This is to certify that the

thesis entitled

Evaluation of The Lake States TWIGS
Diameter Growth Model For Upland Hardwoods
In The Lower Peninsula of Michigan

presented by

Patrick James Guertin

has been accepted towards fulfillment
of the requirements for

M.S. degree in Forestry

Carl W. Ramm

Major professor

Date 2 December 1993

EVALUATION OF THE LAKE STATES TWIGS DIAMETER GROWTH MODEL FOR UPLAND HARDWOODS IN THE LOWER PENINSULA OF MICHIGAN

By

Patrick James Guertin

A THESIS

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Forestry

1993

ABSTRACT

EVALUATION OF THE LAKE STATES TWIGS DIAMETER GROWTH MODEL FOR UPLAND HARDWOODS IN THE LOWER PENINSULA OF MICHIGAN

By

Patrick J. Guertin

Lake States TWIGS, the primary growth and yield model available in the Lake States, was developed with regional data. Validation of the model has never been performed exclusively for Michigan. This study validates Lake States TWIGS for the Manistee National Forest, and investigates alternative distance-independent, individual-tree, diameter growth functions which may improve prediction accuracy.

Diameter growth, basal area, and mortality were compared to five-year projections from Lake States TWIGS for five northern hardwood species in northern lower Michigan. Although results may have been influenced by the 1988 drought and infestations of several species of defoliating insects, Lake States TWIGS appears to accurately project five-year growth and mortality for most upland hardwoods.

Development of a diameter growth function to improve prediction accuracy focused on the Chapmann-Richards growth function, multivariate regression, and other established modeling methods. Results were inconclusive.

ACKNOWLEDGMENTS

First I would like to thank my graduate committee chairman, Dr. Carl Ramm. His guidance and support proved invaluable. I would also like to thank Dr. Larry Leefers and Dr. Scott Winterstein. Their emphasis on the educational aspect of my efforts made my failures as valuable as my successes. Thanks are also due to the staff of the Huron-Manistee National Forest, especially Rose Ingram and Dave Cleland, their assistance was greatly appreciated during the summer field season. I would also like to acknowledge the support of family and friends, especially my parents and Tim, Carol, Greg and Andy. Finally, I would like to thank Frank Sapio and Roger Mech of the Michigan Department of Natural Resources. It is what I learned from working with them that provided the confidence and understanding to pursue the forestry profession.

This research was supported by the Agricultural Experiment Station of Michigan State University and by the McIntire Stennis Cooperative Forestry Research fund, and in part by the U.S.D.A. Forest Service, North Central Forest Experiment Station.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Problem Definition

Michigan has approximately 17.3 million acres of commercial forest land, including 7.8 million acres of oak-hickory and northern hardwood forest (Smith and Hahn, 1986). The increasing public demand for old growth forests and forest recreation has put increased, and often conflicting, demands on these resources and on the silvicultural practices that are used in their management. To properly manage the state's forest resources under these pressures, reliable growth and yield information is a necessity. The key to providing this data are accurate growth and yield models.

The major growth and yield model available for the Lake States, TWIGS (Miner *et. al.*, 1988), was based on data collected to conform to regional rather than individual state needs. Hardwood data used in the development of the model consisted primarily of stands from Wisconsin and Minnesota. These stands are quite different from stands in the Lower Peninsula, especially in regard to northern hardwood composition and site quality. Projections of hardwood growth and yield for the Lower Peninsula of Michigan are therefore suspect.

TWIGS is widely used as a planning tool by state and federal agencies in Michigan (Ramm and Miner, 1986). Although it was designed for comparative studies of alternative management regimes (Miner *et. al.*, 1988), TWIGS is often used for straight stand projection. The objective of this study is to evaluate the accuracy of the TWIGS growth model for Michigan.

Literature Review

A survey of industry, universities and government agencies found that TWIGS was the primary growth and yield model used in the North Central region (Ramm and Miner, 1986). TWIGS is an individual tree, distance-independent system developed by the USDA Forest Service North Central Forest Experiment Station (Miner *et. al.*, 1988). The history of TWIGS is rooted in a general tree growth projection system developed by the North Central Forest Experiment Station (USDA Forest Service, 1979). This effort grew into a mainframe projection system known as STEMS (Belcher *et. al.* 1982). STEMS was later updated for the Lake States region in 1985, this version was named Lake States STEMS85. The STEMS85 version incorporated a diameter adjustment factor and a new mortality function (Holdaway and Brand, 1986). The adaptation of STEMS85 to the microcomputer was the final step in the evolution of TWIGS.

There were two versions of TWIGS developed for the North Central region. The first is Lake States TWIGS, developed for use in Wisconsin, Michigan and Minnesota. The second is Central States TWIGS, developed for use in Indiana, Illinois, and Missouri. This study focuses on Lake States TWIGS. The growth model for this version was calibrated with 80,000 trees from 1,500 plots in Wisconsin, Michigan and Minnesota (Miner *et. al.*, 1988). Representation from Michigan in the STEMS system was limited to red pine (*Pinus resinosa*) and jack pine (*Pinus banksiana*) plantations in the Lower Peninsula. Although additional plots were added for the TWIGS model, no hardwoods were included from the Lower Peninsula. Most of the data for the oak - hickory and northern hardwoods timber types is from Wisconsin (Christensen *et. al.*, 1979). The regional dimensions of the calibration data set prompted Miner *et. al.*, (1988) to warn against using TWIGS as a tool for obtaining exact projections. This restriction limits it's use as an aid in decision-making.

The regional aspect of TWIGS is the first of many concerns with the model's predictive power. Both Holdaway (1985) and Smith (1983) have questioned TWIGS' ability to accurately represent local growth potentials. In using TWIGS for projections of northern hardwoods in the Lower Peninsula of Michigan, the model's predictive abilities have been extended outside of the geographic range of calibration. If the model is extended into an area with different macroclimatic conditions, the regional TWIGS coefficients are inappropriate (Smith, 1983). The northern hardwood calibration data obtained in Wisconsin came from areas with homoclines dissimilar to the Lower Peninsula of Michigan (Rauscher, 1984). These differences are in average seasonal temperatures, precipitation and solar radiation. The importance of macroclimatic influences on soil and vegetation development has been discussed by Spurr and Barnes (1980) and by Rauscher (1984). Early validation of the STEMS model showed that its predictive powers decreased as the model application moved east and south in the Lake States region (Smith 1983; Leary *et. al.*, 1979).

The STEMS model has been adjusted for sub-regional variations with positive results. Holdaway (1985) developed an additive diameter adjustment factor with Wisconsin data, and reduced the ten year mean diameter growth error from .17 inches to .03 inches. This adjustment factor is currently incorporated into Lake States TWIGS. Smith (1983) developed an adjustment factor based on ratios of actual and predicted diameter at breast height (dbh). Smith's adjustment was calibrated with data from Michigan's Upper Peninsula; he reported a 94 percent decrease in mean annual diameter growth error from .033 inches to -.002 inches. These adjustments provide evidence of TWIGS weakness at a sub-regional level.

In addition to its regional dimension, the research plots used to calibrate TWIGS also raise questions about its reliability. Data sources for the growth model included plot records from cutting experiments, demonstration woodlots, industrial continuous forest inventory, and personal records of forest growth. In all cases data was from permanent research plots (Christensen *et. al.*, 1979). Research plots are usually set up in areas that provide easy access, have minimal natural damage and are more intensely managed. These stands are generally more uniform than the majority of forested lands. When models are developed from such data there is a tendency for over prediction of individual tree and stand characteristics (Holdaway, 1985; Bruce, 1977). Ideally models should be developed to account for the variability of general forest conditions.

After a model is developed and before it is applied to a specific use its performance must be validated (Buchman and Shifley, 1983). This step is even more important if model performance is suspect. TWIGS' performance has never been validated on a sub-regional basis in Michigan, however early tests on a regional level found that STEMS predictive capabilities diminished as its use moved south and east in the region (Smith, 1983; Leary *et. al.*, 1979). Twenty-seven year mean dbh was overestimated by 12% for northern hardwoods in southern Wisconsin (*Leary et. al.*, 1979). Holdaway and Brand (1983) validated STEMS' at the regional level and found that mean ten year dbh predictions for white ash (*Fraxinus americana*), sugar maple (*Acer saccharum*), basswood (*Tilia americana*), and several members of the red oak group had errors of at least 0.4 inches. Substantial errors were also found in predictions of red oak mortality. When tested in Illinois, the Central States version of TWIGS (version 3.0) overestimated change in sugar maple dbh, trees per acre, and basal area growth by over 20% in 15 years (Kowalski and Gertner, 1989). The relative error in survival for all species, in general, was 22%.

When investigating the source of the errors produced during projection, there are two possible directions to examine. The first source of error arises from the regional scope of the projection systems and the research-oriented data base used in model development. Any inadequacies introduced by these factors are compounded during the projection process. In addition, these errors will interact with the second source of error, model structure, to propagate error.

Lake States TWIGS uses a set of three linked equations to form its annual diameter growth model (Miner *et. al.*, 1988):

Annual Diameter Growth = Potential Growth * Competition Modifier + Diameter Adjustment Factor [1]

Potential Growth = $b_1 + b_2 D^{b3} + b_4 SI * CR * D^{b5}$ [1a]

Where:

Potential growth = potential annual dbh growth (inches/yr)

D = current tree diameter (dbh in inches)

SI = site index (feet at age 50)

CR = tree crown ratio code

(0-10%=1, 11-20%=2, ... 81%+=9)

$b_1, \ldots, b_5$ = species specific equation coefficients

(Hahn and Leary, 1979)

Competition Modifier $= 1 - e^{-f(R)g(AD)*SQRT[(BAmax - BA)/BA]}$ **[1b]**

Where:

Competition modifier = Competition index bounded by 0 and 1

BAmax = maximum basal area (ft^2/acre) expected for the species

BA = current basal area (ft^2/acre)

R = ratio of tree dbh to average stand dbh

AD = average stand dbh (inches)

f(R) = a function of characterizing the individual tree's relative effect on the modifier

$f(R) = b_1[1 - e^{b2R}]^{b3} + b_4$

g(AD) = a function characterizing the average stand dbh effect on the modifier

$g(AD) = c_1(AD + 1)^{c2}$

$b_1, \ldots, b_4, c_1, c_2$ = species specific equation coefficients

(Holdaway, 1984)

Diameter Adjustment Factor $= a_1D + a_2D^2 + a_3$ **[1c]**

Where:

Diameter adjustment factor = adjustment in annual diameter gr growth (inches/yr)

D = current tree dbh (inches)

a_1, a_2, a_3 = species specific equation coefficients

(Holdaway, 1985)

When TWIGS is run over multiple projection cycles the diameter growth model interacts with the system's mortality model to project stand dynamics (Miner *et. al.* 1988). The TWIGS mortality function is:

$$Survival = b_1 - [1/(1 + e^n)] \quad [2]$$

Where:

Survival = the tree's annual probability of survival

$n = b_2 + b_3DGR^{b4} + b_5(D - 1)^{b6} * e^{-b7(D-1)}$

DGR = predicted annual diameter growth (inches)

D = current tree dbh (inches)

$b_1, \ldots, b_7$ = species specific equation coefficients (Buchman, *et. al.*, 1983; Buchman, 1983; Buchman and Lentz, 1984)

Sources of error related to this model structure are rooted in suspect variables in the diameter growth model, and in the way that different functions within the system inter-relate. For example, TWIGS uses site index (base age 50 yrs.) as a measure of site quality. Site index only has meaning in undisturbed, normally stocked, even-aged stands, where the codominant and dominant trees measured are uninjured and free growing, and where total age and height has been accurately determined. Given these stringent standards, and the more detailed concerns brought up by Carmean (1975) and Monserud (1984), there are few stands that are eligible to meet the restrictions of site index.

Another model-related problem is TWIGS' use of crown ratio to measure tree vigor. This variable is seldom measured during inventory, and when measured is estimated ocularly. If crown ratio data is not present TWIGS will estimate it (Miner et. al. 1988), which may induce further error into projections. Validations of the crown ratio model for the northern-lower peninsula of Michigan found that the model overestimated crown ratio codes by 0.32 units (Holdaway, 1985). Crown ratio should therefore be considered another source of introduced error.

The models used in TWIGS for determining potential diameter growth and survival are directly or indirectly a function of current diameter, site index and crown ratio (Miner *et. al.*, 1988; Hahn and Leary, 1979; Buchman *et. al.*, 1983). As noted above, site index and crown ratio are readily susceptible to measurement error while current diameter for any period of time after the initial projection will be biased. Given these circumstances, error in growth projections over repeated cycles is bound to be magnified.

Given the potential sources of error in TWIGS, it is clearly necessary to determine if its diameter growth model provides accurate estimates for upland hardwoods in Michigan's Lower Peninsula. Buchman and Shifley (1983) have outlined key areas to examine when evaluating a forest growth projection system. Validation procedures have been detailed by Burk (1986), Reynolds (1984) and Snee (1977). These procedures focus on the construction of a validation data base and the use of validation statistics to determine the accuracy of model predictions. ATEST, a program developed by Rauscher (1986) and the SASATEST template written by Gribko and Wiant (in press) provide a simple means of comparing predictions with validation data to determine model accuracy.

If the error of estimates produced by the TWIGS projection system are inordinate, corrections should be made. These corrections can be achieved through two methods: first, a sub-regional adjustment to the current model; second, development of new models with structures that include variables that better explain environmental conditions and which are less prone to propagating error.

Two methods have been used to adjust the STEMS regional model for sub-regional use (Holdaway, 1985; Smith, 1983). Working with permanent research plot data from Michigan's Upper Peninsula, Smith (1983) developed a modifier which is applied to the STEMS projected diameter. This adjustment factor was based on the ratio of actual to predicted diameter growth of the individual trees on the study plots. It is applied by multiplying the adjustment factor to new dbh predictions. As previously discussed, the results were lowered errors of estimated dbh. Holdaway (1985) developed an additive adjustment factor for Wisconsin which is now an integral part of the TWIGS model. Holdaway's adjustment factor can be calibrated to reflect growth differences in

Michigan. This modifier also reduced errors of estimated dbh.

In addition to the methods used by Smith (1983) and Holdaway (1985), Gertner (1984) proposed localizing a regional diameter growth model using sequential Bayesian procedure. This method adjusts regional model parameters in accordance with the precision of subregional estimates of diameter growth. Gertner (1984) has outlined examples of how this procedure could be applied to a variant of STEMS used in Oregon, however, actual application of the method has not been done.

If model inadequacies are found, the second method for correcting TWIGS is to develop a new individual tree, distance-independent means of projecting diameter growth to replace the existing diameter growth model. Several methods are discussed in the literature, which range from basic growth tables to complex models developed to forecast hardwood diameter growth.

A simplistic method of projecting diameter growth is a tabular summarization of growth and other characteristics. An example of this method is Smith and Shifley's (1984) work summarizing growth and survival characteristics of Indiana and Illinois tree species. The authors compiled data from over 15,000 trees by size class (dbh) and species to produce tables forecasting growth and yield over 10 years.

A more complex, yet more manageable (in terms of use) solution is to develop a new distance-independent, individual-tree, diameter growth model. Several alternative models are available, utilizing numerous methods of development (Hahn and Leary, 1979; Bailey, 1980; West, 1981; Wykoff *et. al.*, 1982; Mawson, 1982; Shifley and Brand, 1984; Hilt, 1983; Hilt, 1985; Harrison *et. al.*, 1986; Shifley, 1987; Hilt and Teck, 1987; Zeide, 1989; Bolton and Meldahl, 1990; Wykoff, 1990). In addition, Amateis and McDill (1989) published a framework for the use of dimensional analysis in predicting individual tree growth.

During the initial development stage of what was to become known as the STEMS model, Hahn and Leary (1979) tested four potential diameter growth models:

1) $\Delta D/\Delta t = b_1SI+b_2D^{b3}+b_4CR*D$

2) $\Delta D/\Delta t = b_1CR+b_2D^{b3}+b_4SI*D$

3) $\Delta D/\Delta t = b_1+b_2D^{b3}+b_4SI*CR*D$

4) $\Delta D/\Delta t = b_1+b_2D^{b3}+b_4SI*CR*D^{b5}$

Where:

$\Delta D/\Delta t$ = change in dbh over change in time

CR = tree crown ratio code (0-10%=1, 11-20%=2, ... 81%+=9)

D = current tree dbh (inches)

SI = site index (feet at age 50)

$b_1...b_k$ = species specific equation coefficients

All four models predicted change in ddh over time as a function of crown ratio, site index, and current dbh. The overall best of the four models is used as the potential dbh growth model in Lake States TWIGS (model 4). The criteria used for this selection was the ability of the model to produce accurate predictions, residual plots, and coefficient of determination (R^2). If the model used in TWIGS does not predict adequately then there is the possibility one of the other three models may produce better results.

Another alternative is the potential diameter growth model used in Central States TWIGS (Shifley, 1987; Miner *et. al.*, 1988). This model is based on the growth form of the Chapmann-Richards function (Pienaar and Trumball 1973) with additional variables added to represent the effects of crown ratio and site index.

$$POT = (b_1 TBA^{b2} - b_3 TBA) * (b_4 + b_5 SI + b_6 CR)$$

Where:

POT = potential annual tree basal area growth (ft_2/yr)

TBA = current tree basal area (ft_2)

SI = site index of dominant species on plot (ft at age 50)

CR = crown ratio class (0-10%=1, 11-20%=2, ... 81%+=9)

$b_1 \ldots b_i$ = species specific regression coefficients

The Central States TWIGS model was initially calibrated with Indiana, Ohio, and Missouri data, with some degree of success (Shifley, 1987). Initial validation of the model linked with the Central States competition modifier resulted in dbh prediction errors of less than .02 inches (in a ten year period) for a majority of the oak species found in the Central States region. In addition, Shifley (1987) reported R^2s as high as 0.91 during the initial stages of model development.

Shifley and Brand (1984) have proposed using the Chapmann-Richards growth function constrained for maximum tree size for predicting change in individual tree basal area over time:

$$\Delta TBA/\Delta t = (b_1 TBA^{b2} - b_3 TBA/A^{(1-b2)})$$

Where:

$\Delta TBA/\Delta t$ = Change in tree basal area (cm^2) over time.

TBA = current tree basal area (cm^2)

A = Maximum tree basal area (cm^2)

$b_1 \ldots b_i$ = species specific regression coefficients

When individually fitted to six hardwood species in Missouri, including several oak species, the model produced favorable goodness-of-fit statistics. R^2s ranging between 0.74 and 0.98, and standard error of estimates between 1.9 and 6.1 cm^2 were reported. Four of the six species-specific models were also significant at an alpha = .01 probability level. The model was not validated.

An additional diameter growth model that has been incorporated into a computer simulation is in OAKSIM. OAKSIM is a two-stage tree basal area growth model developed by Hilt (1985) with individual tree data from Ohio and Kentucky. Hilt's (1983) model predicts tree basal area growth as a function of initial tree diameter, site index, mean stand diameter, and percent stocking. Hilt published model R^2s ranged between 0.58 and 0.78 in different stages of the modeling process. As for model performance, Hilt reported a .08 ft^2/acre difference between actual and predicted basal area growth after 15 years.

West (1981) developed another two-stage model for three species of eucalyptus in Tasmania. The model predicts average annual diameter increment of an individual tree as a function of the tree's current dbh, stand age, and stand stocking. When validated with data from 21 test plots, the model predicted frequency distributions of tree basal areas and stocking levels that did not significantly differ from actual tree basal area and stocking distributions ($P = .05$).

Several other models have been proposed. One such model was developed by Hilt and Teck (1987) for hardwoods in northern New England. This model is based on a modified Chapmann-Richards growth function and projects diameter growth as a conversion of predicted tree basal area growth. Validation showed that for a one year projection period the model consistently underestimated diameter growth by 15 to 30 percent for all species involved.

Mawson (1982) proposed three regression models for predicting diameter growth in small forests. These models include a linear function, a quadratic function, and a log transpose model, all of which use current diameter to predict periodic diameter increment. When tested with hardwood data from Massachusetts, the log transpose model performed best. Over an unspecified period of time the model overpredicted diameter growth of northern red oak and other hardwoods by less than four percent. Mawson recommends using these equations for forests under 3,000 acres in size and that models should be calibrated for each forest.

Bolton and Meldahl (1990) developed a system of predictive equations for pine, oak, and other hardwoods in Georgia. These equations included an annual diameter increment growth model and were developed using a combination of regression and cluster analysis. No validation statistics were published.

Harrison *et. al.* (1986) developed a series of individual tree basal area increment equations for mixed-hardwoods in the Blue Ridge areas of Virginia, North Carolina, Tennessee, and Georgia. These equations predict periodic annual tree basal area increment using current tree basal area, stand basal area before and after thinning, and stand age at thinning. As apparent through the variables used, these models are intended for use only in managed stands. The published goodness-of-fit statistics for the three models including R^2s of between 0.41 and 0.77 depending on species and model.

Two additional diameter increment models which may be suitable for use in the TWIGS system were developed for conifers in the Inland Empire (eastern Washington, northern Idaho, and western Montana) (Wykoff *et. al.*, 1982; Wykoff, 1990). The first is used as the growth function in the Stand Prognosis Model. This model predicts diameter as a function of current dbh, stand aspect, stand slope, stand elevation, a crown competition factor, crown ratio, basal area per acre greater than the subject tree, a rating for stand habitat, and a rating for stand location within the Inland Empire. The second growth function is a variant of the first, which omits terms for habitat and location.

An alternative to these existing methods is to develop a new model. Due to its flexibility and ease of development, the multivariate linear model is preferred. One advantage to its use is that ordinal data, in addition to continuous data, may be used. This facilitates the use of ecological land classification codes as a replacement for site index. Ecological land classification codes are believed to better express the biotic and abiotic potential that effect site quality (Crow and Rauscher, 1984; Pregitzer and Ramm, 1984). In addition, other variables not found in the existing models may be used if they were appropriate (*i.e.* crown class).

