitive interaction. Previous models assumed that a certain amount of overlap indicated the same competitive effect, whether from one big tree or several small trees. Bella modified the competitive overlap effect by using a weighted diameter ratio of the competing and study trees to give greater weight to larger trees. Bella's model was compared by Moore to the APA model mentioned above. He found the APA model accounted for a significantly greater amount of growth variation.

Keister (1971) used a more direct approach to relate tree size to the competition circle influence zone. He set the radius of the tree's influence circle equal to the perpendicular distance between the tip of the tree and the intersection of a line from the base of the tree through the outer edge of the crown base. The result was an inverted cone, the projected base of which formed the influence zone. The area of overlap of the circular influence zones was used to estimate competition.

Mitchell (1969) used the concept of competition circles to develop a growth simulation model for white spruce (Picea Glauca (Moehch.) Voss.). Maximum crown width was utilized as a measure of aerial growing space or light interception ability. To evaluate competition he expressed crown width as a function of the maximum crown

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width that the tree could have attained had it been open-grown.

Ek and Monserud (1974) developed a model for simulating the growth and reproduction of mixed species forests, using competition circles to determine competitive status. Circle size was set as a function of crown radius and the area of circular overlap was used to measure competition. The final competitive index was adjusted according to the shade tolerance of the study tree. The tolerance adjustment factor was set as a function of tree size, ranging from close to zero for small, intolerant trees to one for mature trees.

Krajicek et al. (1961) worked with competition circles in developing a crown competition factor as a measure of stand density. An observed relationship between crown diameter and d.b.h. of open-grown trees formed the basis for this measure. To determine the crown competition factor the crown width of forest-grown trees was compared with the average crown size of open-grown trees of the same diameter. The sum of the maximum crown area projections for the trees was expressed as a percentage of actual ground area occupied, on a per acre basis. The crown competition factor is thus a measure of average growing space, or the area available to the average tree in a stand in relation to the maximum it could use if open-grown. It is not a true measure of individual tree competition.

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The competition circle models outlined above do not account for the true spatial distributions of tree crowns in competitive interactions, since two-dimensional projections are utilized. Competition circle models are also limited by the implicit assumption that competition does not exist unless competition circles overlap. Most of the models also fail to express the effect of relative tree size on competitive interactions.

Spatial Functions

Horner (1972) proposed a height-density concept based on the relationship between crown width and tree height. The point density for any tree was defined as the ratio of the area required by a tree growing free of competition to the actual area available under competitive conditions. The squared crown width/height relationship of open-growth trees defined the optimal area required. The square of actual crown width represented the area available. Since height is relatively independent of density, whereas diameter is not, height was used in developing this measure. The height-density concept is similar to Krajicek's crown competition factor, but attempts to express the degree of spatial utilization in terms of a tree's aerial dimensions.

Horn (1971), in developing a theory of forest succession, examined the light interception of a tree through analysis of its geometric crown surface area. The cr

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crown was sliced into thin, transverse segments parallel to the path of the sun, and a one-dimensional projection was determined for each segment. This projection represented the amount of light flux intercepted by the segment for a given sun angle. Total light interception for a tree was then obtained by integrating the projection function for each segment over all angles of the half circle over which the sun moves during the day, and summing all segments. Using this procedure the total projection of a tree over the period of a day is proportional to the convex surface of its crown.

Horn recognized three factors in describing the shape of a tree crown; size, convexity, and the ratio of height to width. Using these factors, most tree shapes could be generated from the following equation:

$$X^a + (bY)^a = c^a \qquad (1)$$

where X and Y are variable Cartesian coordinates in the equation and a, b, and c are constants representing convexity, the ratio of height to width, and absolute size respectively.

Horn's measurement of crown light interception ability is unique in the consideration of three-dimensional crown geometry. However, the measure was used only in the development of a successional theory for various tree species. No attempt was made to relate competitive effects of neighboring trees to light interception ability for individual trees.

A trend towards recognition of the importance of relative tree size, spatial position and three-dimensional form can be seen in the above measures of competitive ability. More detailed study is necessary, however, to fully assess competition for growing space in terms of aerial tree dimensions.

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CHAPTER III

CROWN VIEW FACTOR

In solar radiation studies, a method used to determine total radiation received at a point on an object is to measure the amount of radiation contributed by each portion of the view of the object (Reifsnyder and Lull, 1965). The geometric concept used to express this proportion is called the view factor of the object. This is the solid angle formed as a function of the diameter of the opening and the height of the surrounding objects.

The crown view factor proposed for the development of this study is an extension of the view factor concept. The crown view factor is defined as the surface area of a hypothetical tree crown unobstructed by adjacent tree crowns. This area is proportional to the segment of the sky hemisphere viewed by the tree from its geometric center. The crown view factor is assumed to represent the competitive ability of the tree to intercept light.

In developing the crown view factor, an elliptical solid is generated for each tree, geometrically centered at

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the point of maximum crown radius. Total height, height to maximum crown radius, and crown radius parameters are required for this purpose. An elliptical form was chosen to represent the tree crown since it allows a wide range in the expression of crown form. This formulation corresponds closely to that developed by Horn, when the convexity parameter in equation 1 is set to two.

A three-dimensional ellipsoid is formed by rotating the ellipse determined by the tree crown radius and crown length values about the vertical tree axis. Crown radius is positioned at the point of maximum crown radius height to establish the spatial position of the tree crown. The portion of this ellipsoid above its centroid is taken to represent the crown solid for the tree. The exact form of the tree crown will vary depending on the relationship between crown length and crown radius. For any particular tree, the crown solid may vary in shape from a vertical to a horizontal ellipsoid. The geometry of the tree crown formulated above is shown in Figure 1.

The surface area of the crown solid is assumed to represent the maximum surface area available for light interception for a forest-grown tree. This is not an expression of surface area for an open-grown tree of the same size. Rather, it is the amount of crown surface area that an average tree of the given size would have when growing under competitive stand conditions. The crown view

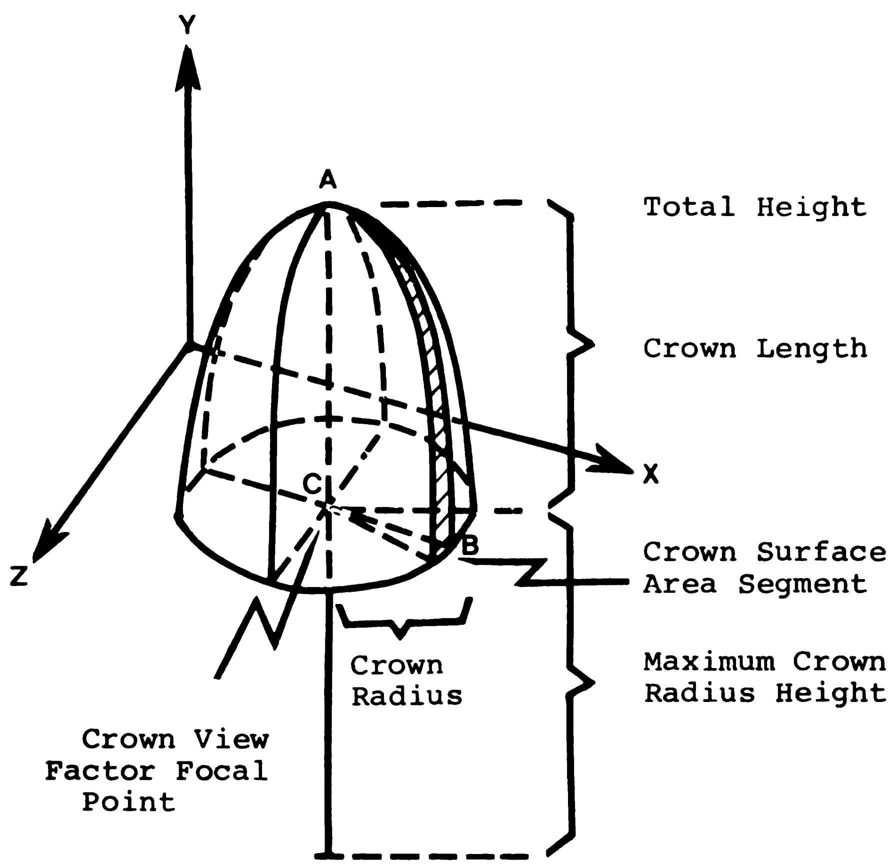

Figure 1. Geometry of tree crown solid.

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factor is the proportion of this area which has a direct view of the sky when viewed from the centroid of the crown solid.

The use of crown surface area for open-growth trees is a possible alternative measure of optimal surface area, since open-growth trees tend to have larger crowns than forest-grown trees. Minckler and Gingrich (1970) studied the relation between crown width and tree diameter for open-grown and forest-grown oak and hickory. They found that the diameter/crown width relationships were similar for well-stocked, uneven-aged stands, although variation in crown width was greater for the forest-grown trees. The relationship was also independent of site, crown class, and species.

The only apparent advantage for establishing the crown surface area in terms of open-grown trees is greater crown length. However, this effect is negated under forest-grown conditions. The hypothesized crown surface area based on crown length and crown radius parameters for forest-grown trees should provide a reliable measure for development of the crown view factor.

Having established the functional form of the tree crown, it is necessary to devise a means of segmenting the crown such that each portion is uniquely identified. This is required to allow discrete treatment of an otherwise continuous area and to facilitate computer storage and retrieval of relevant information. For this purpose, the

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crown solid is divided into 360 one-degree wedge shaped segments (see Figure 1). Each segment is assigned a directional position value based on relative azimuth, with one (1) assigned as the due north segment. Subsequent segments are numbered progressively in a counterclockwise direction. Each segment is thus a unique surface area unit for evaluation purposes, allowing treatment of the crown as a series of 360 discrete areas.

No particular significance is given to the value of 360 selected above for segmenting the crown surface area. It was chosen primarily to attain a reasonable compromise between the need for making the units small enough to adequately distinguish progressive obstructional differences about the tree, and the need to keep computational time within reasonable limits.

Once the crown form is established for a tree, the crown view factor is determined in relation to the frequency, location, crown form, and spatial position of competing trees. A definition of competitors is developed in Chapter VI for this purpose. For each such tree, the distance and directional position in relation to the study tree is determined, as well as the crown form. To determine the obstructional effect of each competing tree on the crown view of the study tree, a projection is made from its crown perimeter to the crown centroid of the study tree (the focal point for the crown view factor). The surface area within the intersection of this projection on the

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study tree is considered as an obstructed portion of the crown view factor. The obstructed area is assumed to be unavailable for light interception.

Each competing tree is similarly projected on the study tree and corresponding obstructed crown surface area determined. After all competing trees have been considered, the remaining or unobstructed surface area determines the crown view factor for the study tree, and hence the competitive ability of the tree to intercept light.

In developing the crown view factor as outlined above, it should be recognized that this is not a direct measure of light interception or photosynthetic ability. Rather, it is the view of the sky hemisphere above the tree crown solid. The unobstructed surface area represents the portion of the crown open to light incidence. It is assumed to be a reasonable approximation of the light interception ability of the tree.

Implicit in the definition of the crown view factor is the assumption that light eminates simultaneously from all points on the sky hemisphere and is directed at the tree crown centroid. This is a substantially different approach from that taken by Horn, in which the tree crown was segmented in transverse slices parallel to the path of the sun. Such a procedure is a more realistic approximation to the actual light source. However, his model was aimed primarily at the determination of light interception and not at determining a tree's competitive ability in relation to neighboring trees. If competing trees were considered, projections made only parallel to the sun path would in effect ignore those competing trees which are located in a more or less perpendicular direction in relation to the sun path. The view factor approach on the other hand recognizes trees in any direction as blocking a certain amount of the light source and growing space. The view factor assumption of light eminating from all points on the hemisphere also recognizes the possibility of indirect as well as direct radiation.

CHAPTER IV

THE STUDY AREA AND DATA BASE

The Lansing Woods, a 40-acre oak-hickory woodlot, located near Maple Rapids in Clinton County, Michigan, was selected for the proposed study. The area was made available to the former Lake States Forest Experiment Station for research purposes in 1952 by the Lansing Company, owners of the tract. The data gathered in subsequent research efforts form the basis for this project. This included size and growth information, as well as ground coordinate locations, for each tree of at least five inches in diameter. Gerrard (1967) utilized this same area for evaluation of his competition quotient index of competitive stress. Portions of the area description below are taken from his outline of the area.

The Lansing Woods was relatively unique from a research standpoint in that it was essentially a virgin stand. No cutting had taken place in the stand prior to the initialization of research data collection in 1952. White oak (Quercus alba L.), red oak (Quercus rubra L.), hi

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hickory (Carya sp.), and red maple (Acer rubrum L.) were the principal components of the stand. The white oak segment was first established on the area and formed a population which is approximately 300 years old. The remaining stand, estimated to range in age up to 120 years, was not established until the original white oak had attained maturity. Basal area averaged about 115 square feet per acre in 1952, prior to any cutting in the area.

The Lansing Woods is in the Gray-Brown forest soil region of Michigan. Soils in the area are generally fine-textured, of the Blount and Morley silt loam types, with approximately 12 inches of silty clay loam overlaying glacial till deposits. Topography in the area is flat to gently rolling, with elevations ranging from 733 to 768 feet above sea level. Site conditions are generally mesophytic. The combination of moist but well-drained loams and generally even terrain mark the area as a very good oak site for Michigan (Gysel and Arend, 1953).

Research data were collected in the Lansing Woods in a sequence of complete inventories which preceded partial cuttings. These occurred in the spring of 1952, 1956, and again in 1962. To facilitate the relocation of trees during these inventories, a grid system was installed during the initial survey, in which each two-chain square unit within the area was established as a separate plot. Each plot was subdivided into four one-chain square quadrants. All trees were identified on a quadrant basis.

The survey information recorded for each tree included plot and quadrant number, tree number, species, diameter breast height (d.b.h.), and tree status. The tree status value was indexed according to six categories as follows:

0--no tree (subsequent ingrowth)

1--d.b.h. less than or equal to 11 inches

2--d.b.h. greater than 11 inches

3--tree cut

4--tree damaged in logging

5--tree dead

Additional data collected, although not used in this study, included measures of merchantable height, soundess, vigor, and management potential.

The partial cuttings which took place in the Lansing Woods included first a light improvement cutting, in 1952, involving a twelve acre strip along the southern boundary of the woodlot. The second cutting, in 1956, took place along the northern boundary and included a strip of approximately 16 acres. The third cutting, in 1962, removed most of the remaining old-growth white oak throughout the area. This cutting occurred during the final inventory and prevented the remeasurement of about one hundred old-growth white oak. An outline of the Lansing Woods, showing areas affected by the 1952 and 1956 cuttings, is presented in Figure 2.

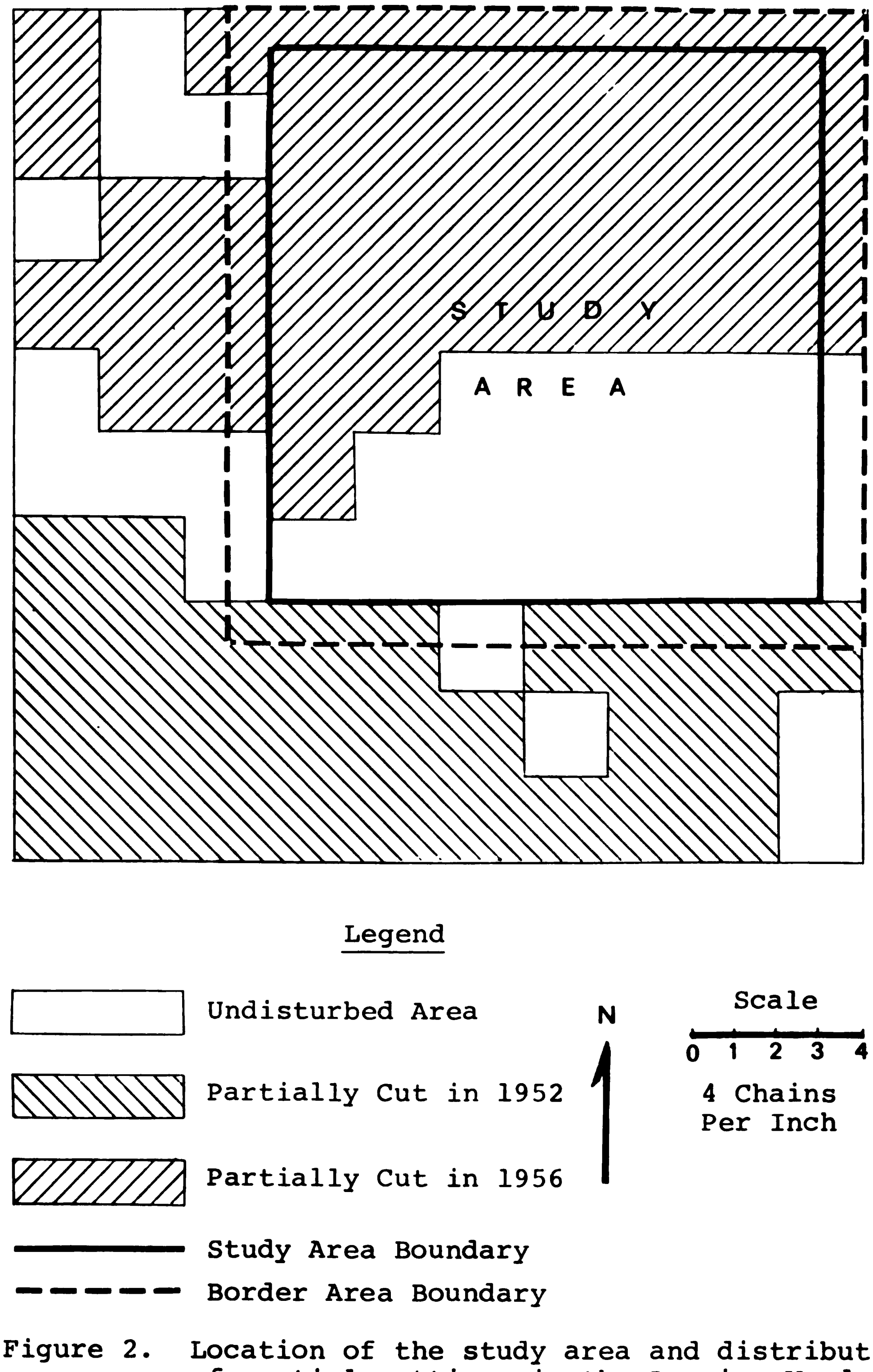

Figure 2. Location of the study area and distribution of partial cuttings in the Lansing Woods.

