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Modeling the change of stem form in plantations of young loblolly pine (Pinus teada)

Gary W. Beard

To the Graduate Council:

I am submitting herewith a thesis written by Gary W. Beard entitled "Modeling the change of stem form in plantations of young loblolly pine (Pinus teada)." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Forestry.

John C. Rennie, Major Professor

We have read this thesis and recommend its acceptance:

Garland R. Wells, Edward R. Buckner

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

To the Graduate Council:

I am submitting herewith a thesis written by Gary W. Beard entitled "Modeling the Change of Stem Form in Plantations of Young Loblolly Pine (Pinus taeda)." I recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Forestry.

John C. Rennie

John C. Rennie, Major Professor

We have read this thesis and recommend its acceptance:

G. R. Wells

Edward R Buckner

Accepted for the Council:

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MODELING THE CHANGE OF STEM FORM IN PLANTATIONS OF YOUNG LOBLOLLY PINE (*PINUS TAEDA*)

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Gary W. Beard

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ABSTRACT

When predicting future stand volumes using present mensurational methods, stem form is often considered as a static variable and thus ignored. This may lead to incorrect estimates since stem form may change during the time period considered. These changes can be further influenced by natural occurrences or by management practices such as thinning.

The objectives of this study were to: (1) develop a model to describe the changes in stem form with age in a plantation, and (2) correlate the effects of age at which a loblolly pine (*Pinus taeda* L.) plantation was thinned with changes in form.

The data used were obtained by stem analysis on randomly selected trees in a young loblolly pine plantation which had four thinning treatments: a control (with no thinning), and thinnings at ages 10, 15, and 20 years.

Three types of models were used to describe the change in stem form. They consisted of past growth models, taper equations, and the use of the primary units of volume, surface, and length as predictors. The accuracy desired for the past growth models and the taper equations was the capacity to predict the radius inside bark at known heights within 0.25 of an inch 95 percent of the time. In the models using the primary units of volume, surface and length the desired accuracy was predicting these units in 1975 within 5 percent of the means 95 percent of the time. None of the models tested were able to describe the form of the whole length of the stem within the desired accuracy. However the model using the radius at breast height inside bark growth (1970 to 1975) was able to satisfactorily predict the form of the stem up to 50 percent of the total height of the tree.

Evaluations of the taper equations showed that for the years 1970 and 1975 there were significant differences in the populations. For the year 1965 no significant differences were found, and evaluation of the regression equations showed no significant differences in stem form between the thinning regimes for that year. Thus it was concluded that thinning at age 10 had no significant effect on the change in stem form, but thinnings at ages 15 and 20 had a significant effect on the change in stem form.

Models using the primary units of volume, surface, and length showed that surface and length could be predicted from past values of the primary units within reasonable limits. This was shown for both total (from stump height to the tip) and sectional (based on the tree being composed of bolts of a fixed length) values of the primary units. Predicting volume within reasonable limits was not possible for either total or sectional values.

Evaluation of curves showing the change in Girard form class for ages 10 to 22, revealed that the older the stand when thinned the less pronounced is the reduction in the rate of natural increase of Girard form class with young trees overtime.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

The volume of a standing tree is dependent on the height, diameter breast height (dbh), and stem form. Spurr (1952) stated that this relationship had a multiple correlation coefficient of 0.992, and others have stressed the importance of the inclusion of form in volume estimation (Bruce, Curtis, and Vancoevering, 1968; Husch, Miller, and Beers, 1972).

Stem form is the relative rate of diameter change with increasing height (Larson, 1963). Thus individual trees with the same height and dbh do not always have the same volume. This is because the form of a tree can vary between sites, species, or within a species on a site. Most volume tables are based on an average form by species for a specific geographic region. The assumption made in the table construction is that errors due to form will balance to give a reasonable estimate of volume.

In predicting future volumes, form is often considered to remain constant for the time period of the prediction. This could result in significant errors when there is considerable form change with age. For each unit change in Girard form class (G.f.c.) (the ratio between dbh and the diameter inside bark at 17.3 feet), there is a 3 percent change in volume (Girard, 1933). Thus, if the form changed by five units over the prediction period, the volume estimate could be in error as much as 15 percent, in addition to the error inherent to the particular prediction method itself. Also disturbances that alter stocking may cause a change in stem form.

In young managed plantations the most common disturbance is thinning. This could be by natural mortality such as overtopping and suppression of smaller or slower growing trees, also by low thinning practices commonly found in plantation management. Thus it is important to understand the responses of trees to thinning in a plantation situation. The study's objectives were: (1) to derive a model to describe changes in stem form with age in plantations of young loblolly pine (*Pinus taeda*, L.), and (2) to correlate the effects of different thinning regimes on the change in form.

CHAPTER II

LITERATURE REVIEW

Stem Form

Definition of Stem Form

Stem form is defined as the relative rate of change in stem diameter with increasing tree height; this definition is synonymous with stem taper. In the strictest sense, stem form refers to the shape of the bole, while taper is the progressive decrease in diameter from the base to the tip of the stem (Larson, 1963; Grosenbaugh, 1966).

Expressions of Stem Form

Many methods of expressing stem form have been proposed. Generally the most useful expressions fall into six categories: form factor, form quotient, form point, and taper tables, curves, and formulas. Using the primary units of volume, surface, and length as expressions of stem form has been proposed (Grosenbaugh, 1966).

Form Factor. Form factor is the ratio of the volume of a geometrical solid, usually a cylinder, cone, or conic frustum, with the same height and diameter as the tree to the tree volume. Form factor is unique in that it can be calculated only after the volume of the tree is known.

The concept of form factor was derived in an attempt to correlate stem form and volume. The objectives of early studies were to derive a standardized law of stem form which could be applied in the computation of the volume of a standing tree when used with a correction factor. But in stands of varying form its usefulness in estimating volume was limited (Belyea, 1931; Husch, Miller, and Beers, 1972).

Form Quotient. Form quotient is the ratio of a diameter measured at some height above breast height to the diameter at breast height (Husch, Miller, and Beers, 1972). In 1899 Schiffel first applied the idea of form quotients to the study of tree form. In this application the form quotient is the ratio between the diameter one-half the total height of the tree and at breast height (4.5 feet); this is called normal form quotient. In cases where the total height of the tree is nine feet, the two measurements coincide (Husch, Miller, and Beers, 1972).

Jonson (1910, 1911) corrected for this discrepancy by changing the position of the upper diameter to a point halfway between the tip of the tree and breast height in the absolute form quotient. This was a better expression of form than normal form quotient, but was still dependent on height and diameter measurements for its determination.

The Girard form quotient has received the most acceptance in the United States as a measure of form. Girard form quotient is the ratio of diameter inside bark at the top of the first standard log, 17.3 feet from the ground, to dbh, outside bark (Girard, 1933). If this quotient is expressed as a percentage, it is Girard form class. In an attempt to eliminate the more difficult 17.3 foot measurement, Horn (1956) suggested using the measurements of diameter at 7.0 feet inside bark and 2.25 feet outside bark as an estimate of G.f.c. This was found to be accurate within ±2 units of G.f.c.

Form Point. Form point is the ratio of the height to the center of wind resistance on the tree, approximately at the center of gravity of the tree, to the total tree height expressed as a percentage (Johnson, 1912). It was based on the hypothesis that the form of a tree stem depends upon the mechanical stress to which the tree is subjected. The higher the form point the more cylindrical the shape of the tree. The main value of form point is in predicting the absolute form quotient, because there exists a good correlation between form quotient and form point. In cases where form point has been used, the average form points for various diameter classes of a stand are obtained by sampling; these values are then used as independent variables to read form classes from curves or tables (Fogelburg, 1953).

Taper Tables, Curves, and Formulas. Taper tables can be constructed for trees of the same shape or form if there are enough diameter measurements taken along the bole of the tree (Avery, 1967). The idea of taper tables is to organize the data on stem form so that stem volume or volume tables can be computed. Chapman and Meyer (1949) suggested preparing taper tables by averaging upper-log taper rates for fixed lengths according to breast and merchantable heights.

A taper curve is in essence a taper table in graphic form, with the axes being height and taper. Heger (1965) stated the main disadvantage of taper curves was their awkward description of stem form along with the difficulty of obtaining the measurements needed to construct the curves themselves. Bruce, Curtis, and Vancoevering (1968) presented a method of calculating volume which uses taper curves. They suggested that the use of form in addition to dbh and height would improve the fit of the basic taper equation.

A taper equation is a mathematical relationship which estimates the amount of taper between points of different diameters a known distance apart on the bole. Jonson (1918) modified the existing Höejer logarithmic taper formula by adding a biological constant to correct for errors in the upper diameters of a stem. Behre (1923, 1927) presented a hyperbolic formula which was more successful for estimating stem form than those of Höejer and Jonson. Bruce (1972) developed equations which permit the flexible transformation of Behre's formula from one top diameter to another.

Fries (1965), through the use of eigenvector analysis, showed similar form in birch and pine in Sweden, and British Columbia. Kozak and Smith (1966) described multivariate and other methods for analysis of tree taper, and suggested that simpler methods are best. Kozak, Munro, and Smith (1969) presented the derivation of simple yet effective taper functions, based on a parabolic relationship.

Demaerschalk (1971, 1972) discussed the desirability of developing a system by which taper equations could be derived from existing volume equations, based on the premise that total volume estimates should be identical to those given by existing volume equations.

Ormerod (1973) suggested that taper equations be based on step functions in cases where the taper curve for a species or population is sigmoid. The basis for this is that the inflection point for the curve would be at a constant percentage of the total tree height. With the bole divided in this manner, taper curves can be derived for each section by a least squares approach.

Volume, Surface, and Length. Grosenbaugh (1966) presented the concept of describing the stem of a tree as the product of a number of short sections, related only by having a common diameter at junction points and by a requirement of monotonicity of profile.

Using this concept, the volume, surface, and length (V.S.L.) of each section can be calculated and accumulated for each tree. These variables represent the most important quantitative information on tree stems that can be obtained from either an explicit polynomial equation or a graphic description. Also these three variables are directly additive for more than one tree, which greatly facilitates the definition of the average form of a stand of trees (Grosenbaugh, 1966).

Effects of Silvicultural Treatments on Stem Form

Fertilization. Pegg (1966) found significant increases in G.f.c. after application of nitrogenous fertilizer in a 23-year-old unthinned loblolly pine plantation. Significant changes in G.f.c. were also detected in a phosphate application in the same stand. In a study of the response of a thinned loblolly pine plantation to fertilizer trials using nitrogen, phosphorus, and potassium, Richeson (1976) found no significant difference in G.f.c. over a five-year period.

Thinning. Newnham (1965) showed that as the intensity of thinning increases, the amount of stem taper also increases. Badoux (1939) found that of stems in the same diameter class, those subjected to the heaviest thinning treatments had the greatest stem taper. Meyer (1931) found that prior to thinning all trees in a ponderosa pine (*Pinus ponderosa*, Laws) stand decreased in stem taper with increasing age. Following the thinning, trees which had been decreasing in taper showed an increase in stem taper, while those individuals which had the greatest taper prior to thinning showed a decrease in stem taper. Behre (1932) and Lohrey (1961) indicated that the rate of stem taper converges to a common range of values as the result of extreme thinning treatments. Naslund (1943) and Nyyssonen (1952) stated that trees with little taper prior to thinning will increase in taper while trees with the greatest taper will exhibit either no change or a decrease in taper.