Objectives:

Based on the problem definition, the objectives of this research are to:

1.) evaluate the Lake States TWIGS growth model for upland hardwoods in Michigan's Lower Peninsula.

2.) modify, if necessary, the existing model or develop new models to accurately predict the growth potential of Michigan's hardwood resources.

Field Methods and Data:

Data:

The data used for this study came from 50 northern hardwood stands on the Manistee National Forest in Manistee, Wexford, Mason, Lake and Newaygo counties (Figure 1.). These stands were chosen from seventy-six stands used in the development of an ecological classification system (ECS) for upland hardwoods of the Manistee National Forest (Host *et. al.* 1988). The ECS stands were chosen with specific rejection/acceptance criteria to minimize differences in stand histories. The criteria set for these stands were as follows:

1) Stand ages between 60-80 years.
2) High stem density ("normal stocking").
3) Minimal evidence of disturbance since stand establishment.
4) Minimum size of 2.47 acres.
5) Aspen (*Populus grandidentata* and *Populus tremuloides*) accounted for less than 7 m^2/ha in stand basal area.

These criterion, along with landform maps, aerial photos, and the USDA Forest Service database were used to develop a list of suitable stands. Stands were chosen using a stratified random design, with strata defined as three

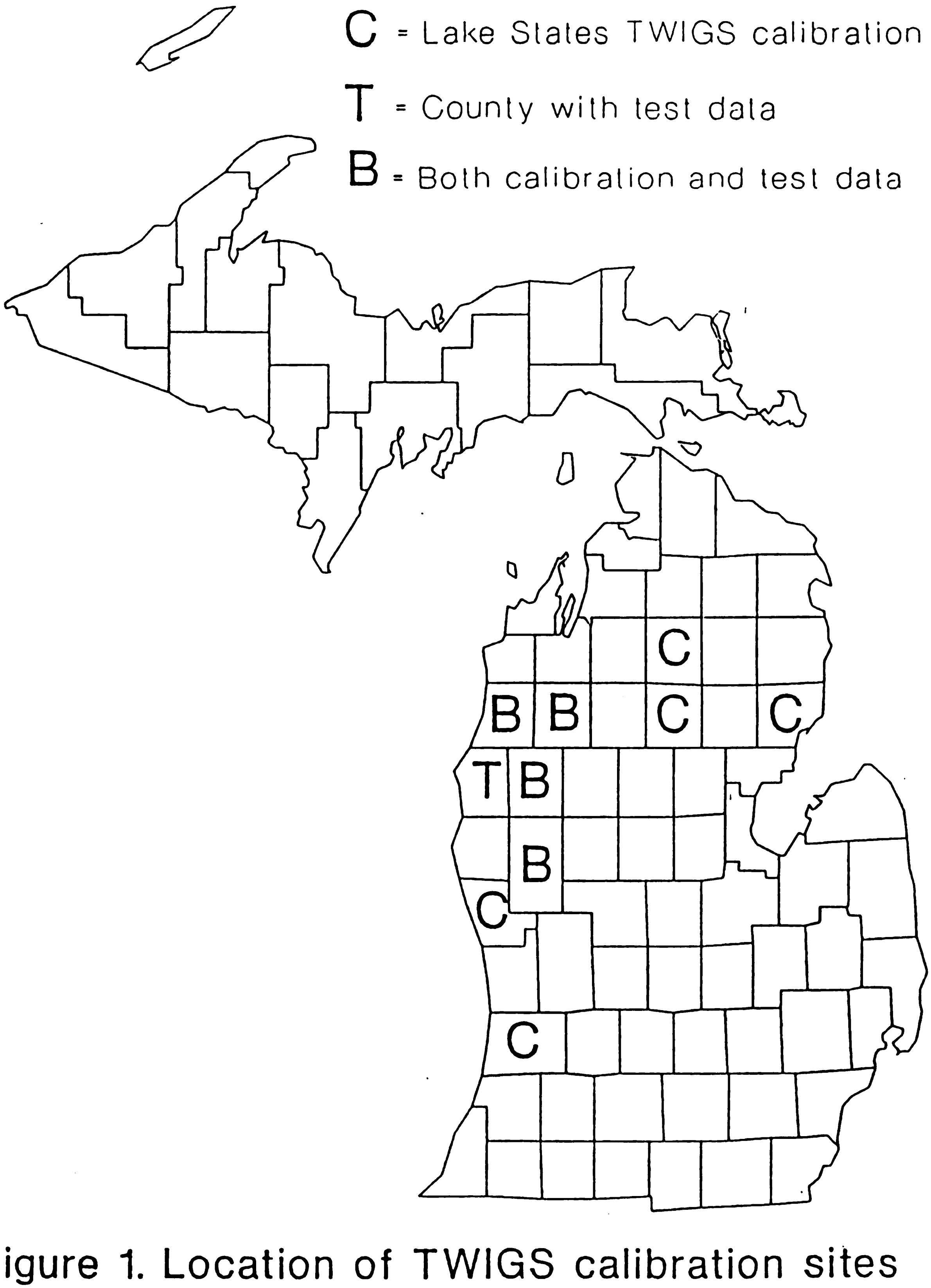


Figure 1. Location of TWIGS calibration sites and test sites in Michigan

major landforms: outwash plains, ice contact hills and moraines. Once a stand was located, evaluated, and accepted four prism points were randomly established within each stand. These points were all referenced to a central soil pit in each stand. Tree species, dbh (inches), total height (ft.), merchantable height (ft.), crown ratio (%) and crown class were measured on all tally trees 1" and above dbh. Increment cores were taken from a sub-sample of trees to estimate an average age for site index (base age 50 years) and ten year radial growth. Average species site index for each sample point was estimated using equations developed by Hahn and Carmean (1982).

In the summer of 1986, 50 of the original ECS plots were selected and converted to permanent plots. The method of selection was a random sampling stratified across the 10 ecological land type phases (ELTPs) developed by the ECS project (Table 1). These plots fell within the boundaries of Manistee, Wexford, Mason, Lake and Newaygo counties. In 1986, selected sites were relocated, mapped, sample points were permanently marked, and all tally trees 1" dbh and above were retagged and measured. Methods used in marking the plots included installing rebar at point centers, tagging tally trees with numbered aluminum tags at the base of the trunk, and marking three witness trees per point so that triangulation could be used to find plot center. The only short-coming to this process was that distances and azimuths were not recorded from point centers to witness trees.

Table 1. Definition of ELTPs

1.	Pin oak-white oak/Deschampsia on excessively well-drained sands of outwash plains.
10.	Black oak-white oak/Vaccinium on excessively well-drained sands of outwash plains.
12.	Black oak-white oak/Vaccinium on sub-irrigated excessively well-drained sands of outwash plains.
20.	Mixed oak-red maple/Viburnum on well-drained sands on moraines, kames, and outwashed plains.
21.	Mixed oak-red maple/Viburnum on well-drained sands underlain by sandy loam bands on moraines, kames, and outwashed plains.
35.	Red oak-red maple/Viburnum on well-drained sands with fine loamy substrata on moraines and lacustrine deposits.
37.	Red oak-red maple/Desmodium on well-drained sands over loamy substrata on moraines and lacustrine deposits.
40.	Sugar maple-beech/Lycopodium on well drained moraines.
43.	Sugar maple-beech/Lycopodium on well drained sands with fine texture substrata on moraines.
45.	Sugar maple-white ash/Osmorhiza on well-drained sands with fine textured substrata on moraines.

Data from the 1986 field season was then compiled into a database. Information compiled included stand number, plot number, subplot (point) number, tree number, tree species, dbh, total height, merchantable height (to a four inch top for softwoods and eight inches for hardwoods), crown ratio, and crown class.

1991 Field Measurements:

The 1991 field measurements again focused on the 10 BAF prism point. All points located within the original 50 stands were re-tallied from the original point centers. If point centers could not be located, approximations were made and noted on point record sheets. Trees found to be in (*i.e.* tally trees) in both 1986 and 1991 were measured for dbh, crown ratio, and crown class. Trees found to be 1991 ingrowth (trees which were tallied in 1991 but not in 1986) were measured for these characteristics as well as total height and merchantable height. Dbh measurements were made at 4.5 feet using the same staff used in 1986 as a guide. If cankers or other deformations interrupted dbh measurements at 4.5 ft., adjustments were made and recorded on point record sheets. These adjustments usually involved moving the point of measurement above the deformity. All crown ratio and height measurements were made using the Spiegal Relaskop. Crown class was ocularly estimated.

In addition to these measurements, observations were also made on disturbance conditions within each stand. The nature of these disturbances ranged from forest pest infestations to human disturbances. All disturbances were recorded on the 1991 point record forms.

White Oaks (*Quercus alba*), red oak species and Bigtooth aspen (*Populus grandidentata*) throughout several of the stands showed signs of defoliation caused by gypsy moth (*Lymantria* *dispar*). American Basswood (*Tilia americana*) on all plots were defoliated to some degree by Lindon looper (*Erannis tiliaria*). All cases of defoliation were recorded for each tree on the plot tally sheets. Degree of defoliation was recorded as an ocular estimate of the percentage of crown defoliated.

Sources of human disturbance were either active forest management or vandalism. Stands that had evidence of thinning or other management practices (i.e. slash piles, etc.) were noted in plot records. Such stands were dropped from further analysis, as thinning and other similar silvicultural practices alter growth potentials in residual trees (Smith 1986). These influences on the natural growth rates of the research plots were not desired. In addition to management disturbances, several plots were defaced by vandals. These plots were reconstructed as accurately as possible using 1986 records and noted in plot records.

Data Processing and Compilation:

The database used for the 1986 field data was enlarged after the 1991 season to incorporate the new field data. In addition to adding the variables mentioned above, five year change in dbh and 1991 tree status were also added. The resulting database consisted of 2,495 tree records from fifty stands.

The process of developing the database into work-sets to meet research objectives began by eliminating all trees that were accounted for as mortality from 1986 and all ingrowth 1991 trees. This left tree records with complete five year growth data. Stands which had signs of active management were deleted next. Finally all plots (groupings of 4 to 6 prism points within a stand) that were disturbed and could not be reconstructed were deleted. The final dataset contained trees from 44 of the original 50 stands.

At this point the subplot (or prism point) was adopted as the sample unit. This provided for a maximum number of samples which could be used to produce both individual tree data (i.e. dbh, crown ratio) and stand level data (i. e. basal area). When split into subplot-units the 44 stands produced 176 sample units.

Next the database was randomly split into a calibration subset and a validation subset. The calibration data would be used to construct alternative growth models, if necessary, and the validation data would be used to validate TWIGS and compare TWIGS results with the results of any alternative models. The process used for splitting the database was a random sample stratified across ELTPs. As for the proportion to be allocated per subset, Snee (1977) reports that the common practice involves a fifty percent split between data sets. However, due to the small sample size (176 subplots), it was decided to allocate one-third of the data to the validation subset and two-thirds to the calibration set. The total number of subplots and their distribution is listed in Table 2:

Table 2. Subplot Distribution per Data Set

ELTP	Total Subplots	Number in Validation Set	Number in Calibration Set
1	16	5	11
10	14	5	9
12	12	4	8
20	18	6	12
21	19	6	13
35	26	9	17
37	20	7	13
40	22	7	15
43	11	4	7
45	18	6	12
Total	176	59	117

Model Validation and Development:

To fulfill research objectives a predetermined series of steps were followed. The first of these procedures was to examine the TWIGS growth model using the validation subset. After obtaining results, new growth models were developed using the calibration subset. Validation data was then to be used to test the new models and results would be compared to Lake States TWIGS. However, model development was unsuccessful, so a final validation of TWIGS was performed using the combined calibration and validation data.

TWIGS VALIDATION:

DATA:

Before model validation began, tally tree characteristics from each point's 1986 measurement were expanded to a per acre basis using TREEGEN (Miner *et. al.*, 1988) and then five year projections were made using TWIGS. Projections were made using TWIGS' "individual tree option" and actual crown ratios were used to avoid over-prediction in dbh growth as cited by Holdaway and Brand (1983). TWIGS' results were grouped in the five diameter class option (an option in the initial program setup menu). These diameter classes were 0.0-2.9", 3.0-4.9", 5.0-10.9", 11.0-16.9", and 17.0"+. These size classes were selected because they produced the most detailed individual tree output, and because validation results could be directly related to TWIGS' output without any adjustment. General recommendations for best results with TWIGS given by Miner *et. al.* (1988) were followed. Each tree list included at least ten trees, tree lists were dominated by trees over 2" dbh, and projection intervals were set to five years.

The five year projections were compared to 1991 field measurements in the validation process. Evaluations involving dbh were based on differences between projected versus actual diameter for individual trees, while basal area and trees per acre projections were compared to density calculated from the 1991 point sample remeasurements. The methods used to convert point sample data into pseudo-fixed radius plots for comparisons follow the recommendations of Grosenbaugh (1958) and Beers and Miller (1964). Only tree data from the original 1986 tally trees were used for 1991 basal area and trees per acre expansions. Trees which were too small to be tallied in 1986, but which grew on to the plot in 1991 (ongrowth) were ignored.

Validation Statistics:

Tree and stand characteristics selected for evaluation were individual tree dbh, stand basal area (BA), and trees per acre (TPA). Dbh was chosen to evaluate the performance of TWIGS' individual tree diameter growth model. TPA was used to judge TWIGS' projections of tree mortality, and stand BA was used as an indicator of overall model performance (Kowalski and Gertner, 1989). The basic sample unit for dbh was the individual tree, while BA and TPA were evaluated at the stand level.

TWIGS validation was carried out with five northern hardwood species: northern red oak (*Quercus rubra* L.); other red oak (*Quercus velutina* Larmarck and *Quercus palustris* Muenchh); white oak (*Quercus alba* L.); sugar maple (*Acer saccharum* Marsh.); and red maple (*Acer rubrum* L.). Sample sizes varied widely across species. More than a dozen species were tallied across all plots, but it was felt that these five species were the only ones with ample representation to allow testing.

TWIGS' volume equation was not tested because the equation used for acceptable tree class volume (Raile *et. al.*, 1982) incorporated coefficients developed for Michigan's Upper Peninsula. These coefficients are the same for northern red oak, white oak, and other red oak, unlike the coefficients developed for the Lower Peninsula.

Initial validation procedures (a second validation followed in the study) were carried out using error statistics described by Kowalski and Gertner (1989). These error statistics were selected to have a basis for comparison with other studies of TWIGS.

Error Statistics:

The error statistics used were (Kowalski and Gertner, 1989):

Mean Error = $[\Sigma(O_i-P_i)]/n$ (A measure of bias)

Mean Percent Error = $100[\Sigma((O_i-P_i)/O_i)/n]$ (A measure of precision)

Standard Deviation of Error = $[[\Sigma(e_i-e)^2]/(n-1)]^{1/2}$

Where:

Pi = TWIGS prediction
Oi = Observed value
n = sample size
ei = error, defined (Oi-Pi)
e = mean error, defined as (Σ ei)/n for all i

Due to the nature of the equations, overestimations appear as negative values, while underestimations have positive values. Sample sizes and results are shown in Table 3.

Table 3. Initial TWIGS Validation Results (5 years)

Characteristic	Species	n	Mean Error	STD DEV	Percent Error
DBH (inches)	N. Red Oak	197	.05	.54	.04
BA (sq.ft./acre)		35	.71	8.93	.60
TPA		35	21.89	91.48	3.13
DBH (inches)	O. Red Oak	64	-.01	.79	-.22
BA (sq.ft./acre)		16	5.10	7.26	9.38
TPA		16	16.99	31.81	13.36
DBH (inches)	White Oak	98	-.24	.84	-1.88
BA (sq.ft./acre)		32	-2.52	4.68	-8.90
TPA		32	-13.17	92.08	-16.80
DBH (inches)	Sugar Maple	53	-.16	.22	-2.17
BA (sq.ft./acre)		13	-.48	9.25	-10.26
TPA		13	-23.44	115.80	-22.01
DBH (inches)	Red Maple	51	.01	.31	.13
BA (sq.ft./acre)		23	1.11	8.67	.11
TPA		23	8.23	44.33	.32

Overall, the validation sample sizes were small for a comprehensive evaluation of a model so widely used. However, Lakes States TWIGS did perform well in regards to diameter projections for all five species. Percent mean errors for 5 year diameter predictions were less than 3% percent for all species. White oak showed the highest mean error for estimated dbh, a .24 inch overprediction in dbh over five years. BA and TPA results were less accurate. Percent mean errors were over 8 percent for BA of three of the five species tested, although northern red oak and red maple were less than 1 percent. Three of the five species tested also had TPA percent mean errors of over 12 percent. Mean errors for basal area projections over 5 years ranged from an underestimation of 5.10 ft^2/acre (other red oak) to an overestimation of 2.52 ft^2/acre (white oak). Mean errors for trees per acre ranged from underestimations of 21.89 trees per acre (northern red oak) to overestimation of 23.44 trees per acre (sugar maple) for the five year period.

Although diameter projections were not grossly inaccurate, it was thought that a new diameter growth model would improve accuracy. The primary reason for this focused on the role of basal area in the Lake States TWIGS diameter growth model. Basal area is an integral part of the competition modifier (equation 1b) (Holdaway, 1985), which is multiplied by the product of the potential diameter growth and the adjustment factor to produce annual diameter growth (equation 1). Given the five year errors in basal area projections, the possibility exists that longer term projection errors will be compounded. In addition, errors in TPA projections suggest a flaw in the Lake States TWIGS survival model. Given that TPA and dbh are the components of basal area, the survival model has a direct link to dbh projections. Considering these circumstances, a new diameter growth model that avoids the use of the current competition and survival functions could improve accuracy.

Model Development and Results:

Before model development began one final alteration to the calibration data set was performed. This alteration was to eliminate all conifers and noncommercial tree species from the data set and then split the remaining trees into species-specific sets. The reasoning for eliminating the conifers and noncommercial tree species is inherent with the goals of the study: evaluation and development of diameter growth models for upland hardwoods. Species-specific data sets were necessary to develop models with unique coefficients for each species. This is a logical step considering differences in growth patterns among species (Oliver and Larson, 1990; Godman et.al., 1990: Walters and Yawney, 1990; Tubbs and Houston, 1990; Schlesinger, 1990; Rogers, 1990; Sanders, 1990a; Sander, 1990b). Splitting the data produced five species-specific data sets (Table 4).

Table 4. Calibration Data: Sample Size by Species Group

Species	Number of Trees
Northern Red Oak	457
White Oak	258
O. Red Oak	176
Sugar Maple	157
Red Maple	89

The five species data sets contained a combined total of 1,137 trees and the variables listed in Table 5.

Table 5. Variables Used in Model Development

Variable	Definition
DBH86	1986 diameter at breast height (inches)
DBH91	1991 diameter at breast height (inches)
DD	Five year change in diameter (inches)
BAG5YR	Five year change in tree basal area (ft2)
CR	Tree crown ratio code (0-10%=1, 11-20%=2, ... 81%+=9)
CC	Crown Class (ordinal variable)
SI	Site Index (ft. at base age 50 yrs.)
TBA	1986 tree basal area (ft^2/acre)
BA	1986 basal area of stand (ft^2/acre)
DENSE	1986 tree basal area divided by 1986 stand basal area (used to describe tree position in stand).
ELTP	Ecological land type phase (ordinal variable)

In addition to these variables, various transformations were made during the modeling process to improve the linear relationships between independent and dependant variables. These transformations were either a natural log transformation or using the variable inverse. Any variable altered in either of these ways was noted with the prefix "LN" for log transformation or "INV" for inverse.

It is also important to note that the initial data sets did not include stand level variables other than BA. This is because 40 of the subplots were missing center points in 1986 (roughly 19%). Basal area measurements were estimated for these points in 1986, and these measurements were retained. However, stand level variables including trees per acre, average dbh, and quadratic stand diameter (QSD) could not be calculated. Due to the already small sample size, it was not deemed prudent to eliminate more records.

The Multivariate Linear Model:

Initial attempts at developing alternative diameter growth models centered on the multivariate linear model. This format was chosen for ease of development and overall flexibility.

The conceptual model for this approach was:

$$DGROW = b_0 + b_1TD + b_2COMP + b_3VIGOR + b_4QUALITY$$

Where:

DGROW = 5 year increment of diameter or tree basal area growth

TD = Current tree diameter or basal area

COMP = A representation of competition in the stand

VIGOR = A representation of tree health and vigor

QUALITY = A representation of site quality

These factors were chosen for the conceptual model because they are thought to have an effect of diameter growth (Spurr and Barnes, 1980), are integral components of established grow models (Miner *et. al.*, 1988; Shifley, 1987; Wykoff *et. al.,* 1982; Hilt, 1983), and they can be represented in the database. The TD component can be either dbh, tree basal area or a derivation of either. Stand basal area, the DENSE variable and similar variables which represent stand structure and competition were suitable for the COMP component. Crown ratio and class are the only variables that may be represented as VIGOR from the data set. Site quality variable options were either SI or ELTP.

Before model development began, assumptions of normality were tested for the individual variables in each species set. A series of Kolmogorov - Smirnov tests (Conover, 1980) indicated that less than 10% of the variables were normally distributed. Stem-leaf diagrams were also constructed to produce a graphic view of the distributions. The stem-leaf diagrams appeared normally or near-normally distributed. Given these findings and the robustness of ordinary least squares procedures, model development continued with the assumption of normally distributed data.