Since the original data gathered in the Lansing Woods did not include tree coordinate information, Gerrard reestablished the grid network in 1966, and determined the rectangular coordinates for all trees to the nearest foot. Trees previously harvested were identified during this reconstruction on the basis of stump diameter and species. All trees recorded were collated with tree data from area inventories.

All data was subsequently checked for consistency, and faulty records were either corrected or deleted from the data base, depending on the inconsistency involved. The previously mentioned white oak not having 1962 d.b.h. values were not deleted from the data base. Instead, these trees were considered only for their competitive effect and not in growth response determination. Less than 1 percent of all records for the 40 acres were deleted because of errors.

To avoid confounding the analytical task of growth prediction with trees cut at different times over the growth prediction interval, only the northeast portion of the 40 acre block was selected for study purposes. The area chosen is 16.9 acres in size, exclusive of the boundary area (see Figure 2). This is the same area which Gerrard utilized, with the exception of a small size reduction due to the use of the border strip along the north and east boundaries. This correspondence is not wholly accidental, as it facilitates a direct comparison of the crown view factor index of competition proposed here to Gerrard's competition index quotient.

Since cutting occurred in the study area chosen in 1956, a six year growth period is available for evaluation purposes. The cutting also provides an opportunity to examine the sensitivity of the crown view factor to varying degrees of release from competition.

The study area outlined above includes 3112 trees of five inches in diameter and above, of which 838 are in the border strip section. Of the remaining 2274 trees, 108 were ingrowth trees which entered the lower diameter class following the 1956 inventory. These trees were ignored for study purposes. Another 287 trees were either removed in the 1956 cutting, or died subsequently due to either logging damage or natural causes. These trees were included in the study for the purpose of measuring the release response on neighboring trees. Determination of trees assigned to either the ingrowth or release categories was based on tree status recorded in the 1956 and 1962 inventories. The remaining 1879 trees were utilized in the investigation for growth response evaluation. The distribution of these trees, by species and diameter class, is shown in Table 1.

Table 1.--Response tree distribution by species and diameter class.

DBH Class	White Oak	Red Oak	Black Oak	Pignut & Bitternut Hickory	Shagbark Hickory	Red Maple	White Ash	Amer. Elm	Misc.	Total
5	10	6	2	49	12	58	1	2	0	140
6	20	22	2	90	20	92	8	0	3	257
7	20	18	5	79	17	97	9	4	1	250
8	14	22	6	64	20	86	4	1	2	219
9	18	26	11	48	11	48	8	0	4	174
10	9	22	12	34	12	46	7	1	0	143
11	14	35	18	28	7	27	3	1	0	133
12	8	27	13	5	5	16	4	3	2	83
13	13	18	14	11	1	9	0	2	1	69
14	4	28	5	2	6	4	2	0	0	51
15	9	23	5	3	2	5	3	1	0	51
16	10	17	2	2	6	0	1	3	0	41
17	7	11	1	3	5	1	0	3	0	31
18	12	6	1	5	4	1	0	0	1	30
19	10	5	0	3	1	2	1	1	0	23
20	15	2	1	0	1	2	1	0	0	22
21	28	3	0	0	0	0	0	0	0	31
22	20	2	0	0	0	2	0	1	0	25
23	20	0	0	0	1	0	0	1	0	22
24	20	0	1	1	0	0	0	0	0	22
25	11	0	0	1	0	0	0	0	0	12
26	14	0	0	0	0	1	0	0	0	15
27	12	0	0	0	0	0	0	0	0	12
28	9	0	0	0	0	0	0	0	0	9
29	5	0	0	0	0	0	0	0	0	5

Table 1.--Continued.

DBH Class	White Oak	Red Oak	Black Oak	Pignut & Bitternut Hickory	Shagbark Hickory	Red Maple	White Ash	Amer. Elm	Misc.	Total
30	2	0	0	0	0	0	0	1	0	3
31	3	0	0	0	0	0	0	0	0	3
32	2	0	0	0	0	0	0	0	0	2
33	1	0	0	0	0	0	0	0	0	1
Total	340	293	99	428	131	497	52	25	14	1879

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CHAPTER V

CROWN FORM DEVELOPMENT

Original inventory data collected for the Lansing Woods unfortunately did not include information with respect to total height or crown form. To carry out the proposed study, additional height and crown form parameters were necessary to establish the forest on a three-dimensional basis.

The elapsed time differential prohibited the determination of required parameters for each tree. A sample survey was therefore conducted to obtain this information. Results of the sample were used in developing predicting equations applicable to the predominant species. Although a time differential exists between collection of original inventory data and the sample data, it is assumed that trees of a given diameter have corresponding height and crown form parameter values, regardless of time.

Oak, hickory, and red maple account for 95 percent of the fourteen different species represented in the study area. White ash (*Fraxinus americana* L.) and American elm

(*Ulmus americana* L.) make up most of the remaining 5 percent. The miscellaneous grouping, representing less than 1 percent of the stand, consists of two or three stems each of sugar maple (*Acer saccharum* Marsh.), slippery elm (*Ulmus fulva* Michx.), black ash (*Fraximus nigra* Marsh.), black cherry (*Prunus Serotina* Ehrh.) and cottonwood (*Populus deltoides* Bartr.).

Due to the small number of individuals occurring within some of the categories, a certain amount of grouping based on silvicultural similarities and physical characteristics was deemed necessary. White oak, due to its unique age distribution was maintained as a single species group. Red oak and black oak (*Quercus velutina* Lam.) are both considered generally intermediate in tolerance. Since black oak does not occur in any great number, these two species were combined to form a second group. For much the same reasons, shagbark hickory (*Carya ovata* (Mill.) K. Koch) was combined with pignut hickory (*Carya glabra* (Mill.) Sweet) and bitternut hickory (*Carya cordiformis* (Wangenh.) K. Koch) to form a hickory group. Red maple, due to its low tolerance level, was maintained as a single species group. Three miscellaneous sugar maples were included within the group, however. White ash and American elm were insufficient in numbers to justify separate groupings. They were included in the hickory group, since they are similar in tolerance level. The miscellaneous species, ot

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other than sugar maple, were likewise included within the hickory group.

The four major species groupings established above are outlined in Table 2. Only the major species within each group (white oak, red oak, red maple, and hickories) were measured in the sampling procedure to obtain height and crown form information pertinent to the group. Three parameters were measured for each tree, including total tree height, height to the point of maximum crown width, and maximum crown width.

Since no information was available with respect to parameter variance, 25-30 trees were measured in the sample for each of the species groups. This was judged to be sufficient for reliable sample means. The sampling procedure was not conducted on a purely random basis and is therefore somewhat biased. The reason for this is that most white oak in the larger diameter classes were removed in the 1962 cutting. This was also true for the other species, but to a lesser extent. To obtain information for d.b.h. classes of 16 inches and greater it was necessary to measure most of the remaining trees. The bias in the sample is thus a bias toward obtaining adequate information in the upper diameter categories. Because of the small number of trees remaining in the upper d.b.h. categories for white oak, there is a possibility that the trees measured were not representative in height and crown form.

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Table 2.--Species group representation.

Species Group	Tree Count	Percent Representation
White Oak		
White oak	340	100.00
	340	100.00
Red Oak		
Red oak	293	74.74
Black oak	99	25.56
	392	100.00
Maple		
Red maple	497	99.40
Sugar maple	3	0.60
	500	100.00
Hickory		
Bittnut & Pignut hickory	428	66.15
Shagbark hickory	131	20.25
White ash	53	8.04
American elm	25	3.86
Black Cherry	3	0.46
Slippery elm	3	0.46
Cottonwood	3	0.46
Black ash	2	0.30
	647	100.00
Total all species	1879	

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At the time of the sample, no identifying numbers remained on the trees and diameter values no longer corresponded to recorded inventory values. Therefore, trees could not be selected for sampling on any random drawing basis from the inventory data. Since most trees in the upper d.b.h. categories were included in the sample, computer plots of the data were used to determine location. Trees in the lower categories were selected for inclusion by walking through the area and selecting trees on a general random basis according to species and diameter class.

Once a tree was selected for inclusion in the sample, the diameter breast height was measured to the nearest tenth inch by diameter tape. Two subsequent sets of total height, height to maximum crown width, and crown width measurements were taken at approximately right angles on each tree. Averages of these two measurements were used to determine parameter values for each tree. All measurements were recorded to the nearest two-foot interval.

All measurements were made by means of a specially designed transparent template, allowing the simultaneous recording of both height and width measurements. More precise instruments were considered for this purpose, but visibility proved to be a limiting factor in all cases. Measurements refined beyond the two-foot interval were not possible due to the interwoven and obscure nature of the tree crowns. Ocular judgment of the point to select for

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measurement was more critical than refinement of the instrumental accuracy.

The template was made of transparent plexiglass to allow complete visibility of the tree crown. Scaling of the template was formulated on the basis of similar triangles, such that each subdivision of scale represented two feet in height or width when standing at a distance of fifty feet from the tree and holding the grid one foot from the eye. The distance of fifty feet was found to be optimal for this purpose. Greater distances caused progressively greater obstruction in viewing the crown and lesser distances hindered the determination of the outer edge points of the crown. Total dimensions of the template measured 12 by 30 inches, allowing measurements of up to 120 feet in height and 50 feet in width.

In field use, the template was mounted in a sliding track on a seven foot pole. A leveling bubble on the pole was used to assure a constant vertical position. Once the distance was established and the pole positioned, the template could be adjusted so that the base coincided with the base of the tree. All measurements could then be read directly from the template.

Examination of the assembled data revealed an obvious discrepancy for white oak heights. Both total height and height to maximum crown width assumed a negative response in relation to diameter, commencing around the 18 inch diameter class. Since height growth, from a

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from a biological standpoint, cannot be a negative or decreasing function, the data presented somewhat of a dilemma. The reason for this discrepancy may be attributed to stand development. The initial white oak stand apparently developed in a rather open-grown environment and did not develop in height to the extent of subsequent invading trees. Two distinct populations of white oak, with different crown forms, are therefore present in the stand.

Since no height or age information was collected in the original inventories, the most reasonable factor for distinguishing the white oak populations seemed to be diameter. In reviewing the stand table for the study area (Table 1), a noticeable decline in stem frequency occurs for all species other than white oak at about the 18 inch diameter class. White oak, on the other hand, increases in frequency at this point and continues into the lower 30 inch diameter classes. Therefore, it was decided to segregate white oak into two distinct populations based on diameter. White oak of 18 inches d.b.h. or less were considered as one population, consisting of younger invading trees. Trees greater than 18 inches d.b.h. were considered as a second population of old-growth trees. Although this distinction is somewhat arbitrary, it seems justified by the data at hand.

White oak crown width did not show any anomaly with respect to higher diameter values. This corresponds with the finding of Minckler and Gingrich (1970) concerning the crown width relationship between open-grown and forest-grown trees.

Finally, equations were fitted to each of the parameter and species groups using multiple regression techniques. Various functions of diameter were considered as independent variables to obtain the best possible fit for the data. Diameter, diameter squared, logarithmic and reciprocal functions were tested for this purpose. Optimal equations were selected on the basis of resultant multiple correlation coefficients.

To distinguish white oak populations, the equations for total height and height to maximum crown width were fitted using only those trees having a d.b.h. value of 18 inches in diameter or less. White oak trees greater than 18 inches in diameter presented somewhat of a problem in development of predicting equations, since insufficient data was available in this category to develop independent equations.

The use of a constant predicting value for each of the height parameters was considered, based on averages from the information available. However, this was rejected as being biologically unreasonable. More reasonable results were obtained by combining all white oak data. For the combined data, the portion of the response curve for d.b.h. values greater than 18 inches was lower than the same segment of the projected curve for white oak less than 18 inches, and was only slightly positive. This lower diameter/height relationship would normally be expected for mature trees grown under open stand conditions. Because of this, the combined data for all white oak was used for determining the response function beyond 18 inches d.b.h. for old-growth white oak total height and height to maximum crown width parameters.

Prediction equations, multiple correlation coefficients and plotted curves for the parameters of total height, height to maximum crown width, and crown width are shown in Figures 3-5 respectively for each species group. Crown length is determined from these equations as the difference between total height and height to maximum crown width. Crown radius is taken as one-half of the crown width value.

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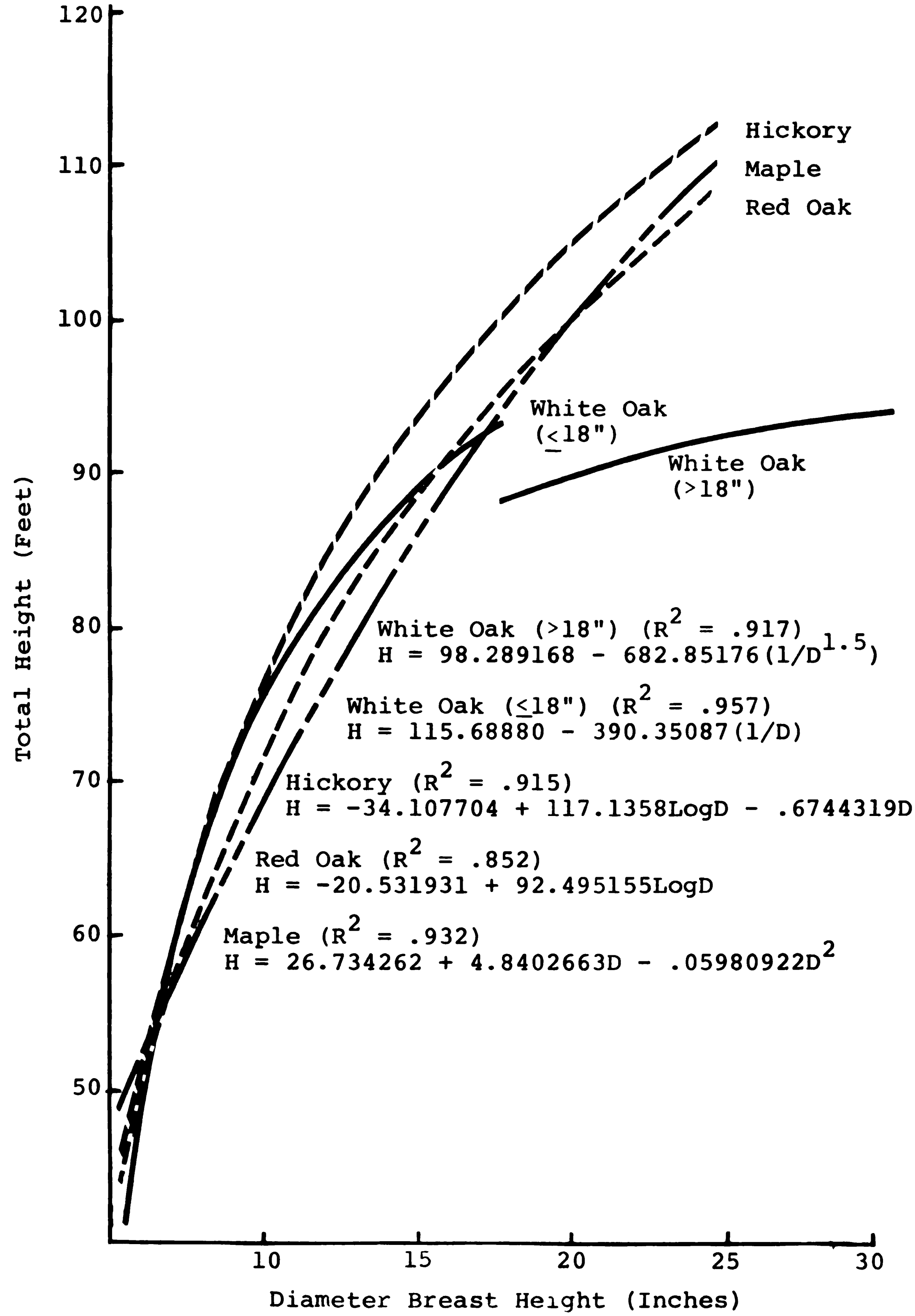

Figure 3. Regression of total height on diameter.

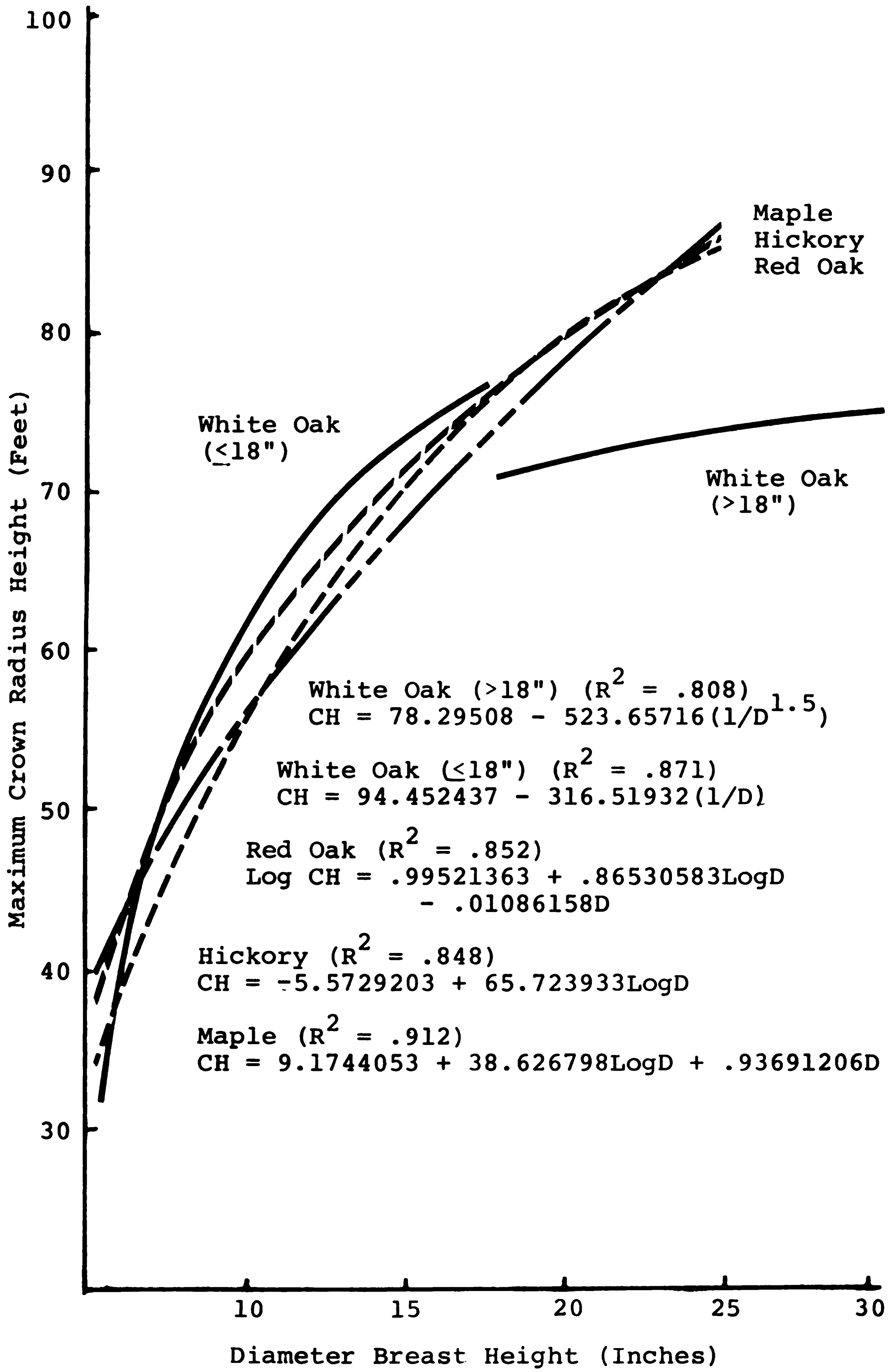

Figure 4. Regression of maximum crown radius height on diameter.