Pruning. Bickerstaff (1946) stated that while thinning causes an increase in stem taper, pruning can be regarded as having the opposite effect on taper as thinning. Metzger (1893) said that increases in taper caused by thinning can, to a certain extent, be compensated for by pruning. Young and Kramer (1952) found that pruning resulted in increased growth in the upper stem with a subsequent decrease of stem taper. Marts (1949) showed that the reduction of crown size in longleaf pine (*Pinus palustris*, Mill.) caused a reduction in stem taper. In his monograph on stem form Larson (1963) stated that no citation had been found that showed an increase in stem taper due to pruning.

Cubic Foot Volume

Definition of Volume

Volume is a three-dimensional representation of the space occupied by an object. Volume is expressed in cubic units derived from the basic units of length, width, and depth.

Standard Formulas

The shape of a tree stem is commonly modeled with a neiloid, cone, parabolid, or cylinder. Based on these shapes several formulas have been derived to estimate cubic volume of a tree stem. Often the shape of the stem does not agree exactly with the shape to which it is being compared, so a correction term has to be added (Husch, Miller, and Beers, 1972).

Cubic Volume by Displacement

The exact volume of a solid can be obtained by the total immersion in and the subsequent displacement of a liquid by the solid; the volume displaced will equal the volume of the solid. This method is more appropriate for irregular or uneven surfaced solids.

Volume by Graphic Estimation

Volume of tree stems can be determined graphically by plotting diameters at successive heights along the bole of a tree. The volume can then be obtained by determining the area under the curve and converting to cubic volume by the use of an appropriate conversion factor. This solution is an appropriate universal method, in that it is applicable to all solids of revolution regardless of surface area (Husch, Miller, and Beers, 1972).

Growth

Growth Defined

Growth in a biological sense is the change in size of an organism or the number of organisms in a population. Tree growth is the increase in volume expressed over a period of time.

If tree growth is measured as the difference of volume or dimensions over a period of years, then the increase is called periodic increment. If the time period is only one year, then it is called current annual increment (c.a.i.). If the periodic increment is divided by the number of years it represents, then it is termed periodic annual increment (p.a.i.). The mean annual increment (m.a.i.) is obtained by dividing cumulative size by age (Husch, Miller, and Beers, 1972).

Stem Analysis

Stem analysis is a method by which past height and diameter growth are obtained by the careful study of growth rings at predetermined heights along the bole. Change in stem form can be examined as the tree grew from these measurements.

One disadvantage of stem analysis lies in the vast amount of computation that must be performed, along with the time-consuming plotting of data for the graphic presentations. In recent years the introduction of stem analysis programs has reduced the amount of labor required in the analysis of data (Bruce and Mager, 1968; Pluth and Cameron, 1971; Herman, DeMars and Woolard, 1975).

Growth Prediction

Growth prediction equations apply to static stand conditions: they are not growth projections in time, but rather estimates of growth for combinations of stocking, age and site index (Brender, 1966). Clutter (1963) developed five equations to describe growth and yield relationships for loblolly pine. This included equations for both projected basal area and cubic foot volume. Lemmon and Schumacher (1963) developed a model to predict theoretical growth and yield of hypothetical ponderosa pine stands under different thinning managements. Nelson (1964) attempted to relate expressions of diameter distribution in even-aged, managed stands to cubic foot volume growth, age, site, stockings and interactions of these variables. Van Hooser (1970) developed a prediction model for growth of uneven-aged stands of loblolly pine based on the relationships of initial basal area and average diameter to growth. Sullivan and Clutter (1972) presented a simultaneous growth and yield model to project cubic-foot volume from initial age, site index, and basal area for natural stands of loblolly pine. Peden, William, and Frayer (1973) developed a stochastic model for stand projection, from which different equations were derived for expectations, variances, and covariances of tree counts. Space (1973) discussed the modification of Grossenbaugh's STX-Fortran 4 program to determine an estimate of growth using radial growth information.

Volume, Surface, and Length

The concept of using the primary units of cubic foot volume, lateral surface, and length in the derivation of yield relationships is not new. Clark (1906) originally based the International 1/8 inch log rule on a logarithmic function of V.S.L. The derivations of the International 1/4 inch, Scribner, and Doyle log rules required explicit volume and surface formulas not published until later (Boyce, 1975).

Grosenbaugh (1954) presented the concept of height accumulation based on the selection of tree diameters above dbh in a diminishing arithmetic progression, with the heights to each diameter being estimated, recorded, and accumulated. Using this concept, summaries of V.S.L. for each tree are calculated. This reversed the classical approach to tree measurement in which the height of the tree is considered as the evenly spaced independent variable used to derive volume. The calculated variables of V.S.L. are expressed in terms of invariant reproducible primary units of measure and are suitable for linear programming (Grosenbaugh, 1963).

Grosenbaugh (1967a) and Boyce (1975) suggested that the primary units of V.S.L. can be used in the estimation of not only the total biomass of a stand, but also any component of the total biomass. This could be timber products utilized from the stand such as lumber, veneer, pulpwood, or even the unutilized components such as limbs, sawdust, bark, or defective material. This possibility exists since the distribution of the majority of the organic matter in a stand can be expressed in terms of the three primary units of measure.

Little work has been done on the relationship between surface and stand parameters of interest. Lexan (1943) illustrated that bole surface could be important in the prediction of future growth. Until recently (Grosenbaugh, 1963, 1971) surface was more difficult to measure than dbh and height. Grosenbaugh (1967b) demonstrated that the inclusion of surface as a primary unit with volume and length permits reliable estimates of a multitude of forest products from standing tree measurements.

V.S.L. is being used for timber inventories (Van Hooser, 1973; Space, 1973), but has not been applied to large forested areas (Boyce, 1975). The availability of accurate and easily used dendrometers (Grosenbaugh, 1963) and associated computer programs (Grosenbaugh, 1971) made the extension of V.S.L. measurements to large tracts a possibility. Grosenbaugh's (1967b) STX-Fortran 4 program provides summaries of V.S.L. which can be used to derive the more commonly used values of volume or growth.

CHAPTER III

STUDY AREA

Location

This study was conducted in a thinning experiment applied to a loblolly pine plantation south of Crooked Fork Creek on the Cumberland Forestry Field Station (C.F.F.S.). The C.F.F.S. is located 1.5 miles south of state highway 62 in east central Morgan County; it is 6.75 miles southeast of Wartburg and 3.5 miles southwest of Petros, Tennessee.

Climate

The C.F.F.S. is characterized by cool winters and mild summers, with the monthly mean temperature ranging from 37 degrees Fahrenheit (F) in January to 74 degrees F in July. Annual rainfall averaging 54 inches a year is well distributed with average monthly extremes of 3 inches in October and 6 inches in January. The average annual snowfall is over 10 inches; damaging ice and glaze storms occur occasionally.

Site Description

The thinning study is on a flat, wet site, subject to yearly flooding, most commonly occurring in late fall or early winter. Corn had been raised on the site for many years. The soil is a Whitwell loam. Based on a soil test at establishment the pH was 4.7 and the soil was low in phosphorus and potassium. Based on site index curves for a base age of 25 years by Clutter and Lenhart (1968) and Smalley and Bower (1971), the site index was 74 at age 23. The site index fell under the highest curve by Clutter and Lenhart (1968), but their site index curves only used two sample trees above 70 site index in the construction of their curves. The highest site index curve presented by Smalley and Bower (1971) was for a site index of 70.

In 1953 the area was planted with loblolly pine seedlings from a north Georgia seed source, using planting bars and prison labor.[1] The pines were planted on a six foot by six foot spacing, giving a density of approximately 1210 trees per acre.

Thinning Study Design and Purpose

In 1963 when the stand was ten years old, four blocks with four 0.1 acre plots each were established. Four thinning regimes were used as treatments in each block: a control (with no thinning), and thinning at 10, 15, and 20 years of age, respectively. The treatments consisted of low thinnings to a basal area of 120 square feet per acre.

The purpose of the study was to: (1) determine the effect of thinnings on subsequent timber yields; (2) evaluate techniques for the management of loblolly pine plantings; and (3) determine the economic returns from various products such as pulpwood, posts, poles, and saw logs as they develop and are removed from the stand (Kring, 1963).

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[1]The planting site is nearby the "infamous" Brushy Mountain State Prison.

CHAPTER IV

METHODS AND MATERIALS

Field Procedures

Plot Location

The sixteen 0.1 acre plots were relocated and all missing corners were reset. To minimize border effect of the adjacent plot treatments, temporary 0.05 acre subplots were established in the center of each existing plot. In some cases the temporary plots were shifted a few feet to prevent one or more trees from falling on the plot boundaries.

Tree Selection and Measurements

Total height and dbh were measured on all trees within the 0.05 acre subplot. A Suunto clinometer and 100 foot cloth tape were used to measure total height to the nearest 0.5 foot. A steel diameter tape (d-tape) was used to measure dbh to the nearest 0.1 inch.

Within the temporary plot five sample trees were randomly selected. Increment cores were taken from each sample tree starting at one foot above ground (stump height), than at dbh (4.5 feet), and thereafter at five foot intervals to either a point 49.50 feet above the ground or a four inch top. Tree climbing ladders were used to obtain upper-stem cores. Danger of breakage due to the small diameters above 49.5 feet was the criterion used to establish this limit.

At each measurement point along the stem, diameter outside bark (dob) and the bark thickness were measured with a d-tape and bark gauge.

Bark thickness was the average of two measurements taken at right angles at each point. As recommended by Mesavage (1969), if the pair of bark thickness measurements deviated more than 30 percent, then another pair of measurements were taken perpendicular to the axis between the first pair. If the sum of the first pair deviated more than 30 percent from the sum of the second pair, the process was repeated until an acceptable pair of measurements were obtained.

At the upper measurement point total tree height was measured by extending a 25-foot pole, marked at half foot intervals, up from that point until the tip of the pole and the tip of the tree were the same height as judged by a man on the ground. Flagging was attached to the pole tip to aid visibility.

When an increment core missed the pith, a second core was taken at the same height. If both cores missed the pith, they were retained to aid in pith location in the lab. Increment cores were sealed in a plastic drinking straw which was labeled with an adhesive sticker indicating dbh, bark thickness, and the height it was taken. All cores from an individual tree were sealed in a plastic bag as soon as possible to reduce the moisture loss. They were labeled with block, plot, and tree identification number. To further insure dimensional stability of the cores, all were frozen until needed for stem analysis in the laboratory.

Laboratory Procedures

Ring Counts and Measurements

The cumulative ring widths, from the pith, were measured to the nearest 0.01 of an inch. At the same time a total ring count was made. The ring widths for all cores were measured with the aid of an eight power binocular scope and a scale which read to 0.01 of an inch. The scale was mounted on a strip of plexiglass to provide a stable base from which to measure.