After normality was judged, summary statistics were run on each species data sets (Table 6). Scatter plots were constructed with each independent variable graphed versus the dependant variable (5 year diameter change). The summary statistics showed that variable means and ranges differed widely between species. This further supported the decision not to combine species data. The scatter plots, Appendix A, all showed slight linear relationships between the dependant and independent variables. For the most part, however, these relationships provided little evidence that a linear model would be successful. A number of transformation were also tried on the variables with little success.

Table 6. Summary Statistics for Calibration Data Set

Species	n	Statistic	DD	DBH86	DBH91	BA	CR	DENSE
			(....inches	....)		(ft2/ac.)		
N. Red Oak	457	Minimum	-0.20	3.10	3.10	40.00	1.00	.000
		Maximum	2.30	33.60	35.10	190.00	5.00	.038
		Mean	0.57	12.77	13.35	126.67	3.69	.008
		Std Dev	0.32	4.45	4.68	29.59	3.94	.006
O.Red Oak	176	Minimum	0.00	4.20	4.20	40.00	1.00	.000
		Maximum	2.22	23.20	23.60	170.00	6.00	.048
		Mean	0.53	12.28	12.81	102.77	3.28	.010
		Std Dev	0.96	4.17	4.17	22.35	0.95	.008
White Oak	258	Minimum	-0.20	2.60	2.80	40.00	1.00	.000
		Maximum	1.00	22.20	22.80	190.00	6.00	.028
		Mean	0.23	9.37	9.60	111.63	2.93	.005
		Std Dev	0.22	3.58	3.69	28.72	1.13	.005
Sugar Maple	157	Minimum	-0.20	2.10	2.10	70.00	2.00	.000
		Maximum	1.90	21.10	21.10	190.00	8.00	.016
		Mean	0.29	8.07	8.35	145.10	4.17	.003
		Std Dev	0.27	3.18	3.28	33.18	1.14	.003
Red Maple	89	Minimum	-0.10	2.30	2.40	50.00	1.00	.000
		Maximum	1.10	17.10	17.30	190.00	7.00	.014
		Mean	0.33	6.57	6.89	126.74	3.75	.003
		Std Dev	0.26	3.49	3.62	29.11	1.33	.003

Because the independent variables in the data set had poor linear relationships with five year change in diameter (and with the log transpose of diameter change), model construction focused on trying all possible variable combinations versus diameter growth (both transposed and not). It was not assumed that this approach would yield adequate results (Coefficient of determination desired above .8), however it was the only reasonable chance of remaining with the simple model form.

The results of this approach were not satisfactory. The overall "best" model, based heavily on R^2, was:

$$DD = b_0 + b_1 LNDBH86 + b_2 * 1/BA + b_3 DENSE + b_4 CR + b_k ELTP_k$$

WHERE: DD = 5 year change in diameter growth

LNDBH86 = Natural log of 1986 DBH

BA = 1986 Basal area (ft^2/acre)

DENSE = Ratio of tree BA to stand BA 1986

$ELTP_k$ = Dummy variables representing ELTP membership

$b_0 \ldots b_k$ = Regression coefficients

Regression analysis were run for each of the five species data sets and species-specific models were constructed. The R2's for these models ranged from 0.194 to 0.507 (Appendix B). Standard error of the estimated dbh's ranged between 0.158 and 0.240 inches. Student's t-test varied depending on the variable and species; only log(dbh) was consistently significant for all models. The ELTP variable appeared a combined thirty-three times throughout the five models, and in only eight occurrences did it test significant (alpha level of

0.10 or below). Residual plots for the three oak species (Appendix C) appeared randomly distributed and suggested no quadratic or other relationships overlooked. Residual plots for the two maple species had patterns that suggested heteroscedasticity; the distribution of residuals around 0 increased as X increased in value. Weighing observations in regression or transforming the dependant variable can correct heteroscedasticity (Rawlings, 1988). Because the oak models had poor fit statistics and any corrections for the maple models would produce a model inconsistent with the oak models, corrections for heteroscedasticity were not made.

The results of this approach were unsatisfactory, however further efforts were made in an attempt to remain with the mutlivariate linear form. These final efforts centered on using forward and backward stepwise regression procedures to find a model format that would best fit all species. Although these procedures are often discouraged because they find the best statistical model and not the best biological model, they were used because all variables were considered biologically significant and these methods offered the best option for a solution. Several regressions were run using these procedures and the different species data sets. The results produced no overall model form that would fit all species. The process was abandoned.

Before moving to other possible models it is important to discuss why this method provided poor results. The only variable that produced consistent significance of 0.05 or less was log(dbh). Some form of dbh (or tree basal area) is present in all published diameter growth models. Given this fact and that it was successful in the multivariate model, there is no indication that the poor performance can be attributed to this variable.

Basal area and DENSE proved erratic in significance between models. Given the relationship between dependant and independent variables in the scatter plots this was expected. There may be several reasons why. The inverse of basal area was used due to the relationship of this value with change in diameter. The greater the BA the smaller the value of the inverse, which should be matched with a smaller diameter growth (Appendix A). This would coincide with the fact that a stand with lower density allows the individual tree more resources to grow. Overall stand basal area as calculated in prism sampling may not represent the actual density conditions faced by an individual tree. Using the prism, trees are tallied as a result of their distance from plot center and their diameter. Therefore trees are tallied from a variety of areas within a stand. The stand densities from the micro-environments that these trees occupy may differ considerably from the overall stand.

This would also apply to the DENSE variable (ratio of tree BA (TBA) to stand BA) as stand BA is a component. In this case, the larger the tree diameter the higher it's basal area (the numerator), therefore the DENSE value is greater. This provides for a larger DENSE value to coincide with a greater diameter growth, which would agree with the TBA vs. DD scatter plot (Appendix A.) Combining the effects of TBA over stand BA was an attempt to represent the tree's position in the stand. Modeling results show that this attempt was not successful.

Crown ratio also proved erratic in significance. For the maples and white oak, crown ratio variables were significant at levels of at least 0.10, while for the red oaks they were not significant at any reasonable level. Possible explanations for this include crown structure and measurement error. Crown ratio measurements indicate that the proportion of the tree in foliage but does not account for the actual leaf area and structure of the crown. These differences in leaf area and structure were most prevalent among red oaks, varying with site quality. On the more mesic, higher quality sites, red oak crowns were full and had extended forms. On the drier, poor sites where red oak species dominated the hardwoods, crowns were more cylindrical in form and gaps in foliage were prevalent. Trees with identical crown ratio values occupying these different sites would not necessarily have the same leaf area and photosynthetic potentials. Another reason for the differences in CR significance among species models may be measurement error. Of all the data collection techniques used, crown ratio measurement was the most variable in terms of accuracy. Even with the aid of a clinometer or other similar device, crown ratio is an ocular estimation. In addition, crowns that have gaps and other irregularities often have their crown ratio values adjusted to compensate. These factors leave room for guess work and bias. The result is a variable open to a large degree of error. Given the circumstances of red oak crowns on the study plots, this may explain part of negative results.

The final variable in question is ELTP. This variable was rarely significant in the models, and when significant there was no discernable pattern between species and site quality. This would suggest that either the use of an ordinal variable does not fully capture the influences of the site, or that the differences between ELTPs do not fully differentiate between site quality potentials for these stands.

The Modified Chapmann-Richards Function:

The next approach to developing a diameter growth model followed the work of Hilt and Teck (1987). Using data on 5,313 northern hardwood trees from 1/5-acre forest inventory and analysis plots in New England, Hilt and Teck developed a diameter growth model based on a modified Chapmann-Richards function. Their's was a three stage model as outlined below:

POTBAG = b_1*SI*(1.0-exp(-b_2*DBH))

BAG = POTBAG*(exp(-b_3*BAL))

DGROW = SQRT((DBH^2*C+BAG)/C)-DBH

Where: POTBAG = Potential basal area growth

BAG = Basal area growth

DGROW = Diameter growth

SI = Site Index

DBH = Diameter at breast height

BAL = Basal area greater than tree size class

C = Constant (.005454)

$b_1 \ldots b_3$= Unique coefficient

The potential growth function (POTBAG) was calibrated using the top 10% of trees in terms of basal area growth per species. To repeat this procedure on this study's data would involve relatively small sample sizes for model development. Using the sample sizes shown in Table 2, the 10% level used in POTBAG calibration would produce sample sizes from 44 to 3.

Although there were concerns over sample size, model calibration for POTBAG was done for northern red oak data. The adjusted R^2 for this model was 0.20. With so little of the variation in Y being explained by the model, and the small sample sizes, it was decided to abandon this model.

Species/ELTP specific Modeling:

The poor performance of the initial modeling approaches lead to a reexamination of the data sets. ELTPs were initially represented as dummy variables, with little success. These results were not expected. ELTPs are delineated by landform, climate, geology, and vegetation; therefore, they are associated with site quality. This association with site quality can be seen in the field by comparing stand composition and condition between the high and low range ELTPs. ELTP 45 stands are composed of well stocked sugar maple-ash stands, while ELTP 1 typed stands have a major (poorly stocked) jack pine - black oak component. This correlation with site quality was expected to appear in the models, however ELTP variables were rarely significant.

The fact that ELTPs performed poorly as variables led to the reconstruction of scatter plots. In the process the species-specific data sets were further divided into ELTP/species-specific data sets. In addition, the diameter growth variable was converted to five year basal area growth (individual tree) or BAG. When BAG was plotted versus DBH86 the resulting plots appeared to have a slight J-shaped curve. This curve was further exaggerated when the independent variable was changed to $DBH86^2$. This pattern was very close to the plots Hilt (1983) described. Thus, the next attempt at producing a diameter growth model focused on Hilt's conceptual model:

$$BAG5YR = f(DBH\ SI\ D\ PS)$$

Where:

BAG5YR = five year basal area growth (ft^2)

DBH = diameter at breast height (inches)

SI = site index (ft. at base age 50 yrs.)

D = mean stand diameter (inches)

PS = percent stocking
(Calculated with Gingrich's stocking equation (1967): $PS_{ij} = -.005066 + .016977DBH_{ij} + .003168(DBH_{ij})^2$)

Hilt worked with tree data from seventy-seven 0.25 to 1.0 acre permanent growth and yield plots. The following equation was fit to each stand using individual tree data:

$$BAG5YR = b^i * DBH^2$$

Where: BAG5YR = 5 year tree basal area growth (ft^2)

DBH = diameter at breast height squared (inches)

b_i = unique coefficient per stand

He then fitted the b_is to the following equation:

$$b_i = g_1 SI g_2 * \exp(g_3 D + g_4 PS)$$

Where: b_i = unique coefficient per stand

SI = site index (ft. at base age 50 yrs)

D = mean stand diameter (inches)

PS = percent stocking
(Calculated with Gingrich's stocking equation (1967): $PS_{ij} = -.005066 + .016977DBH_{ij} + .003168(DBH_{ij})^2$)

$g_1 \ldots g_4$ = unique coefficients

The result is a two stage model where site and stocking effects are considered in the second equation, which in turn is used for basal area growth projection in the first equation.

Initial work with this model focused on fitting the white oak data sets to the BAG5YR model. White oak was chosen at random from the five species available. Results were positive, with R^2s ranging between 0.518 and 0.772. Problems arose, however, when the second stage model was to be fitted.

The stage two model is composed of stand level independent variables. The trees in the ELTP/species data sets came from several stands brought together to form a composite stand with similar characteristics. This grouping provided for the largest possible sample size involving species from the same ecological environments. It does not, however, provide for stand level variables. This prevents the second equation from being used.

There were two possible solutions to this problem. The first was to redefine the data sets to be species-specific sets with trees only from individual stands. The second solution was to find a replacement for the "b_i" equation. As the first solution would produce a large number of relatively small data sets, it was deemed impractical. Further work was then directed towards finding possible substitutes for the second equation.

In pursuing a substitute for the second equation, reasonable alternatives had to be found to capture the functions of the variables in that equation. The first variable examined for replacement was percent stocking (PS). 1986 stand basal area (BA86) was thought to be a substitute for PS, a stand density variable. Scatter plots and new models, however, failed to demonstrate any relationships between the dependant variable (in any form) and the independent variable BA86 or any of its transformations. Considering the success of the ELTP/SPP - specific data and equation one, the data sets were further stratified by basal area. This was accomplished by developing three basal area classes that could be associated with stocking levels. These classes and their associated stocking levels are shown in Table 7.

Table 7. Basal Area Classes

Basal Area Classes (ft2/acre)	Associated Stocking Level
Basal Area > 130	Highly stocked
Basal Area 90 to 130	Normally stocked
Basal Area < 90	Under stocked

After the data sets were split the BAG equation was fitted with the new white oak data. The resulting R^2s ranged from 0.426 to 0.828. This increase in the coefficient of determination prompted further calibration of the northern red oak data sets.

The product of this line of modeling was a simple equation that explained a large portion of variation in the dependant variable (BAG5YR). Instead of expressing stand density as a independent variable, basal area characteristics are included as an integral part of the data set. This same concept is further brought into play with the site quality variable. Initially site index was represented as an independent variable in the second stage equation. However, by breaking the data sets down across ELTPs, the maximum range in site index between sites per data set was 15 feet, with a majority of the ranges being within 10 feet. Therefore, the need for an independent variable was circumvented by expressing site quality in the data set.

Although initial results seemed positive, there were two principle shortcomings to this model. The first is the small sample size involved with the calibration of each model (Table 8). The initial species-specific data sets were relatively small to begin with (Table 2). After stratifying each species-specific data set further down to the SPP/ELTP/BA level, and after removing outliers, the final data sets ranged in size from 5 to 69 trees. It is doubtful that models calibrated with so few trees have any practical use.

The second shortcoming was the large number of model coefficients needed to represent all the specific tree groupings. This unmanageable aspect resulted in halting the modeling process to look at still other options.

Table 8. Results of BAG5YR Models

DATA SET	N	BETA	RSQUARED	SEE
G20B	25	1.4E-05	0.696	0.001354
F20A	7	5E-07	0.478	9.37E-05
F20B	12	1.3E-06	0.622	0.000169
F20T	19	1E-06	0.518	0.000158
E20A	8	1.9E-06	0.828	6.89E-05
E20B	10	5E-06	0.798	0.000299
E20T	20	3.9E-06	0.755	0.000222
D20A	7	3E-06	0.892	0.000106
D20B	28	1.9E-06	0.68	0.000114
D20T	37	2.1E-06	0.702	0.000119
C20B	39	5.2E-06	0.679	0.00034
C20C	12	4.6E-06	0.426	0.000777
C20T	48	4.8E-06	0.656	0.000351
B20A	16	1.5E-06	0.717	7.52E-05
B20B	14	1.5E-06	0.428	0.000115
B20C	6	3.7E-06	0.659	8.42E-05
B20T	38	1.6E-06	0.563	9.44E-05
A20B	14	5.7E-06	0.805	0.000184
A20C	23	8.7E-06	0.748	0.000371
A20T	24	7.9E-06	0.772	0.00033
J21A	5	1.26E-05	0.898	0.002394
I21A	5	2.04E-05	0.632	0.011288
I21B	28	9.8E-06	0.879	0.00117
H21A	8	2.8E-06	0.899	0.0001
H21B	44	1.15E-05	0.892	0.000532
G21A	13	1.43E-05	0.756	0.001768
G21B	69	1.52E-05	0.738	0.002299
G21C	15	1.71E-05	0.894	0.001396
F21A	46	1.39E-05	0.803	0.000988
F21B	47	1.37E-05	0.841	0.00103
F21C	42	7.8E-06	0.712	0.001245
E21B	15	5.7E-06	0.68	0.000795
E21C	5	1.22E-05	0.701	0.000582
D21B	28	8.9E-06	0.757	0.000862
D21A	8	1.41E-05	0.921	0.000584
C21B	8	1.64E-05	0.982	0.000663
B21A	17	1.73E-05	0.823	0.000408
B21B	20	1.24E-05	0.919	0.000357
D22B	39	7.20E-06	0.634	0.000940

KEY: G22B

G = ELTP: 45 43 40 37 35 21 20 12 10 1
J I H G F E D C B A

= Species: 22 = O.Red Oak
21 = N.Red Oak
20 = White Oak

B = BA (ft2/acre) range: A = 130>
B = 90 to 130
C = <90
T = Full Range

Stand Level Variables:

The last effort in the modeling process was to re-examine the parent database and calculate stand level variables. Because several of the prism points were missing plot center in 1986, stand basal area was estimated and several trees were unaccounted for. Therefore, there was initial concern that calculating these variables would require eliminating some of the 40 sample points, thus decreasing an already small database. It was decided that this was the last chance at developing an alternative diameter growth model. The variables calculated are defined in Table 9.

Table 9. Stand Level Variables

Variable	Formula
Average Stand Diameter	$ASD86 = \Sigma dbh_i/N$ Where: dbhi = Individual tree diameter N = sample size
Quadratic Mean Diameter	$QSD = SQRT(1/N * \Sigma dbh^2_i)$ Where: dbhi = Individual dbh N = sample size
Basal area greater than tree class	GBA = Stand BA - BAL Where: BAL = Basal area of current size class and less.
Trees per acre	An expansion of point data

The quadratic stand diameter and trees per acre (TPA) variables should reflect stand density. The basal area greater than tree class variable should determine a tree class' position within the stand. ASD86 represents the average tree diameter within a stand and therefore may be useful in explaining aspects of stand structure.

Once derived, all stand level independent variables were plotted versus the dependent variable and its transformations. These plots were made at all levels of the data sets (i.e. species - specific sets, SPP/ELTP sets and SPP/ELTP/BA sets.). Inspection of the scatter plots revealed no distinct patterns at any level.

Modeling Termination:

The choices in model development to this point were three models that were thought to be best able to provide an alternative to Lake State TWIGS diameter growth model. Poor results and sufficient data (i.e. sample size, variable selection) resulted in no adequate replacement developed. Other possibilities still exist, such as Mawson's (1982) models and the predecessors to the current TWIGS' model (Leary *et. al.,* 1979), however, time constraints limited their exploration. Since the small sample sizes resulted in the initial validation of the TWIGS' model to be far less than comprehensive, it was decided to use all available data to perform a larger scale validation of the Lake States TWIGS growth model.

Final TWIGS Validation:

DATA:

Originally one-third of the database was set aside for validation. However, after the modeling phase failed to produce satisfactory results the calibration and validation data sets were combined into one validation set. Summary statistics for the combined data are presented in Table 10. The initial sample unit for validation remained the plot (prism point), with the individual tree being used for diameter comparisons. As with the initial validation, all plots were expanded to the per acre basis using TREEGEN and five year projections were run with TWIGS. The same methods were used in each validation in regards to TREEGEN and TWIGS options and data manipulation.

Table 10. Summary Statistics for the 156 Sample Points by Strata (ELTPs)

						Site Index[a]						
ELTP	n[b]	STT	TPA[c]	BA	AVEDBH[d]	WO	NRO	BO	RM	SM	WA	AGE
1	12	mean	218	86	8.1	44		51				74
		min	113	50	7.2	37		42				71
		max	321	120	10.4	53		63				75
10	13	mean	514	108	6.3	40	53	48				79
		min	94	50	4.3	27	45	44				70
		max	1113	170	10.6	55	62	54				95
12	11	mean	299	95	7.8	49		59				71
		min	126	60	5.3	40		52				61
		max	601	140	10.9	63		70				84
20	19	mean	328	114	7.7	54	59	58				84
		min	189	70	4.3	48	45	40				77
		max	788	160	9.9	63	75	70				93
21	17	mean	503	114	6.6	49	64	60	48			73
		min	149	70	3.4	38	55	47	48			64
		max	1302	180	10.8	57	71	73	48			83
35	24	mean	347	138	8.6	66	80					73
		min	62	50	5.9	59	63					63
		max	809	220	16.2	77	106					84
37	19	mean	146	114	11.9	64	87		67			75
		min	76	80	8.3	51	72		44			66
		max	289	150	16.1	73	103		88			79
40	17	mean	384	107	7.3		78		66	60	70	62
		min	146	70	3.6		65		52	49	50	59
		max	785	150	11.7		83		80	67	82	65
43	8	mean	391	128	7.5		90			71		63
		min	159	80	4.6		79			66		61
		max	804	160	10.4		100			76		68
45	16	mean	424	139	7.7		77			74	84	62
		min	123	80	4.8		77			57	73	56
Overall Mean			352	116	8.1							72
Std. Dev.			229.6	32.4	2.5							9.7

a WO - white oak; NRO - northern red oak; BO - black & pin oaks; RM - red maple; SM -sugar maple; and WA - white ash.
b Number of sample points per ELTP
c trees/acre, calculated for all trees > 1.0" DBH
d AVEDBH = arithmetic mean dbh

Validation Statistics:

Tree and stand characteristics selected for evaluation were again individual tree dbh, stand BA, and stand TPA. Dbh was chosen to evaluate the performance of TWIGS' individual growth model. TPA was used to judge TWIGS' projections of tree mortality, and BA was used as an indicator of overall model performance (Kowalski and Gertner, 1989). The basic sample units also remained the same. Due to small sample sizes, the same five species were selected for validation.

Final validation procedures were carried out in two phases. The first phase was the use of error statistics outlined by Kowalski and Gertner (1989). The second phase was characterized by the use of ATEST, developed by Rauscher (1986) for testing prediction accuracy. This method was chosen because it provides a means of constructing confidence intervals around future prediction.

Error Statistics:

Depending on the characteristics judged, statistics were calculated at two levels. Diameter growth comparisons were made at an individual tree level with results aggregated by TWIGS diameter classes within species (Table 11, Figures 2, 3 and 6). Errors for BA and TPA were calculated at the plot level for each species. In this case the stand (expanded point sample) was the sample unit. These errors were then compiled by species to produce a summary (Table 12, Figures 4 - 6).