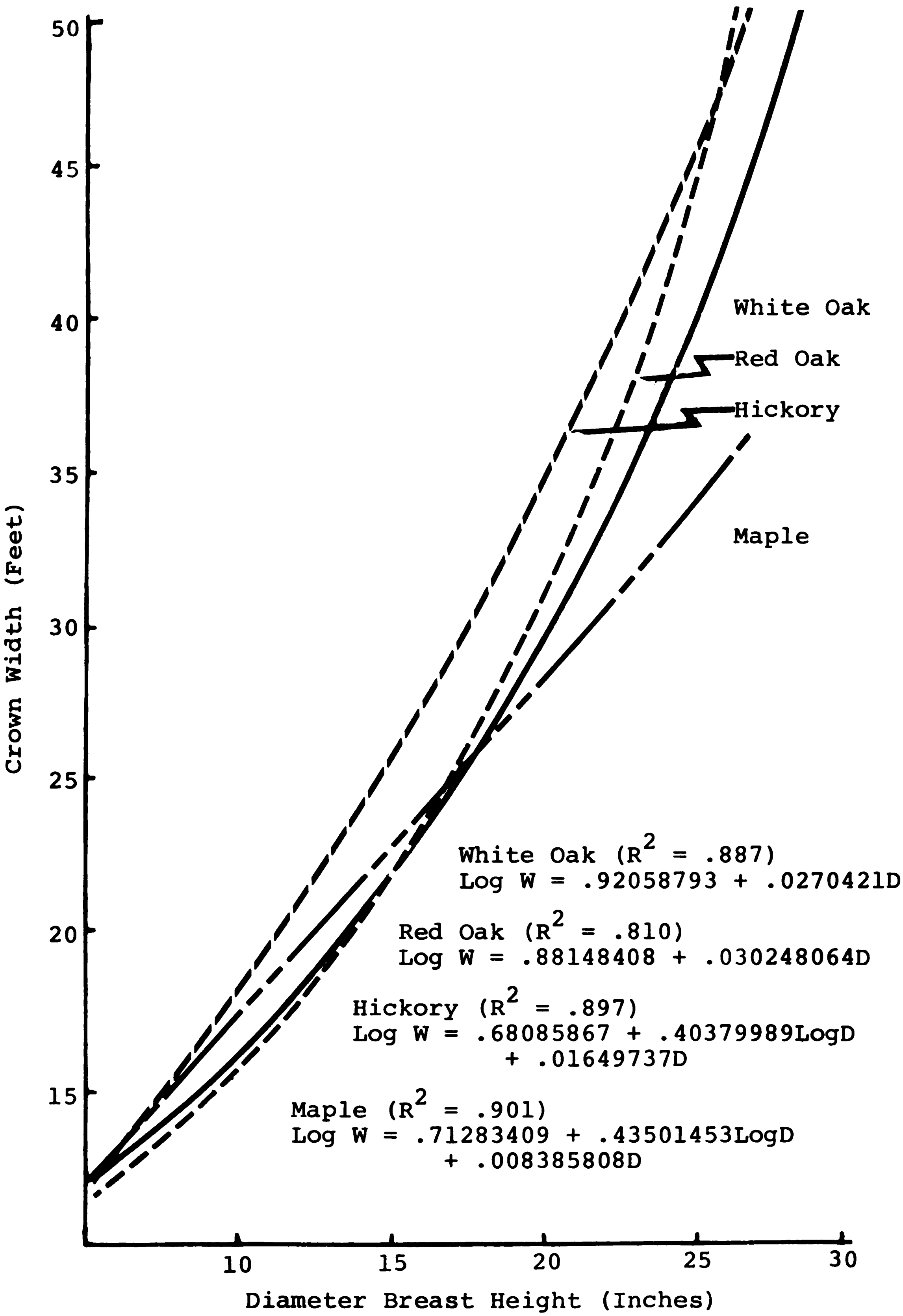

Figure 5. Regression of crown width on diameter.

CHAPTER VI

DEFINING COMPETITORS

One of the first problems to be resolved in studying the competitive relationships between individual plants is to define competitors. Competition, in this case, is taken to mean the relationship between plants with respect to required components of the environment, wherein neighboring individuals alter each other's environment by utilizing available supplies from that environment (Kozlowski, 1962). The resulting stress caused by over-utilization is reflected in reduced growth, and possible death, of some individuals. Competition by this definition is most reasonably assumed to occur between immediately adjacent individuals. A vagary remains, however, for the term 'adjacent' requires a more definitive meaning for purposes of mathematical modeling.

To resolve the question of determining competitors, several different methods have been postulated by various authors. Researchers utilizing the concept of competitive influence circles resolved the question by considering only those trees whose influence circles overlapped to be competitors. Competition circle radius was generally established for this purpose on the basis of tree diameter or crown width. Gerrard (1969) found the optimal influence circle radius factor for the Lansing Woods to be about 1.5 times d.b.h.

Using diameter or crown width alone in determining influence circle size is a possible solution to the problem of distances over which trees compete, but does nothing to explain the effect of relative tree size in competition. To account for this Bella (1971) extended the influence zone concept to account for the tree size differential. For this purpose, he established the influence circle radius on the basis of open-grown crown radius for equivalent size trees, adjusted by a species specific factor. The ratio of the competing tree influence circles, multiplied by the ratio of their respective diameters and weighted by an exponent factor, determined the competitive influence zone overlap. Several exponent and species characteristic factors were studied to determine optimal factors for the model. Using these factors, greater competitive weight was given to larger trees in determining competitive stress. Bella concluded from his study that large trees apparently receive competition only from immediate neighbors, while small trees may be affected by bigger competitors from a considerable distance.

Keister (1971) combined the factors of height, diameter, and crown width to determine the radius of the influence circle. Assuming that the size of a tree's crown is a measure of tree vigor, he used these factors to give trees with larger, more vigorous crowns a larger influence circle. For this measure he set the radius of a tree's influence circle equal to the distance between the tip of the tree and the intersection of a line from the base of the tree through the outer edge of the crown base and a line from the tip of the tree perpendicular to the trunk. The ground projection of the base of this inverted cone formed the influence zone. Crown form and total height were thus the predominant factors in determining the influence circle.

The assumption that only those trees whose influence circles overlap are in competitive status is fundamental to the influence circle concept of defining competitors. Moore et al. (1973), in using the APA approach, allowed the inclusion of trees other than nearest neighbors as possible competitors. This was recognized as desirable in that, just as Bella concluded, large trees generally receive competition primarily from immediate neighbors, while small trees may be affected by large competitors a greater distance away. They also concluded that relative tree size was probably the most important tree characteristic to consider in competitive interrelationships because of possible influence of species and age differences in the tolerance of trees to competition.

In view of the above, important factors to consider in determining competitive status of individual trees would seem to include crown form, height, relative tree size, and inter-tree distance. Large trees should compete primarily with immediate neighbors, whereas small trees should be in a competitive status with larger trees at a progressively greater distance as the diameter size differential becomes greater.

A conical influence space about each tree was formulated for defining competitors in this study. The size of this influence space is determined by the tree crown form and total tree height. Any tree crown which intersects this space is considered to be in a competitive relationship with that tree. Under this formulation, the larger a study tree is in relation to the competitor, the closer it must be to fall within the influence zone of the competitor. When the trees are equal in size, the crowns must actually contact. The location of respective tree crowns in space thus determines competitive status. This spatial location accounts for the factors of total height, crown form, tree size, and inter-tree distance in defining competitors.

To establish the influence space projection a line is extended from the tip of the tree to, and beyond, the outer point of the line perpendicular to the tree trunk formed by the maximum crown radius. This is illustrated in Figure 6 by the triangular transect AEF of the conical influence projection for tree A.

Mathematically, the possibility of a tree being a competitor is determined by the following equation:

$$DT = (CRC(THC-CHS))/CLC$$

where: DT is the competitive distance, parallel to the base AE, at the point along line FE equal to the crown radius height of the study tree,

CRC is the crown radius of the competing tree,

THC is the total height of the competing tree (CLC+CHC),

CHS is the maximum crown radius height of the study tree,

and CLC is the crown length of the competing tree.

Once the competitive distance (DT) is determined at the point equivalent to the maximum crown radius height for any particular study tree, it is compared to the inter-tree distance (DBT) less the crown radius length of the study tree (CRS). If the competitive distance is greater than or equal to the difference of DBT-CRS, the tree is in fact a competitor.

The differential effect of tree size in relation to inter-tree distance in determining competitive status is illustrated in Figure 6. Of the three possible trees

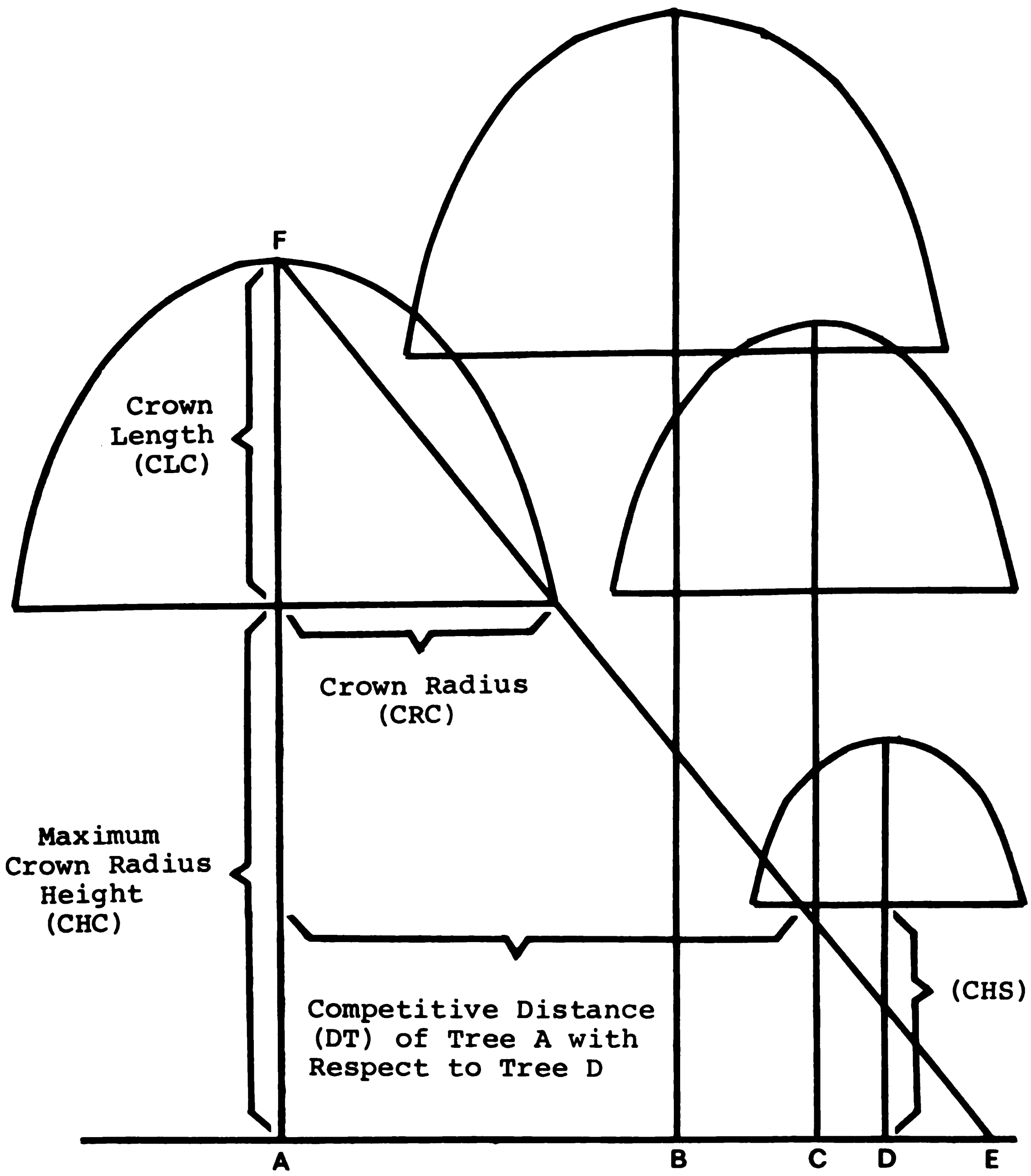

Figure 6. Conical influence space projection and tree size differential relationships.

(B, C, and D) which could be affected by possible competition from tree A, only tree D is considered to be in a competitive relationship. Trees B and C, due to relatively greater size, do not receive competitive stress from tree A. If tree B were to be considered for possible competitive relationship to the other trees, it would be in direct competition with each.

The competitive spatial relationships for each of the four species groups considered in this study are shown in Appendices B-E. Four different diameter levels are given for each species, and crown form is drawn to scale according to the predicting equations developed in Chapter V.

CHAPTER VII

THE MATHEMATICAL MODEL

One of the first problems encountered in formulating the analytical model was to develop a search procedure for locating all possible competing trees for any study tree selected. An efficient search procedure was necessary to avoid undue processing time due to the large number of trees involved. To resolve this problem, however, it was first necessary to determine approximate maximum bounds beyond which a tree, regardless of size, could be considered to have a negligible competitive effect.

To evaluate the possible competitive effect of varying maximum distance values for competing trees, a test study was conducted on approximately 50 trees. Competitive distance values of 55, 65, and 75 feet were tested for this purpose. All trees within the circular competitive distance area were regarded as competitors in the test, regardless of the conical size differential relationship to the study tree. This has the probable effect of overestimating any possible competitive effect that may exist.

From the resultant analysis it was found that about one and one-half percent average reduction in the crown view factor occurred in increasing the competitive zone radius from 55 to 65 feet, and about the same percentage reduction occurred in increasing from 65 to 75 feet. The average number of competing trees also increased by about 30 percent for each ten foot radius increment.

In view of the results obtained, 55 feet would seem to be an adequate competitive zone radius. To allow for the possible competitive effect on small trees of large trees at greater distances, however, the 65 foot radius factor (set to 66 feet) was finally chosen. This distance is within the plot size dimensions used in the inventory data collection. Since data base information included both plot and individual tree coordinates, this provided a ready made feature for development of a simple and efficient file search procedure.

The initial step in modeling the crown view factor is to select a study tree and its competing neighbors. The FORTRAN program (Appendix G) developed for the model performed this task by utilizing the plot coordinates, and study trees were analyzed on this basis. For each plot selected, all trees within the plot were loaded to a temporary study tree work file. The same trees plus all trees in the eight immediately adjacent plots were loaded to a temporary competitor tree work file. This allowed the establishment of a maximum circular competition zone of 66 feet about any study tree, since even a tree on the border of the study plot would have at least a distance of 66 feet to the edge of the next adjacent plot. File search time was greatly reduced in this manner.

For each study tree, the total crown surface area is first calculated based on the crown ellipsoid generated from the crown length and crown radius values for the given species and diameter. This may result in either a vertical or a horizontal ellipsoid, depending on which crown parameter is greater. Equation 3 gives the general formula for the case of a vertical ellipse, where crown length is the major axis.

$$Y^2/A^2 + X^2/B^2 = 1 \qquad (3)$$

where: A is the crown length,

B is the crown width,

and X and Y are crown coordinate parameters.

If crown width forms the major axis of the ellipse, A and B are interchanged in this formulation.

Once the crown form is established, the surface area is determined by integrating the appropriate ellipsoidal equation from the crown base (O) to total crown length (A). The solution of this integral, developed in Appendix F, is given in equation 4 for a vertical ellipse.

$$S = 2\pi B/A^2K \left[(YK/2)(A^4-K^2Y^2)^{1/2} - (A^4/2)\mathrm{Sin}^{-1}(YK/A^2)\right]_O^A \qquad (4)$$

where: S is the surface area in square feet,

and K is a constant equal to $(A^2 - B^2)^{1/2}$.

The surface area for a horizontal ellipse would be identical, with the exception of the reversal of A and B where ever they occur in the equation. Expansion of the equation over the range O to A merely results in the substitution of A for Y in the equation, since $\mathrm{Sin}^{-1}(O)$ is zero. Once the total surface area is determined, each surface segment, as described in Chapter III, is assigned an initial value of 1/360th of the total surface area.

All trees within the maximum competitive influence zone of 66 feet are next located and evaluated for possible competitive effect. Total height is first determined for each such tree. If it is less than the maximum crown radius height of the study tree, the tree is considered as effectively non-competitive and is ignored. If not, the conical influence space of the competing tree is next calculated and a check made to determine if the study tree crown contacts the space by means of equation 2. If contact is made, the tree is established as a competitor.

Once a competing tree is found, the distance and azimuth of the competing tree in relation to the study tree are determined from the ground coordinate locations. The crown surface segment having an index value matching the azimuth is then set as the base directional segment for purposes of evaluating the crown projection of the competing tree on the study tree.