Core Preparation

In some cases it was necessary to shave the cores to increase ring visibility. The cores were shaved by hand with a single-edged razor blade by holding the core in one hand and cutting with a sawing action parallel to the cross sectional surface. Although light oil or kerosine was recommended to increase ring visibility (Herman, Demars, and Woolard, 1975), water was found to provide excellent results.

Missing Pith Procedure

For cores that completely missed the pith, a pith locator was used to determine the actual location of the pith and to estimate the number of rings missing (Applequist, 1958). The pith locator was a clear plastic sheet with several sets of concentric circles of increasing radii. The pith locator concept assumes that the ring widths of the missing portion of the core are uniform. The increment core is placed on the locator with annual rings aligned as closely as possible with the rings on the locator. The number of missing rings indicated by the locator are added to the total number counted on the core; ring widths for that section are recorded also.

Raw Data Preparation

As the measurements were taken in the laboratory they were recorded on computer data sheets. The field measurements for each tree were recorded at the same time. The data were punched onto data processing cards and the radial measurements for each height were rescaled using the computer program "Stemanal" (Herman, DeMars, and Woolard, 1975). The program uses dob and bark thickness at each height to proportionally adjust the radial measurements. The program was used first to provide a printed output of the rescaled radial measurements which were checked to detect errors. Once the data were checked and all errors corrected, then a rescaled data card deck of the radial measurements was generated. Also height-age relationships by one year intervals were printed for later use in determining total height for selected years. A more detailed description of the program "Stemanal" and its capabilities is in the Appendix.

Data Analysis

Initial Constraints

Since the trees were measured in midsummer during a period in which the trees were still actively growing, the 1976 increment was ignored, and only those years previous to 1976 were used. The years 1965, 1970, and 1975 were chosen as the basis of the models describing form. The models were based on the original treatments of the thinning study to determine if significant correlations existed between thinning treatments and form change. The mean radius inside bark (rib) was determined for each height by treatment for a later comparison of models.

Form of Models Used

There were three main categories from which six models were built. These categories were: linear additive models, taper equations, and models based on the primary units of volume, surface, and length. The linear additive models consisted of adding past growth at a known height to the rib in 1970 and comparing the resulting value with the actual rib in 1975. The taper equations were based on a hyperbolic expression of the taper present for the years 1965, 1970, and 1975. The models based on the primary units of V.S.L. used the values of these primary units in 1965 and 1970 to predict the 1975 values. This was done for both total and sectional values of the primary units.

The accuracy desired in the first two categories was predicting rib at any height within 0.25 of an inch 95 percent of the time. Accuracy desired in the last type of model was predicting the values of V.S.L. for each tree within 5 percent of the means 95 percent of the time.

Determining Model Accuracy

The models were tested by use of a modified Chi-square test to determine the accuracy which could be expected of the models 95 percent of the time. This was expressed as the maximum number of units which the predicted value would deviate from the actual value, and was called the error limit. The modified Chi-square test is as follows:

$$E = \left(\frac{(Z^2) * \sum_{i=1}^{n} (X_i - \mu_i)^2}{\chi^2(n,\alpha)} \right)^{0.5} \qquad (1)$$

where:

E = error limit which includes (1-1/Z) of the deviations between X_i and μ_i,

Z = standard normal deviate for a probability of 1/Z,

χ^2 = calculated value of Chi-square with n degrees freedom and probability of α,

X_i = value of the ith individual by the new procedure, and

μ_i = value of the ith individual by the accepted procedure.

This test gives the error limit (E) which is the maximum number of units that the new procedure will deviate from the accepted standard (1-1/Z) percent of the time, unless the sample was rare (probability of α) (Freese, 1960; Rennie and Wiant, 1977).

Modeling Attempts

The first attempt to model form was with a linear additive model in which, at each height, the rib-growth increment 1965 to 1970 was added to the rib in 1970 and the resulting value compared with the 1975 rib.

In the second model the radius breast height inside bark (rbhib) growth increment 1965 to 1970 was added to the rib in 1970 at each height measured and compared to the rib present at that height in 1975.

For the third model the growth increment 1970 to 1975 at rbhib was added to the rib in 1970 at each height measured and compared with the rib present at that height in 1975.

Next, taper curves were constructed for each treatment for the three selected years. The modification of Matte's (1949) equation proposed by Kozak, Munro, and Smith (1969) was used as a model for stem form. The equation is as follows:

$$\left(\frac{rib_k}{rbhib}\right)^2 = b_0 + b_1\frac{ht_k}{tht} + b_2\frac{ht_k^{\,2}}{tht^2} \qquad (2)$$

where:

rib_k = radius inside bark at height k,

rbhib = radius inside bark at breast height,

ht = height above ground associated with dib,

tht = total height of the tree, and

b_0, b_1, b_2 = regression constants.

Regression lines were tested for significant differences between treatments for each year. First, the variances for each year were compared with Bartlett's test of homogeneity of variance. If the variances were homogeneous, then slopes and elevations of the regressions were tested for significant differences with an analysis of covariance. If variances were heterogeneous, then a significant difference in the populations was assumed.

Next, Grosenbaugh's concept of form and its extrapolation by use of V.S.L. was applied to the problem of modeling changes in form. First the volume and surface for each tree section (including the tip section) was computed by use of equations 3 and 4:

$$S = (\pi * L/12) * (d + (D-d/2) * (1 + (D-d)^2 /(576 * L^2))^{0.5} \quad (3)$$

$$V = (\pi * L/576) * (D*d + (D-d^2/2) \quad (4)$$

where:

S = lateral surface of each section in square feet,

L = length of the section,

V = volume in cubic feet,

D = lower dib of the section, and

d = upper dib of the section.

The surfaces and volumes for the sections of each tree were summed to give total surface area and total volume for each tree. Total length was defined as the total height minus stump height. The mean V.S.L. for each treatment was calculated for later use in comparing models.

Regressions were performed by treatment, using total V.S.L. in 1975 as dependent variables and the 1965 and 1970 values of V.S.L. as the independent variables. Equations which had error limits within 5 percent of the 1975 means 95 percent of the time were desired.

Next, the concept of V.S.L. was applied by section of the sample trees. The section lengths used were the distances between points bored along the bole. Only the years of 1970 and 1975 were used to eliminate the problem of the creation of new sections as the tree grew. The mean values for section volume and surface for each treatment were calculated. Then regressions were performed by treatment using sectional values of volume and surface in 1975 as dependent variables, and the 1970 sectional values of V.S.L. and the height of the top and bottom of the section as the dependent variables. Again equations which had error limits within 5 percent of the 1975 means for the sectional values were desired.

Girard Form Class Curves

The initial diameters inside bark at breast height (dbhib) in 1963 were rounded to 0.1 inch diameter classes. Diameter classes which were represented in all treatments were then selected from the overall data. From these selected trees the Girard form class was calculated for each tree for the ages 10 to 22 inclusive. The bark thickness at breast height was obtained through a regression of the relationship of bark thickness at breast height to dbhib from measurements obtained in 1976, by treatment. Trees with the same initial dbhib and treatment were averaged for each year. Then the G.f.c. of each dbhib class by treatment was plotted over age. Thus a graphic presentation of change in G.f.c., by treatment, with increasing age was obtained.

CHAPTER V

RESULTS AND DISCUSSION

Evaluation of Stem Form Models

Model One: Radius inside Bark Growth (1965 to 1970)

Stem growth was modeled using the rib growth (1965-1970) at known heights along the stem. The 1975 rib was estimated by adding the growth (1965-1970) at that height to the 1970 rib at that height. Then the estimated rib was compared with the actual rib using the modified Chi-squared test. The desired accuracy was predicting the rib at any height in 1975 from the growth (1965-1970) at that height within 0.25 of an inch 95 percent of the time. None of the treatments or all treatments combined (overall) achieved the desired accuracy (Table 1). The total error limits for the treatments ranged from 0.7367 inch to 0.8778 inch, with the overall being 0.8348 inch.

The amount of cumulative error from stump height to each height sampled was compared to determine the error limit up to that point. As height increased the error limit increased also (Table 1).

Model Two: Radius Breast Height inside Bark Growth (1965 to 1970)

Next, stem growth was modeled using rbhib growth (1965-1970) of each tree sampled. The desired accuracy of 0.25 inch was not achieved for any treatment or overall with this model. The total error limits ranged

TABLE 1

CUMULATIVE ERROR LIMITS TO KNOWN HEIGHTS OBTAINED FROM THE EVALUATION OF THE PREVIOUS RADIUS INSIDE BARK GROWTH (1965 TO 1970) MODEL BY THE USE OF THE MODIFIED CHI-SQUARED TEST

Height (Feet)	Error Limits by Treatment (Inches)[1]				
	Control	Thin 10	Thin 15	Thin 20	Overall
1.0	0.4178	0.3831	0.2572	0.4520	0.4214
4.5	0.4029	0.3546	0.2702	0.4375	0.3992
9.5	0.4250	0.3881	0.3197	0.4382	0.4204
14.5	0.4643	0.3954	0.3791	0.4561	0.4492
19.5	0.5339	0.4515	0.4467	0.5111	0.5120
24.5	0.6289	0.5282	0.5169	0.5924	0.5946
29.5	0.7297	0.6222	0.6068	0.6842	0.6910
34.5	0.8156	0.7230	0.6702	0.7701	0.7768
39.5	0.8851	0.7944	0.7283	0.8344	0.8435
44.5	0.8879	0.8048	0.7523	0.8389	0.8480
49.5	0.8778*	0.7964*	0.7367*	0.8162*	0.8361*

*Total error limit width.

[1]Error limit expected to include 95 percent of deviations.

from 0.4322 inch to 0.4805 inch for the treatments and 0.4829 inch overall (Table 2).

The cumulative error limit from stump height to each height sampled was compared. At no height sampled was the error limit acceptable at the desired accuracy level (Table 2). The portion of the stem where the largest increase in the error limits occurred was from 9.5 feet to 34.5 feet of height. This was due to the base of the live crown ascending during the years compared. Thus growth increased at a faster rate at these points on the stem.

Comparing the total error limits of model two with those of model one, model two had narrower error limits. This was due to the growth at breast height being more representative of the average growth along the stem than the growth at each height for the same period.

Model Three: Radius Breast Height inside Bark Growth (1970 to 1975)

Using the rib growth at breast height (1970-1975), the rib at each height sampled was estimated. None of the treatments or overall achieved the desired accuracy of 0.25 inch for all heights sampled (Table 3). Treatments had error limits ranging from 0.4546 inch to 0.4682, while the overall was 0.4778. Comparing the cumulative error limits from stump height to each height sampled, all treatments achieved the desired accuracy up to the 34.5 feet sample point. The overall maintained the desired accuracy up to 39.5 feet. Upward from these points the error limit widened rapidly as height increased (Table 3). This is due to the rbhib growth being faster than the growth rate on the stem at these upper points.