Mean errors for five year predictions of dbh varied by species and size class (Table 11). In general, TWIGS overestimated dbh growth across species and diameter classes. All white oak and sugar maple size classes were overestimated, while predictions for the other three species varied with size class. When totaled across all size classes, northern red oak, white oak and sugar maple dbh were overestimated and other red oak and red maple dbh were underestimated. Overall, red maple, other red oak, and northern red oak predictions were the best (in descending order) with percent errors under 1% in all cases. These results were similar to Brand and Holdaway's (1986) validation tests on Manistee data, white oak and sugar maple had the largest over-predictions of dbh growth. Prediction intervals for future projections of single trees are given in Table 12.

Mean errors for TPA projections (Table 12) were all within +35 trees per acre. White oak and northern red oak performed best, with errors of +12 trees per acre respectively. The validation of STEMS85 with Manistee data (Holdaway and Brand, 1986) found that both species were over-predicted by at least 20 trees per acre. Overall percent errors were all under 20%. White Oak performed poorest with an over-prediction of 18.6%. Northern red oak had the best results with an underestimation of 3.9 trees per acre.

Errors for mean basal area were all within +5 ft2/acre (Table 11). Other red oak showed the most bias with an underestimation of 4.4 ft2/acre. All other species were within +3 ft2/acre. In terms of percent error, all species had less than 12% in projection bias. Northern red oak had the lowest percent error, 2.2% (underestimation). In Holdaway and Brand's (1986) validation of STEMS85 with Manistee data (10 year growth), northern red oak was shown to be overpredicted by 4.7 ft2/acre; this study found an underprediction of 2.2 ft2/acre over 5 years. Overall, percent errors were relatively high for BA projections in comparison to dbh projections. As noted by Holdaway and Brand (1986), slight overpredictions in dbh growth will lead to overpredictions in BA growth due to the nature of the relationship between the two variables.

Table 11. Calculated Error for Estimated DBH (5 year projections) by Species and Size Class

Species	n[a]	Diameter Class	Mean Error	STD DEV	% Error
N. Red Oak	15	3.0 - 4.9	-0.15	0.10	-3.36
	209	5.0 - 10.9	-0.20	0.92	-1.61
	300	11.0 - 16.9	0.02	0.58	0.01
	109	17.0 +	0.07	0.36	0.28
	633	TOTAL	-0.05	0.83	-0.56
Other Red Oak	11	3.0 - 4.9	0.03	0.02	0.55
	87	5.0 - 10.9	-0.02	0.68	-0.11
	95	11.0 - 16.9	0.07	0.20	0.45
	28	17.0 +	0.12	0.30	0.06
	221	TOTAL	0.04	0.46	0.25
White Oak	23	3.0 - 4.9	-0.17	0.11	-4.14
	196	5.0 - 10.9	-0.26	0.76	-2.46
	95	11.0 - 16.9	-0.08	0.23	-0.64
	7	17.0 +	-0.40	0.25	-2.01
	321	TOTAL	-0.20	0.61	-2.03
Sugar Maple	26	3.0 - 4.9	-0.25	0.88	-2.68
	118	5.0 - 10.9	-0.23	0.27	-3.10
	32	11.0 - 16.9	-0.15	0.26	-1.08
	0	17.0 +	--	--	--
	176	TOTAL	-0.22	0.42	-2.67
Red Maple	42	3.0 - 4.9	-0.03	0.18	-1.04
	60	5.0 - 10.9	0.09	0.46	1.22
	17	11.0 - 16.9	-0.23	0.39	-1.88
	6	17.0 +	0.12	0.32	0.64
	125	TOTAL	0.01	0.38	0.01

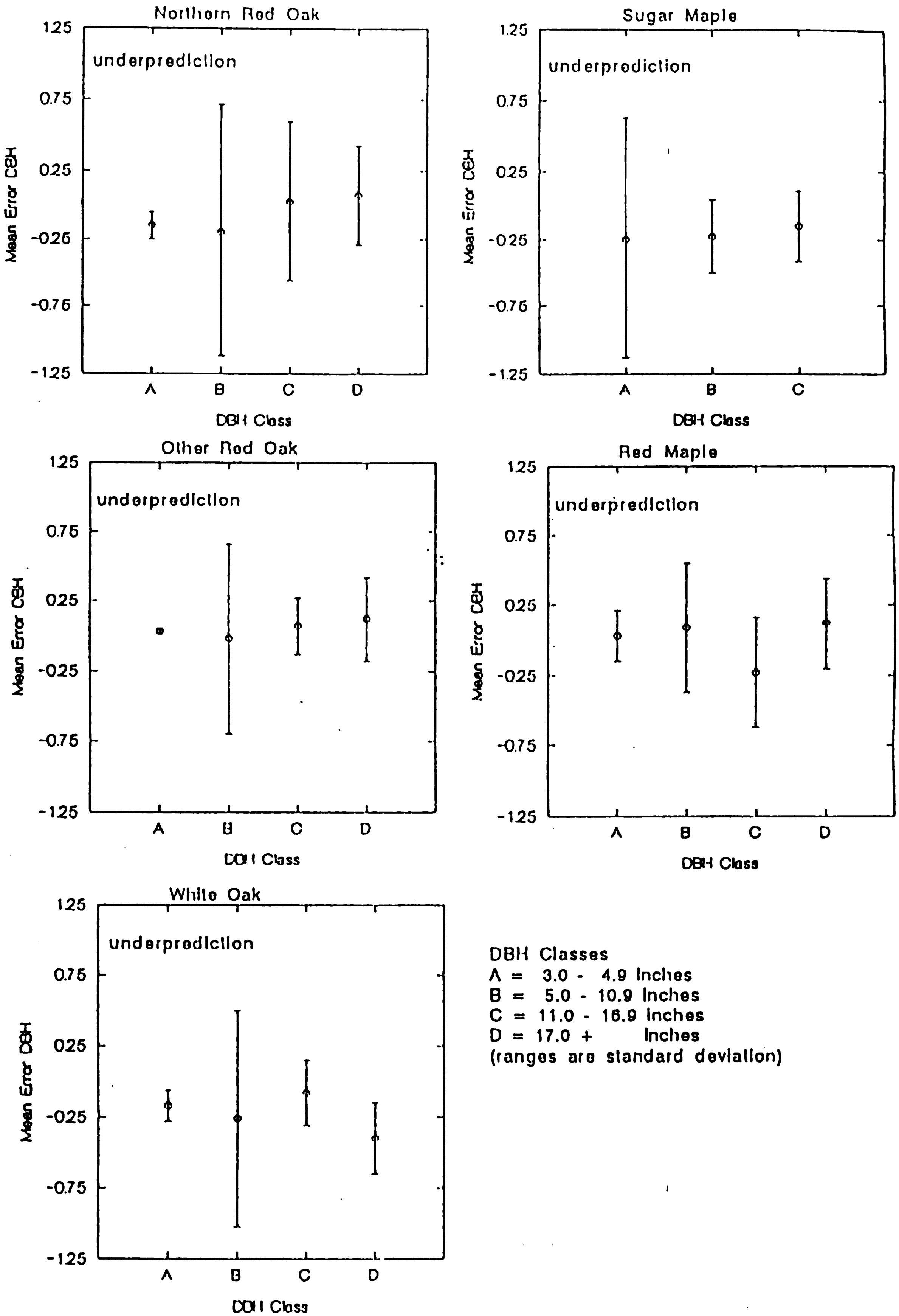
a - number of sample trees

Table 12. Calculated Error for Estimated BA and TPA by Species (5 year projections)

	Basal Area ft2/acre			Trees/Acre			
Species	Mean Error	STD DEV	% Error	Mean Error	STD DEV	% Error	Number Points[a]
N. Red Oak	2.2	7.6	2.2	12	43	3.9	97
Other Red Oak	4.4	5.8	8.6	33	87	14.4	56
White Oak	-2.7	6.0	-11.5	-12	50	-18.6	65
Sugar Maple	-1.0	10.5	-3.0	-16	78	-10.9	38
Red Maple	2.2	5.0	8.4	21	45	7.7	95

a = number of sample points, out of 156, used for error calculations.

Figure 2 . Mean error (inches) by DBH class and species.



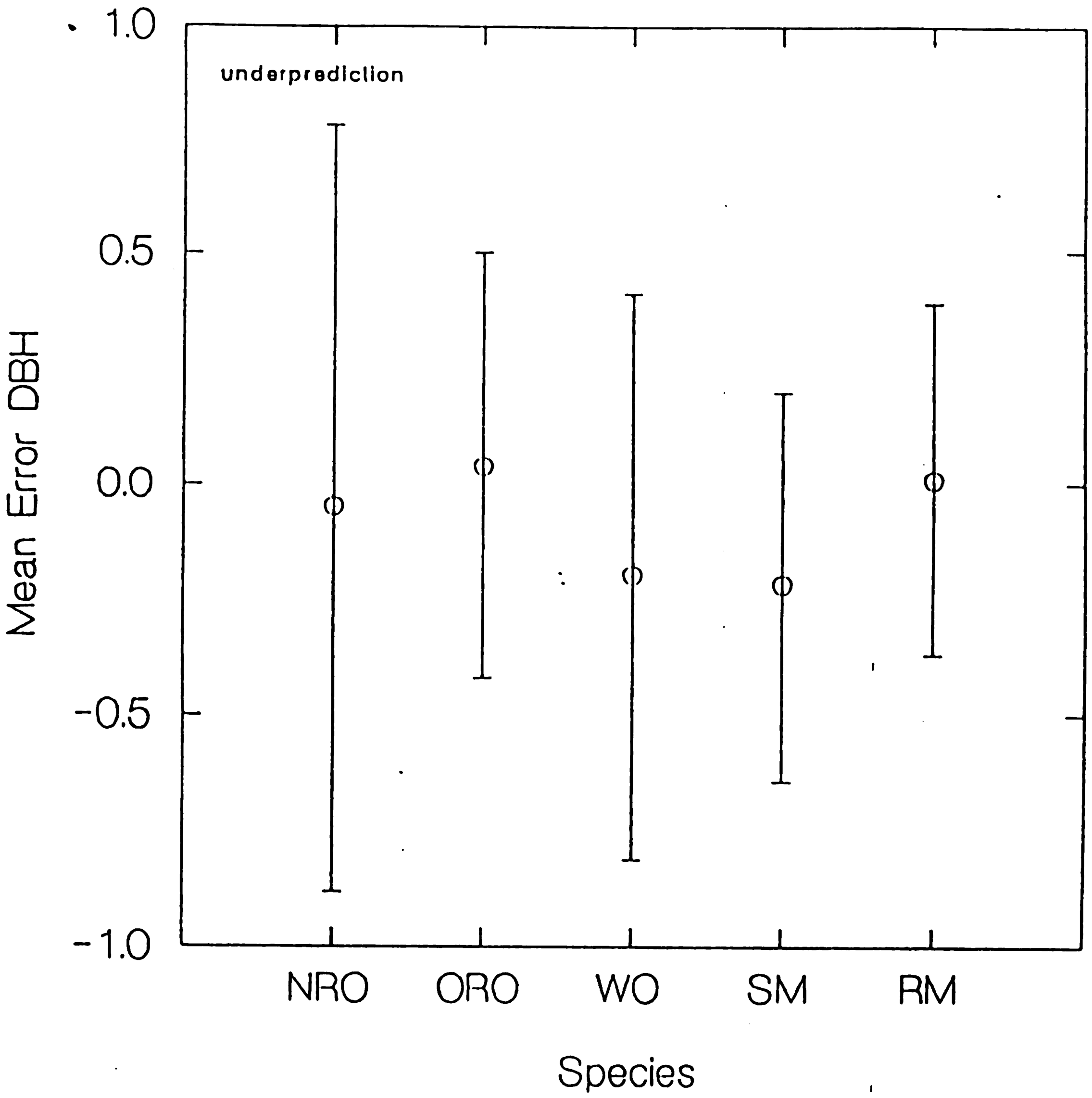


Figure 3. Mean and standard deviation for mean error of predicted DBH over 5 years (positive values are underpredictions)

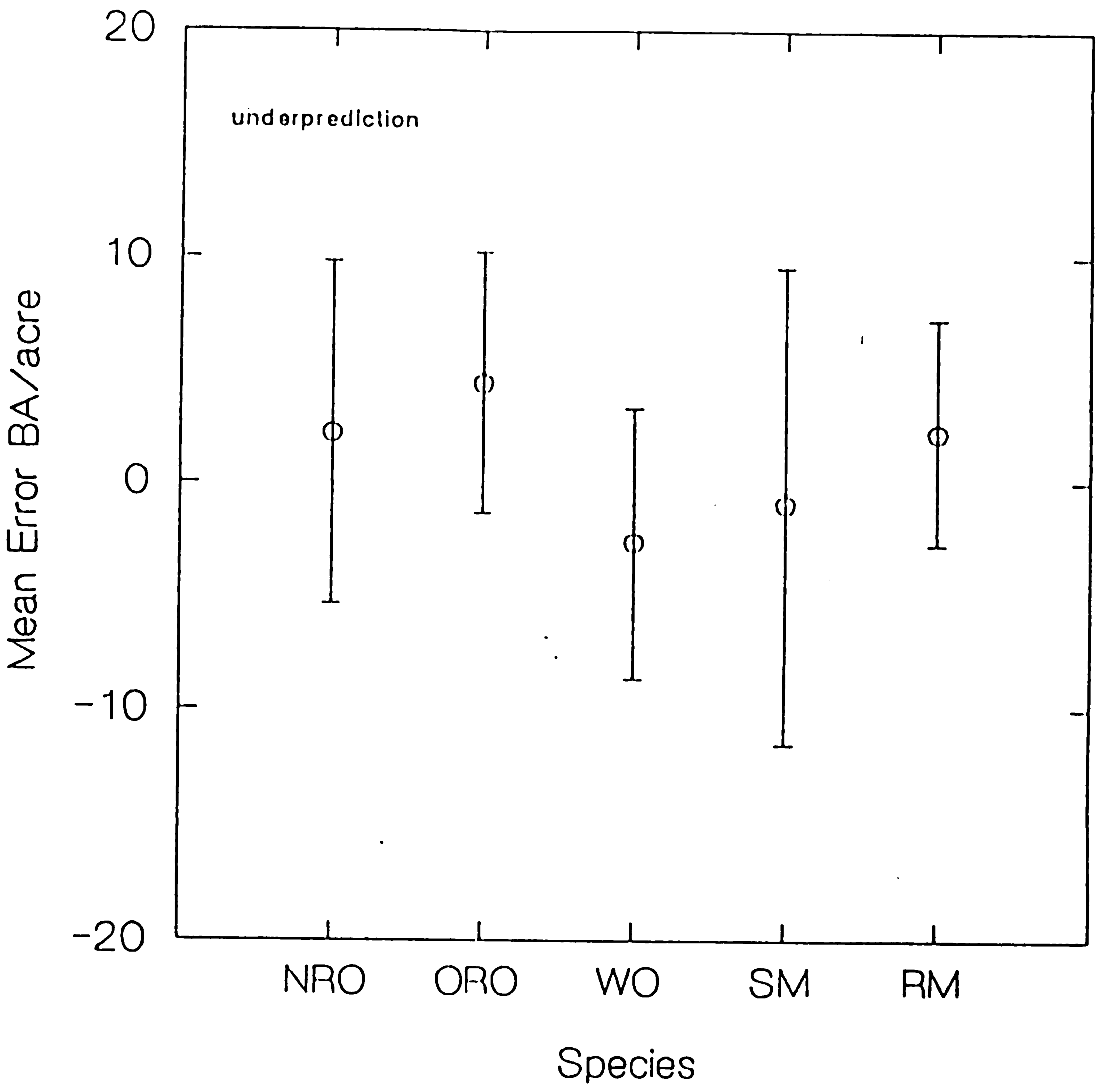


Figure 4. Mean and standard deviation for mean error of predicted BA/acre over 5 years (positive values are underpredictions)

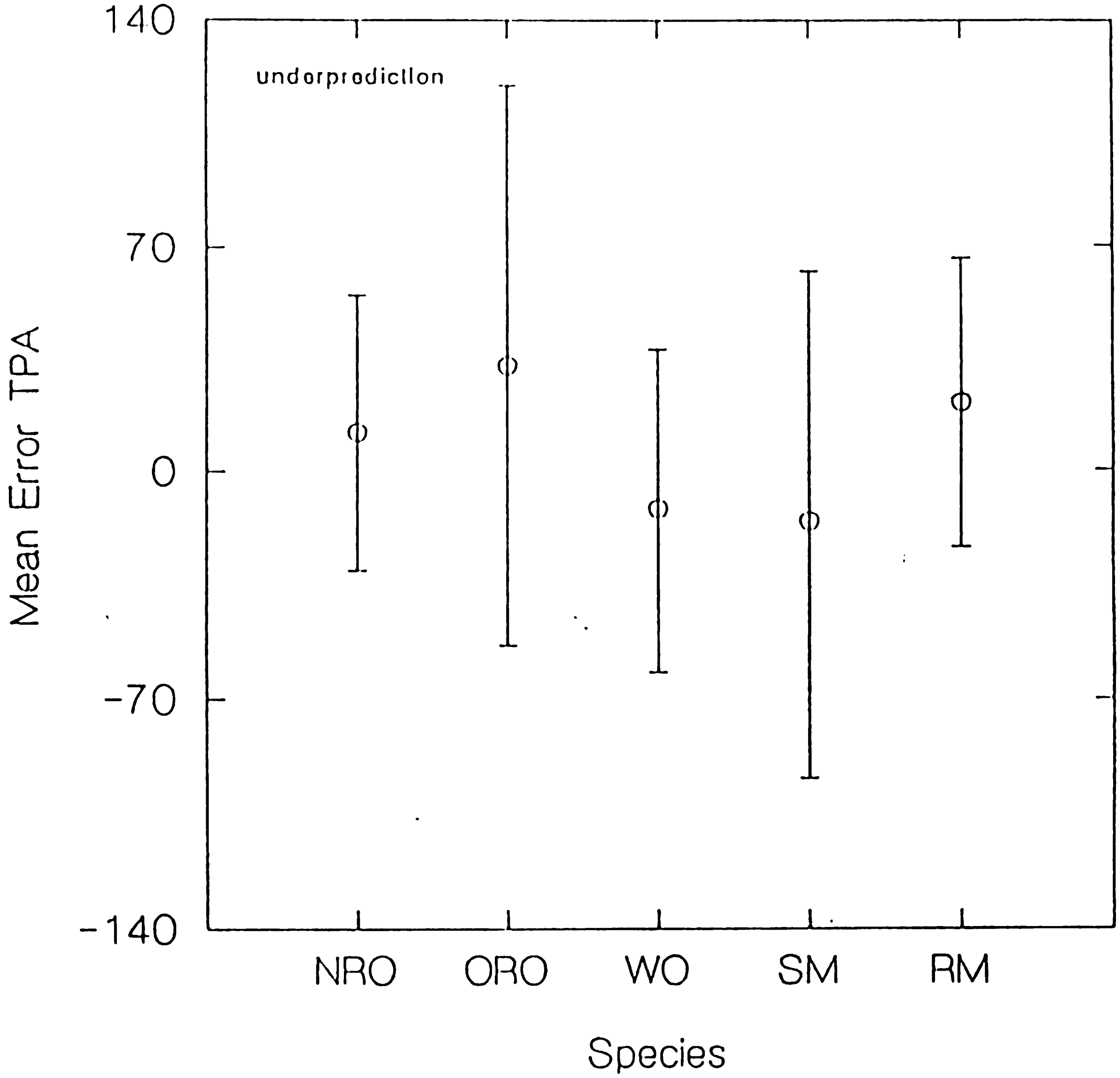


Figure 5. Mean and standard deviation for mean error of predicted TPA over 5 years (positive values are underpredictions)

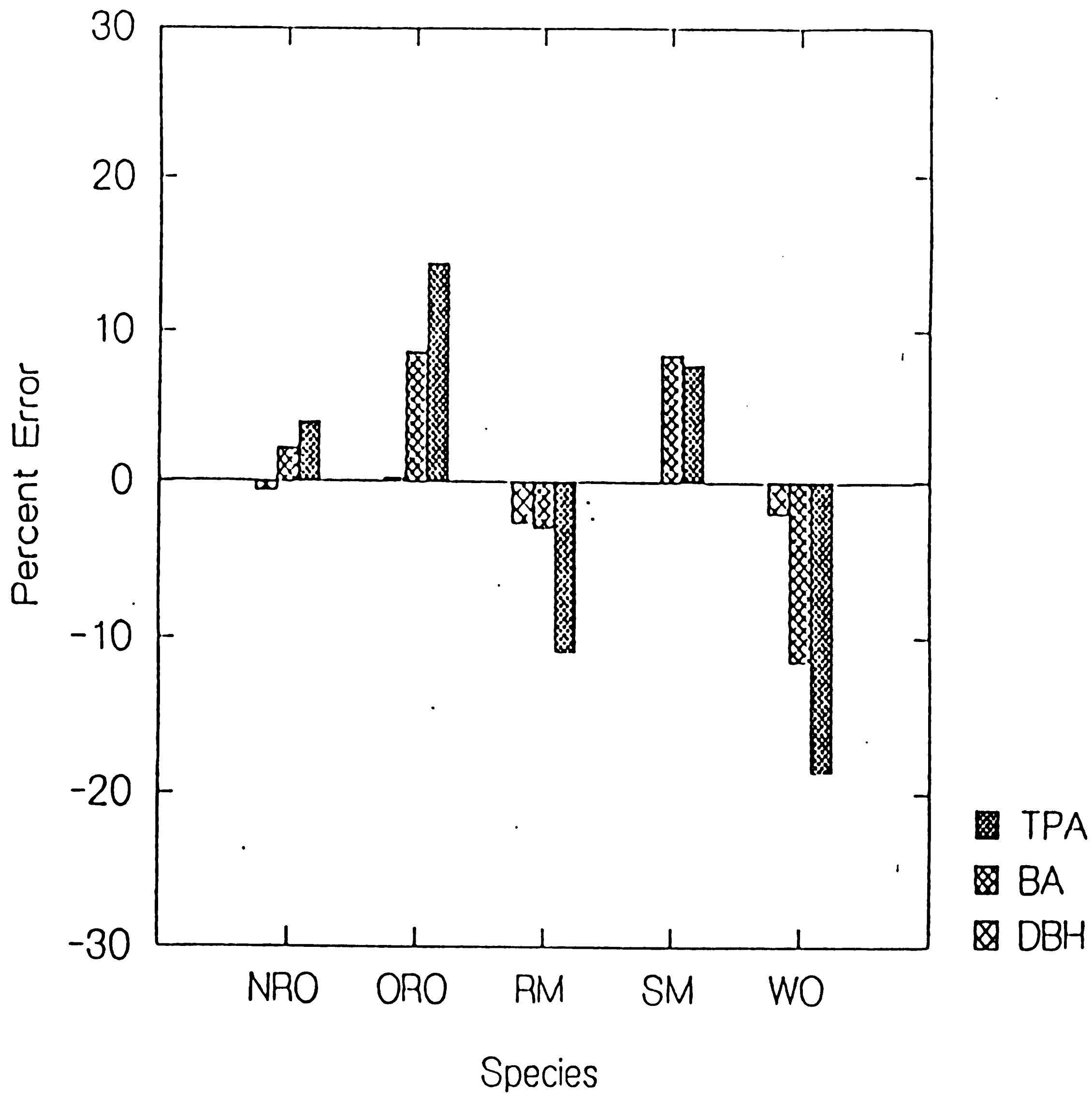


Figure 6. Mean percent errors between observed and predicted values over 5 years (positive values are underpredictions)

ATEST Validation:

Rauscher (1986) developed ATEST, a computer program written in Basic, as a tool to simplify the testing of prediction accuracy. The program determines prediction bias as the difference of prediction minus observed values. Results are presented on both an absolute and percentage basis. In addition, confidence intervals are calculated for future predictions. The methods used for constructing these intervals depend on the distribution of sample errors. If the errors are normally distributed Student's t is used for placing the intervals. If errors are not normally distributed, a trimmed mean and a jackknifed variance is used to determine the intervals.