To determine the crown projection surface area of intersection on the study tree it is first necessary to determine the maximum horizontal crown projection angle (alpha), in degrees, subtended by the competing tree crown. This is the angle formed by the study tree axis and the crown radius of the competing tree. Maximum crown radius is used directly for angle calculation when the maximum crown radius height of the competing tree is equal to or greater than that of the study tree. Alpha is then calculated as shown in equation 5.

$$\text{Alpha} = \text{Tan}^{-1}(\text{CR}/\text{DBT}) \qquad (5)$$

where: CR is the crown radius of the competing tree,

and DBT is the distance between trees.

For competing trees having a maximum crown radius height less than that of the study tree, however, a crown radius correction is necessary to avoid overestimation of the projection angle. In this case, the horizontal crown projection angle of the competing tree is determined by measuring its crown radius at a height equivalent to maximum crown radius height of the study tree, as depicted in Figure 7. The corrected crown radius in this case is determined by equation 6.

$$\text{CR} = (\text{CRC}^2 - (\text{CRC}^2(\text{CHS}-\text{CHC})^2)/\text{CLC}^2)^{1/2} \qquad (6)$$

where: CR is the corrected competing tree crown radius,

CHC is the maximum crown radius height of the

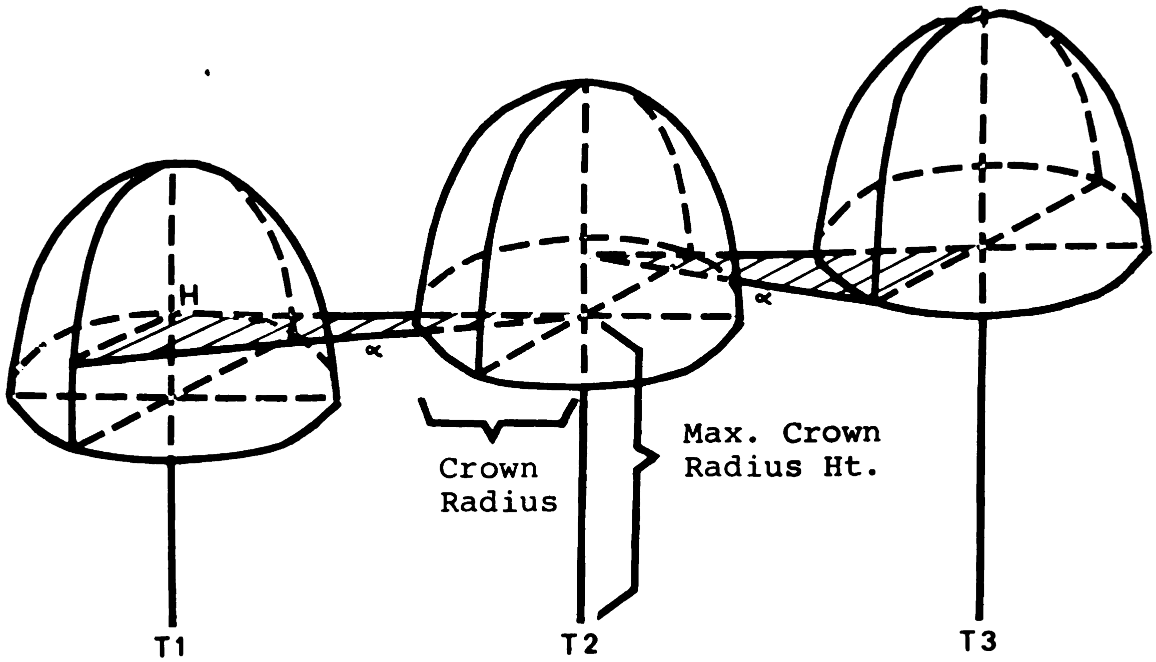

Figure 7. Horizontal crown projection angle evaluation. In this illustration, if T2 is the study tree, the horizontal crown projection angle (α) for T3 is computed using the maximum crown radius value. For T1, however, an adjusted crown radius value is necessary to compensate for the fact that its maximum crown radius height is less than that of T2. The crown radius is therefore measured at the point (H) equivalent to the maximum crown radius height of T2.

competing tree,

CLC is the crown length of the competing tree,

and CHS is the maximum crown radius height of the study tree.

The horizontal crown projection angle calculated by equation 5 determines directly which study tree crown surface segments are affected by the competing tree crown projection in that the base segment, plus and minus 'alpha' segments on each side, are within the competing tree crown projection.

Having determined which segments are to be evaluated, the actual vertical projection on each segment remains to be ascertained. For this purpose, each angular segment value from one to alpha is evaluated on a cumulative basis to determine the associated length of the competing tree crown radius subtended by the given angle. Once this crown radius distance for a particular segment is known, the corresponding point on the crown perimeter directly above the crown radius point can be determined by substitution into the competing tree crown form equation. (The competing tree crown perimeter is taken as the transect through the central axis of the tree, perpendicular to the study tree.) Knowing the surface point coordinates, the slope of the line extended from the centroid of the study tree crown to the calculated perimeter point of the competing tree can be determined.

The intersection of the slope line on the crown surface segment of the study tree is found by solving simultaneously the equations for the slope line and the study tree crown solid. The surface area equation (4) for the crown solid is then evaluated from the point of intersection for the segment to total tree height and divided by 360. The resulting value is the one-degree segment area unobstructed by the competing tree. Because of crown symmetry, the corresponding segment on the opposite side of the base segment is also assigned this value.

The integration process above is repeated for each study tree crown surface segment affected by the projection of the competing tree crown. Figure 8 illustrates the construction of the intersection of a competing tree crown projection on a study tree.

If multiple competing tree projections intersect the same directional crown segment, the largest obstructional value is used in determining available surface area for the segment. Once all competing trees have been analyzed for a study tree, the view factor components for each of the 360 segments are summed to give the crown view factor value for the tree. Each tree in the study plot is processed in the same manner. When all trees in the plot have been evaluated, the next study plot and competing tree plots are loaded to the temporary work files and processing continues until all plots have been evaluated.

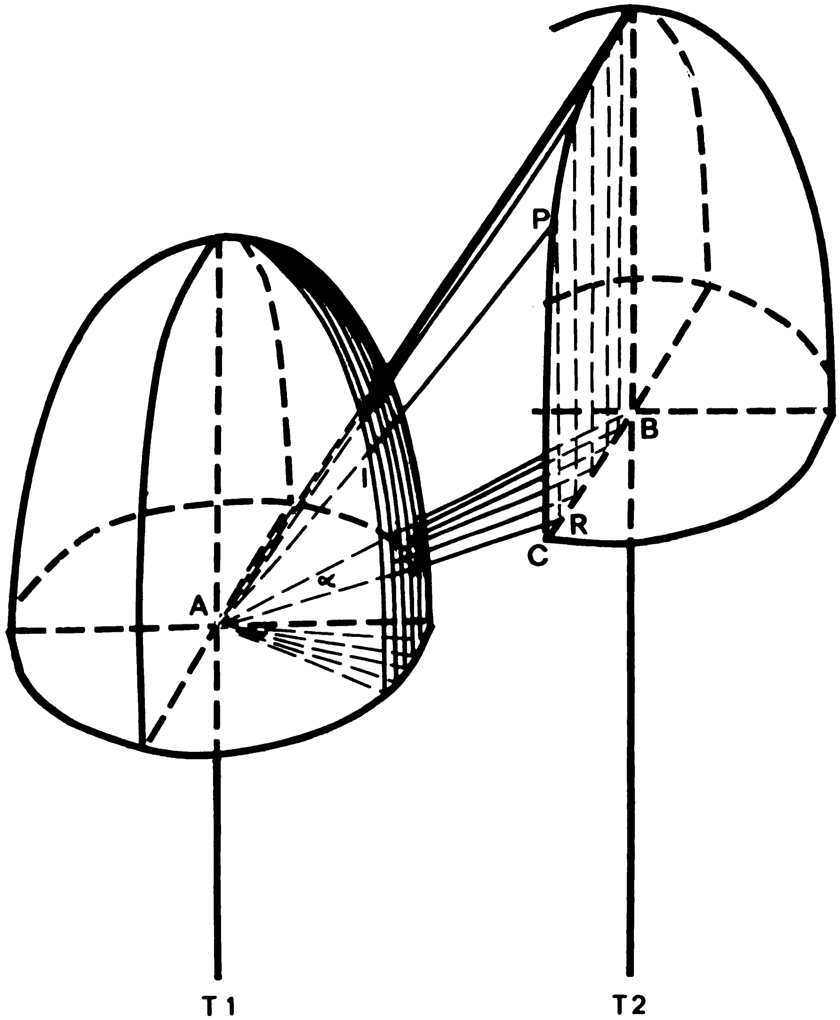

Figure 8. Surface area intersection geometry of competing tree crown projection. This figure illustrates the projection of a five degree horizontal crown projection angle (α) of a competing tree (T2) on a study tree (T1). Each of the five segments within the projection angle subtend a given distance (R) of the crown radius (BC) of the competing tree. A corresponding crown perimeter point (P) can therefore be established. The slope of the line drawn from P to the view factor focal point (A) determines the intersection point (I) on the corresponding crown surface segment of the study tree. Points marked in the diagram are for the fifth segment, or the total projection angle.

A gross logical flowchart of the analytical procedures outlined above is shown in Figure 9. A FORTRAN program listing is also included in Appendix G, with sample output for one plot of study trees.

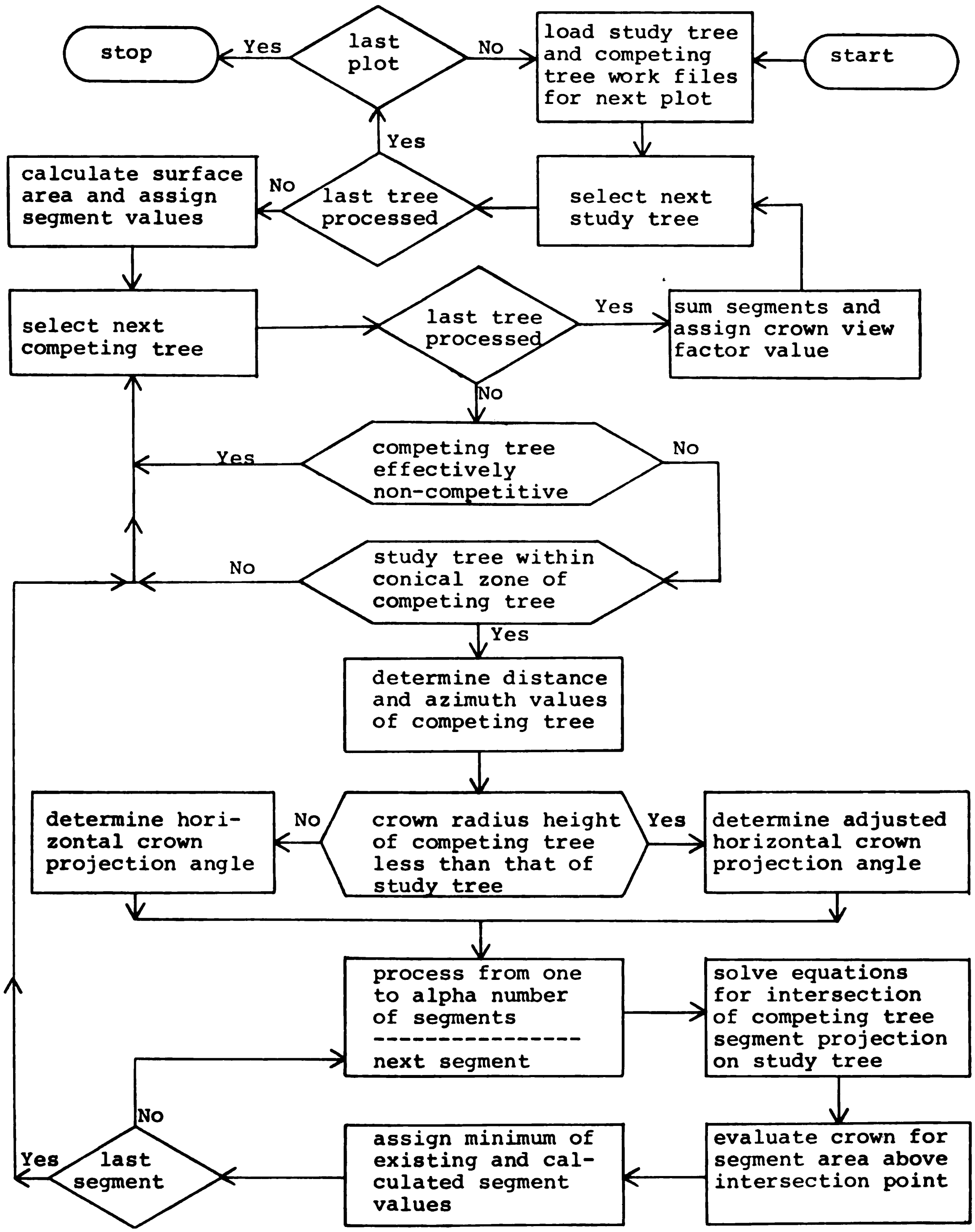

Figure 9. Gross logical analytical flowchart.

CHAPTER VIII

THE GROWTH EVALUATION MODEL

Tree growth represents the culmination of inherent tree capabilities, internal physiological processes, and environmental influences affecting the tree. Because of the many factors and complex interactions involved, most growth prediction models do not attempt to describe growth in terms of causal functions. Rather, growth is related to more discernable parameters which measure some characteristic of the source of variation in growth. Parameters commonly used for this purpose include measures such as tree diameter, total height, crown size and position, species type, tolerance level, and site quality.

The amount of growth variation accounted for by models utilizing descriptive parameters depends on the specific parameters included, the extent of their correlation with tree growth, and the manner in which they are incorporated in the model. A fairly elaborate model is normally required to adequately distinguish extraneous sources of growth variation from variation due to competitive effects.

Model Parameters

Independent variables are considered in the proposed growth prediction model that are meant to account for both extraneous and competitive sources of variation. Variables incorporated to account for sources of variation other than competition include tree diameter, total tree height, and species type. Variables relating to competitive ability are crown view factor index, crown view factor surface area, release response factor, and the number of competitors. Of these variables, diameter, total height and crown view factor surface area have been defined in previous chapters. A description of the remaining variables is presented below.

A measure of the growth differential due to species is important in developing a satisfactory response function. Such a measure would presumably account for differences in tolerance levels and other physiological species characteristics. Tolerance, however, is a rather subjective concept and is difficult to quantify in meaningful terms. So also are the many physiological differences which distinguish species.

Since quantification of these terms was not possible, indicator variables were developed to isolate species differences in growth response. Three qualitative species indicator variables were established as shown in Table 3. Only three variables are created in order to maintain linear independence between all variables in the data matrix. The value of the fourth possible variable is completely determined by the first three. If the fourth variable were included in the model, linear dependence would exist within the data and the normal equations would be unsolvable.

Table 3.--Indicator variables for species groups.

Species Group	Indicator Variable		
	S_1	S_2	S_3
Hickory	1	0	0
Red Oak	0	1	0
White Oak	0	0	1
Maple	0	0	0

In formulating the qualitative indicator variables, one (1) is assigned for each of the first three species groups if the variable represents the group, and zero (0) if otherwise. Zero is assigned to all three variables for the fourth species group (maple). The assignment of all zero values for maple does not result in the loss of information for this group. Rather, this group becomes the reference category by which the effects of the other variables may be evaluated. This can be illustrated by considering the nature of a simplified response function for growth (G), using only diameter (D) and species indicators (S_1, S_2, and S_3) as independent variables. The general response function for this model would be as follows:

$$E(G) = B_O + B_1D + B_2S_1 + B_3S_2 + B_4S_3 \quad (7)$$

For the maple group, where $S_1=0$, $S_2=0$, and $S_3=0$, this reduces to the form:

$$E(G) = B_O + B_1D \quad (8)$$

For the remaining species groups, the response function would be as follows:

$$E(G) = (B_O + B_2) + B_1D \quad \text{(Hickory)} \quad (9)$$

$$E(G) = (B_O + B_3) + B_1D \quad \text{(Red Oak)} \quad (10)$$

$$E(G) = (B_O + B_4) + B_1D \quad \text{(White Oak)} \quad (11)$$

It is apparent in the above equations that the regression coefficients B_2, B_3, and B_4 provide a measure of the differential effect of the indicator variable on the height of the response function with respect to the maple group. The coefficients may also be compared to one another to assess the effect between all groups. If a particular coefficient is non-significant, the function for the group will assume the form of equation 8.

If interaction terms are considered in the model, the results would indicate whether the particular species group has a unique regression function, with a different slope as well as intercept. This can be illustrated by extending the previous model to include diameter and species interaction terms as follows:

$$E(G) = B_O + B_1D + B_2S_1 + B_3S_2 + B_4S_3 + B_5DS_1 + B_6DS_2 + B_7DS_3 \quad (12)$$

The response function for maple again reduces to the form given in equation 8. Remaining species groups assume functions as shown below:

$$E(G) = (B_O + B_2) + (B_1 + B_5)D \quad \text{(Hickory)} \quad (13)$$

$$E(G) = (B_O + B_3) + (B_1 + B_6)D \quad \text{(Red Oak)} \quad (14)$$

$$E(G) = (B_O + B_4) + (B_1 + B_7)D \quad \text{(White Oak)} \quad (15)$$

When significant interaction terms for the indicator variables are present, the effect of these must be considered by comparing the regression functions for each of the species group classes.

Crown surface area represents an important element in overall competitive ability. When considering the surface area represented by the crown view factor, however, it is necessary to distinguish between a given area for a large tree which has extensive obstruction of its view, and an equal area for a smaller tree with an unobstructed view. The crown view factor index of competitive ability was developed for this purpose. This index is taken as the proportion of the total crown surface area represented by the crown view factor surface area. Values for the index range from zero for a completely obstructed tree crown to one for an unobstructed crown. Net crown view factor surface area is used in the model to express physical crown size. It is calculated as the difference between total view factor surface area and release factor surface area.