TABLE 2

CUMULATIVE ERROR LIMITS TO KNOWN HEIGHTS OBTAINED FROM THE EVALUATION OF THE PREVIOUS RADIUS AT BREAST HEIGHT INSIDE BARK GROWTH (1965 TO 1970) MODEL BY THE USE OF THE MODIFIED CHI-SQUARED TEST

Height (Feet)	Error Limits by Treatment (Inches)[1]				
	Control	Thin 10	Thin 15	Thin 20	Overall
1.0	0.3066	0.3082	0.2628	0.3334	0.3328
4.5	0.3432	0.3116	0.2731	0.3741	0.3520
9.5	0.3701	0.3549	0.3207	0.4185	0.3910
14.5	0.3911	0.3738	0.3435	0.4498	0.4134
19.5	0.3996	0.3780	0.3510	0.4590	0.4192
24.5	0.3970	0.3845	0.3537	0.4549	0.4176
29.5	0.3865	0.3775	0.3450	0.4483	0.4080
34.9	0.3726	0.3704	0.3406	0.4347	0.3966
39.5	0.3638	0.3768	0.3672	0.4206	0.3977
44.5	0.3839	0.4173	0.4105	0.4357	0.4257
49.5	0.4322*	0.4781*	0.4696*	0.4805*	0.4829*

*Total error limit width.

[1]Error limit expected to include 95 percent of deviations.

TABLE 3

CUMULATIVE ERROR LIMITS TO KNOWN HEIGHTS OBTAINED FROM THE EVALUATION OF THE PREVIOUS RADIUS AT BREAST HEIGHT INSIDE BARK GROWTH (1970 TO 1975) MODEL BY THE USE OF THE MODIFIED CHI-SQUARED TEST

Height (Feet)	Error Limits by Treatment (Inches)[1]				
	Control	Thin 10	Thin 15	Thin 20	Overall
1.0	0.1674	0.2272	0.2073	0.1525	0.2092
4.5	0.1244	0.1689	0.1541	0.1134	0.1525
9.5	0.1532	0.1688	0.1838	0.1403	0.1726
14.5	0.1651	0.1523	0.1887	0.1568	0.1808
19.5	0.1851	0.1739	0.1896	0.1555	0.1855
24.5	0.1916	0.1780	0.1887	0.1578	0.1878
29.5	0.1977	0.1841	0.1863	0.1650	0.1916
34.5	0.2260	0.2041	0.2099	0.1902	0.2163
39.5	0.2772	0.2668	0.2847	0.2523	0.2810
44.5	0.3591	0.4756	0.3853	0.3482	0.3687
49.5	0.4624*	0.4595*	0.4546*	0.4682*	0.4778*

*Total error limit.

[1]Error limit expected to include 95 percent of deviations.

Comparing the total error limits for model three (Table 3) to the error limits for model two (Table 2), model three is less precise. But model three has acceptable error limits over the lower portion of the stem and model two does not.

Matte's Modified Taper Equation

Regressions were performed using Matte's (1949) modified taper equation (Kozak, Munro, and Smith, 1969) for each treatment and overall for the three selected years. The equations were unable to predict rib within 0.25 inch at any height 95 percent of the time. Error limits ranged from 0.507 to 0.787 inch for the treatments and 0.579 to 0.756 overall (Table 4). The general trend was for the error limits to be larger as age increased. The percent of variation explained by the regressions ranged from 91.3 to 94.8 for the treatments and 92.3 to 94.8 overall (Table 4). The regressions for all treatments and overall were significant at the 99 percent confidence level.

Using Bartlett's test for homogeneity of variance, it was determined that the variances for years 1970 and 1975 were heterogeneous, while the variances for 1965 were homogeneous. When the 1965 treatments were compared at the 95 percent confidence level, no significant difference was found between the slopes or the elevations of the regression lines. This indicates that in 1965 the taper of all sample trees was the same. Thus at this point of the stand's development there has not been any significant change in stem taper due to the thinning regimes. Heterogeneous variances for 1970 and 1975 suggest that the populations for these years are significantly different. This implies that there are

TABLE 4

RESULTS FROM REGRESSIONS ON TAPER USING THE MODIFIED VERSION OF MATTE'S (1949) TAPER EQUATION (2)

Treatment	Year	Coefficients			F-value	R^2	Error Limit[1]	Error Limit[2] (Inches)
		b_0	b_1	b_2				
Control	1965	1.302	-2.291	0.979	1798.88*	0.948	0.181	0.507
	1970	1.212	-1.801	0.588	1890.85*	0.946	0.163	0.544
	1975	1.163	-1.743	0.611	1147.01*	0.914	0.187	0.693
Thin 10	1965	1.334	-2.305	0.959	2019.99*	0.952	0.179	0.536
	1970	1.264	-1.995	0.734	2138.58*	0.949	0.164	0.594
	1975	1.211	-1.877	0.700	1454.84*	0.927	0.177	0.727
Thin 15	1965	1.319	-2.156	0.834	1552.69*	0.939	0.200	0.614
	1970	1.245	-1.829	0.579	2260.96*	0.941	0.160	0.604
	1970	1.195	-1.742	0.574	1834.81*	0.941	0.157	0.690
Thin 20	1965	1.333	-2.208	0.873	1976.91*	0.951	0.180	0.556
	1970	1.243	-1.889	0.649	2055.33*	0.947	0.165	0.619
	1975	1.166	-1.715	0.578	1197.01*	0.913	0.188	0.787
Overall	1965	1.322	-2.241	0.913	7184.88*	0.923	0.193	0.579
	1970	1.241	-1.879	0.638	8315.71*	0.948	0.169	0.613
	1975	1.184	-1.768	0.615	5465.92*	0.946	0.184	0.756

*Significant at 99 percent confidence level.

[1]Error limit derived for the ratio rib to rbhib expected to include 95 percent of deviations.

[2]Error limit derived as the product of the average rbhib and the ratio of rib to rbhib expected to include 95 percent of deviations.

differences due to the thinning regimes at these two ages in the stand's development.

Evaluation of Primary Units

Total Volume, Surface, and Length

In applying Grosenbaugh's concept of primary units (volume, surface, and length), the desired accuracy for the models was estimating the total primary unit values in 1975 within 5 percent of the mean for each treatment and overall.

Volume. Using the primary unit of volume in 1975 as the dependent variable, and the primary unit values of volume, surface and length in 1965 and 1970 as independent variables, equation five was found to have the narrowest error limits for all treatments and overall.

$$Vol_{75} = b_0 + b_1(Vol_{70}) \qquad (5)$$

where:

Vol_{75} = total volume in 1975,

Vol_{70} = total volume in 1970, and

b_0, b_1 = regression constants.

The error limits found ranged from 10.31 to 14.12 percent of the 1975 mean for the treatments, and 16.48 percent overall (Table 5). None of the treatments or the overall achieved the desired accuracy. The regressions of volume 1975 on volume 1970 were significant at the

TABLE 5

RESULTS OF REGRESSIONS ON THE TOTALS OF THE PRIMARY UNIT VOLUME IN 1975 USING EQUATION (5)

Treatment	Coefficients		F-value	R^2	E^1 (Cubic Feet)	$E/\bar{X}$ (Percent)
	b_0	b_1				
Control	-0.848	1.569	172.32*	0.905	1.430	13.96
Thin 10	-1.742	1.748	254.19*	0.934	1.318	10.33
Thin 15	-3.706	2.040	101.08*	0.849	2.063	14.12
Thin 20	-1.630	1.652	156.70*	0.897	1.323	10.31
Overall	-1.619	1.720	1253.02*	0.941	2.104	16.68

*Significant at 99 percent confidence level.

[1]Error limit expected to include 95 percent of deviations.

99 percent level for all treatments and overall. The percent variation explained by the regressions ranged from 84.91 to 93.39 percent for the treatments and 94.14 overall. The regressions failed to achieve the desired accuracy because of changes in form over the period compared. This caused changes in the rate of volume growth, thus introducing error into the regressions which was not explained.

Surface. Regressions for total surface in 1975 provided the narrowest error limits, for the treatments and overall, when total volume in 1965, its second power, and total surface in 1970 were used as the independent variables.

$$Sur_{75} = b_0 + b_1(Vol_{65}) + b_2(Vol_{65})^2 + b_3(Sur_{70}) \qquad (6)$$

where:

Sur_{75} = total surface in 1975,

Vol_{65} = total volume in 1965,

Sur_{70} = total surface in 1970, and

b_0, b_1, b_2, b_3 = regression constants.

The error limits ranged from 4.00 to 6.46 percent of the mean for the treatments and 7.52 percent overall (Table 6). Only the plots thinned at age 20 achieved the desired accuracy. The regression equation explained 94.9 to 98.1 percent of the variation for the treatments and 96.4 percent overall. The regressions were significant at the 99 percent confidence level.

TABLE 6

RESULTS OF REGRESSIONS ON THE TOTALS OF THE PRIMARY UNIT SURFACE IN 1975 USING EQUATION (6)

Treatment	Coefficients				F-value	R^2	E^1 (Square Feet)	$E/\overline{X}$ (Percent)
	b_0	b_1	b_2	b_3				
Control	- 9.613	06.453	2.494	1.553	277.70*	0.981	5.122	6.41
Thin 10	-23.397	-0.500	-0.854	1.816	167.86*	0.969	5.639	6.19
Thin 15	-11.400	-6.194	4.774	1.328	98.36*	0.949	6.382	6.46
Thin 20	-26.499	-4.976	-0.197	2.037	353.96*	0.985	3.675	4.00
Overall	-18.696	-8.978	0.444	2.042	661.34*	0.963	6.798	7.52

*Significant at 99 percent confidence level.

[1]Error limit expected to include 95 percent of deviations.

Although the desired accuracy was not achieved for all treatments, the deviation of the actual error limits from the desired was not that large. The change in form for the years compared had a greater effect on volume that it had on surface. Comparing the error limits obtained for total volume (Table 5, page 33) with those obtained for total surface (Table 6), the error limits for total surface were approximately 50 percent less than the error limits obtained for total volume.

Length. Regressions for total length in 1975 which used the total length in 1970 as the independent variable provided the narrowest error limits for the treatments and overall (Equation 7).

$$Length_{75} = b_0 + b_1(Length_{70}) \qquad (7)$$

where:

$Length_{75}$ = total length in 1975,

$Length_{70}$ = total length in 1970, and

b_0, b_1 = regression constants.

In this case the desired accuracy was achieved for all treatments and the overall. The error limits ranged from 2.27 to 3.49 percent for the treatments and 3.48 percent overall (Table 7). The regressions explained 82.3 to 95.6 percent of the variation for the treatments and 93.4 percent overall. All regressions were significant at the 99 percent confidence level. The desired accuracy was achieved because the heights throughout the stand increased at a uniform rate for the years compared.

TABLE 7

RESULTS OF REGRESSIONS ON THE TOTALS OF THE PRIMARY UNIT LENGTH IN 1975 USING EQUATION (7)

Treatment	Coefficients b_0	Coefficients b_1	F-value	R^2	E^1 (Feet)	$E/\overline{X}$ (Percent)
Control	13.343	0.966	208.60*	0.960	2.275	3.49
Thin 10	-0.154	1.200	116.60*	0.931	1.522	2.27
Thin 15	11.212	1.017	37.79*	0.823	2.348	3.44
Thin 20	7.393	1.066	195.00*	0.957	1.708	2.54
Overall	10.778	1.012	534.30*	0.934	2.328	3.48

*Significant at 99 percent confidence level.