Rauscher's ATEST requires programming before use and demands a large quantity of user input while running. Gribko and Wiant (in press) have converted Rauscher's program into a template for SAS statistical software, SASATEST. The template requires minimal input from the operator: an ASCII file containing prediction data and information on the level of the desired confidence intervals. It was this version of ATEST that was used in this study.

SASATEST validations were run using the same validation data set used in calculation of the validation statistics. Results of these runs included both percent and absolute bias and standard deviations, as with the previous error statistics. The only note here is that the ATEST results have opposite signs (+/-) in comparison to previous statistics, due to the nature of the calculations. In addition, prediction intervals were calculated on future samples of size one, to allow for some idea of how accurate a projection of a single stand or tree would be. Although most of the work of SASATEST duplicates previous efforts, the value of the future prediction intervals warranted its use.

Results of dbh comparisons are presented in Table 13, TPA comparisons are in Table 14, and Table 15 provides BA results. Prediction interval values are interpreted as a 95% probability that a mean of one future error will fall within the interval presented (Gribko and Wiant (in press)). The level of the interval was set at 95% because of the relatively large range of the intervals. Another important note is that data with error distributions judged non-normal (indicated with "*" in the tables) may have some discrepancies in sample size. This is due to the jackknife procedures.

Table 13. SASATEST Calculated Errors for DBH

SPECIES	DBH CLASS	ERROR	n	BIAS	CONFIDENCE INTERVAL (BIAS +/-)	PREDICTION INTERVAL (BIAS +/-)	STD DEV
N. Red Oak	3.0 - 4.9	ABS	15	.15	.06	.22	.10*
		PCT	15	3.38	1.31	5.22	2.36*
	5.0 - 10.9	ABS	209	.20	.13	1.82	.92
		PCT	207	1.61	.96	13.83	7.00
	11.0 - 16.9	ABS	300	-.01	.07	1.14	.58
		PCT	300	-.00	.50	8.69	4.41
	17.0 +	ABS	327	-.07	.04	.71	.36
		PCT	327	-.28	.18	3.31	1.68
	Total	ABS	633	.05	.05	1.35	.69
		PCT	631	.56	.40	10.15	5.16
O. Red Oak	5.0 - 10.9	ABS	87	.02	.15	1.37	.68
		PCT	87	.11	1.48	13.91	6.96
	11.0 - 16.9	ABS	95	.07	.04	.39	.19
		PCT	95	.47	.28	2.77	1.39
	17.0 +	ABS	28	-.12	.12	.62	.30*
		PCT	28	-.58	.60	3.21	1.54*
	Total	ABS	220	-.04	.06	.91	.46
		PCT	220	-.25	.60	8.93	4.52
White Oak	3.0 - 4.9	ABS	23	.17	.05	.23	.11
		PCT	23	4.27	1.22	5.96	2.81*
	5.0 - 10.9	ABS	196	.26	.11	1.49	.76
		PCT	194	2.46	.37	5.11	2.58
	11.0 - 16.9	ABS	95	.09	.05	.45	.23
		PCT	95	.64	.34	3.33	1.67
	Total	ABS	321	.21	.07	1.20	.61
		PCT	319	2.03	.28	5.01	2.54
Sugar Maple	3.0 - 4.9	ABS	26	.25	.36	1.84	.88
		PCT	25	2.68	3.68	18.74	8.90
	5.0 - 10.9	ABS	118	.23	.05	.54	.27
		PCT	118	3.10	.72	7.81	3.93
	11.0 - 16.9	ABS	32	.15	.09	.53	.26
		PCT	32	1.01	.67	3.84	1.85*
	Total	ABS	176	.22	.06	.82	.42
		PCT	175	2.67	.71	9.39	4.74
Red Maple	3.0 - 4.9	ABS	42	.03	.06	.37	.18*
		PCT	42	.86	1.42	9.29	4.55*
	5.0 - 10.9	ABS	60	-.09	.12	.92	.46
		PCT	60	-1.21	1.72	13.43	6.65
	11.0 - 16.9	ABS	17	.23	.20	.86	.39
		PCT	17	1.88	1.62	6.88	3.15
	Total	ABS	125	-.01	.07	.76	.38
		PCT	125	-.01	.98	11.03	5.55

* = non-normally distributed errors

Table 14. SASATEST Calculated Errors for Estimated TPA

SPECIES	ERROR	n	BIAS	CONFIDENCE INTERVAL (BIAS +/-)	PREDICTION INTERVAL (BIAS +/-)	STD DEV
N. Red Oak	ABS	96	-11.51	8.71	86.20	43.19
	PCT	96	-3.90	3.47	34.30	17.20
O. Red Oak	ABS	56	-33.16	21.57	175.22	87.02
	PCT	56	-14.44	8.67	70.41	34.97
White Oak	ABS	95	11.99	10.26	100.57	50.38
	PCT	94	18.77	13.61	132.64	66.43
Sugar Maple	ABS	38	15.59	26.04	160.55	78.10
	PCT	38	10.94	16.94	104.43	50.80
Red Maple	ABS	65	-21.11	11.15	90.56	44.98
	PCT	65	-7.74	2.48	20.17	10.02

Table 15. SASATEST Calculated Errors for Estimated BA

SPECIES	ERROR	n	BIAS	CONFIDENCE INTERVAL (BIAS +/-)	PREDICTION INTERVAL (BIAS +/-)	STD DEV
N. Red Oak	ABS	97	-2.17	1.53	15.12	7.58
	PCT	97	-2.22	2.57	25.42	13.74
O. Red Oak	ABS	56	-4.35	1.45	11.77	5.85
	PCT	56	-8.64	3.15	25.67	12.90
White Oak	ABS	95	2.73	1.22	11.95	5.99
	PCT	94	11.59	5.71	55.68	27.89
Sugar Maple	ABS	37	1.01	3.56	21.67	10.52
	PCT	37	3.05	6.35	35.58	18.77
Red Maple	ABS	65	-2.15	1.24	10.07	5.00
	PCT	65	-8.45	5.68	46.15	22.92

Discussion:

Modelling:

The failures and shortcomings of each model are discussed in the methods section following the model in question. The only model which merits extended discussion is Hilt's.

Rejection of Hilt's model as a candidate for an alternative diameter growth model was based on the small sample sizes of data possible for calibration, the large number of models needed to represent all species/site conditions, and the lack of sufficient data to calibrate the second stage model. In respect to variation explained in the dependent variable, a majority of the R^2s ranged between .6 and .8. In addition, all independent variables were significant at a .10 level. These results were the most promising of all methods examined.

Although Hilt's two stage model format was rejected, it provided important insights on how a simple model form can account for a large portion of variation in diameter (or basal area) growth. Hilt (1983) reported coefficients of determination in excess of 0.7 for stand data fitted to the BAG5YR equation. These stands were composed mainly of white oak, chestnut oak, black oak, scarlet oak, and northern red oak; and in all cases growth patterns between species over-lapped. In this study the first stage model was fitted with white oak and northern red oak data. This produced results that mirrored those of Hilt's. The major difference between the data sets used was that Hilt's tree data was grouped by stand, while data for this study was grouped in sets with common ELTPs, stand basal areas, and species. The grouping of trees under similar natural conditions in essence form artificial stands similar to Hilt's stand data sets. With density and site quality conditions at a near constant within these "stands", a large portion of diameter growth can be explained by tree dbh.

The second stage model, which provides a means of calibrating the first stage model for any general stand, was not fitted in this study. Given the assumption that stands representative of all conditions can be compiled, this equation may not be needed. The limiting factor of this assumption is the extreme amount of data needed. Another approach that could be used, which would negate the second equation, is similar to that which Mawson (1982) describes. Mawson presents a simple diameter growth equation which relies only on dbh as an independent variable. This equation is fitted to stands with either increment core data or extended growth record data.

Mawson's model:

$$\ln DG = \ln a + b(1/dbh)$$

Where: DG = periodic diameter increment (inches)

dbh = diameter at breast height (inches)

a and b = unique coefficients

Validation:

As with the initial validation, dbh results were judged acceptable. Of the nineteen species-size class combinations evaluated only five exceeded a mean error of 0.20 inches, while percent errors were under 3% in all but three cases. Again, the highest errors in terms of percent resulted in stand basal area and trees per acre projections. This would make the Lakes States mortality equation suspect. It is therefore suggested that future research be focused on developing an alternative survival model. Possibilities for such a model include the function used in Central States TWIGS (Miner et. al., 1988) and several functions developed by Monserud (1976) and Buchman (1979). These alternatives utilize several methods of development including discriminant analysis, probit analysis, and logit analysis.

Future Considerations:

If the current research plots are to be used for future evaluations of TWIGS' diameter growth or mortality functions, several considerations should be made in regards to sample size, environmental conditions, and plot design.

It was apparent in this study that sample size was insufficient to produce both a validation and calibration data set. In the future there is a possibility that the database will further decrease in size due to human disturbance and gypsy moth. Between 1986 and 1991 one stand and several plots were lost due to change in forest boundaries and human disturbance. These and similar phenomenons are sure to claim more trees in the future. Additionally, the Manistee National Forest is beginning to experience wide-scale gypsy moth infestations. Past experiences on the Huron National Forest and adjoining state forests have shown that until the gypsy moth population establishes itself (which takes roughly twenty years), varying degrees of annual defoliation can be expected (Sapio, 1992 personal communications). This repeated stress on the trees will probably increase mortality (Nichols, 1968) and decrease the data base size. If continued study is to be done in this area a possible alternative to this data base is the USDA Forest Service continuous forest inventory data.

In addition to reducing sample size, gypsy moth and other similar natural disturbances may effect individual tree growth and mortality. The Manistee National Forest experienced forest tent caterpillar (Malacosoma disstria) outbreaks and drought in the mid-1980's, is currently having Lindon looper problems throughout the forest, and will continue to experience large scale gypsy moth defoliation throughout the 1990's. Defoliation and drought stress trees, resulting in the introduction of secondary pathogens, decreased radial growth, and increased mortality (Sapio, 1992 personal communications; Nichols, 1968). Lake States TWIGS' models were calibrated with data that was collected over periods of thirty years or more (Christensen et. al., 1979).

In this period of time, calibration stands were most likely to have experienced some degree of insect and drought problems, but probably not to the degree that now exists on the Manistee National Forest. This raises the question of how such disturbance affected data used in this study, if relationships between dependant and independent variables were affected; and if so could this explain poor modeling results, and if similar validation results can be expected in the future under different environmental conditions. Additionally, gypsy moth defoliation and its affects can be expected to influence future measurements and the results of future examinations of the Lake Sates TWIGS' growth model and mortality function.

A final concern is the design of research plots used in this study, especially in regards to the use of variable radius plots. Concern has already been expressed as to the ability of stand basal area calculated with the aid of a prism to represent the conditions under which individual trees are growing. In addition, Zeide (1992) has raised question to the appropriateness of using point sampling in research oriented inventories. Because of the reliance on human vision and the lack of precision inherent in point sampling, he has expressed concern that the accuracy of estimating stand basal area may be substantially less than expected. If the current research plots are to be used in the future, it is suggested they be converted to fixed radius plots.

In summary, results of this study are limited by time (5 years), sample size, and the environmental conditions which existed during the period of measurements. These factors may have biased both model development and validation results. If future research is to follow, it would be advised to explore the possibility of using an alternate data source, examine the Lake States TWIGS' mortality function in addition to the diameter growth function, and explore the accuracy of variable radius plots in comparison to fixed radius plots.

APPENDICES

APPENDIX A

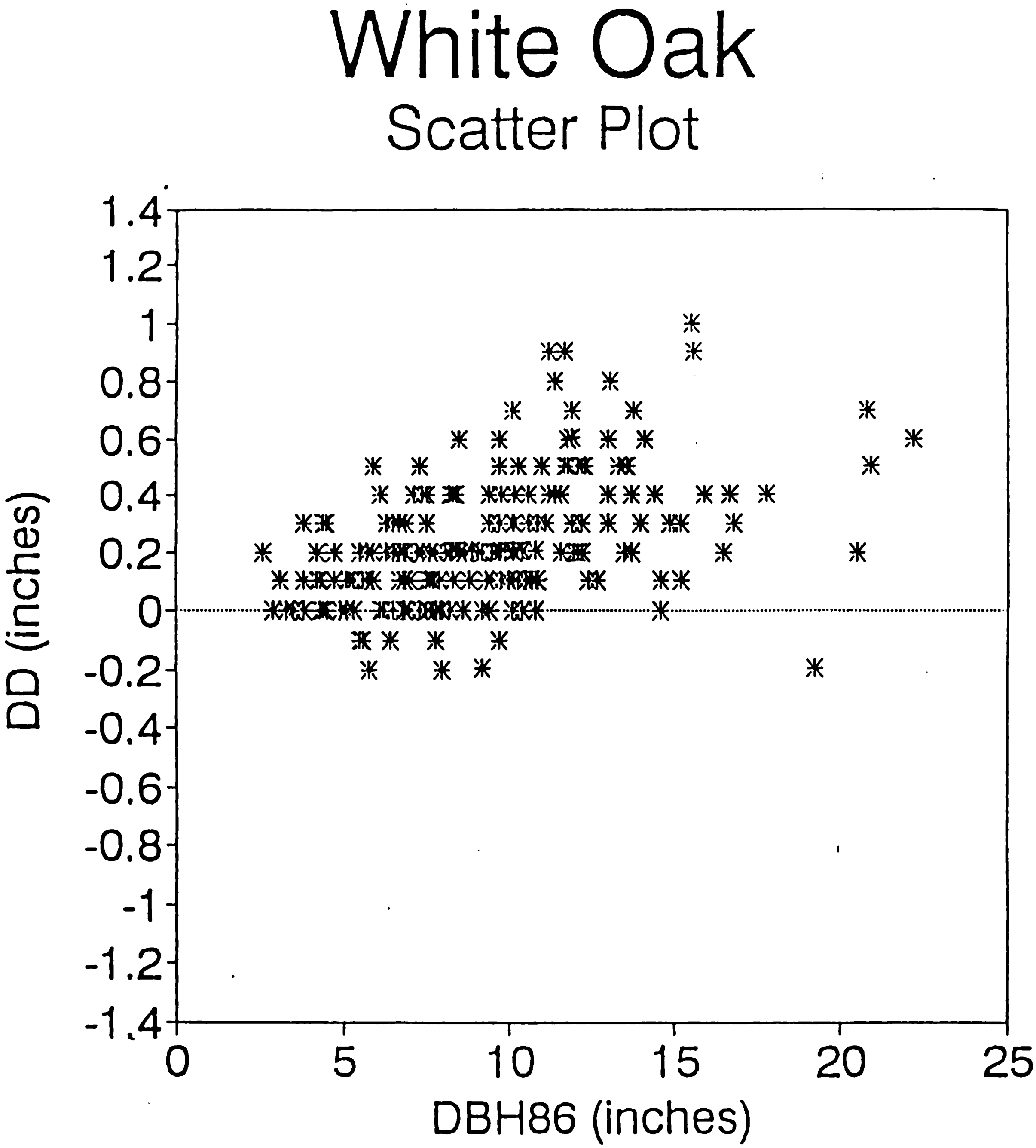


Figure 7. Five year change in DBH vs. 1986 DBH

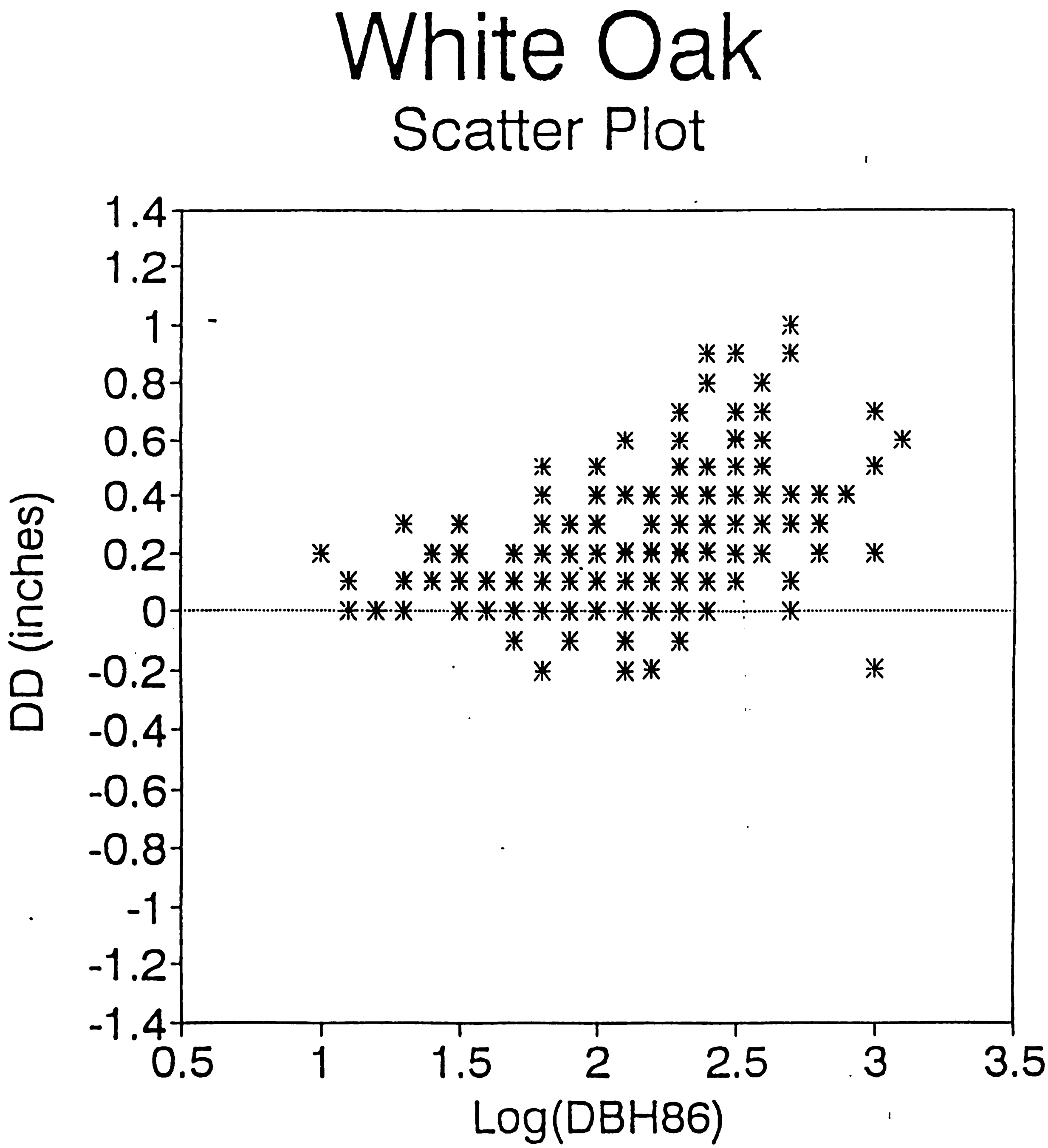


Figure 8. Five year change in DBH vs. log(DBH)