A partial cutting of over-mature white oaks was carried out in the study area at the beginning of the 1956 growth period. This cutting, together with trees which subsequently died due to logging damage or natural causes, removed a total of 287 trees from the 16.9 acre area. The release of trees by such cutting presumably leads to a net reduction in competition, the extent of which depends on the spatial relationship of the trees involved. The difference in crown view factor surface area before and after cutting would seem to be a reasonable measure of the degree of this release from competition. It considers both the spatial distribution of the trees involved and the frequency of competing trees. This expression of surface area difference was used in the model to express the variation in growth due to competitive release. The release factor should provide a measure of the validity of the crown view factor concept for detecting variations in competitive ability due to silvicultural treatment.

The relative density of neighboring competitors is another important element in determining competitive ability. The number of competing trees involved in determining the crown view factor for each tree provides such a measure of density and was incorporated in the model for that purpose. It is expected that this term may account for growth variation in the case where similar view factors are obtained, with a wide range in the frequency of competitors involved.

Multicollinearity

A situation which commonly arises when multiple descriptive parameters are included as independent variables in a regression model is the correlation of these variables among themselves. When this is true, a condition of intercorrelation or multicollinearity is said to exist.

It is important to recognize the existence of multicollinearity, since several possible problems might arise when independent variables are correlated among themselves (Neter and Wasserman, 1974). One such problem is that the regression coefficient for any independent variable depends on which other variables have previously been included in the model. The coefficient represents only the marginal effect on the dependent variable unaccounted for by correlated variables already included in the model. This has the effect of changing regression coefficients as independent variables are either added to or deleted from the model. The regression sum of squares is affected by the correlation among the independent variables in the same manner.

Another consequence of multicollinearity relates to tests performed on all individual regression coefficients. Individual tests may indicate a lack of significance for each, even though a definite statistical relation exists between the dependent and independent variables. This is possible since each test of significance for an individual coefficient is a marginal test of the contribution of that variable given that all others are included in the model. Thus, the true relationship between the dependent and independent variables may not be recognized when severe multicollinearity exists if only tests of the individual coefficients are studied.

The presence of multicollinearity does not of itself inhibit the ability to obtain a good fit for a regression; nor does it affect prediction of new observations within the range of data observations. A large degree of correlation among the independent variables, however, does tend to cause the estimated regression coefficients to be rather imprecise and to fluctuate greatly from sample to sample. When this happens, the true regression coefficients also tend to be imprecise and lose their meaning. Severe multicollinearity also has the effect of causing the determinant of the sum of squares and cross product matrix to approach zero. This subjects the regression coefficients to large round-off errors.

It is apparent that the choice of variables to be included in a regression model is quite important due to the possible effects of multicollinearity. The model proposed is primarily concerned with the prediction of new observations; and a consideration of multicollinearity is important in the context of computational accuracy and regression coefficient precision.

A number of possibly highly correlated independent variables are considered in the regression function proposed. These include diameter, total height, net crown view factor surface area, crown view factor index, and release response factor. The latter four variables are all defined as rather complex functions of diameter and are likely candidates for a high degree of multicollinearity. These variables should be given close scrutiny in model evaluation to determine whether deletion of one or more is in order.

Regression Function

Using the parameters previously outlined, the regression function proposed for the study of growth response and competition was formulated as follows:

$$G = b_0 + b_1D + b_2D^2 + b_3S_1 + b_4S_2 + b_5S_3 + b_6H + b_7H^2 + b_8V + b_9V^2 + b_{10}R + b_{11}R^2 + b_{12}A + b_{13}A^2 + b_{14}N + b_{15}N^2 + b_{16}VS_1 + b_{17}VS_2 + b_{18}VS_3 + b_{19}RS_1 + b_{20}RS_2 + b_{21}RS_3 + \text{(other first-order interaction terms)} \quad (16)$$

where: G is the estimated 10-year basal area growth (based on 6 years of actual growth),

D is initial d.b.h. in inches,

S is the indicator variable for species group,

H is total tree height in feet,

V is the crown view factor index of competitive ability,

R is the release factor surface area in square feet,

A is the net crown view factor surface area in square feet,

and N is the number of competitors.

CHAPTER IX

THE ANALYSIS

Two problem areas required consideration prior to the statistical analysis of the proposed. model. One concerned the applicability of including extremely old-growth trees in the growth prediction function. The second was the possible intercorrelation of independent variables.

Old-Growth White Oak

The problem encountered in Chapter V, in which white oak greater than 18 inches in diameter were established as a unique population due to over-mature age status, was a cause of concern in model evaluation. One hundred and seventy-two trees were included in this category, or about 9 percent of the total population. These trees were not representative of the stand in general, due to their age and likely senescence. Their value in substantiating model validity was therefore questionable. It was assumed that basal area growth for these trees would not correlate consistently with any of the model variables.

To check this premise, simple correlations between basal area growth and model parameters were calculated for the two populations. It was found that old-growth white oak had only a 11 percent correlation with diameter, as compared to 69 percent for the younger white oak category. Other parameters had substantially smaller correlation values. Basal area growth for these trees is apparently very sporadic in nature, probably due to age status, and their inclusion in the model would result in unwarranted loss of predictive power. Since these trees were generally atypical and were not likely to be affected by competitive stress, it was decided to exclude all old-growth white oak for purposes of growth response evaluation.

Evaluation of Multicollinearity

One consideration in model analysis was the review of independent variables to determine the extent of multicollinearity. Correlation coefficients were generated for all variable combinations to examine this relationship. These are listed in Table 4 below for the variables generated as functions of tree diameter (D). The variables are total height (H), net crown view factor surface area (A), release factor surface area (R), and crown view factor index (V).

Inspection of Table 4 shows that total tree height correlates to a very high degree with both diameter and net crown view factor surface area. Net crown view factor

Table 4.--Correlation coefficients for variables functionally related to tree diameter.

H	.96845			
A	.90960	.87385		
R	.06657	.07112	.00339	
V	.64568	.68916	.68018	.33867
	D	H	A	R

surface area is also strongly correlated with diameter. This degree of multicollinearity which exists between diameter, total height, and net crown view factor surface area would have an adverse effect on the regression function as formulated in equation 16. Total tree height is the major offending variable and for this reason it was decided to delete the variable from the regression function. Since net crown view factor surface area did not correlate with diameter quite as strongly as total height, it was retained in the model. The regression model stated in equation 16 was consequently amended to the formulation shown below.

$$G = b_0 + b_1 D + b_2 D^2 + b_3 S_1 + b_4 S_2 + b_5 S_3 + b_6 V + b_7 V^2 + b_8 R + b_9 R^2 + b_{10} A + b_{11} A^2 + b_{12} N + b_{13} N^2 + (\text{first-order interaction terms}) \qquad (17)$$

Statistical Analysis

Three aspects of equation 17 are of importance in analyzing statistical results. These are (1) the contribution of diameter and species in accounting for extraneous sources of growth variation; (2) the contribution of factors relating to competition and release; and (3) the contribution of first-order interaction terms to the model.

The regression function for growth response (equation 17) was developed by the successive addition of individual terms to the model. The relative contribution of each, as determined by the percentage increase in the multiple correlation coefficient (R^2), was computed and tested for significance at the 1 percent confidence level. The results of the regression model so developed are presented in Table 5. Tabular values listed include variable designation, R^2 in percent, and R^2 change attributed to the variable.

The first stage in model development required the removal of extraneous sources of growth variation to disclose the pure effects of competitive stress and release. Diameter and species variables were included in the model for this purpose. The terms considered form a reduced model as shown in equation 18.

$$G = b_0 + b_1D + b_2D^2 + b_3S_1 + b_4S_2 + b_5S_3 \qquad (18)$$

Table 5.--Percentages of variation[a] removed by successive addition of individual terms to the regression model.

Variable	R Square	R Square Change
D	46.252	46.252*
D^2	46.576	0.324*
S1	49.372	2.796*
S2	51.357	1.985*
S3	51.357	0.000
V	55.981	4.624*
V^2	56.973	0.992*
R	58.832	1.859*
R^2	59.056	0.224*
A	62.617	3.561*
A^2	62.679	0.063
N	62.806	0.126
N^2	62.924	0.118
VS1	62.957	0.033
VS2	63.025	0.068
VS3	63.026	0.001
RS1	63.333	0.307*
RS2	63.462	0.130
RS3	63.935	0.472*
DV	64.353	0.418*

[a]Variables included in the model at the 1 percent significance level are denoted by an asterisk.

Diameter is an important predictor of basal area growth, as is evident from the large percentage of variation accounted for by these terms. Significant differences also exist between species groups, accounting for an additional 5 percent of growth variation. Species distinction is obviously an important element in accounting for growth variations in mixed species stands. Response differences for species groups can be attributed to differences in tolerance levels and micro-site conditions.

One puzzling aspect of the species groups is that hickory (S1) and red oak (S2) differed from the reference category (maple), whereas white oak (S3) did not. All groups were expected to differ from maple, which is much lower in tolerance. This unlikely relationship may be due to the relative frequency difference for the two species. For this reduced model, however, white oak and maple have a similar growth response in relation to tree diameter. Hickory and red oak have response levels differing from the maple reference level.

Four variables relating to competition and competitive release were included in developing the second stage of the growth model. These include the crown view factor index (V), the release factor (R), the net view factor surface area (A), and the number of competitors (N). The addition of these terms results in the model function as shown in equation 19.

$$G = b_0 + b_1D + b_2D^2 + b_3S_1 + b_4S_2 + b_5S_3 + b_6V + b_7V^2 + b_8R + b_9R^2 + b_{10}A + b_{11}A^2 + b_{12}N + b_{13}N^2 \qquad (19)$$

The model as formulated in equation 19 accounted for 11.5 percent of the variation in basal area growth beyond that considered by the model of equation 18. Half of this was attributed directly to the crown view factor index, making it the single most important term expressing competitive ability. The relative smallness in percentage of variability accounted for by individual terms is due in part to the biological and functional correlation of these terms with diameter, a factor already accounted for in the model. The biological association between bole size and crown size may also involve hidden correlations already accounted for by the inclusion of tree diameter in the model.

The number of competitors was the only non-significant variable expressing competition. The small contribution accounted for in this case may be due to correlations between the number of competitors and the other terms expressing competitive status. Variations due to such association would already be accounted for in the model since the number of competitors was included subsequent to all other terms.

The measure of release from partial cutting, represented by the difference in crown view factor surface area before and after cutting, removed approximately

2 percent of growth variability. This small improvement is statistically significant, but is not large enough to be of great practical importance. The statistical significance does indicate, however, that the release factor is sensitive to growth response resulting from partial cutting.

The final stage in model development was the inclusion of first-order interaction terms. Ten interaction terms not shown in Table 5 were included in the initial analysis. These terms accounted for less than one-half of 1 percent of the remaining growth variation. When tested against the model containing only those terms listed in Table 5, the additional ten terms were found to be non-significant at the 1 percent confidence level. Therefore, these first-order interaction terms were excluded from further consideration in model evaluation.

Three of the seven interaction terms included in the model were significant at the 1 percent inclusion level, accounting for 1.5 percent of remaining basal area growth variation. No single term accounted for any great amount of variability. The significance of the interaction terms between release factor and species group was of particular interest as they accounted for the major portion of the variation. Apparently the influence of release on basal area growth is species dependent. This is a rather well established silvicultural principle.

Considering the weak contribution of interaction terms, the question of practical as opposed to statistical significance must be considered. A practical significance for the release-species interaction terms would result in a difference in response function slopes for the different species groups. To relate species differences, this would require the comparison of separate functions for each of the groups, rather than a simple comparison of response level only.

To evaluate practical significance, a comparison of the predictive ability of the full model containing the seven interaction terms was made with the model containing no interaction terms. It was found that average basal area growth (based on 150 trees) as calculated for the full model was 3 percent closer to actual average basal area growth than was the reduced model. This suggested practical as well as statistical significance for the interaction terms.

Species Group Comparisons

The presence of significant species interaction terms in the model prevented the direct comparison of species group regression coefficients alone for the determination of response function differences among the various groups. The interaction terms resulted in a difference in slope as well as in level. To establish species group differences it was decided to perform a series of comparisons for each pair of species groups.

Indicator variables were developed for all two-way species group comparisons. Each set was constructed so as to equalize relative frequency differences between groups by balancing corresponding factors and using positive and negative terms. In this manner, any significant differences between the model containing species groups and a reduced model in which no species groups are recognized could be attributed to a difference between the two species groups considered. While it is recognized that a series of such tests are not statistically independent, it does provide a means of exposing species group differences in response functions that is not otherwise possible. Indicator variables developed for the six sets of species group comparisons are shown in Table 6. The reduced and full models used for testing purposes are shown in equations 20 and 21 respectively.

$$G = b_o + b_1D + b_2D^2 + b_3V + b_4V^2 + b_5R + b_6R^2 + b_7A + b_8A^2 + b_9N + b_{10}N^2 + b_{11}DV \quad (20)$$

$$G = b_O + b_1D + b_2D^2 + b_3S_1 + b_4S_2 + b_5V + b_6V^2 + b_7R + b_8R^2 + b_9A + b_{10}A^2 + b_{11}N + b_{12}N^2 + b_{13}RS_1 + b_{14}RS_2 + b_{15}DV \quad (21)$$

Since interaction terms for view factor and species group were non-significant in the general model, these terms were not included in the two-way species group comparisons.

Table 6.--Indicator variable construction for species group differentiation based on relative stem frequency.

Species Group		Indicator Variable	
		S_1	S_2
1.	Red Oak	1	0
	White Oak	0	-2.419
	Other	0	0
2.	Maple	1	0
	Red Oak	0	-1.278
	Other	0	0
3.	Hickory	1	0
	Red Oak	0	-1.648
	Other	0	0
4.	Maple	1	0
	White Oak	0	-3.093
	Other	0	0
5.	Hickory	1	0
	White Oak	0	-3.988
	Other	0	0
6.	Hickory	1	0
	Maple	0	-1.289
	Other	0	0

The percentage changes in R^2 accompanying successive additions of terms to the regression model shown in equation 21 are given in Table 7 for each of the six species group comparisons. Since diameter terms are identical in each case to that listed in Table 4, they are not included.

A few inferences can be drawn from the results of these tests. Most importantly, all species group comparisons tested significantly different at the 1 percent level from the reduced model as given in equation 20. Thus, a difference in response function exists for all species groups. The red oak-white oak comparison was the only one having non-significant release/species interaction terms. They consequently assume the same response slope, although differing in response level. A significant release factor interaction exists for all other species group comparisons. A difference in both slope and level of the regression function therefore exists between these species groups.

The significance of the release factor in both additive and interaction terms indicates that species react differently to release from competitive stress. This is quite reasonable from a biological standpoint, since tree response to release is generally assumed to be related to tree age and tolerance level. The use of the crown view factor to determine competitive release is apparently a sensitive measure of such response.

Table 7. Percentage changes[a] in R^2 for successive addition of individual terms in species group comparison model.

Variable	Species Group Comparisons[b]: White Oak-Red Oak	White Oak-Maple	White Oak-Hickory	Hickory-Maple	Maple-Red Oak	Hickory-Red Oak
S1	0.009	0.009	0.009	2.796*	0.017*	2.796*
S2	3.982*	0.013	3.005*	0.957*	4.407*	1.985*
V	3.923*	4.100*	5.057*	4.462*	4.612*	4.577*
V^2	0.965*	1.134*	1.077*	0.999*	1.106*	0.980*
R	2.203*	1.890*	1.611*	1.884*	1.851*	1.898*
R^2	0.190*	0.146	0.213*	0.205*	0.217*	0.222*
A	4.585*	7.005*	4.096*	3.160*	3.877*	3.326*
A^2	0.027	0.003	0.073	0.093	0.078	0.070
N	1.084	0.039	0.127	0.134	0.137	0.129
N^2	0.116	0.168*	0.157*	0.082	0.110	0.089
RS1	0.122	0.128	0.111*	0.352	0.794*	0.409*
RS2	0.001	0.500*	0.459*	0.401*	0.002	0.001
DV	0.523*	1.017*	0.525*	0.374*	0.318*	0.251*

[a]Variables included in the model at the 1 percent significance level are denoted by an asterisk.

[b]The first species listed in each species group refers to the S1 species group and the second species listed refers to the S2 species group.

Evaluation of the Crown View Factor Model with Respect to Gerrard's Competition Quotient Model

Gerrard's competition quotient model is representative of the competition circle approach to evaluating competitive ability. A comparison between Gerrard's model and the crown view factor model presented in this study provides a means of relating the two approaches to measuring competition. Since basically the same data was used in each of these studies, a general comparison of the results of the two models is possible. No statistical significance can be assigned to such a comparison. It should, however, provide a reasonable measure of the effectiveness of the crown view factor concept in relation to the competition circle approach.

Gerrard's evaluation was based on the independent analysis of each of five species groups (black oak and red oak were considered separately). He did not account for growth variation due to species differences. To allow general comparisons to be made between the two models, it was assumed that the averages of R^2 values over the five species groups was representative of the values which would be obtained by combining all species as in the crown view factor model.

The two regression models differ slightly in parameters in that Gerrard incorporated a measure of site quality, whereas the crown view factor model included measures of view factor surface area, number of competitors and species indicator variables. In total, the crown view factor model accounted for approximately 10 percent more of the variation in basal area growth, or 64.3 percent as compared to 53.8 percent for the competition quotient model.

In comparing individual terms, diameter values were almost identical at about the 46 percent level. Release factors were also identical in accounting for approximately 2 percent of the variation. Differences did occur for competition indices, however. The crown view factor accounted for 5.6 percent of growth variation as opposed to 1.5 percent for the competition quotient. The addition of net view factor surface area accounted for an additional 3.5 percent of variation relating to a competitive ability. In this respect, the crown view factor model accounted for approximately 8 percent more of the growth variability due to competitive ability. The recognition of variation due to species differences in the crown view factor model accounted for the remaining difference between the two models.

Although the above comparisons do not have any statistical basis and must be viewed with caution, the similarity of response for like terms of diameter and release would suggest a degree of validity to the comparison of other terms. On this basis, the crown view factor and associated surface area provide a more sensitive measure of competitive ability. It also indicates that the crown view factor concept is a better measure of competition than the competition circle approach.

CHAPTER X

SUMMARY AND CONCLUSIONS

The survival and growth of an individual tree in a forest stand is essentially determined by its ability to compete for limited resources and growing space. Light interception is one of the most critical aspects of this competitive struggle. The purpose of this study has been to evaluate a proposed index of simulated crown light interception by individual trees in an uneven-aged, mixed forest stand. The basis for judging the relative merits of this index was (1) its ability to express the effect of competition on basal area growth, and (2) its sensitivity to changes in competitive stress caused by partial release cutting.