[1] Error limit expected to include 95 percent of deviations.

Evaluation of Primary Units by Section

Volume and Surface by Fixed Section Length

For the evaluation of primary units by section, the desired accuracy was predicting the primary units of volume and surface in 1975 within 5 percent of the means 95 percent of the time.

Volume. Using the sectional volumes in 1975 as the dependent variable, a three variable second order regression using volume, length, and dib at each section base in 1970 as independent variables gave the best results when the error limits obtained from the modified Chi-squared test were compared (Equation 8).

$$Vol_{75} = b_0 + b_1(Vol_{70}) + b_2(Len_{70}) + b_3(dib_{70}) + \quad (8)$$

$$b_4(Vol_{70})**2 + b_5(Len_{70})**2 + b_6(dib_{70})**2 +$$

$$b_7(Vol_{70} * Len_{70}) + b_8(Vol_{70} * dib_{70}) +$$

$$b_9(Len_{70} * dib_{70})$$

where:

Vol_{75} = volume of the section in 1975 expressed in cubic feet,

Len_{70} = length of section in 1970 in feet,

Vol_{70} = volume of section in 1970,

dib_{70} = diameter inside bark of section base in 1970, and

$b_0, \ldots, b_9$ = regression constants.

The error limits obtained ranged from 15.67 to 18.28 percent of the mean for the treatments and 20.07 percent overall (Table 8). None of the treatments or the overall achieved the desired accuracy. The regression (Equation 8) explained 94.8 to 97.3 percent of the variation for the treatments and 95.2 percent of the overall variation. The regressions were significant at the 99 percent confidence level. Comparing the error limits obtained for total volume (Table 6, page 35) with the error limits for accumulated volume by fixed section length (Table 8), the error limits are greater for the regressions using volume by section, but the percent of the variance explained by the regressions is larger for volume by sections. This is because when the tree is broken down into sections the variation is isolated to specific sections; in the total volume regressions error was cumulative.

Surface. Regressions performed using the sectional surface area in 1975 as the dependent variable, and the sectional volume, surface, diameter inside bark at the section base, length of the section, and the heights to the base and top of the section as independent variables, provided the best error limits for the treatments and overall (Equation 9).

$$Sur_{75} = b_0 + b_1(Vol_{70}) + b_2(Sur_{70}) + b_3(Len_{70}) + b_4(dib_{70}) + b_5(Rht_{70}) + b_6(Arh_{70}) \quad (9)$$

where:

Sur_{75} = lateral surface of the section in 1975 expressed in square feet,

TABLE 8

RESULTS OF REGRESSIONS ON THE SECTIONAL VALUES OF THE PRIMARY UNIT VOLUME IN 1975 USING EQUATION (8)

Treatment	Coefficients										F-value	R^2	E^1 (Cubic Feet)	$E/\overline{X}$ (Percent)
	b_0	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8	b_9				
Control	1.015	1.341	-0.186	-0.263	-0.016	0.005	0.017	-0.040	-0.016	0.031	490.84*	0.963	0.187	18.00
Thin 10	2.472	2.124	-0.353	-0.644	0.129	0.021	0.043	-0.110	-0.108	0.044	728.12*	0.973	0.189	15.67
Thin 15	2.299	1.310	0.864	-0.259	-0.051	0.077	0.013	-0.087	0.036	0.448	376.66*	0.948	0.252	18.28
Thin 20	0.981	1.506	-0.198	-0.255	0.119	0.003	0.013	-0.080	-0.043	0.041	536.84*	0.964	0.196	15.95
Overall	1.330	1.661	-0.335	-0.304	0.056	0.019	0.018	-0.086	-0.041	0.042	1647.99*	0.952	0.244	20.07

*Significant at 99 percent confidence level.

[1]Error limit expected to include 95 percent of deviations.

Vol_{70} = volume of the section in 1970 expressed in cubic feet,

Sur_{70} = surface in 1970,

Len_{70} = length of section in 1970 expressed in feet,

dib_{70} = diameter of each section in 1970 at the base,

Rht_{70} = height of the base of the section in 1970 divided by the total height of the tree,

Arh_{70} = height of the top of the section in 1970 divided by the total height of the tree, and

$b_0, \ldots, b_6$ = regression constants.

The error limits ranged from 7.71 to 9.70 percent of the means for the treatments and 10.23 percent overall (Table 9). None of the treatments or the overall achieved the desired accuracy. The regressions explained 95.2 to 97.0 percent of the variation for the treatments and 95.1 percent overall, and were significant at the 99 percent confidence level. Comparing the error limits obtained from the regressions on total surface area (Table 7, page 37) with those obtained from the regressions on surface by section (Table 9), the error limits are wider for the regressions on surface by section. However, the percent variation explained by the regressions was greater for surface by section than for total surface. When the error limits for both volume and surface by section were compared (Tables 8 and 9), the error limits for surface by section were approximately 50 percent narrower than those for volume by section. The change in form for the years compared had a greater effect on volume than it had on surface.

TABLE 9

RESULTS OF REGRESSIONS ON THE SECTIONAL VALUES OF THE PRIMARY UNIT SURFACE IN 1975 USING EQUATION (9)

Treatment	Coefficients							F-value	R^2	E^1 (Square Feet)	$E/\overline{X}$ (Percent)
	b_0	b_1	b_2	b_3	b_4	b_5	b_6				
Control	-2.215	1.303	0.438	1.055	0.420	19.102	-19.650	649.03*	0.958	0.744	9.70
Thin 10	-3.306	0.518	0.503	1.225	0.629	25.031	-26.364	817.85*	0.964	0.733	8.87
Thin 15	-3.410	0.851	0.639	1.425	0.565	50.708	-50.485	612.21*	0.952	0.802	9.01
Thin 20	-1.340	1.478	0.445	1.803	0.207	58.466	-58.634	983.27*	0.970	0.645	7.71
Overall	-2.738	0.945	0.534	1.106	0.475	23.484	-24.264	2436.19*	0.952	0.850	10.23

*Significant at 99 percent confidence level.

[1]Error limit expected to include 95 percent of deviations.

Evaluation of Change in Girard Form Class with Age

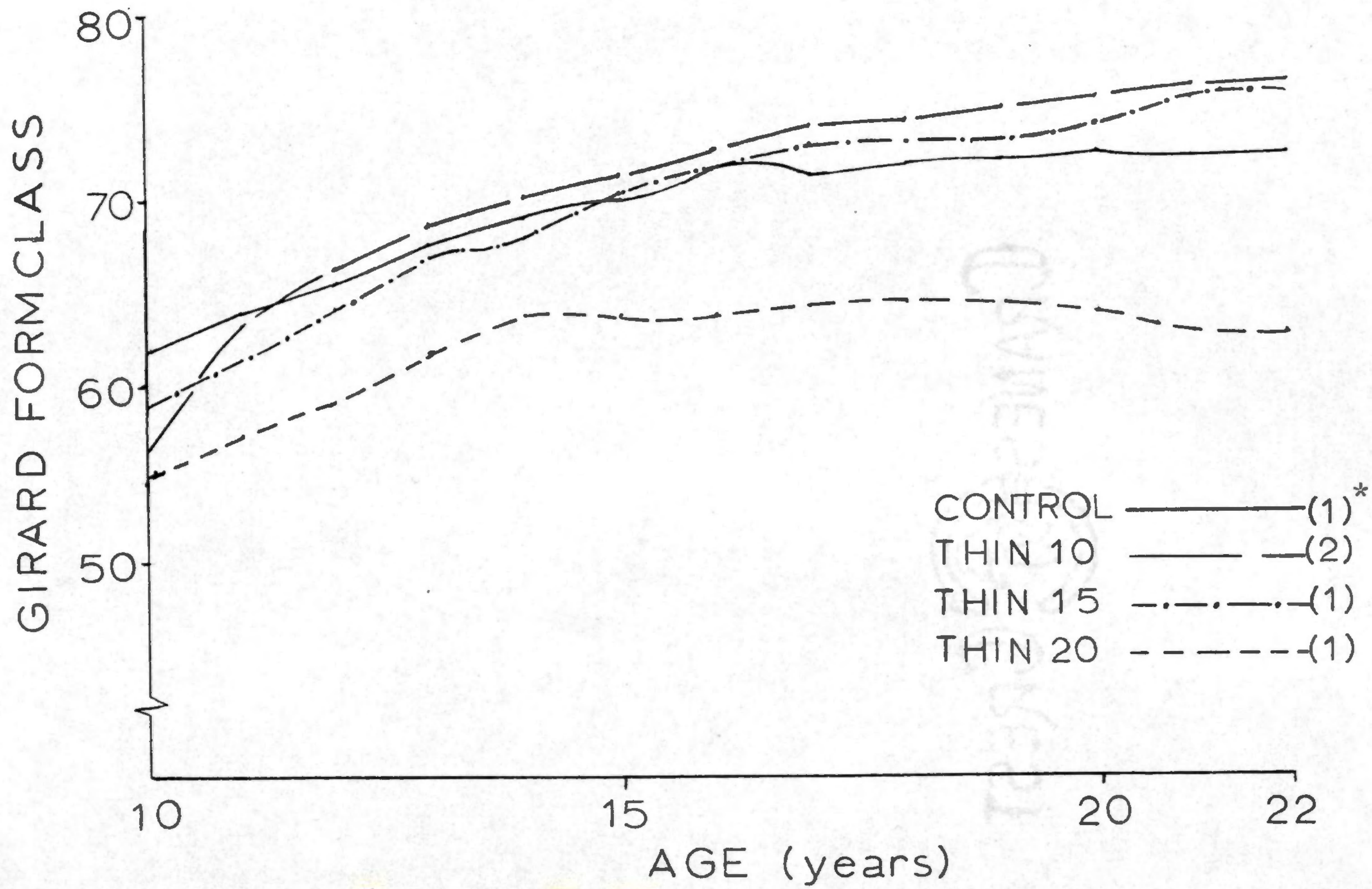
The Girard form class of six initial dbhib classes which were represented in all treatments were plotted for the ages 10 to 22 inclusive. The effects of the thinning regimes were compared between dbhib classes and treatments (Figures 1 through 6). The curves illustrated in some cases are based on only one tree's change in G.f.c. over time.

Control Treatment

The initial dbhib classes of 5.0, 5.6, and 5.8 inches (Figures 1, 3, and 4) show less change in G.f.c. than the dbhib classes of 5.4, 6.0, and 6.8 inches (Figures 2, 5, and 6) for the 13 years plotted. This is because the individual trees represented in the 5.0, 5.6, and 5.8 inch classes were under less competitive stress from surrounding trees; thus the base of the live crown remained lower on the stem for a longer period of time, resulting in less change in G.f.c. The trees in the 5.4, 6.0, and 6.8 classes show a more rapid rate of change in G.f.c. due to more intense competition from other trees for crown space in the canopy (Figures 2, 5, and 6). This causes the base of the live crown to move up the stem at an earlier age and thus cause the rapid change in G.f.c.