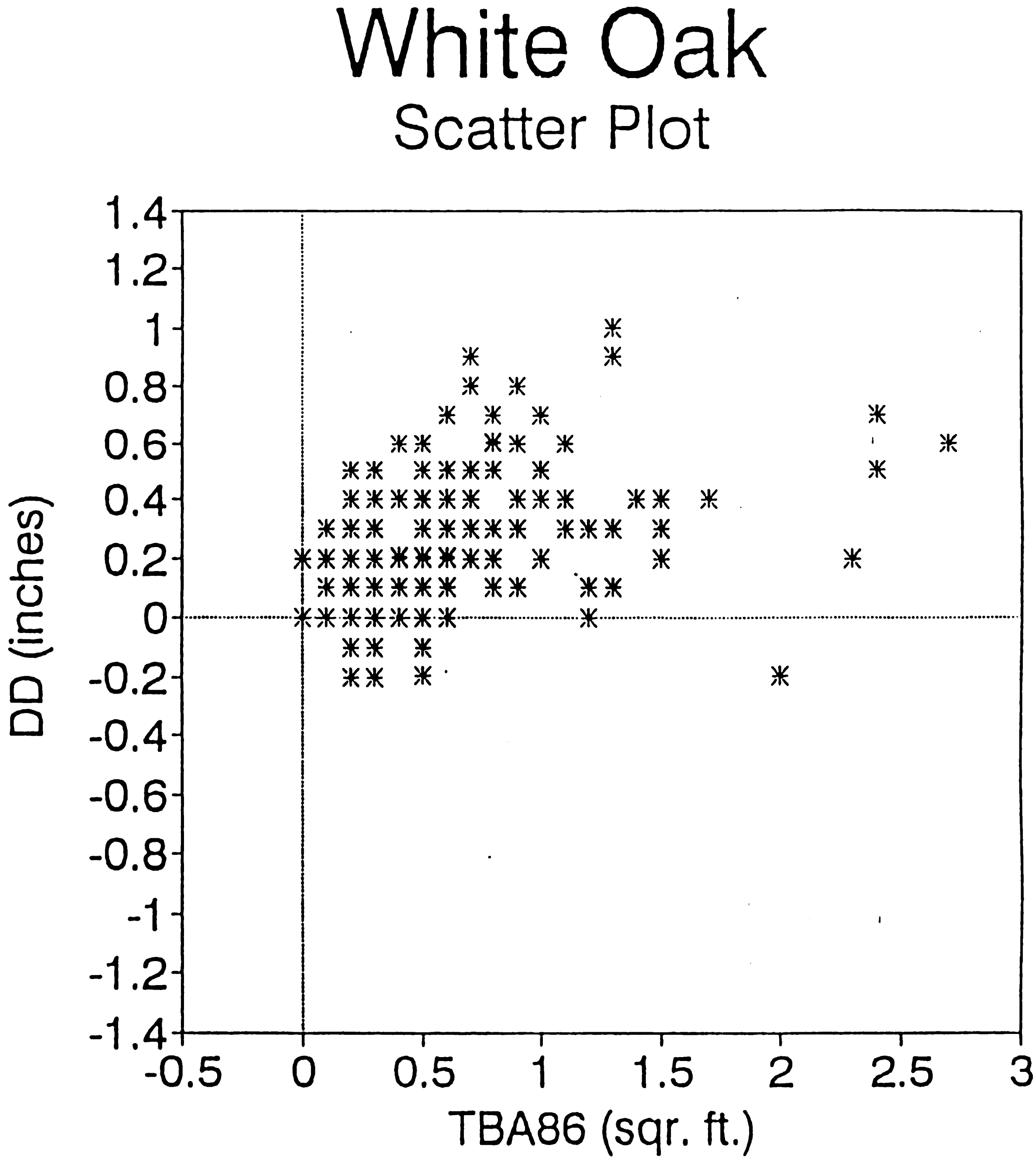


Figure 9. 5 year change in growth vs. 1986 tree basal area

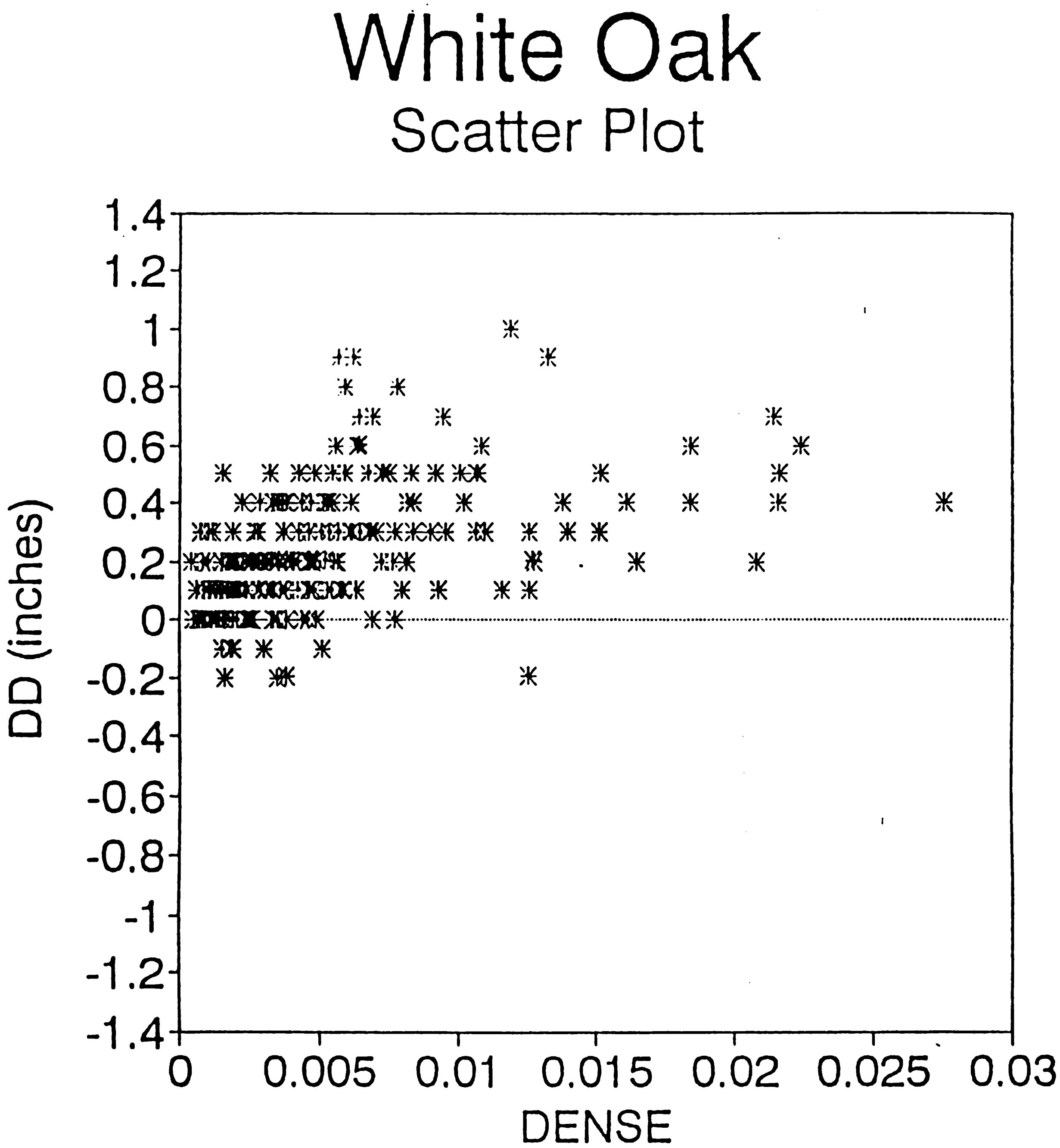


Figure 10. Five year change in DBH vs. DENSE

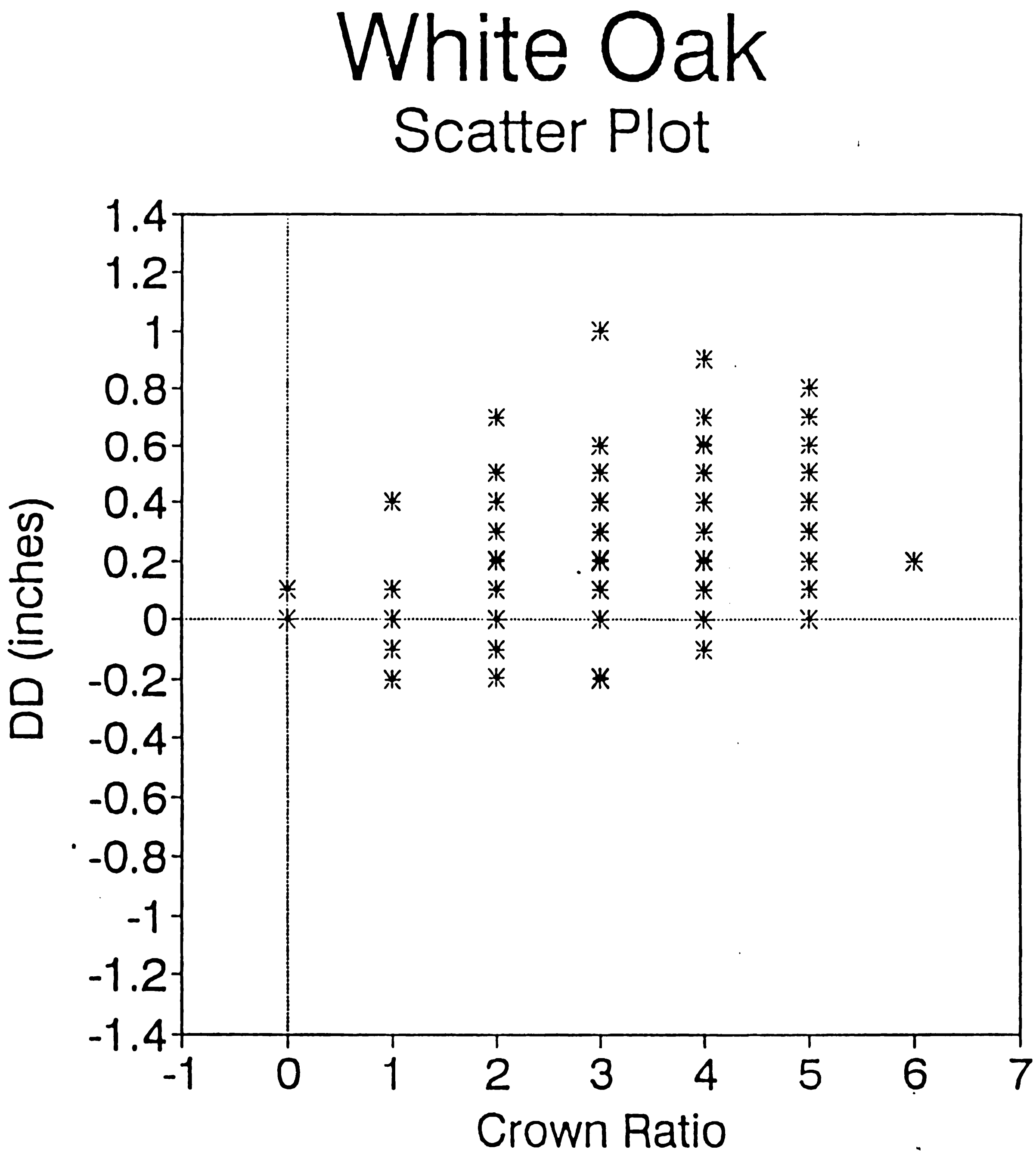


Figure 11. Five year change in DBH vs. crown ratio

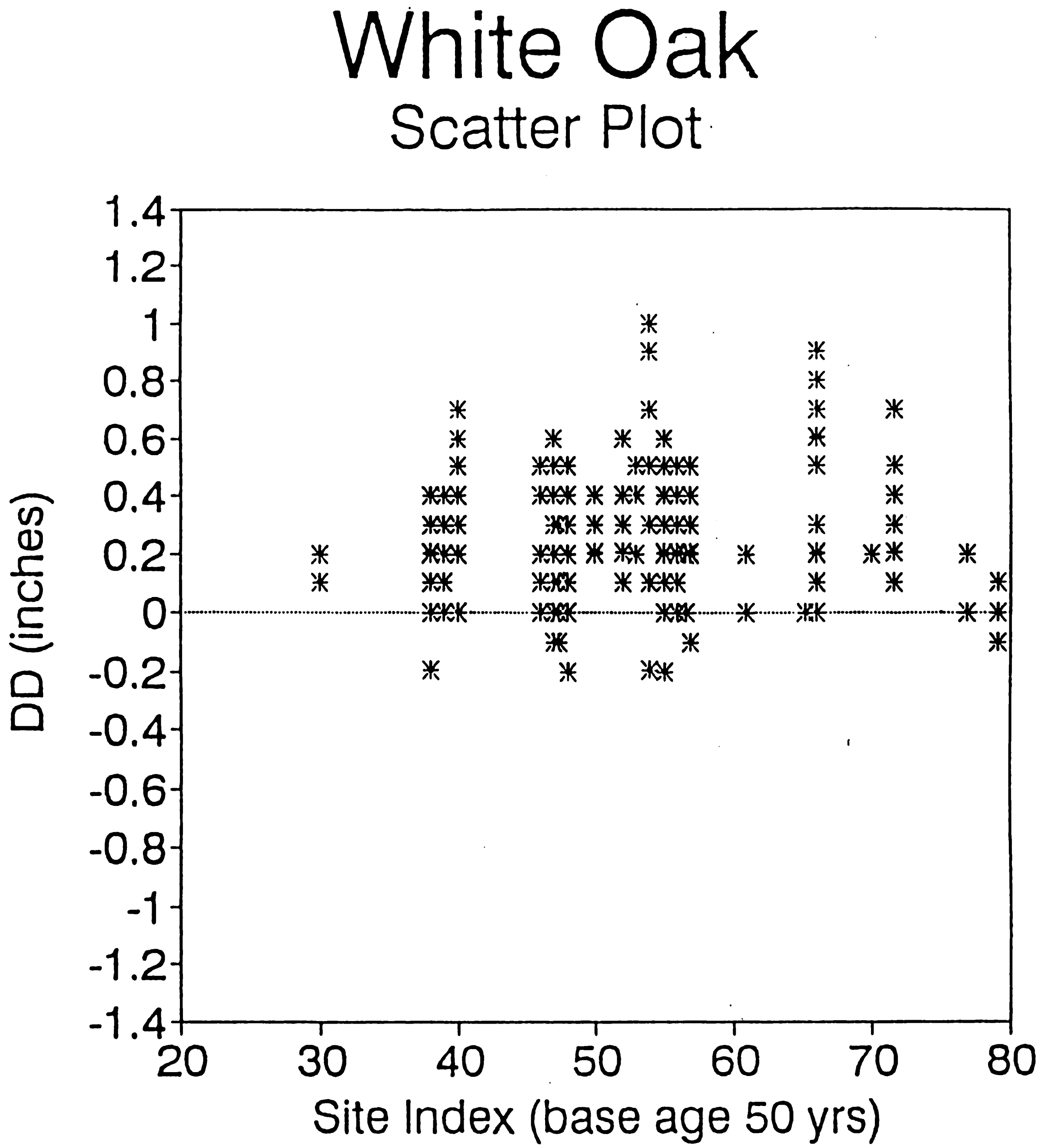


Figure 12. Five year change in DBH vs. site index

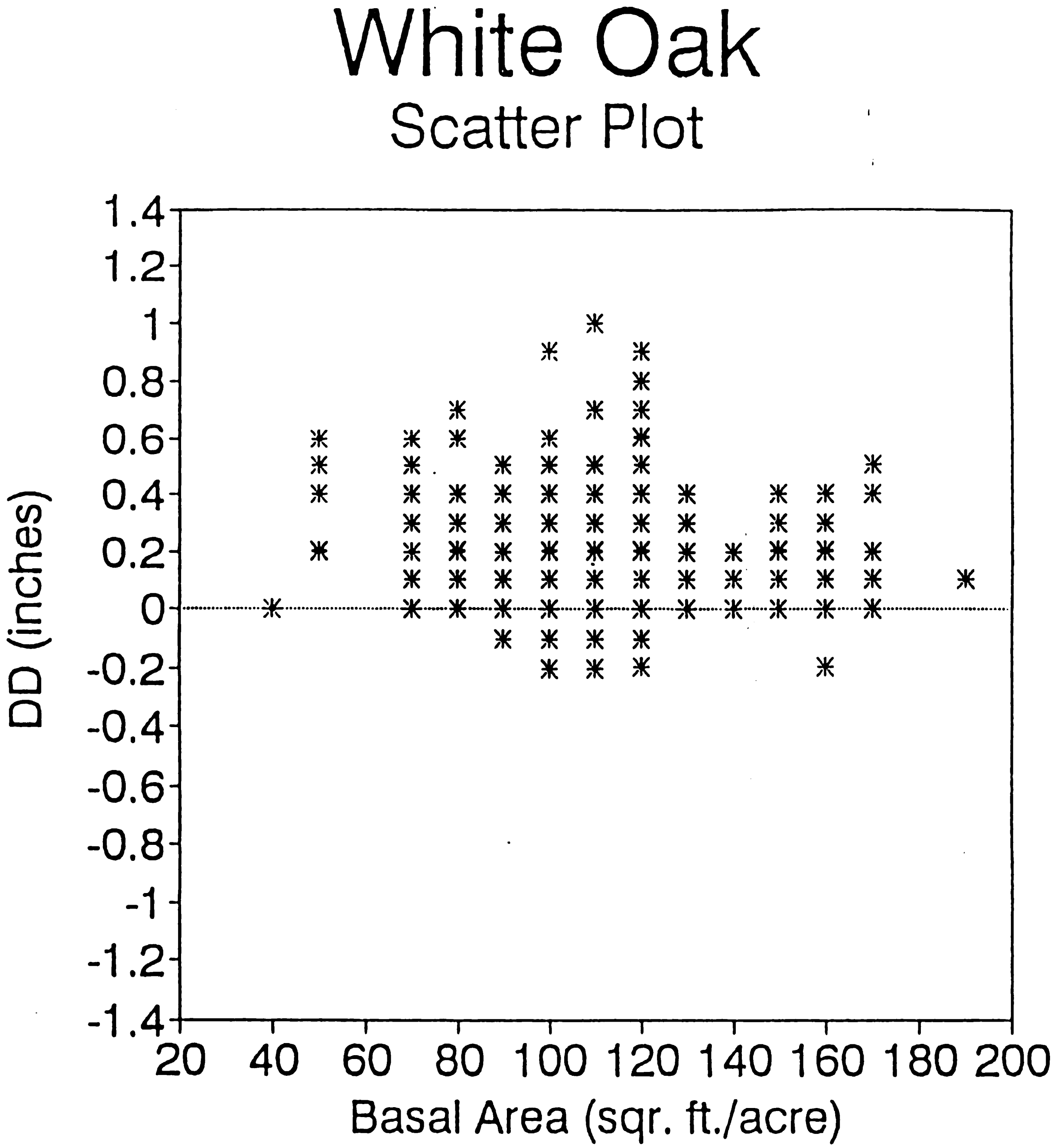


Figure 13. Five year change in DBH vs. BA

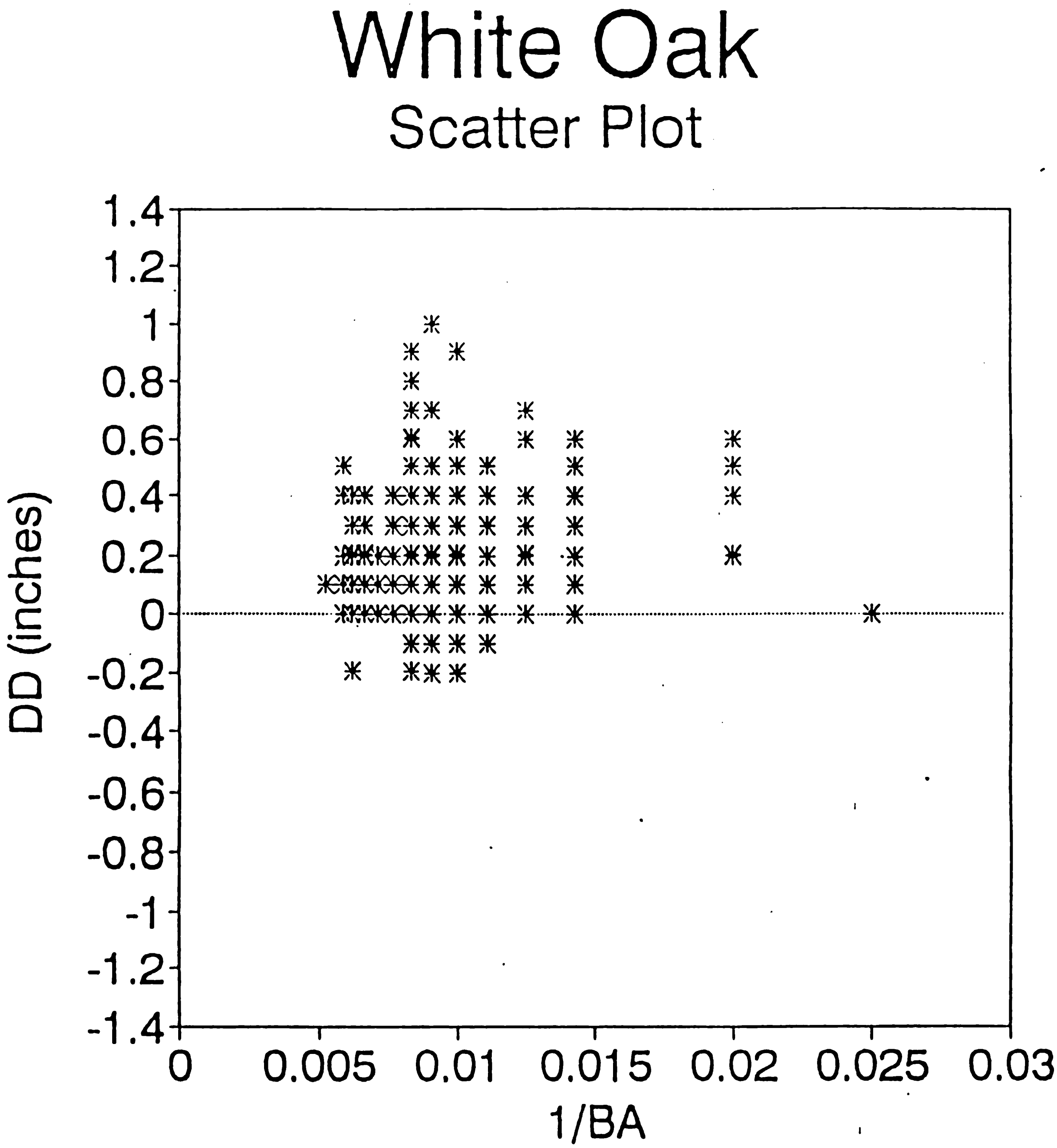


Figure 14. Five year change in DBH vs. 1/BA

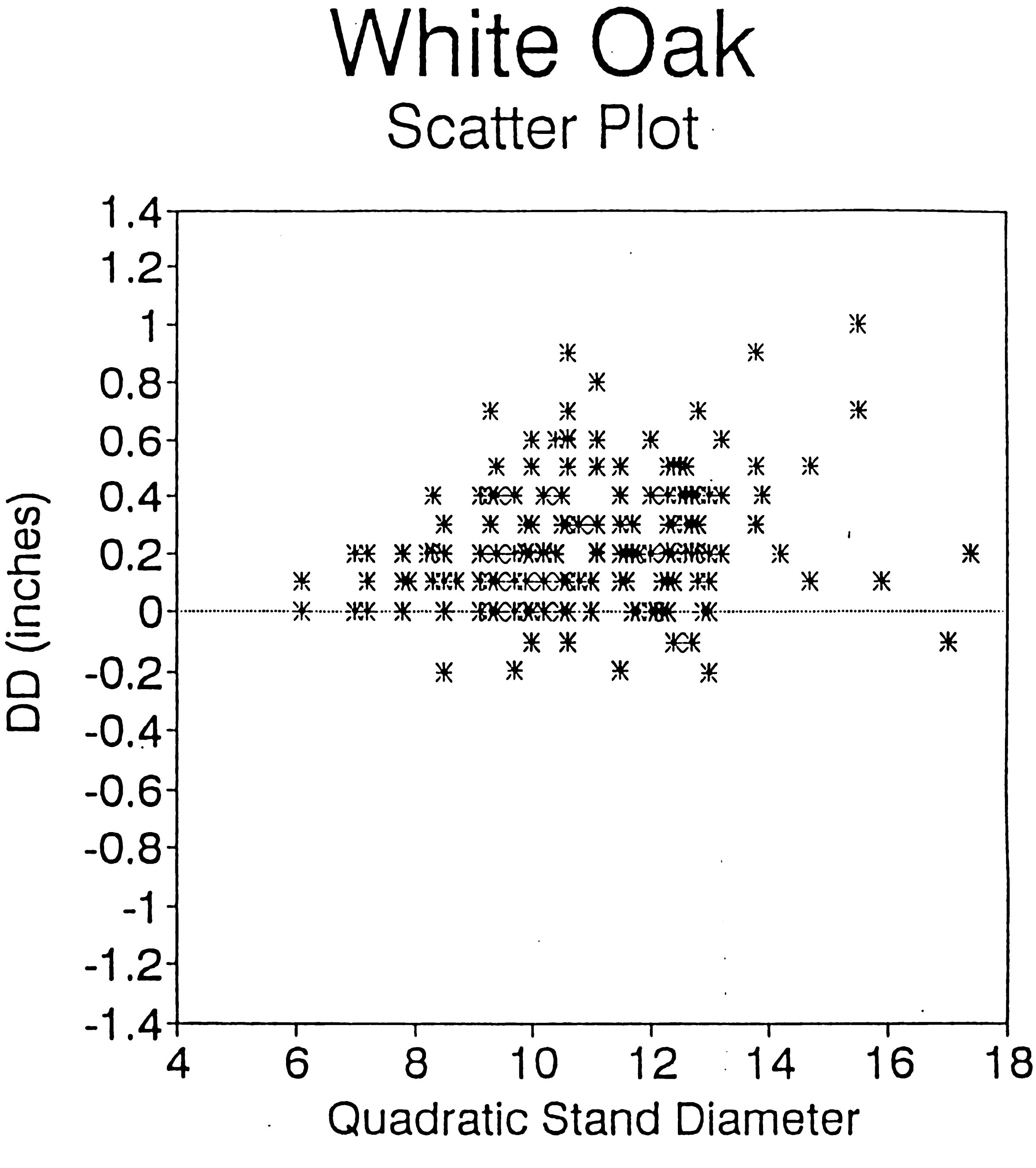


Figure 15. Five year change in DBH vs. QSD

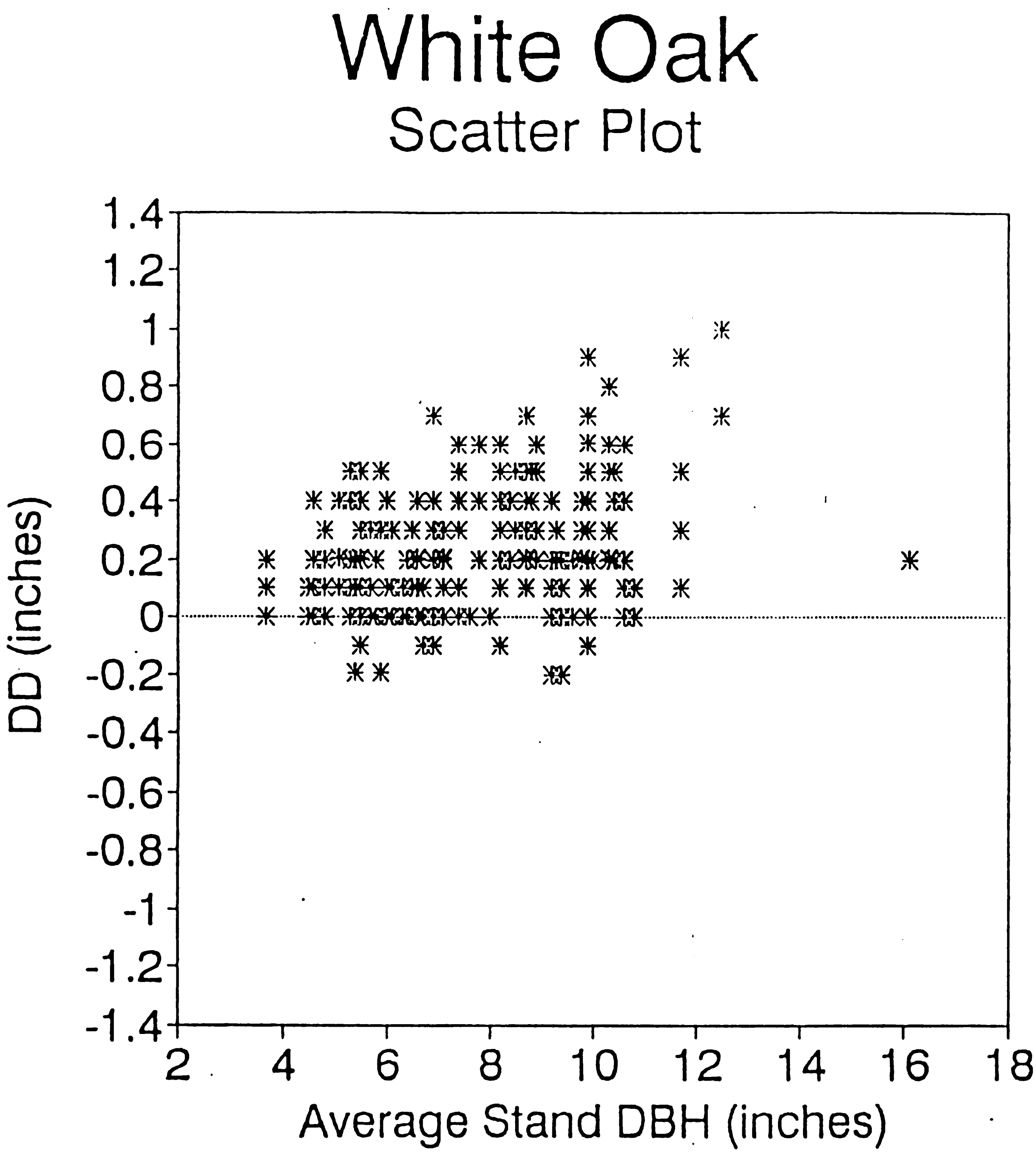


Figure 16. Five year change in DBH vs. ASD

APPENDIX B

Table 16. Northern Red Oak Multivariate Model ANOVA.

N.RED OAK

DEP VAR: DD N: 457 MULTIPLE R: 0.722 SQUARED MULTIPLE R: 0.521
ADJUSTED SQUARED MULTIPLE R: .507 STANDARD ERROR OF ESTIMATE: 0.224

VARIABLE	COEFFICIENT	STD ERROR	T P(2 TAIL)
CONSTANT	-0.292	0.158	0.064
LNDBH	0.352	0.064	0.000
INVBA	-14.252	6.652	0.033
DENSE	16.122	3.977	0.000
CR	0.000	0.003	0.966
E10	0.275	0.615	0.656
E12	0.026	0.105	0.803
E20	-0.072	0.076	0.342
E21	-0.129	0.081	0.114
E35	-0.047	0.068	0.492
E37	0.067	0.072	0.352
E40	-0.068	0.073	0.347
E43	-0.044	0.079	0.582
E45	-0.023	0.124	0.854

ANALYSIS OF VARIANCE

SOURCE	SUM-OF-SQUARES	DF	MEAN-SQUARE	F-RATIO	P
REGRESSION	24.268	13	1.867	37.081	0.000
RESIDUAL	22.302	443	0.050		

Table 17. Other Red Oak Multivariate Model ANOVA.

O. RED OAK

DEP VAR: DD N: 176 MULTIPLE R: 0.497 SQUARED MULTIPLE R: 0.247
ADJUSTED SQUARED MULTIPLE R: .201 STANDARD ERROR OF ESTIMATE: 0.211

VARIABLE	COEFFICIENT	STD ERROR	T P(2 TAIL)
CONSTANT	-0.383	0.267	0.153
LNDBH	0.284	0.089	0.002
INVBA	0.383	7.787	0.961
DENSE	1.570	4.654	0.736
CR	0.015	0.019	0.415
E1	0.101	0.129	0.433
E10	0.069	0.136	0.609
E12	0.103	0.129	0.425
E20	0.031	0.127	0.808
E21	0.104	0.139	0.454