An index of the competitive stress sustained by a tree must be related to the relative size, frequency, and spatial distribution of neighboring trees. For this study, it was theorized that the competitive ability of a tree is directly related to the unobstructed area of its crown surface. The crown view factor concept was formulated to express this area in relation to the size and spatial distribution of neighboring tree crowns. It is an expression of the view of the sky hemisphere from the geometric centroid of the tree crown. The competitive ability, or crown view factor index, is the ratio of the crown view factor surface area for a tree to its maximum surface area expected under forest-grown conditions.

The crown view factor concept is a new approach to measuring competitive ability for individual trees. It differs from measures using the competition circle concept in that the three-dimensional spatial distribution, together with relative crown form and size, are used in constructing the competitive index. Because of this it was expected to provide a more realistic measure of competitive ability.

The determination of total height and maximum crown form was based on a sample survey of trees in the study area. Parameters requiring measurement consisted of total tree height, height to maximum crown width, and crown width. Regression of the sample data on tree diameter for these parameters was used to develop predicting equations on a species basis. The equations were subsequently used to formulate the crown form, size, and spatial position for each tree.

A crucial judgment in evaluating competitive stress is the determination of which neighboring trees are competitors. In competition circle models this decision is made as an adjunct to the setting of circle radius, since only those trees having mutually overlapping circles are considered competitors. The determination of competitors in this study was designed to recognize that large trees receive competition primarily from immediate neighbors, whereas small trees may be affected by large trees a greater distance away. To express this relationship, a conical influence space was established around each tree by projecting a line from the tip of the tree to, and beyond, the outer point of the line perpendicular to the tree trunk formed by the maximum crown radius. Any tree whose crown intersects this space is considered to be in a competitive relationship with that tree. In this manner, the definition of competitors takes into account the crown form, height, relative tree size, and inter-tree distance for the two trees considered. The competition influence space of a tree is really a function of diameter, although a very complex one, since it is determined by the total height and crown form of the tree.

The regression model used to evaluate basal area growth response was formulated as follows:

$$G = b_0 + b_1D + b_2D^2 + b_3S_1 + b_4S_2 + b_5S_3 + b_6V + b_7V^2 + b_8R + b_9R^2 + b_{10}A + b_{11}A^2 + b_{12}N + b_{13}N^2 + \text{(first-order interaction terms)}$$

where D was initial d.b.h. for the growth period; S was the species group indicator variable; V was the crown view factor index; R was the release factor surface area segment; A was the net view factor surface area; and N was the number of competitors.

Diameter and species indicator variables were first examined for their contribution to the model in explaining extraneous variability. Diameter, as expected, accounted for a substantial amount of the variation in basal area growth. Species differences also added significant improvement, indicating a response level difference for red oak and hickory in relation to the maple reference category. White oak, however, did not differ significantly from the reference category. The significance of the two species group indicators is attributed to variations in tolerance levels between species, and possibly to microsite differences. The lack of significance between white oak and maple is somewhat of a mystery, but may be due in part to the low frequency count of white oak with respect to maple.

Variables relating to competitive ability (V, R, A, and N) were included as a second stage in model development. The crown view factor index was of singular importance in accounting for over one-half of the variation removed by these terms. The combination of the crown view factor and net view factor surface area was credited for almost 10 percent of the growth variation beyond that removed by the diameter and species terms. The release factor was also significant in recognizing growth variations due to partial cutting. The number of competitors, however, was not significant, possibly because of its inclusion subsequent to the other terms.

Several interaction terms were found significant at the 1 percent level. The factors of interest were the species-release interaction terms, since a difference in species response functions was indicated. None of the interaction terms accounted for any great amount of improvement in predictive ability over the additive terms of the model.

Since apparent differences existed in species response functions, tests were conducted to evaluate actual differences between each of the species groups. From these tests it was concluded that slope differences in the response function existed between all species combinations other than red oak and white oak. Trees not influenced by release cutting assume response differences in level only.

The crown view factor index and related surface area and release factor terms accounted for a fairly substantial amount of basal area growth variation in this study. To assess their relative merit with respect to the competition circle approach the crown view factor model was compared to a similar study made by Gerrard (1967). Gerrard used the same data base in the development of a competition quotient model based on competition circles. The crown view factor model accounted for a greater percentage of the basal area growth variation, most of which was attributed directly to the measures of competitive stress used. The crown view factor concept appears to be a more sensitive measure of both competitive ability and the release from competitive stress.

Further testing of the crown view factor concept would be desirable to substantiate its biological significance. Some modifications of the basic concept might also be helpful in improving the sensitivity of the crown view factor index. One such modification would be a weighting of the surface area segments into which the crown is divided, such that segments receive proportionally greater weight as they approach a parallel to the path of the sun. Thus, the competitive effect would be greatest in an east-west direction. Another modification of interest would be to test a range of discrete crown surface area segment sizes for evaluating progressive shading differences.

All height and crown form values used in this study were based on sample data. Comparable results would therefore be expected in any application of the crown view factor concept without requiring individual height and crown measurements for every tree. Sample data could be gathered on either a local or regional basis. Also, since height and crown relationships are relatively stable over time, they might only be required on a one time basis. Inasmuch as this study is based on sample data, another consideration for future studies would be to determine how well the model might perform if individual measurements were taken for every tree.

Although this model accounted for a significant amount of basal area growth variation, 35 percent of the variation remained unexplained. Given the multitude of factors relating to tree growth this is not totally surprising. Two possibilities suggest themselves in attempting to account for this remaining variation. One is the use of more comprehensive growth models which give due consideration to all major environmental factors. The other possibility is that perhaps there is a 'non-competitive' factor which needs to be recognized in growth response evaluation for individual trees. Such a factor is present in the form of root grafting between trees. Kozlowski (1962) states that "the existence of continuity of conducting tissues between trees opens the possibility that biological activities in one may be directly influenced by another through biophysical and biochemical forces exerted through natural root grafts. These forces exerted directly by one tree on another may play an important role, along with competition, in shaping the nature of the forest community." The concept of competition may of itself be inadequate to fully express the interrelationships which exist within a forest community.

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APPENDICES

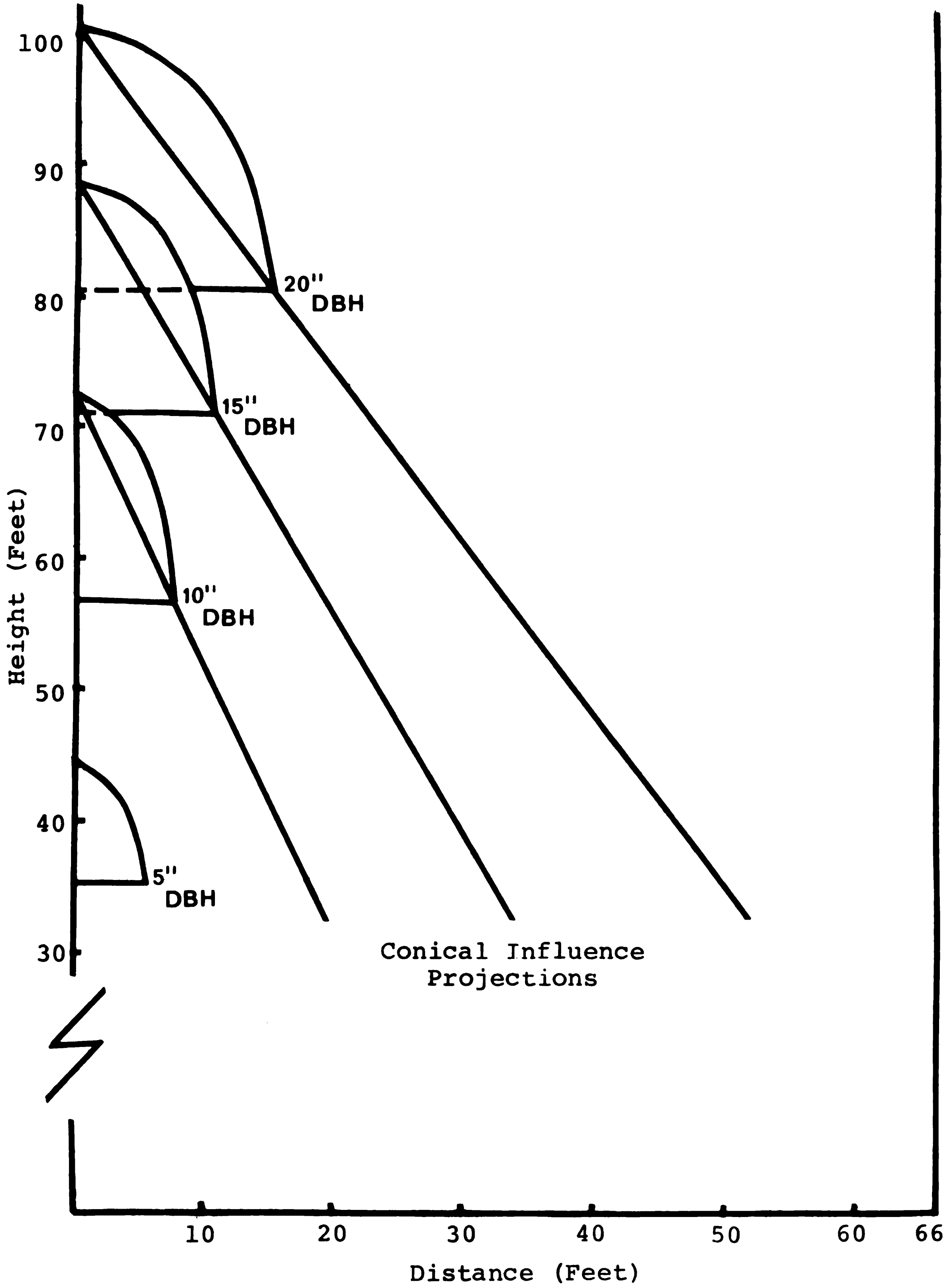
APPENDIX A

BOTANICAL NAMES OF SPECIES CITED IN THE TEXT

Common Name	Botanical Name
White oak	*Quercus alba* L.
Red oak	*Quercus rubra* L.
Black oak	*Quercus velutina* Lam.
Bitternut hickory	*Carya cordiformis* (Wangenh.) K. Koch
Pignut hickory	*Carya glabra* (Mill.) Sweet
Shagbark hickory	*Carya ovata* (Mill.) K. Koch
Red maple	*Acer rubrum* L.
Sugar maple	*Acer saccharum* Marsh.
American elm	*Ulmus americana* L.
Slippery elm	*Ulmus fulva* Michx.
White ash	*Fraxinus americana* L.
Black ash	*Fraxinus nigra* Marsh.
Black cherry	*Prunus serotina* Ehrh.
Cottonwood	*Populus deltoides* Bartr.
White spruce	*Picea glauca* (Moench.) Voss