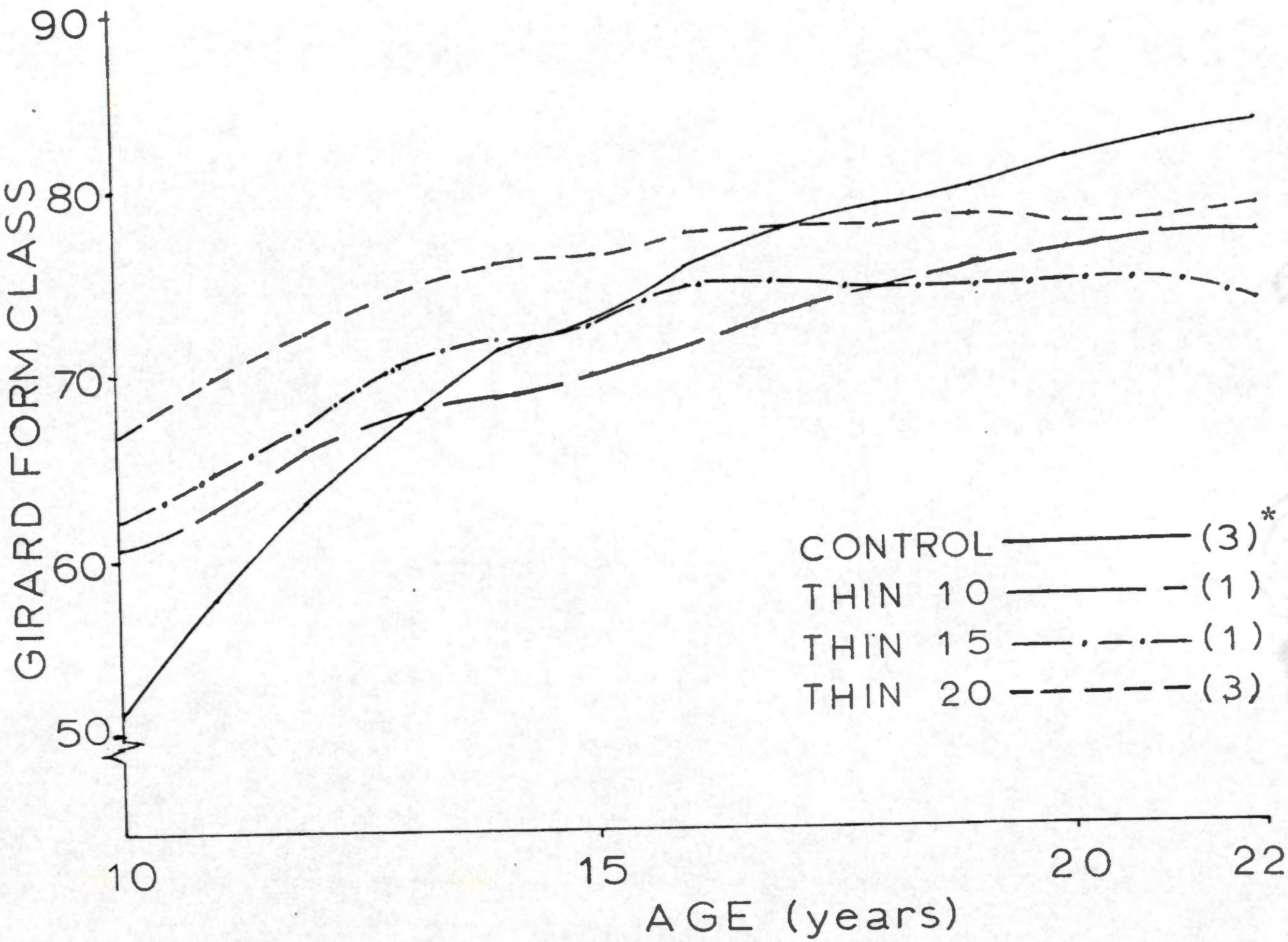
Thin 10 Treatment

In every dbhib class the change in G.f.c. is larger from age 10 to 13 than it is from age 13 to 22. This is due to the effect of the thinning at age ten, which causes a reduction in the rate of natural increase of



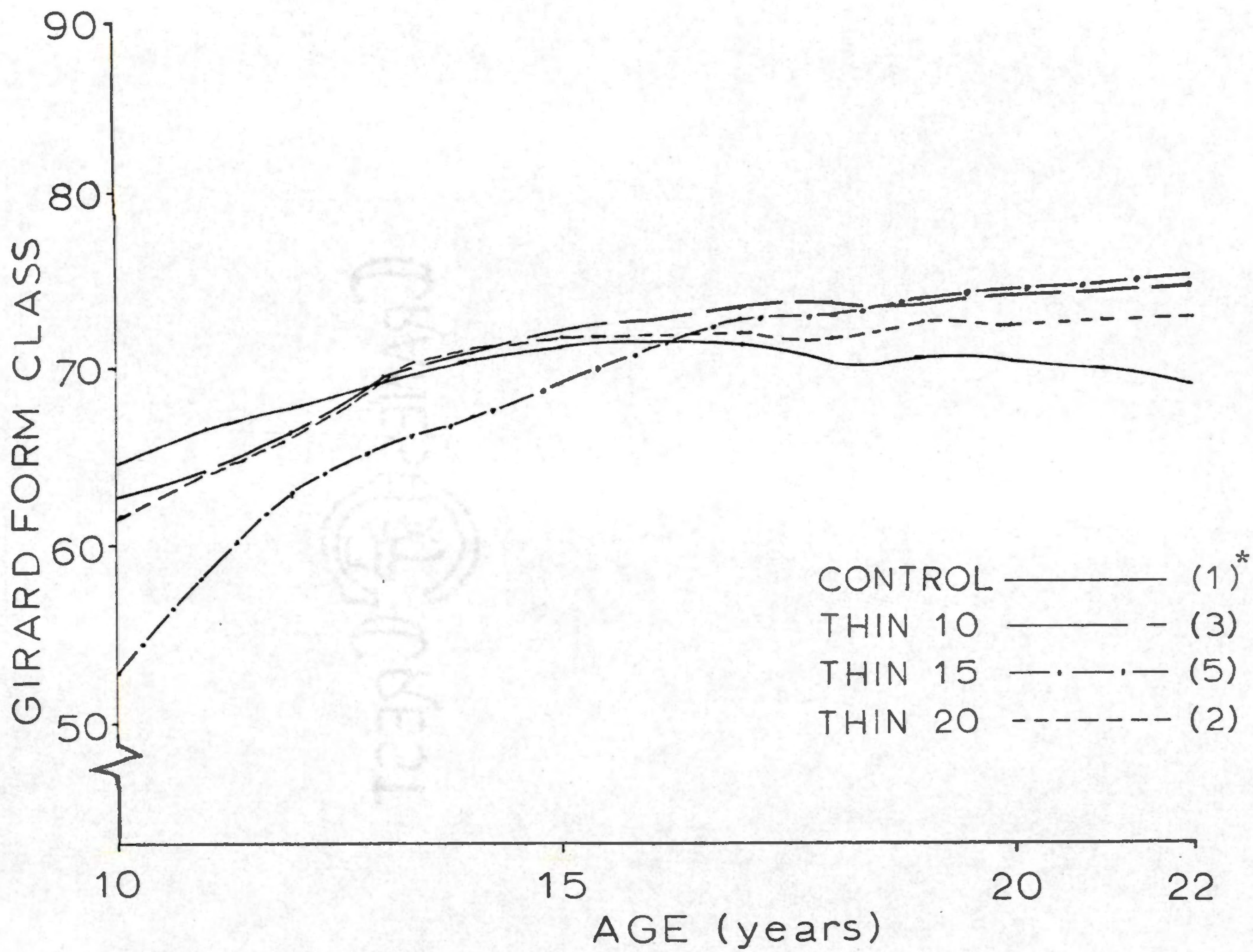
*Indicates number of trees comprising each curve.

Figure 1. Change in Girard form class with increasing age in a plantation of young loblolly pine subjected to four thinning regimes, for 5.0 inch initial dbhib.



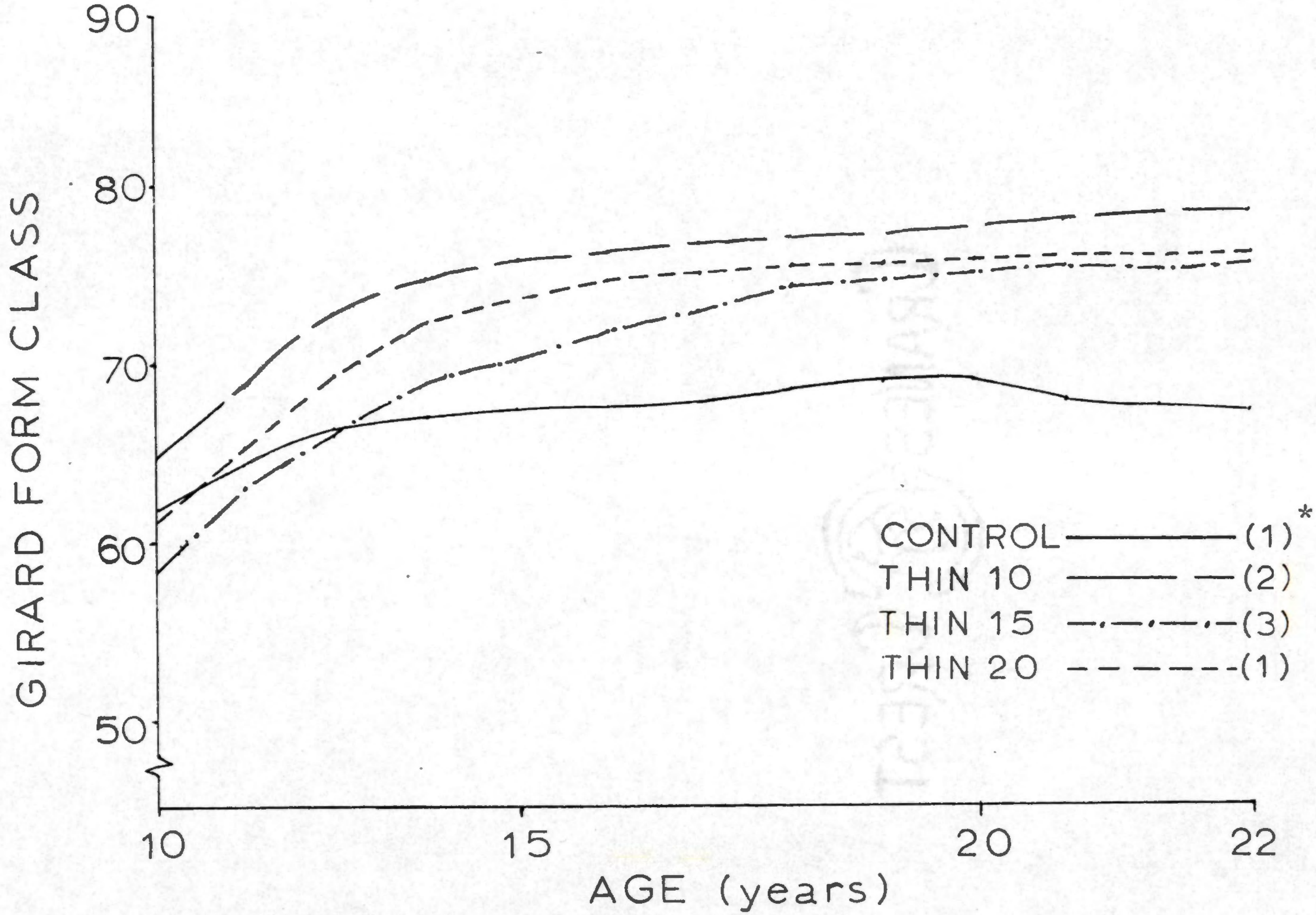
*Indicates number of trees comprising each curve.