E35	-0.062	0.173	0.722

ANALYSIS OF VARIANCE

SOURCE	SUM-OF-SQUARES	DF	MEAN-SQUARE	F-RATIO	P
REGRESSION	2.404	10	0.240	5.401	0.000
RESIDUAL	7.343	165	0.045		

Table 18. White Oak Multivariate Model ANOVA.

WHITE OAK

DEP VAR: DD N: 258 MULTIPLE R: 0.702 SQUARED MULTIPLE R: 0.493
ADJUSTED SQUARED MULTIPLE R: .470 STANDARD ERROR OF ESTIMATE: 0.158

VARIABLE	COEFFICIENT	STD ERROR	T P(2 TAIL)
CONSTANT	-0.258	0.128	0.045
LNDBH	0.164	0.055	0.003
INVBA	1.749	4.883	0.721
DENSE	8.128	4.863	0.096
CR	0.041	0.011	0.000
E1	0.347	0.267	0.196
E10	-0.088	0.043	0.041
E12	-0.039	0.047	0.401
E20	-0.098	0.043	0.025
E21	-0.031	0.049	0.527
E35	-0.223	0.049	0.000
E37	0.112	0.049	0.024

ANALYSIS OF VARIANCE

SOURCE	SUM-OF-SQUARES	DF	MEAN-SQUARE	F-RATIO	P
REGRESSION	5.958	11	0.542	21.709	0.000
RESIDUAL	6.138	246	0.025		

Table 19. Sugar Maple Maltivariate Model ANOVA.

SUGAR MAPLE

DEP VAR: DD N: 157 MULTIPLE R: 0.480 SQUARED MULTIPLE R: 0.230
ADJUSTED SQUARED MULTIPLE R: .194 STANDARD ERROR OF ESTIMATE: 0.240

VARIABLE	COEFFICIENT	STD ERROR	T P(2 TAIL)
CONSTANT	-0.274	0.244	0.264
LNDBH	0.352	0.093	0.000
INVBA	23.559	12.302	0.057
DENSE	-22.840	15.257	0.137
CR	-0.042	0.018	0.022
E35	-0.220	0.283	0.437
E40	-0.112	0.059	0.060
E45	-0.089	0.056	0.117

ANALYSIS OF VARIANCE

SOURCE	SUM-OF-SQUARES	DF	MEAN-SQUARE	F-RATIO	P
REGRESSION	2.561	7	0.366	6.367	0.000
RESIDUAL	8.562	149	0.057		

Table 20. Red Maple Multivariate Model ANOVA

RED MAPLE

DEP VAR: DD N: 89 MULTIPLE R: 0.690 SQUARED MULTIPLE R: 0.476
ADJUSTED SQUARED MULTIPLE R: .393 STANDARD ERROR OF ESTIMATE: 0.201

VARIABLE	COEFFICIENT	STD ERROR	T P(2 TAIL)
CONSTANT	-0.403	0.222	0.073
LNDBH	0.367	0.106	0.001
INVBA	10.753	12.480	0.392
DENSE	-22.349	15.269	0.147
CR	0.047	0.022	0.036
E10	1.161	0.693	0.098
E12	-0.398	0.136	0.004
E20	-0.108	0.104	0.304
E21	-0.087	0.098	0.379
E35	-0.190	0.095	0.049
E37	-0.019	0.119	0.876
E40	-0.064	0.107	0.552
E43	-0.204	0.168	0.227