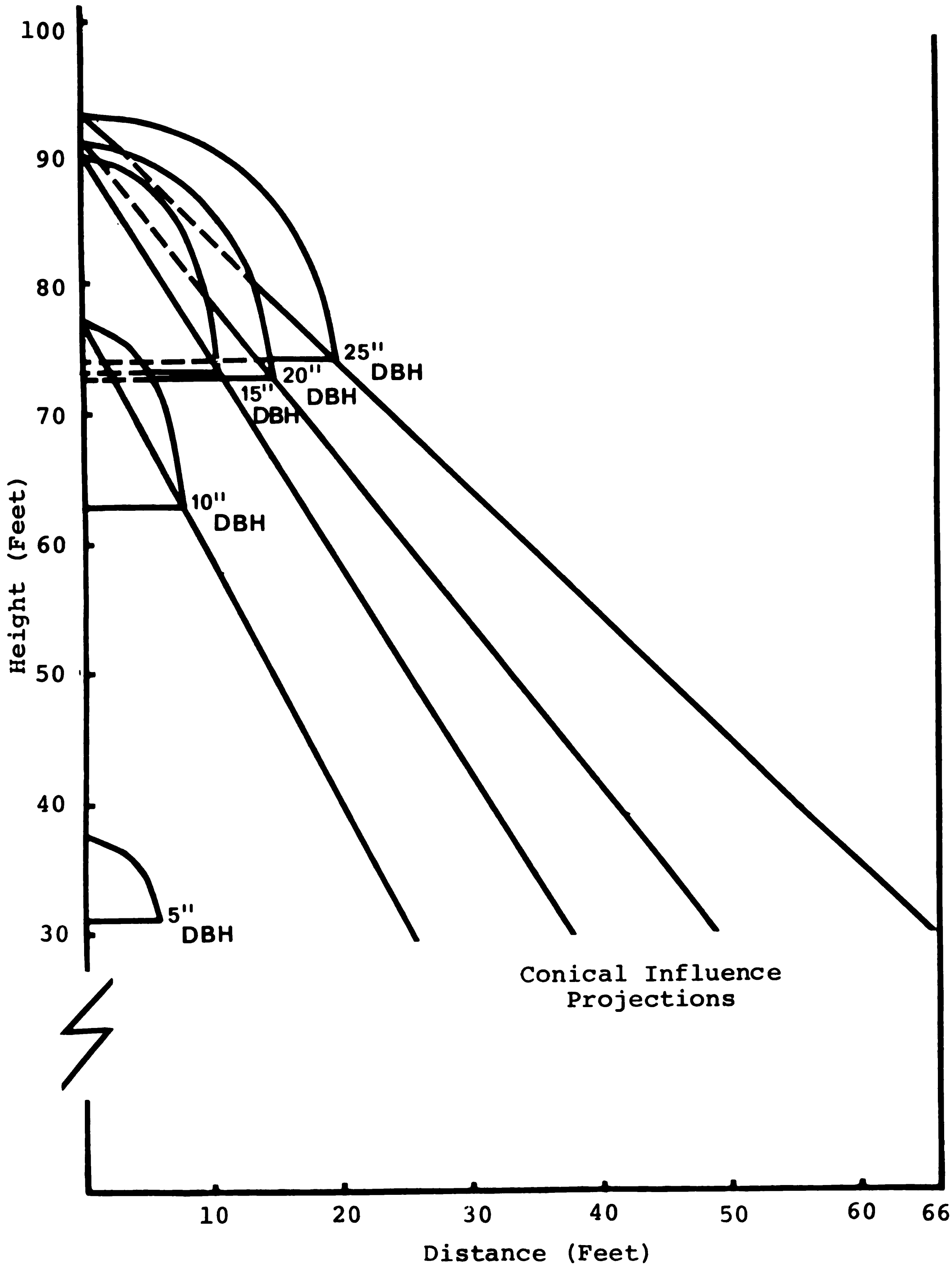
APPENDIX B

RED OAK CROWN FORM AND COMPETITIVE SPACE RELATIONSHIP



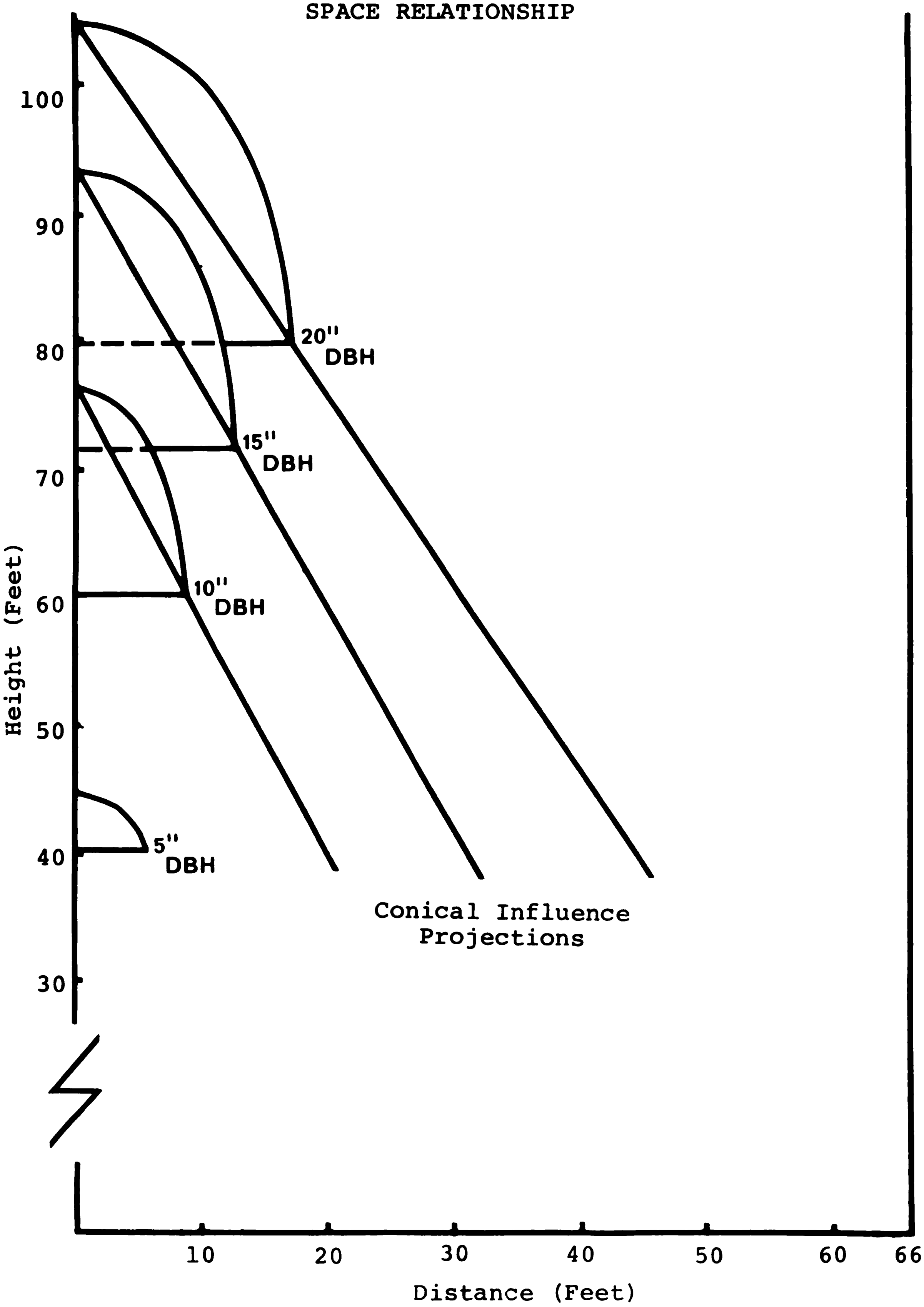
APPENDIX C

WHITE OAK CROWN FORM AND COMPETITIVE SPACE RELATIONSHIP



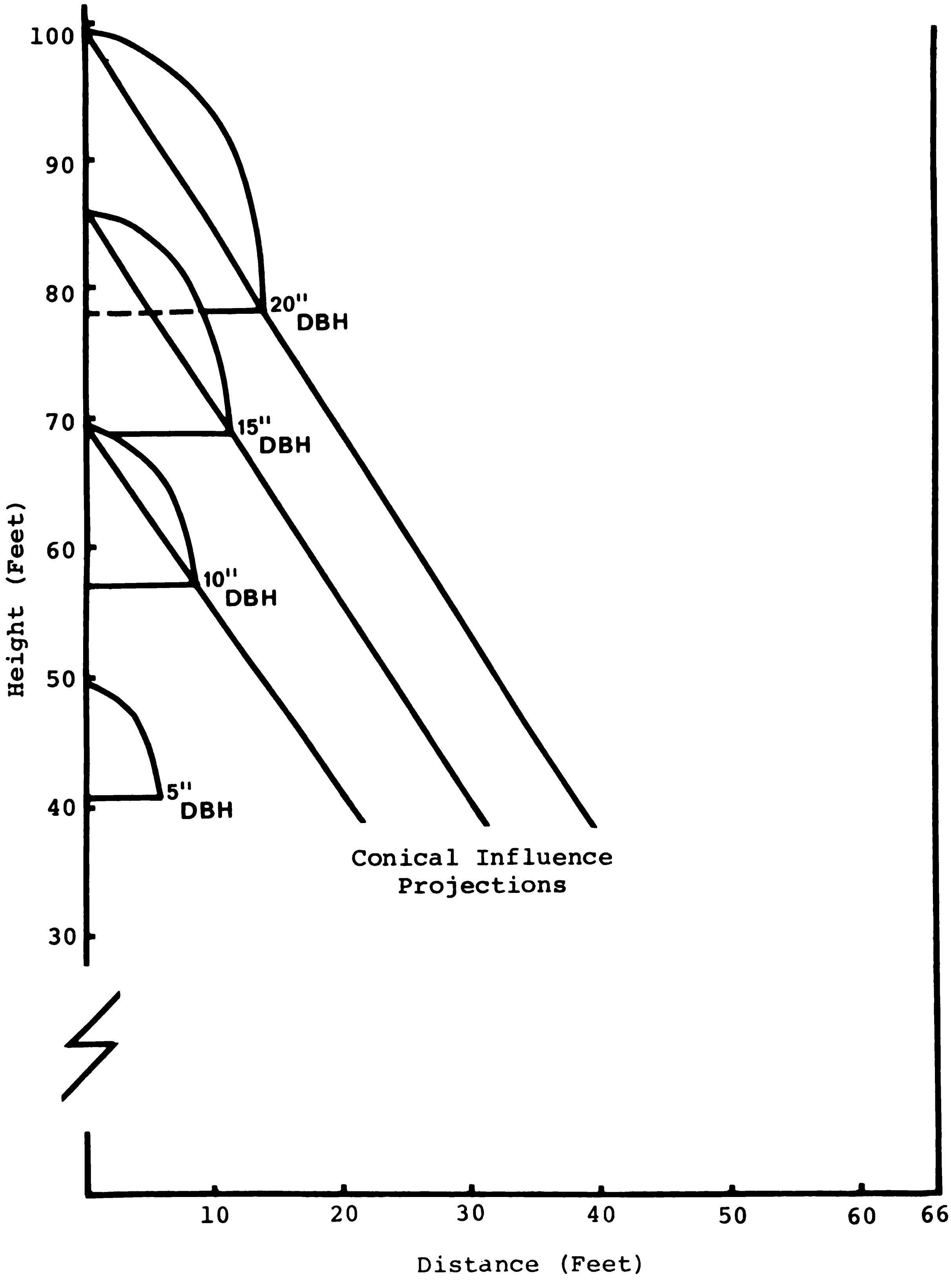
APPENDIX D

HICKORY CROWN FORM AND COMPETITIVE SPACE RELATIONSHIP



APPENDIX E

MAPLE CROWN FORM AND COMPETITIVE SPACE RELATIONSHIP



APPENDIX F

SOLUTION OF CROWN SURFACE AREA INTEGRAL

Figure 1 depicts the hypothetical crown surface area for a tree. A and B are two points on the curve Y = f(X) for this crown surface and since f(X) is continuous and does not change sign over the interval (A LT X LT B), the area generated by revolving AB about the Y axis is given by:

$$S_y = 2\pi \int_B^A X(1+(dx/dy)^2)^{1/2} dy$$

Since $Y^2/A^2 + X^2/B^2 = 1$ is the surface area equation,

then $X = (B^2 - B^2Y^2/A^2)^{1/2}$

$$dx/dy = \tfrac{1}{2}(B^2 - B^2Y^2/A^2)^{-1/2}(-2B^2Y/A^2) = -B^2Y/A^2X$$

and $(dx/dy)^2 = B^4Y^2/A^4X^2$

Thus $S_y = 2\pi \int_O^A X(1+B^4Y^2/A^4X^2)^{1/2} dy$

$$= 2\pi \int_O^A (X(A^4X^2 + B^4Y^2)^{1/2})/A^2X \, dy$$

$$= 2\pi/A^2 \int_O^A (A^4(B^2 - B^2Y^2/A^2) + B^4Y^2)^{1/2} \, dy$$

$$= 2\pi B/A^2 \int_0^A (A^4 - Y^2(A^2 - B^2))^{1/2}\, dy$$

Let $D = A^2 - B^2$

$C = A^2$

Then $S_Y = 2\pi B/A^2 \int_0^A (C^2 - Y^2 D)^{1/2}\, dy$

If $U = D^{1/2} Y$ then $du = D^{1/2}\, dy$

Thus $S_Y = 2\pi B/A^2 \int_L (C^2 - U^2)^{1/2}\, du/D^{1/2}$ where L is the transformed limit

Therefore, by standard integration formula

$$Sy = 2\pi B/A^2 D^{1/2} \left[\tfrac{1}{2} U (C^2 - U^2)^{1/2} - \tfrac{1}{2} C^2 \mathrm{Sin}^{-1}(U/C)\right]_L$$

$$= 2\pi B/A^2 D^{1/2} \left[\tfrac{1}{2} D^{1/2} Y (A^4 - DY^2)^{1/2} + (A^4/2) \mathrm{Sin}^{-1}(D^{1/2} Y/A^2)\right]_0^A$$

$$= 2\pi B/A^2 (A^2-B^2)^{1/2} \Big[(((A^2-B^2)^{1/2} Y)/2 * (A^4 - (A^2-B^2) Y^2)^{1/2}$$

$$+ (A^4/2) \mathrm{Sin}^{-1}(((A^2-B^2)^{1/2} Y)/A^2)\Big]_0^A$$

If let

$K = (A^2 - B^2)^{1/2}$

Then

$$S_Y = 2\pi B/A^2 K \left[(YK/2) * (A^4 - K^2 Y^2)^{1/2} + (A^4/2) \mathrm{Sin}^{-1}(YK/A^2)\right]_0^A$$