Figure 2. Change in Girard form class with increasing age in a plantation of young loblolly pine subjected to four thinning regimes, for 5.4 inch initial dbhib.



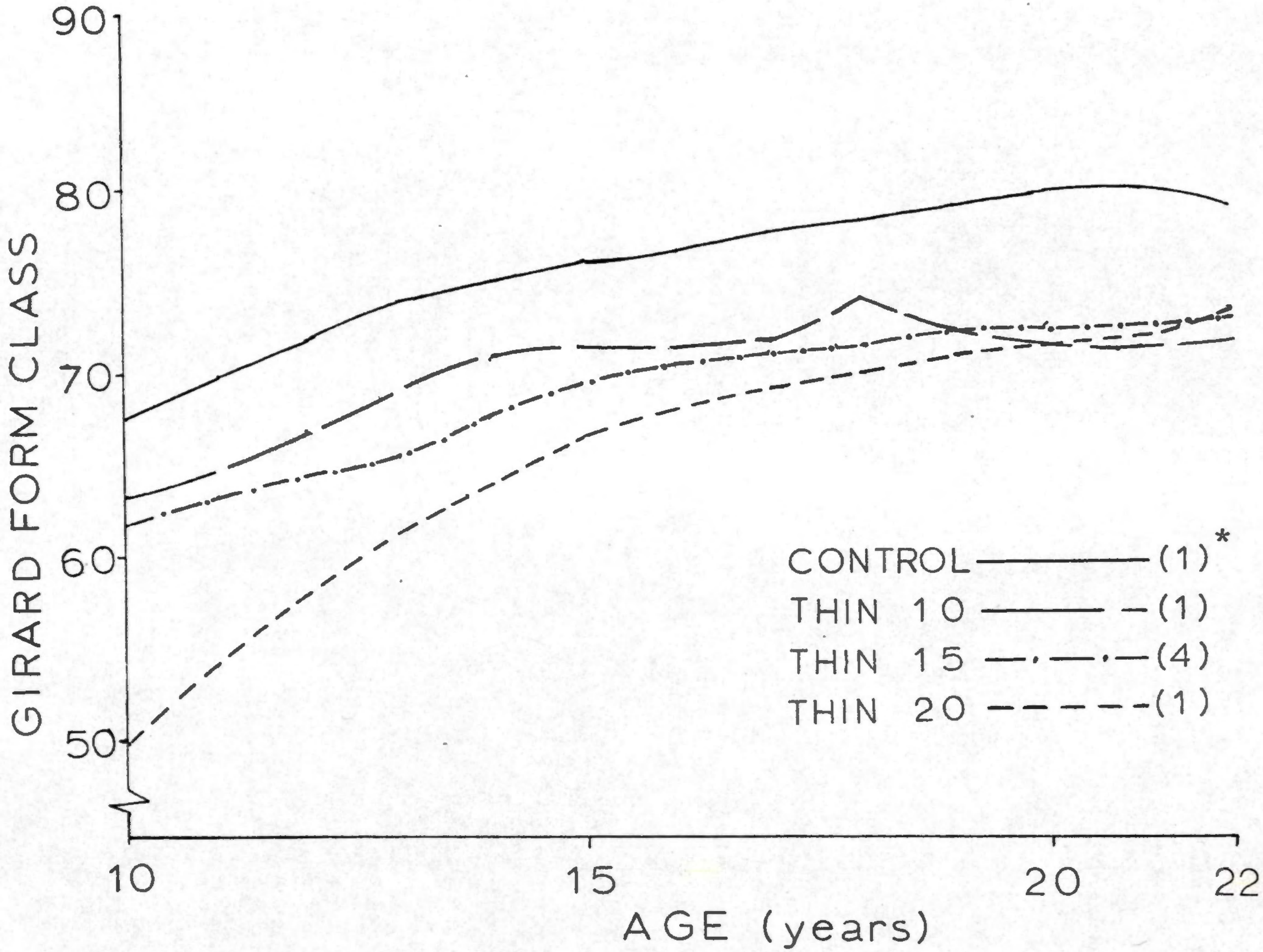
*Indicates number of trees comprising each curve.

Figure 3. Change in Girard form class with increasing age in a plantation of young loblolly pine subjected to four thinning regimes, for 5.6 inch initial dbhib.



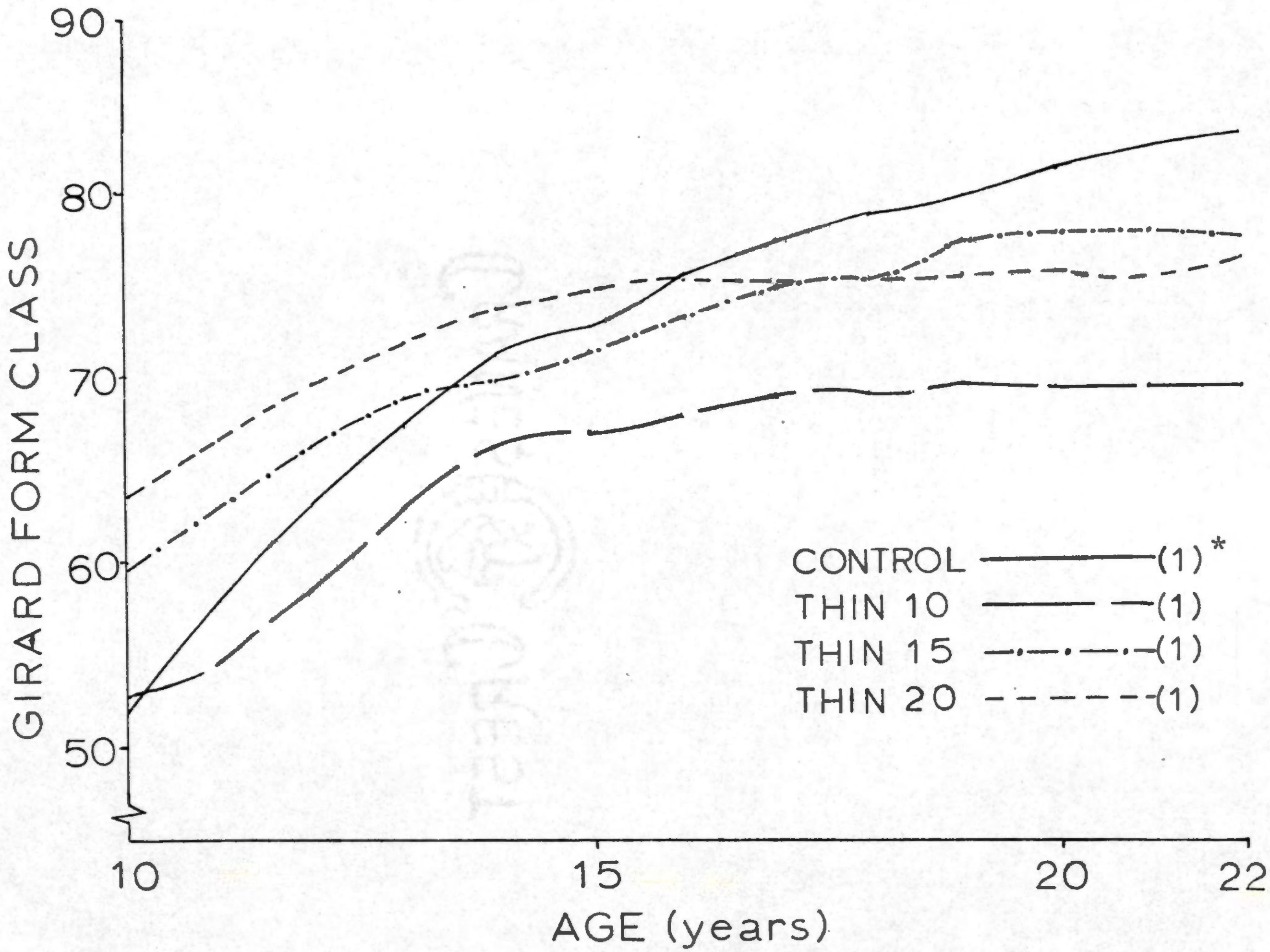
*Indicates number of trees comprising each curve.

Figure 4. Change in Girard form class with increasing age in a plantation of young loblolly pine subjected to four thinning regimes, for 5.8 inch initial dbhib.



*Indicates number of trees comprising each curve.

Figure 5. Change in Girard form class with increasing age in a plantation of young loblolly pine subjected to four thinning regimes, for 6.0 inch initial dbhib.



*Indicates number of trees comprising each curve.

Figure 6. Change in Girard form class with increasing age in a plantation of young loblolly pine subjected to four thinning regimes, for 6.8 inch initial dbhib.

G.f.c. with age. This is best illustrated in the 5.8 inch dbhib class (Figure 4, page 47). The rate of change in G.f.c. proceeds quickly until age 13 when it peaks; then the rate of change is very gradual from age 13 to 22.

Thin 15 Treatment

In all dbhib classes thinning at age 15 reduced the rate at which G.f.c. increased. At age 18 the rate of change peaks, after which it then increases at a slower rate. In all but the 5.4 inch dbhib class (Figure 2, page 45), the curves recover and the G.f.c. begins to increase again by age 22. But the 5.4 inch dbhib class was still decreasing in G.f.c. at age 22.

Thin 20 Treatment

In the plots thinned at age 20, the dbhib classes of 5.6, 5.8, and 6.0 inches (Figures 3, 4, and 5, pages 46, 47, and 48, respectively) deviated from the pattern of change in G.f.c. after the thinning. The 5.4 and 6.8 inch classes (Figures 2 and 6, pages 45 and 49) showed a temporary decrease in G.f.c. after being thinned, but by age 22 the G.f.c. had returned to the previous level. In the 5.0 inch dbhib class (Figure 1, page 44), G.f.c. decreased following thinning and was still decreasing at age 22.

Overall

The curves of all treatments generally follow the trends expected for each thinning regime and crown class. In the treatments which were thinned, the rate of increase in G.f.c. usually decreased for three years after the thinning, and the trees usually recovered to the previous level of G.f.c. within two to three years after the decrease was apparent. From these curves it appears that the older the tree, the less significant the reduction in the natural increase of G.f.c. due to thinning. This is due to the base of the live crown moving above 17.3 feet on the stem and the increased growth which accompanies this movement having less and less influence on the stem at 17.3 feet.

Overall the curves of the treatments which were thinned follow the findings of Behre (1932) and Lohrey (1961) in that the curves approach a mean G.f.c. by age 22 (Table 10).

TABLE 10

AVERAGE GIRARD FORM CLASS FOR SELECTED AGES BY THINNING TREATMENT FOR LOBLOLLY PINE

Treatment	n	Age (Years)			
		10	15	20	22
Thin 10	20	60.46	71.67	74.36	74.13
Thin 15	20	57.48	70.63	74.81	75.24
Thin 20	20	62.29	72.14	73.24	73.40
Control[1]	20	62.04	72.02	74.36	74.13
Overall[2]	80	60.62	71.62	74.17	74.37

[1]Treatments are used as Controls until they are thinned. Note dividing line in table.

[2]Average for all treatments combined.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Results obtained from the evaluation of the stem growth models showed that model three (rbhib growth 1970 to 1975) provided the best estimates of rib at known heights along the stem in 1975. This suggests that the growth at breast height is a good representation of the growth on the stem up to approximately 34.5 feet (50 percent of the total height) for the same time period.

The lack of significant difference among taper equations suggests that thinning at age ten has no significant effect on taper at age 12. Since significant differences were found in the populations for ages 17 (1970) and 22 (1975), it was concluded that thinning at ages 15 and 20 had a significant effect on the taper present for ages 17 and 22.

The changes with increasing age in the primary units of surface (both total and sectional expressions) and total length can be predicted within reasonable limits through the use of past values of the primary units of volume, surface, and length. The reasonable prediction of change in the primary unit of volume (both sectional and total) with increasing age was not possible using the methods tested in this study.

From the evaluation of the curves showing the changes in Girard form class with increasing age, it is concluded that the longer the delay in thinning, the less impact the thinning has on the rate of natural increase in Girard form class.

Although the desired accuracy was not obtained by the majority of the models, the regressions performed had R^2's greater than 90 percent, indicating a good fit. This suggests that the failure of the models was due to the desired accuracy level being greater than the accuracy which could be expected due to natural variations found within the stand. Also it must be noted that the modified Chi-squared test when applied at the 95 percent confidence level is a very difficult test to satisfy, thus contributing to the probability of failure.

Recommendations

Since model three showed promise by providing acceptable error limits over a portion of the stem, further study is justified to attempt to increase the accuracy of this stem growth model. Secondly, since primary units are being incorporated into more and more forest inventory systems, the development of equations which consistently provide accurate estimates of the growth of these units is desirable. These equations should be based on merchantable sections to a known height, diameter, or of a fixed length.

Since the plotted curves of Girard form class as a function of age were based on a small number of trees in comparison to the actual number sampled, it may be beneficial to expand the data base by sampling all trees which were found in the temporary plots. This would give more validity to the curves due to a larger sample, and from this a better representation of the change with age.

Stands with thinning intensities greater than those studied here should be used in future studies to more realistically assess thinning effects.

In light of the varying rates of change in Girard form class overtime, it is not feasible to use Girard form class in prediction of future volume due to errors in predictions resulting from this.

The results of this study are at best only applicable to plantations of loblolly pine which have been subjected to the same treatments, are the same age, and on similar sites. Also the site index of 70 (on a 25 year base) for this stand is unique in that it exceeds the highest of the site index curves constructed by Smalley and Bower (1971), which are the current standards.

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APPENDIX

USERS GUIDE FOR THE PROGRAM STEMANAL

Introduction:

Stem analysis, a method by which a record of the past growth of a tree may be obtained, has regained popularity in recent years. This has been due to the availability of computer programs which relieve the vast burden of computations involved in the rescaling and plotting of the large volume of data obtained. With this in mind this manual was written to provide an insight into the program "Stemanal," its capabilities, and a brief discussion of its execution on the IBM 360/65 computer at The University of Tennessee.

The stem analysis program was obtained from the U.S.D.A. Forest Service Research Paper PNW-194 (Herman, DeMars, and Woolard, 1975). It was debugged and changed to make it compatible with the IBM 360/65 computer system at The University of Tennessee in 1976.

The program has the capacity to handle 30 sections with one of these sections being the tip with a diameter and single bark thickness measurement of 0.0 inches. Also, it has a maximum of 80 incremental measurement intervals which can be handled at one time for any one tree.

Input:

The input to the program consists of the following types:

(1) Control Card
(2) Section Height Card
(3) Section Diameter (Outside Bark) Card
(4) Single Bark Thickness Card
(5) Section Ring Count Card
(6) Sequential Radial Increment Measurements Cards

1. Control Card. The first card in any data deck run with this program must be a control card which supplies information as to which option one wishes to run. See the Control Card example (Figure A-1). The first twenty columns of every card contains data pertinent to each tree.

Column 1	Block number
Column 2	Plot number
Columns 3-4	Tree number
Columns 5-7	Blank
Columns 8-11	DBHOB (one decimal implicit)
Columns 12-15	Breast Height Age (right justified integer)
Columns 16-17	Card deck placement number (control card #00)
Columns 18-19	Number of sections including tip
Column 20	Ring measurement interval 1 = 10 years 5 = 5 years 3 = 1 year
Columns 21-22	Year cut (i.e., 1976 would be 76)
Columne 23-65	Blank
Columns 66-69	Total Height of Tree (one decimal place implicit)
Columns 70-74	Blank

Program Options

Column 75	Rescaled Radial Measurements Card Output
Column 76	Rescaled Radial Measurements Printout
Column 77	Stem Profile (plotter output)
Column 78	Height-Age Card Output
Column 79	Height-Age Printout
Column 80	Height-Age Graph (plotter output)

To suppress any of the program options punch a "1" in the corresponding card column. Default is to generate output.

2. Section Height Card. The section height card indicates the heights from which the radial increment measurements were obtained. One caution is that the section heights are actually distances from the stump to the point where the section measurement was taken.

(i.e., Section Height = Actual Section Height - Stump Height)

(Stump height coded as actual value)

One decimal place is implicit in section heights, coded columns 21-80,I4 format, right justified). See Figure A-1.

3. Section Diameter Card. This card contains the diameters outside bark of each section measured to the nearest hundredth of an inch (note a blank field must be left for the diameter at the tip.) See Figure A-1. Two decimal places implicit in diameter. Coded: Columns 21-80, I4 format, right justified.

4. Single Bark Thickness Card. This card contains the single bark thickness measurements for each section height. (Note that one field must be left blank for the single bark thickness at the tip). (Two decimal places implicit in bark thickness.) Coded: Columns 21-80, I4 format, right justified. See Figure A-1.

5. Section Ring Count Card. This card contains the ring counts for each section including a blank field for the age of the tip. Each section's ring count coded: I4 format, right justified. See Figure A-1.

6. Sequential Radial Increment Measurements Card. This card contains the radial increment measurements for the tree (note that this is only one card of many which are required for each tree). Also note that the last card must be numbered 99. Two decimal places implicit in Radial Measurements. Coded: columns 21-80, I4 format, right justified. See Figure A-1.

```
4415      96. 21  12376                                    715.    1  1
```

Control Card

```
4415      96  21 1123. 10.  35  85. 135 185 235 285 335 385 435 485 705
```

Section Height Card

```
4415      96  21.21231110 970 960 850 840 800 750 700 650 580 530
```

Section Diameter Card

```
4415      96  21.3123. 55. 50. 50. 40. 40  40  35  35  35  30  30
```

Single Bark Thickness Card

```
4415      96  21 4123  22. 21. 21. 19  17  17  15  15. 14  11  10
```

Section Ring Count Card

```
4415      96  2199123 500 435 430 385 380 360 340 315 290 260 235
```

Sequential Radial Increment Measurements Card

Figure A-1. Examples of input cards required for the program "Stemanal."

A more complete description on the formats of the previously mentioned cards is found in the publication from which this program was obtained.

RESCALE PROCESS:

The program is capable of rescaling radial increment measurements to correct for eccentric pith location in a core. The rescale process is based on the following formulas:

```
CRAD(ILL) = (DIA(ILL) - 2. * BT(ILL))/2.0
```

where:
CRAD = correct radius
DIA = diameter of section outside bark
BT = single bark thickness
ILL = the section number.

The above formula gives the correct radius.

```
RESCL(ILL, IXD) = (CRAD(ILL)/RADII(IC,ILL)) * RADII(IXD,ILL)
```

where:
ILL = the section number
IXD - the increment number
IC = the largest increment number
CRAD = correct radius
RADII - radial increment measurement
RESCL = the rescaled radial increment measurement.

The above formula gives the corrected radial increment measurement.

OUTPUT:

This program is capable of six types of output on any given tree. The output consists of two types of plotter output, two types of punched card output, and two types of printed output.

JOB CONTROL LANGUAGE FOR IBM 360/65 AT THE UNIVERSITY OF TENNESSEE COMPUTER CENTER:

```
        //STEMANAL JOB (******,******, R-192K,T-1),name
        //STEPL EXEC FORTGCLD,REGION=192K
        //FORT.SYSIN DD *
                         Program Deck

***     //GO.PLOTTAPE DD SYSOUT=P
        //GO.SYSTIN DD *
                           Data Deck

        / *
```

The above JCL is for when one desires to run the program and get plotter output along with the printed output. If one desires punched output there is no special JCL required since HASP will supply substitution JCL to allow for card output. If one expects a card output of over 500 cards, the card option must be raised above the default level of 500. (i.e., add C-1000 which means that you have raised the default to 1000 cards.) Also one may have to raise the number of lines default if a large amount of printed output is expected. Since it takes approximately twenty seconds to compile, and about three seconds per tree, one should set the time option accordingly. If one desires graphic output (plots) then T-2 is sufficient for one plot.

If one does not desire plotter output one must change the card marked *** above as follows:

```
        //GO.PLOTTAPE DD DUMMY
```

This prevents the program from requesting a plotter setup which would result in a name bar output only.

If one desired to run the program and did not want plotter output, then it would be possible to run the program under the G-X JOB control option and get a faster turn around time on the output from the program.

CONCLUSIONS:

This program could be merged with the program by Pluth and Cameron to give a multipurpose stemanalysis program. Also since it takes twenty seconds to compile, it is recommended that it be compiled and placed on a disk for recall if extensive use is expected.

VITA

Gary Wayne Beard was born in Madison, Tennessee, on September 12, 1953. The oldest of two children, he was raised in Lakewood, Tennessee, and attended schools in that area. In 1971 he graduated from Dupont Senior High School, in Hermitage, Tennessee. Upon graduation he entered the two year pre-forestry program at Tennessee Technological University in Cookeville. In 1973 he transferred to the University of Tennessee at Knoxville, where he received a Bachelor of Science in Forestry June 10, 1975.

In September of 1975 he entered Graduate School at the University of Tennessee and served as a Graduate Teaching Assistant until he received a Master of Science in Forestry June 10, 1977. He is a member of the Society of American Foresters and Xi Sigma Pi.