APPENDIX G

FORTRAN PROGRAM LISTING

```
C
C ---   THIS PROGRAM IS DESIGNED TO CALCULATE THE CROWN SURFACE AREA AND
C       THE CROWN VIEW FACTOR INDEX FOR A TREE IN RELATION TO THE THREE-
C       DIMENSIONAL DISTRIBUTION OF SURROUNDING TREES.
C
C ---   VARIABLES USED IN THE PROGRAM ARE DEFINED BELOW.  T1 REFERS TO
C       THE CURRENT STUDY TREE AND T2 REFERS TO THE CURRENT COMPETING
C       TREE IN ALL PROGRAM COMMENTS.
C
C ---   ANG - TREE DIRECTIONAL ANGLE (THETA) RETURNED FROM SUBROUTINE
        PARA
C       ANGD - FRACTIONAL DEGREE PORTION OF THETA ANGLE VALUE
C       BAG10 - ESTIMATED 10-YEAR BASAL AREA GROWTH
C       BAG6 - BASAL AREA GROWTH FOR SIX YEAR GROWTH PERIOD
C       BETA - CROWN RADIUS ANGLE OF T2 WITH RESPECT TO LOCATION OF T1
C       CCR - CORRECTED CROWN RADIUS VALUE FOR T2
C       CH - HEIGHT TO MAXIMUM CROWN WIDTH
C       CHLOG - NATURAL LOG VALUE OF HEIGHT TO MAXIMUM CROWN WIDTH
C       CH1 - HEIGHT TO MAXIMUM CROWN RADIUS OF T1
C       CH2 - HEIGHT TO MAXIMUM CROWN RADIUS OF T2
C       CK - VALUE USED IN SOLUTION OF CROWN SURFACE AREA EQUATION
C       CKST1 - VALUE USED IN SOLUTION OF CROWN SURFACE AREA EQUATION
C       CKST2 - VALUE USED IN SOLUTION OF CROWN SURFACE AREA EQUATION
C       CKST3 - VALUE USED IN SOLUTION OF CROWN SURFACE AREA EQUATION
C       CK2 - SQUARE OF CK
C       CL - CROWN LENGTH
C       CLS - SQUARE OF T1 CROWN LENGTH
C       CL1 - CROWN LENGTH OF T1
C       CL2 - CROWN LENGTH OF T2
C       CL4 - FORTH POWER OF T1 CROWN LENGTH
C       COMP - CROWN VIEW FACTOR INDEX OF COMPETITIVE ABILITY
C       COMPD - MAXIMUM COMPETITIVE DISTANCE OF T2 AT GIVEN HEIGHT OF T1
C       COMPR - CROWN VIEW FACTOR INDEX INCLUDING RELEASE TREES
C       CR - CROWN RADIUS
C       CRS - SQUARE OF T1 CROWN RADIUS
C       CRX - CROWN RADIUS VALUE FOR X≠TH DEGREE SEGMENT OF THETA
C       CR1 - CROWN RADIUS OF T1
```

```
C       CR2 - CROWN RADIUS OF T2
C       CR4 - FORTH POWER OF T1 CROWN RADIUS
C       CWLOG - NATURAL LOG VALUE OF CROWN WIDTH
C       CXC - CELL X-COORDINATE
C       CXC1 - CELL X-COORDINATE FOR T1
C       CXC2 - CELL X-COORDINATE FOR T2
C       CYC - CELL Y-COORDINATE
C       CYC1 - CELL Y-COORDINATE FOR T1
C       CYC2 - CELL Y-COORDINATE FOR T2
C       D - DIAMETER BREAST HEIGHT
C       DBH - DIAMETER BREAST HEIGHT
C       DBHDIF - DIAMETER DIFFERENCE FOR GROWTH EVALUATION
C       DBH0 - DIAMETER BREAST HEIGHT (1952)
C       DBH1 - DIAMETER BREAST HEIGHT (1956)
C       DBH2 - DIMAETER BREAST HEIGHT (1962)
C       DBT - DISTANCE BETWEEN TREES
C       DEGT - DIRECTIONAL ANGLE IN DEGREES OF T2 WITH RESPECT TO T1
C       DIA - INITIAL DIAMETER USED FOR GROWTH PERIOD
C       I - INDEX VARIABLE FOR CELL X-COORDINATE
C       IG - INDEX VARIABLE FOR SPECIES GROUP
C       INC - INCREMENTAL VALUE FOR ONE DEGREE SEGMENTS OF BETA
C       ISGP - SPECIES GROUP DESIGNATOR FOR T1
C       ISP - SPECIES TYPE
C       ISP1 - SPECIES TYPE FOR T1
C       ISP2 - SPECIES TYPE FOR T2
C       IST1 - TREE STATUS VALUE (1952)
C       IST2 - TREE STATUS VALUE (1956)
C       IST3 - TREE STATUS VALUE (1962)
C       J - INDEX VARIABLE FOR CELL Y-COORDINATE
C       JSGP - SPECIES GROUP DESIGNATOR FOR T2
C       L - INDEX VARIABLE FOR BETA
C       L - INDEX VARIABLE FOR BETA
C       LL - INDEX VARIABLE FOR SEGMENT ARRAY
C       MM - INDEX VARIABLE FOR SEGMENT ARRAY
C       NOTC - NUMBER OF TREES IN WORK FILE 7
C       NOTS - NUMBER OF TREES IN WORK FILE 6
C       NT - SEQUENCE NUMBER OF T1
C       NTCK - NUMBER OF COMPETING TREES
C       NTCKR - NUMBER OF COMPETING TREES INCLUDING RELEASE TREES
C       PRF - MAXIMUM DISTANCE BETWEEN COMPETING TREES
C       RELFT - RELEASE FACTOR CROWN SURFACE AREA
C       ROTAN - NEGATIVE CROWN SEGMENT ROTATIONAL ANGLE (FROM THETA)
C       ROTAP - POSITIVE CROWN SEGMENT ROTATIONAL ANGLE (FROM THETA)
C       SA - INITIAL TOTAL CROWN SURFACE AREA
C       SAREA - CROWN SEGMENT SURFACE AREA
C       SEG - CROWN SURFACE AREA SEGMENT ARRAY
C       SEGMT - INITIAL CROWN SURFACE AREA FOR SEGMENTS
C       SEGR - CROWN SURFACE AREA SEGMENT ARRAY INCLUDING RELEASE TREES
C       SLOP - SLOPE OF LINE FROM PERIMETER OF T2 TO CENTROID OF T1
C       TH - TOTAL TREE HEIGHT
C       THETA - DIRECTIONAL AZIMUTH VALUE OF T2 WITH RESPECT TO T1
C       TH1 - TOTAL HEIGHT OF T1
C       TH2 - TOTAL HEIGHT OF T2
```

```
C      TSA - CROWN VIEW FACTOR SURFACE AREA
C      TSAR - CROWN VIEW FACTOR SURFACE AREA INCLUDING RELEASE TREES
C      TXC - TREE X-COORDINATE VALUE
C      TXC1 - X-COORDINATE VALUE OF T1
C      TXC2 - X-COORDINATE VALUE OF T2
C      TYC - TREE Y-COORDINATE VALUE
C      TYC1 - Y-COORDINATE VALUE OF T1
C      TYC2 - Y-COORDINATE VALUE OF T2
C      X - X-COORDINATE VALUE FOR DISTANCE BETWEEN TREES
C      XC - T2 CROWN RADIUS VALUE FOR GIVEN SEGMENT OF BETA
C      XV - X-COORDINATE VALUE OF T1 CROWN INTERSECTION POINT FROM T2
C           CROWN PROJECTION
C      XZCOR - CORRECTION FACTOR FOR CROWN HEIGHT DIFFERENTIAL OF T1
C           WITH RESPECT TO T2
C      X1 - X-COORDINATE VALUE OF T1
C      X2 - X-COORDINATE VALUE OF T2
C      Y - Y-COORDINATE VALUE FOR DISTANCE BETWEEN TREES
C      Y1 - Y-COORDINATE VALUE OF T1
C      Y2 - Y-COORDINATE VALUE OF T2
C      Z - VALUE OF DEGT PARAMETER IN RADIANS
C      ZC - T2 CROWN SURFACE PERIMETER POINT VERTICALLY ABOVE XC
C      ZCVAL - TEMPORARY VALUE CALCULATED IN EVALUATING ZC
C      ZV - Z-COORDINATE VALUE OF T1 CROWN INTERSECTION POINT FROM T2
C           CROWN PROJECTION
C ---  ZV2 - SQUARE OF ZV
C
C     DIMENSION SEG(360),SEGR(360),DBH(4),ISGP(4),JSGP(4)
      INTEGER   TXC,TYC,CXC,CYC       BETA,THETA,TXC1,TXC2,TYC1,TYC2
     1CXC1,CXC2,CYC1,CYC2,ROTAP,ROTAN
C
C --- DUMP TAPE FILE TO DISK
C
 9049 READ(5,9050) ISP,DBHO,DBH1,DBH2,IST1,IST2,IST3,TXC,TYC,CXC,CYC
 9050 FORMAT(7X,I2,   3F4,2,13X,3I1,1X,2I4,2I2)
      IF (EOF(5))9052,9048
 9048 CONTINUE
C --- IF INITIAL DIAMETER IS ZERO, IGNORE TREE - IGNORES INGROWTH
      IF (DBH1.EQ.0.0.AND.DBH2.NE.0.0) GO TO 9049
C --- FOR TREES CUT OR DAMAGED IN 56 WHICH SUBSEQUENTLY DIES, SET STATUS
C --- FOR USE RELEASE FACTOR DETERMINATION ONLY
      IF(DBH1.NE.0.0.AND.DBH2.EQ.0.0) GO TO 25
      IF((IST2.EQ.3.OR.IST2.EQ.4.OR.IST2.EQ.5).AND.(DBH1.EQ.0.0.AND.
     1DBH2.EQ.0.0)) GO TO 24
      GO TO 26
   24 DBH1=DBHO
   25 IST2=3
   26 IF(DBH1.EQ.0.0) GO TO 9049
      WRITE(8.9051) ISP,DBHO,DBH1,DBH2,IST1,IST2,IST3,TXC,TYC,CXC,CYC
 9051 FORMAT(I2,3F5.2,3I1,2I4,2I2)
      GO TO 9040
```

```
 9052 CONTINUE
      REWIND 5
C
C
C --- INITIATE LOOPS TO ADVANCE THROUGH CELLS - C(I,J) IS STUDY CELL
C --- LOAD TEMPORARY WORK FILES FOR CURRENT STUDY CELL
C
      DO 200 I=4,13
      DO 200 J=6,18
      REWIND 6
      REWIND 7
      REWIND 8
C --- SELECT ALL TREES IN NINE CELL STUDY AREA - A(I,J)
      NOTC=0
      NOTS=0
   10 READ (8,9051) ISP,DBH0,DBH1,DBH2,IST1,IST2,IST3,TXC,TYC,CXC,CYC
      IF (EOF(8)) 60,30
   30 CONTINUE
C --- CHECK FOR PLOTS IMMEDIATELY ADJACENT TO STUDY PLOT (I,J)
      IF(((CXC.EQ.I).OR.(CXC.EQ.I-1).OR.(CXC.EQ.I+1)).AND.((CYC.EQ.J)
     1.OR.(CYC.EQ.J-1).OR.(CYC.EQ.J+1))) GO TO 40
      GO TO 10
   40 WRITE (7,41) ISP,DBH1,DBH2,TXC,TYC,CXC,CYC,IST2,IST3
   41 FORMAT (1X,I2,2F6.2,2I4.4I2)
C --- SELECT TREES IN C(I,J) ONLY, IGNORING ALL TREES CUT IN 56 (ST2=3)
      IF(IST2.EQ.3) GO TO 10
      NOTS=NOTS+1
      IF((CXC.EQ.I).AND.(CYC.EQ.J)) GO TO 50
      GO TO 10
   50 WRITE (6,41) ISP,DBH1,DBH2,TXC,TYC,CXC,CYC,IST2,IST3
      NOTC=NOTC+1
      GO TO 10
   60 END FILE 6
      END FILE 7
C --- ALL TREES IN STUDY CELL C(I,J) IN FILE 6 AND ALL TREES IN STUDY
C --- AREA A(I,J) IN FILE 7.
C
C
C --- WRITE STUDY CELL SUMMARY INFORMATION AND HEADINGS
C
      PRF=66.0
      WRITE (3,500) I,J,  PRF,NOTC,NOTS
  500 FORMAT (≠1≠,10X,≠CELL (≠,I2,≠,≠,I2,≠)≠,5X,≠PLOT RF =≠,F5.0,5X,≠CEL
     1L TREES =≠,I5,4X,≠STUDY TREES =≠,I5//,1X,
     2≠             TX    TY  SP  TR  TR   TREE    BA GRW    TREE   CROWN
     3CROWN   CROWN   INI CROWN   AJD CROWN  COMP IND     REL SA   SPEC≠
     4/,25X,≠NO  CK   DBH    10/6YR  HEIGHT  HEIGHT  LENGTH   RADIUS  SU
     5RF AREA   SURF AREA   FACTOR     REL FT≠/)
      REWIND 6
      REWIND 7
      NT=0
```

```
   65 CONTINUE
      NTCK=0
      NTCKR=0
      IF(NT,EQ.0) GO TO 74
   70 REWIND 7
C
C --- SELECT NEXT STUDY TREE (T1)
C
   74 READ (6,41)      ISP1,DBH(1),DBH(2), TXC1,TYC1,CXC1,CYC1
      IF(EOF(6) 199,7401
 7401 NT=NT+1
 7402 DIA=DBH(1)
C --- DETERMINE T1 CROWN PARAMETERS
 7403 CALL PARA (ISP1,DIA,TH1,CH1,CR1,CL1,ISGP)
      IF(ISGP(1).EQ.9) GO TO 74
      DBHDIF=DBH(2)**2-DBH(1)**2
      BAG6=.00545415*DBHDIF
      BAG10=.00909248*DBHDIF
C --- START CALCULATION OF FREE SURFACE AREA FOR EACH TREE IN C(I,J)
      CLS=CL1**2
      CRS=CR1**2
C --- CHECK FOR FLAT TREES
      IF (CR1.LE.CL1) GO TO 72
      CK=SQRT(CRS-CLS)
      CK2=CK**2
      CR4=CR1**4
      CKST1=(6.283185*CL1)/(CRS*CK)
      CKST2=((CL1*CK)/2.0)*SQRT(CR4-(CK2*CLS))
      CKST3=(CR4/2.0* ASIN((CL1*CK)/CRS)
      GO TO 73
   72 CK=SQRT(CLS-CRS)
      CK2=CK**2
      CL4=CL1**4
      CKST1=(6.283185*CR1)/(CLS*CK)
      CKST2=((CL1*CK)/2.0)*SQRT(CL4-(CK2*CLS))
      CKST3=(CL4/2.0)* ASIN((CL1*CK)/CLS)
C --- CALCULATE INITIAL SURFACE AREA OF T1
   73 SA=CKST1*(CKST2+CKST3)
      TSA=SA
      TSAR=SA
C --- INITIATE SURFACE AREA SEGMENT VALUES FOR T1
      SEGMT=SA/360.0
      DO 75 MM=1,360
      SEGR(MM)=SEGMT
   75 SEG(MM)=SEGMT
C
C --- SELECT NEXT COMPETING TREE (T2)
C
   80 READ (7,41)      ISP2,DBH(3),DBH(4),TXC2,TYC2,CXC2,CYC2,IST2,IST3
      IF(EOF(7)) 180,8001
 8001 DIA=DBH(3)
C --- CHECK FOR IDENTICAL TREES
```

```
      IF((TXC1.EQ.TXC2).AND.(TYC1.EQ.TYC2).AND.(CXC1.EQ.CXC2).AND.(CYC1
     1.EQ.CYC2)) GO TO 80
C --- CALCULATE DISTANCE BETWEEN TREES
      X=TXC1-TXC2
      Y=TYC1-TYC2
      DBT=SQRT(X**2+Y**2)
C --- CHECK IF T2 IS IN CIRCULAR PLOT OF PRF FEET FROM T1
      IF(DBT.GT.PRF) GO TO 80
C --- DETERMINE T2 CROWN PARAMETERS
      CALL PARA (ISP2,DIA,TH2,CH2,CR2,CL2,JSGP)
      IF(JSGP(1).EQ.9) GO TO 80
C --- CHECK IF T2 IS EFFECTIVELY NON-COMPETITIVE
      IF(TH2.LE.CH1) GO TO 80
C --- CHECK IF T1 IS WITHIN THE COMPETITIVE INFLUENCE ZONE OF T2
      COMPD=(CR2*(TH2-CH1))/CL2
      IF((DBT-CR1).GT.COMPD) GO TO 80
      IF(IST2.EQ.3) GO TO 90
      NTCK=NTCK+1
   90 NTCKR=NTCKR+1
C --- DETERMINE DIRECTIONAL ANGLE (THETA) OF T2 FROM T1 TO NEAREST
C --- DEGREE
  100 CALL ANGLE (TXC1,TYC1,TXC2,TYC2,ANG)
      THETA=ANG
      ANGD=ANG-THETA
      IF(ANGD.GE.0.5) THETA=THETA+1
C --- DETERMINE CROWN CORRECTION FACTOR OF T2 FOR X,Z PLANE OF T1
      XZCOR=CH2-CH1
C --- CALCULATE CROWN RADIUS ANGLE (BETA) FROM T1 TO T2
      IF (CH2-CH1) 105,104,104
  104 CCR=CR2/DBT
      GO TO 106
  105 CCR=(SQRT(CR2**2-((CR2**2*(CH1-CH2)**2)/ CL2**2)))/DBT
  106 BETA=57.29578*(ATAN(CCR))
      IF (BETA.EQ.0) GO TO 80
      INC=0
C
C --- FIND VALUE FOR EACH ONE DEGREE SEGMENT OF T1 INFLUENCED BY T2
C
      DO 120 L=1,BETA
      CRX=L/57.29578
      XC=TAN(CRX)*DBT
C --- DETERMINE POINT (ZC) ON CROWN PERIMETER OF T2 FOR XC VALUE OF
C --- BETA
      ZCVAL=CL2**2-(((CL2**2*XC**2)/CR2**2)
      ZC=SQRT(ZCVAL)+XZCOR
C --- FIND SLOPE OF LINE FROM P(XC,ZC) ON T2 TO P(0,0) OF T1
      SLOP=ZC/DBT
C --- DETERMINE X AND Z VALUES OF CROWN INTERSECTION POINT (XV,ZV) ON T1
      XV=CL1/(SQRT(CLS/CRS+SLOP**2))
      ZV=SLOP*XV
      ZV2=ZV**2
```

```
C --- CHECK FOR FLAT TREES
      IF (CR1.LE.CL1) GO TO 116
C --- CALCULATE VALUE OF SURFACE AREA SEGMENT ABOVE P(XV,ZV)
      SAREA=(CKST1*((CKST2+CKST3)-((((ZV*CK)/2.0)*SQRT(CR4-(CK2*ZV2)))+
     1((CR4/2.0)* ASIN((ZV*CK)/CRS)))))/360.
      GO TO 117
  116 SAREA=(CKST1*((CKST2+CKST3)-((((ZV*CK)/2.0)*SQRT(CL4-(CK2*ZV2)))+
     1((CL4/2.0)* ASIN((ZV*CK)/CLS)))))/360.
C --- CHECK SEGMENT VALUE CONCERNED AND ASSIGN SMALLEST VALUE.  RESET
C --- SEGMENT INDEX FOR VALUES GT 360 OR LT 1
  117 ROTAP=THETA+INC
      IF(ROTAP.GT.360)  ROTAP=ROTAP-360
      IF(IST2.EQ.3) GO TO 118
      IF(SAREA.LT.SEG(ROTAP))  SEG(ROTAP)=SAREA
  118 IF(SAREA.LT.SEGR(ROTAP)) SEGR(ROTAP)=SAREA
      INC=INC+1
C --- ASSIGN IDENTICAL SEGMENT VALUE MIRRORED ON OPPOSITE SIDE OF THETA
      ROTAN=THETA-INC
      IF(ROTAN.LT.1)  ROTAN=360+ROTAN
      IF(IST2.EQ.3) GO TO 119
      IF(SAREA.LT.SEG(ROTAN))  SEG(ROTAN)=SAREA
  119 IF(SAREA.LT.SEGR(ROTAN)) SEGR(ROTAN)=SAREA
  120 CONTINUE
C
C --- SUM ALL SEGMENT VALUES FOR T1
C
      TSA=0.0
      TSAR=0.0
      DO 130 LL=1,360
      TSAR=TSAR+SEGR(LL)
  130 TSA=TSA+SEG(LL)
      GO TO 80
  180 CONTINUE
      RELFT=TSA-TSAR
      COMP=TSA/SA
      COMPR=TSAR/SA
C
C --- PRINT RESULTS OF STUDY TREE VIEW FACTOR DETERMINATION
C
      WRITE (3,505) TXC1,TYC1,ISP1,NT,NTCK,DBH(1),BAG10,TH1
     1,CH1,CL1,CR1,SA,TSA,COMP,TSAR,(ISGP(IG),IG=1,4),NTCKR,DBH(2),
     2,BAG6,COMPR,RELFT
  505 FORMAT (≠0≠, 8X,2I5,3I4,6F8.2,2F12.3,F8.4,F12.3/≠ ≠,26X,
     1I4,2F8,2,56X,F8.4,F12.3)
  190 CONTINUE
C --- PUNCH OUTPUT DATA
      WRITE(9,195) CXC1,TXC1,TYC1,ISP1,(ISGP(IG),IG=1,4),NTCK,
     1DBH(1),DBH(2),BAG6,BAG10,SA,TSA,TSAR,COMP,TH1
  195 FORMAT (I2,2I4,I2,4I1,I2,2F5.2,2F6.4,3F9.3,F7.5,F6.2)
C --- PROVISION FOR CATALOG OF DATA
      WRITE (10,196) CXC1,CYC1,TXC1,TYC1,ISP1,(ISGP(IG),IG=1,4),NTCK,
     1NTCKR,DBH(1),DBH(2),BAG6,BAG10,TH1,CH1,CL1,CR1,SA,TSA,TSAR,RELFT,
     2COMP,COMPR
```

```
  196 FORMAT (2I2,2I4,I3,4I1,2I3,2F5.2,2F7.5,4F8.3,4F10.5,2F7.5)
      GO TO 65
  199 CONTINUE
  200 CONTINUE
      REWIND 6
      REWIND 7
      REWIND 9
      STOP
      END


      SUBROUTINE PARA (ISP,D,TH,CH,CR,CL,JSGP)
C
C --- DETERMINE BASIC CROWN PARAMETERS FOR TREE WITH SPECIFIED DIAMETER
C
      DIMENSION JSGP (4)
      DO 10 IG=1,4
   10 JSGP(IG)=0
      IF(ISP.EQ.45) GO TO 2
      IF((ISP.EQ.2).OR.(ISP.EQ.11)) GO TO 3
      IF((ISP.EQ.29).OR.(ISP.EQ.30).OR.(ISP.EQ.4).OR.(ISP.EQ.7).OR
     1(ISP.EQ.14).OR.(ISP.EQ.20).OR.(ISP.EQ.3).OR.(ISP.EQ.6).OR.
     2(ISP.EQ.34).OR.(ISP.EQ.69)) GO TO 4
      IF((ISP.EQ.1).OR.(ISP.EQ.5).OR.(ISP.EQ.60).OR.(ISP.EQ.72))GO TO 5
      WRITE (3,1) ISP,D
    1 FORMAT(≠0≠,≠TREE SPECIES ERROR≠,I4,F8.2)
      JSGP(1)=9
      GO TO 7
C --- WHITE OAK GROUP REGRESSIONS
C --- CHECK FOR OLD GROWTH TREES
    2 IF(D.GT.18.0) GO TO 15
      TH = 115.68880 - 390.35087*(1.0/D)
      CH = 94.452437 - 316.51932*(1.0/D)
      GO TO 20
   15 TH = 98.289168 - 682.85176*(1.0/D**1.5)
      CH =78.29508-523.65716*(1.0/D**1.5)
   20 CWLOG=0.92058793+0.027042093*D
      CR=(10.0**CWLOG)*0.5
      JSGP(1)=1
      GO TO 6
C --- RED OAK GROUP REGRESSIONS
    3 TH = -20.531931 + 92.495199*ALOG10(D)
      CHLOG = 0.99521363 + 0.86530583*ALOG10(D) - 0.010861587*D
      CH = 10.0**CHLOG
      CWLOG=.88148408 + .0302480638*D
      CR=(10.0**CWLOG)*0.5
      JSGP(2)=1
      GO TO 6
C --- HICKORY GROUP REGRESSIONS
    4 TH = -34.107704 + 117.1358*ALOG10(D) - 0.6744319*D
      CH = -5.5729203 + 65.723933*ALOG10(D)
      CWLOG = 0.68085867 + 0.40379989*ALOG10(D) + 0.0164973742*D
```

```
      CR = (10.0**CWLOG)*0.5
      JSGP(3)=1
      GO TO 6
C --- MAPLE GROUP REGRESSIONS
    5 TH = 26.734262 + 4.8402663*D - 0.0598092224*D**2
      CH = 9.1744035 + 38.626798*ALOG10(D) + 0.93691206*D
      CWLOG= 0.71283409 + 0.43501453*ALOG10(D) + 0.0083858079*D
      CR = (10.0**CWLOG)*0.5
      JSGP(4)=1
    6 CL=TH-CH
    7 RETURN
      END


      SUBROUTINE ANGLE (X1,Y1,X2,Y2,THETA)
C
C --- DETERMINE AZIMUTH (THETA) OF T2 FROM T1
C
      INTEGER   X1,X2,Y1,Y2
      THETA=0.0
      DEGT=0.0
      X=X2-X1
      Y=Y2-Y1
      IF(X2-X1) 8,7,8
    7 Z=0.0
      GO TO 9
    8 Z=Y/X
    9 DEGT=57.29578*(ABS(ATAN(Z)))
      IF(X2-X1) 10,11,12
   10 IF(Y2-Y1) 20,22,24
   11 IF(Y2-Y1) 30,32,34
   12 IF(Y2-Y1) 40,42,44
   20 THETA=180.0+DEGT
      GO TO 50
   22 THETA=180.0
      GO TO 50
   24 THETA=180.0-DEGT
      GO TO 50
   30 THETA=270.0
      GO TO 50
   32 PRINT 33
   33 FORMAT (≠0≠,6X,≠SAME TREE - ERROR≠)
      GO TO 50
   34 THETA=90.0
      GO TO 50
   40 THETA=360.0-DEGT
      GO TO 50
   42 THETA=1.0
      GO TO 50
   44 THETA=DEGT
   50 RETURN
      END
```

CELL (4, 8) PLOT RF = 66. CELL TREES = 14 STUDY TREES = 104

TX	TY	SP	TR NO	TR CK	TREE DBH	BA GRW 10/6YR	TREE HEIGHT	CROWM HEIGHT	CROWN LENGTH	CROWN RADIUS	INI CROWN SURF AREA	ADJ CROWN SURF AREA	COMP IND FACTOR	REL SA REL FT
275	552	45	1	4	15.20	.06	90.01	73.63	16.38	10.73	987.582	734.082	.7433	734.082
				4	15.40	.03							.7433	.000
278	556	5	2	5	14.10	.22	83.09	66.78	16.32	10.71	982.832	304.605	.3099	304.605
				5	14.93	.13							.3099	.000
284	573	6	3	5	17.43	.10	99.54	76.01	23.53	14.74	1932.455	1566.299	.8105	1566.299
				5	17.74	.06							.8105	.000
284	594	11	4	2	15.32	.22	89.10	71.52	17.58	11.06	1084.230	859.676	.7929	859.676
				2	16.09	.13							.7929	.000
286	589	5	5	5	7.23	.03	58.60	49.13	9.47	7.02	383.564	133.495	.3480	109.391
				7	7.43	.02							.2852	24.104
287	558	45	6	4	11.55	.08	81.89	67.05	14.84	8.55	696.297	289.660	.4160	289.660
				4	11.93	.05							.4160	.000
289	569	5	7	9	7.86	.09	61.08	51.13	9.96	7.37	423.238	38.851	.0918	38.851
				11	8.48	.06							.0918	.000
290	570	5	8	10	5.88	.05	53.13	44.40	8.73	6.25	312.262	67.507	.2162	50.653
				12	6.32	.03							.1622	16.854
294	528	5	9	4	9.97	.03	69.05	57.09	11.95	8.51	581.746	359.499	.6180	307.466
				5	10.11	.02							.5285	52.033
300	539	11	10	3	15.00	.11	88.25	70.79	17.46	10.82	1050.142	773.664	.7367	773.664
				3	15.41	.07							.7367	.000
300	561	45	11	5	23.00	.17	92.10	73.55	18.55	17.44	1992.580	1483.109	.7443	1483.109
				5	23.40	.10							.7443	.000
304	540	5	12	9	6.38	.08	55.18	46.23	8.94	6.54	336.361	60.421	.1796	35.664
				11	7.00	.05							.1060	24.756
314	586	11	13	4	8.89	.34	67.24	52.45	14.79	7.07	557.923	419.752	.7523	336.230
				7	10.78	.20							.6026	83.521
319	537	45	14	2	14.50	.27	88.77	72.62	16.14	10.27	926.578	757.102	.8171	533.390
				4	15.48	.16							.5757	223.713

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Doctor of Philosophy

Final Examination: July 10, 1975

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