ANALYSIS OF VARIANCE

SOURCE	SUM-OF-SQUARES	DF	MEAN-SQUARE	F-RATIO	P
REGRESSION	2.785	12	0.232	5.745	0.000
RESIDUAL	3.070	76	0.040		

APPENDIX C

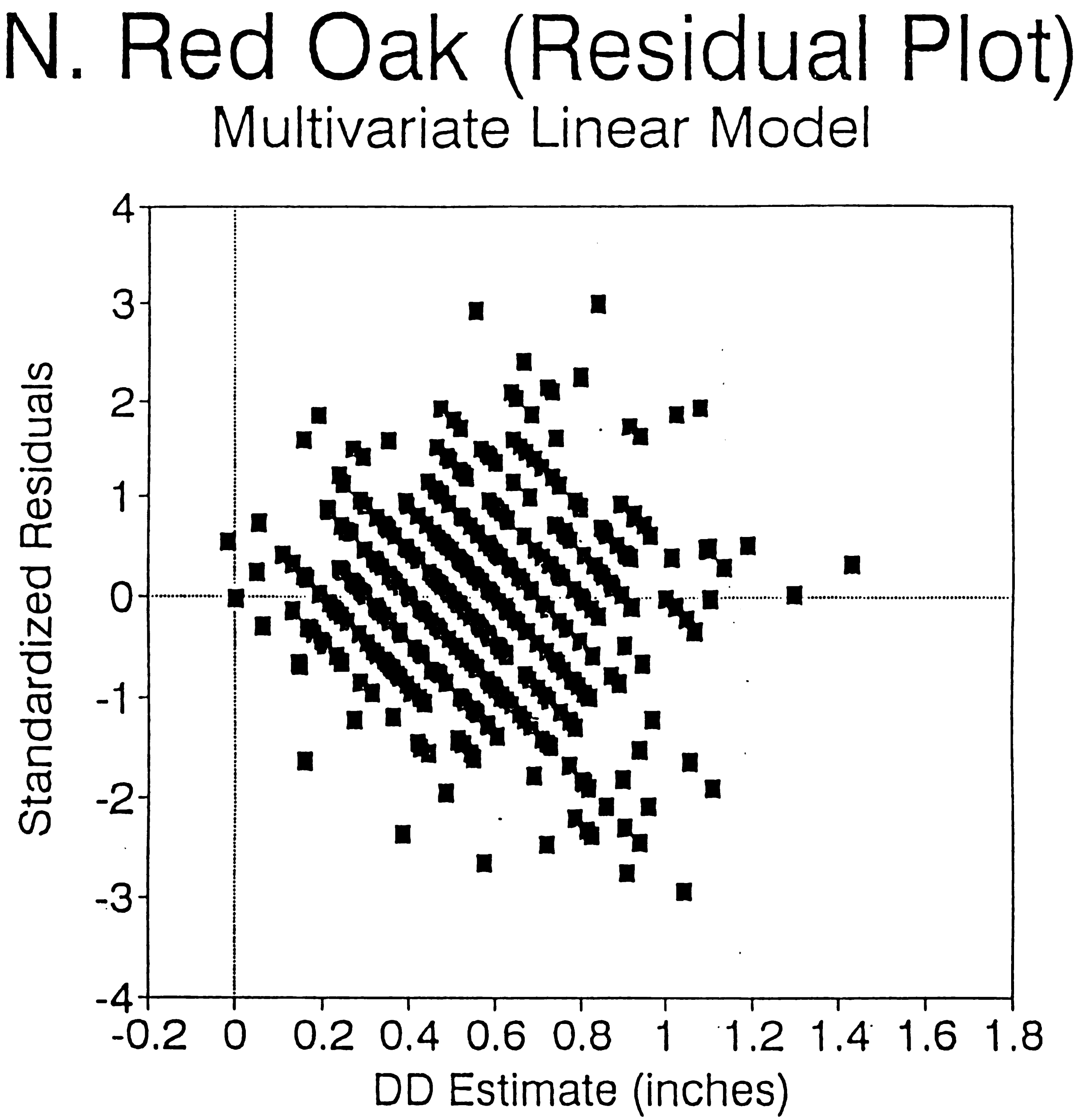


Figure 17. Northern red oak residual plot

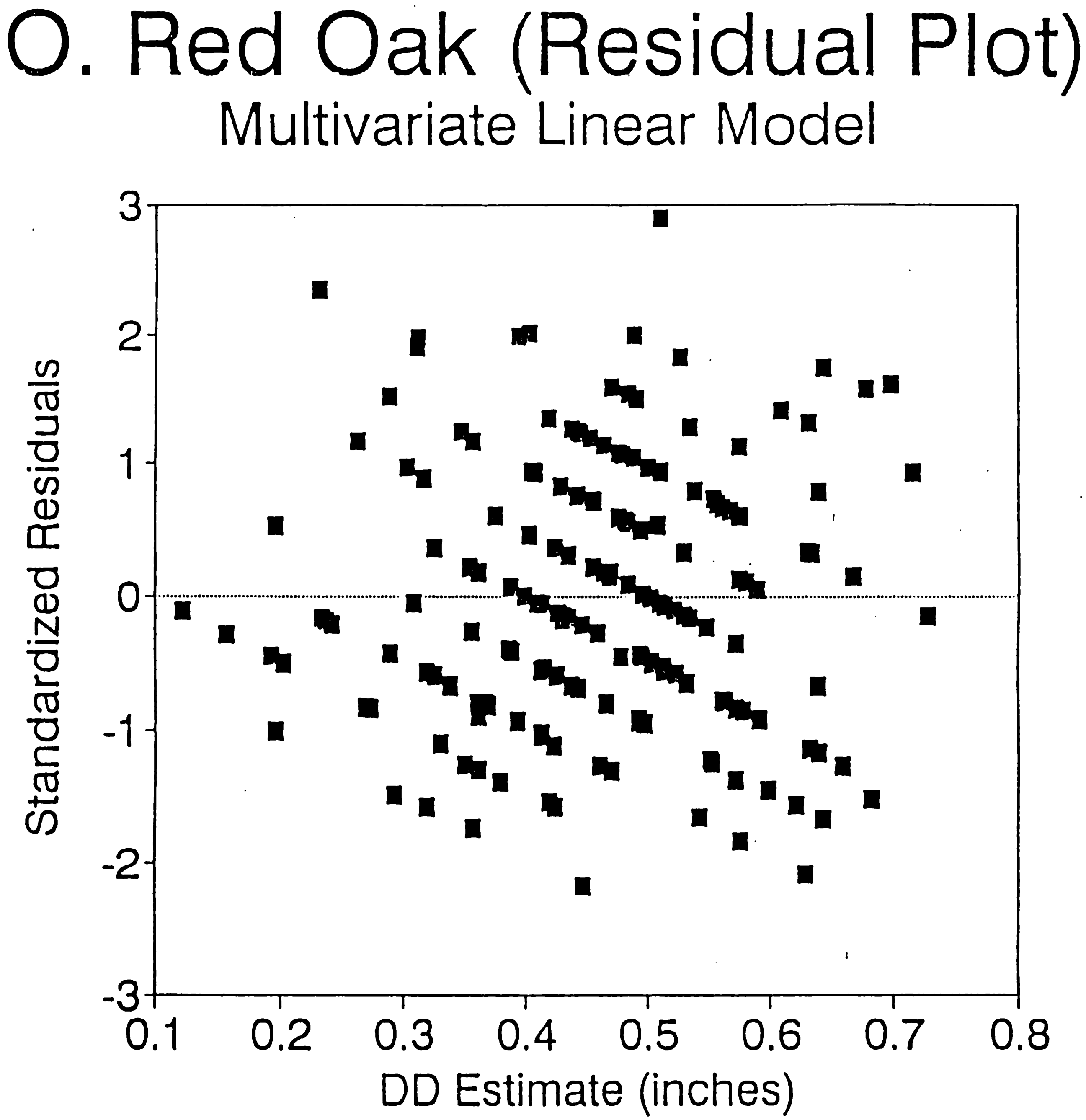


Figure 18. Other red oak residual plot

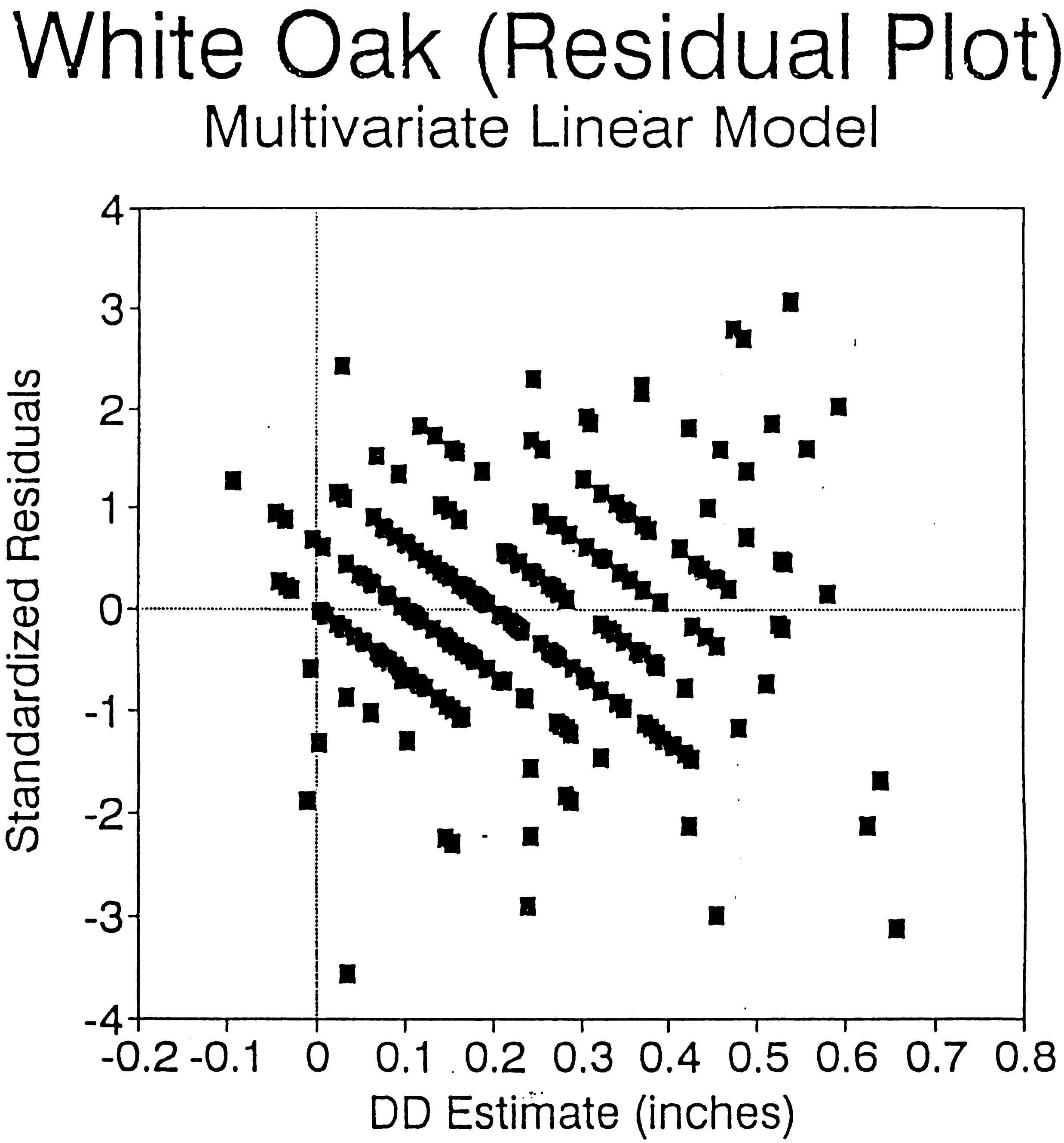


Figure 19. White oak residual plot

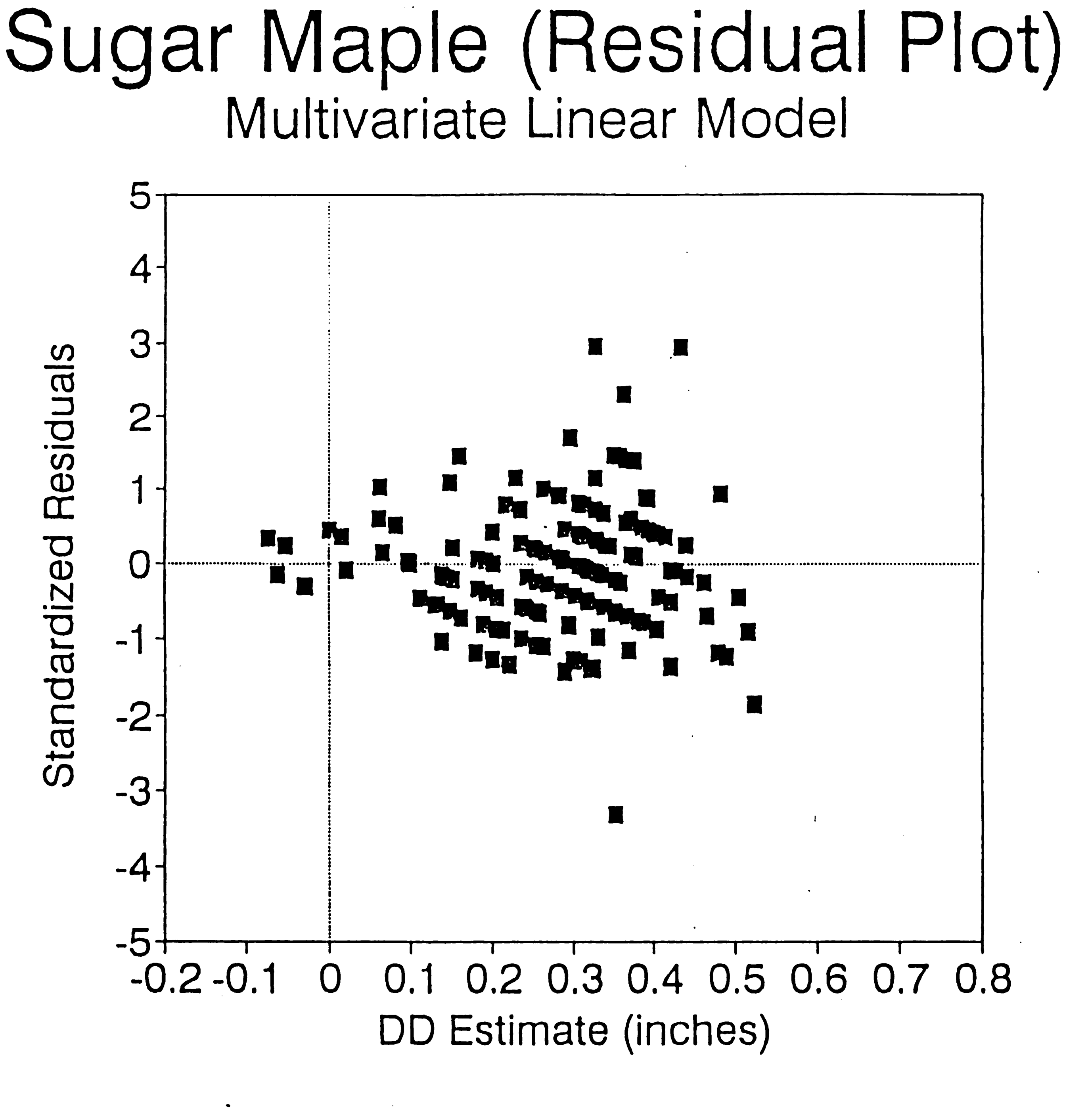


Figure 20. Sugar maple residual plot

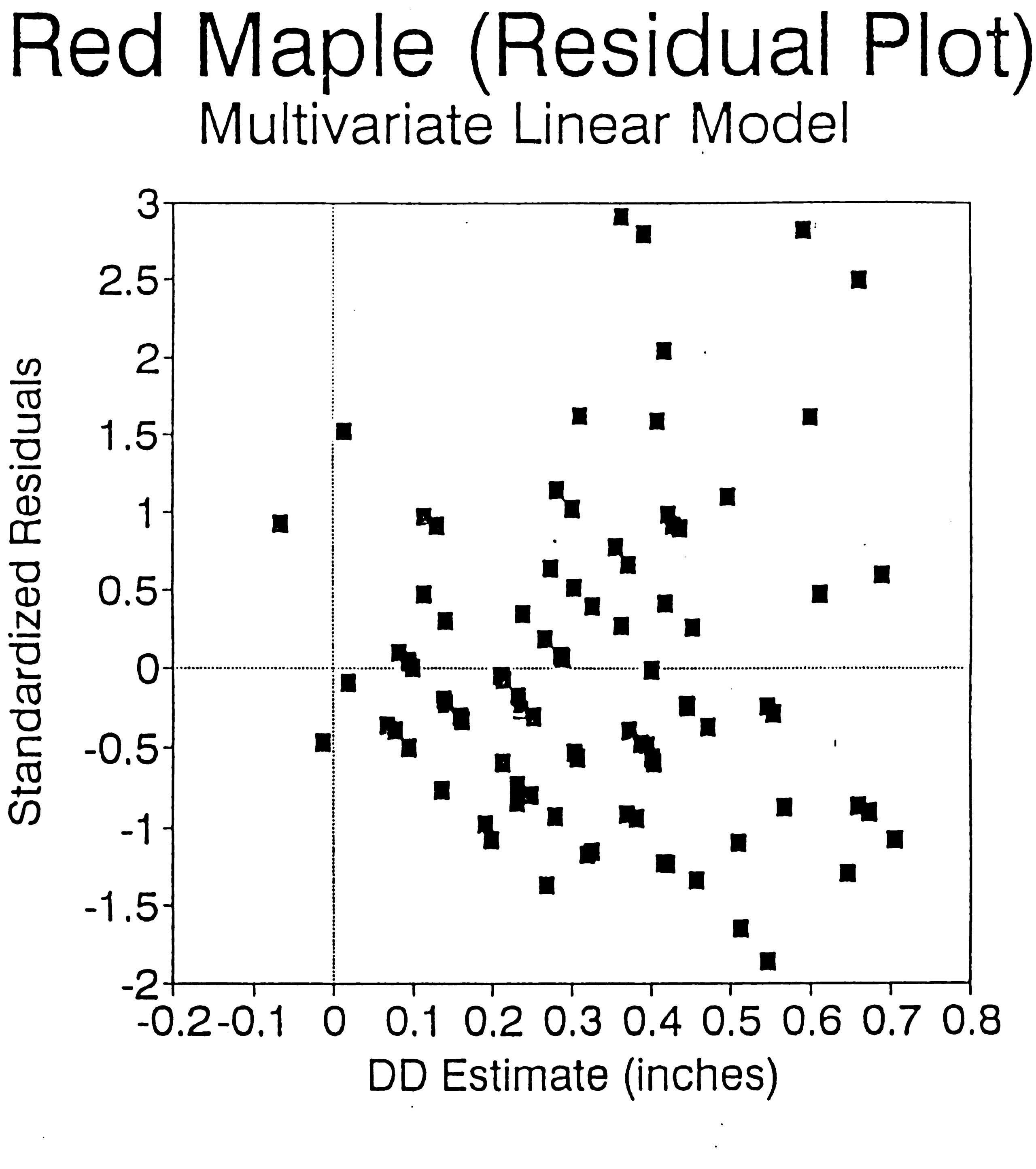


Figure 21. Red maple residual plot

BIBLIOGRAPHY

BIBLIOGRAPHY

Amateis, R.L. and M.E. McDill. 1989. Developing growth and yield models using dimensional analysis. Forest Science. 35(2): 329-337.

Bailey, R.L. 1980. Individual tree growth derived from diameter distribution models. Forest Science 26(4): 626-632.

Beers, T.W., and C.I. Miller. 1964. Point sampling: research results, theory, and application. Resource Bulletin 786. Purdue University Agricultural Exp. Sta., West Lafayette, IN. 56p.

Belcher, D.M., M.R. Holdaway, G.J. Brand. 1982. STEMS - the Stand and Tree Evaluation and Modeling System. Gen. Tech. Rep. NC-79. USDA Forest Service North Central Forest Experiment Station. 18p.

Bolton, R.K. and R.S. Meldahl. 1990. Design and development of a multipurpose forest projection system for Southern forests. Bull. 603. Auburn, AL: Alabama Agricultural Experiment Station, Auburn University: 51p.

Bruce, D. 1977. Yield differences between research plots and managed forest. Journal of Forestry 75:14-17

Buchman, R.G. 1979. Mortality functions. IN: A generalized forest growth projection system applied to the Lake States Region. USDA Forest Service Gen. Tech. Rep. NC-49, pp.79-89. north Central Forest Experiment Station. St. Paul, MN.

Buchman, R.G. 1983. Survival predictions for major Lake States tree species. Res. Pap. NC-233. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Stations. 7p.

Buchman, R.G., and E.L. Lentz. 1984. More Lake States tree survival predictions. Res. Note. NC-312. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 6p.

Buchman, R.G., S.P. Pederson, and N.R. Walters 1983. A survival model with application to species of the Great Lakes region. Canadian Journal of forestry. 13(4):601-608.

Buchman, R.G. and S.R. Shifley. 1983. Guide to evaluating forest growth projection systems. Journal of Forestry. 81(4):232-234.

Burk, T.E. 1986. Growth and yield model validation: Have you ever met one you liked? IN: Data management issues in forestry. Forest Resources Systems Institute, 98p.

Carmean, W.H. 1975. Forest site quality evaluation in the United States. Advances in Agronomy 27:209-269.

Christensen L., J.T. Hahn, and R.A. Leary. 1979. Data base. IN: A generalized forest growth projection system applied to the Lake States Region. USDA Forest Service Gen. Tech. Rep. NC-49. pp.16-21 North Central Forest Experiment Station, St. Paul, MN.

Conover, W.J. 1980. Practical Nonparametric Statistics, second edition. John Wiley and Sons, Inc. New York. 493p.

Crow, T.R. and H. M. Rauscher. 1984. Forest growth models and land classification. pp 190-204. IN(J.G. Bockheim, ed.) Forest land classification: Experiences, problems, Perspectives. March 18-20, University of Wisconsin, Madison. 276p.

Gertner, G.Z. 1984. Localizing a diameter increment model with a sequential Bayesian procedure. Forest Science 30(4):851-864.

Gingrich, S.F. 1967. Measuring and evaluating stocking and stand density in upland hardwood forests in the Central States. Forest Science 13: 38-52.

Godman, R.M., H.W. Yawney and C.H. Tubbs. 1990. *Acer sacchurum* Marsh. Sugar Maple. In: Silvics of North America, volume 2. Hardwoods. U.S.D.A. Forest Service Ag. Handbook 654, pp.75-91.

Gribko, L.S. and H.V. Wiant, Jr.. A SAS Template for the Accuracy Test. The Compiler, In Press.

Grosenbaugh, L.R. 1958. Point-sampling and line-sampling: probability theory, geometric implications, synthesis. Occational Paper 160. New Orleans, LA: USDA Forest Service, Southern Forest Experiment Station, New Orleans, LA. 34p.

Hahn, J.T. and W.H. Carmean. 1982. Lake States site index curves formulated. USDA For. Serv. Gen. Tech. Rep. NC-88. North Central Forest Experiment Station. 5p.

Hahn, J.T. and R.A. Leary. 1979. Potential diameter growth functions. IN: A generalized forest growth projection system applied to the Lake States Region. USDA Forest Service Gen. Tech. Rep. NC-49, pp.22-26 North Central Forest Experiment Station, St. Paul, MN.

Harrison, W.C., T.E. Burk, and D.E. Beck. 1986. Individual tree basal area increment and total height equations for Appalachian mixed hardwoods after thinning. Southern Journal of Applied Forestry 10: 99-104.

Hilt, D.E. 1983. Individual-tree diameter growth models for managed, even-aged, upland oak stands. USDA Forest Service Res. Pap. NE-533, North Eastern Forest Experiment Station 15p.

Hilt, D.E. 1985. OAKSIM: An individual-tree growth and yield simulator for managed, even-aged, upland oak stands. Res. Pap. NE-562. USDA Forest Service Northeastern Forest Experiment Station. 21p.

Hilt, D.E. and R.M. Teck. 1987. Individual-tree diameter growth model for northern New England. IN: Forest growth modeling and prediction (volume 1). USDA Forest Service Gen. Tech. Rep. NC-120, North Central Forest Experiment Station.

Holdaway, M.R. 1985. Adjusting the STEMS growth model for Wisconsin forests. USDA Forest Service Res. Pap. NC-267. North Central Forest Experiment Station. 8p.

Holdaway, M.R. and G.T. Brand. 1983. An evaluation of the STEMS tree growth projection system. Res. Pap. NC-234. USDA Forest Service North Central Forest Experiment Station. 20p.

Holdaway, M.R. and G.T. Brand 1986. An evaluation of Lake States STEMS85. Res. Pap. NC-269. USDA Forest Service North Central Forest Experiment Station. 10p.

Host, G.E., K.S. Pregitzer, C.W. Ramm, D.P. Lusch, and D.T. Cleland. 1988. Variation in overstory biomass among glacial landforms and ecological land units in northern Lower Michigan. Canadian Journal of Forest Research. 18(6): 659-668.

Kowalski, D.G. and G.Z. Gertner. 1989. Validation of TWIGS 3.0 for Illinois Forests. Forestry Research Report No. 87-5, Dept. of Forestry, Agric. Exp Station, Univ. of Ill. at Urbana-Champaign. 25p.

Leary R.A., J.T. Hahn, and R.G. Buchman. 1979. Tests. IN: A generalized forest growth projection system applied to the Lake States Region. USDA Forest Service Gen. Tech. Rep. NC-49, pp.79-89. North Central Forest Experiment Station. St. Paul, MN.

Mawson, J.C. 1982. Diameter growth estimation for small forests. Journal of Forestry 80(4). 217-219

Miner, C.L., N.R. Walters, and M.L. Belli. 1988. a Guide to the TWIGS Program for the North Central United States. USDA Forest Service Gen. Tech. Rep. NC-125. North Central Forest Experiment Station. 105p.

Monserud, R.A. 1976. Simulation of forest mortality. Forest Science 22(4). 438-444.

Monserud, R.A. 1984. Problems with site index: an opinionated review. pp. 167-180. In (J.G. Bockheim, ed.) Forest Land Classification: Experiences, Problems, Perspectives. March 18-20, University of Wisconsin, Madison. 276p.

Nichols, J.O. 1968. Oak mortality in Pennsylvania: a ten-year study. Journal of Forestry 66: 681-694.

Oliver, C.D. and Bruce C. Larson. 1990. Forest Stand Dynamics. McGraw-Hill, Inc. New York 467p.

Pienaar, L.V. and K.J. Trumball 1973. The Chapmann-Richards generalizations of von Bertallanffy's growth model for basal area growth and yield in even-aged stands. Forest Science 19: 2-22.

Pregitzer, Kurt S. and Carl W. Ramm. 1984. Classification of Forest Ecosystems in Michigan. pp114-131. IN(J.G. Bockheim, ed.): Forest land classification: Experiences, problems, Perspectives. March 18-20, University of Wisconsin, Madison. 276p.

Raile, G.K., W.B. Smith, and C.A. Weist 1982. A net volume equation for Michigan's Upper and Lower Peninsulas. Gen. Tech. Rep. NC-80. St. Paul, MN: USDA Forest Service, North Central Forest Exp. Sta. 12p.

Ramm, C.W. and C. Miner. 1986. Growth and Yield programs used on microcomputers in the North Central Region. N. J. Appl. For. 3(2): 44-46.

Rauscher, H. Michael. 1984. Homogeneous macro-climatic zones of the Lake States. Res. Pap. NC-240. USDA Forest Service, North Central Forest Experiment Station. 39p.

Rauscher, H.M. 1986. The Microcomputer Scientific Software series 4: Testing prediction accuracy. Gen. Tech. Rep. NC-107. USDA Forest Service, North Central Forest Experiment Station. 19p.

Rawlings, J.O. 1988. Applied regression analysis. Wadsworth and Brooks/Cole Advanced Books and Software. Pacific Grove, California. 553p.

Reynolds, M.R. Jr. 1984. Estimating the error in model predictions. Forest Science. 30:454-469.

Rogers, Robert. 1990. *Quercus alba* L. White Oak. In: Silvics of North America, volume 2. Hardwoods. U.S.D.A. Forest Service Ag. Handbook 654, pp.605-613.

Sanders, Ivan L.. 1990a. *Quercus rubra* L. Northern Red Oak. In: Silvics of North America, volume 2. Hardwoods. U.S.D.A. Forest Service Ag. Handbook 654, pp.727-733.

Sanders, Ivan L.. 1990b. *Quercus velutina* Lam. Black Oak. In: Silvics of North America, volume 2. Hardwoods. U.S.D.A. Forest Service Ag. Handbook 654, pp.744-750.

Sapio, Frank. 1992. Michigan Department of Natural Resources, Forest Management Division. Personnel communication.

Schlesinger, R.C.. 1990. *Fraxinus americana* L. White Ash. In: Silvics of North America, volume 2. Hardwoods. U.S.D.A. Forest Service Ag. Handbook 654, pp.333-338.

Shifley, S.R. and G.J. Brand. 1984. Chapman-Richards growth function constrained for maximum tree size. Forest Science. 30(4):1066-1070.

Shifley, S.R. 1987. A generalized system of models forecasting Central States tree growth. Res. Pap. NC-279. USDA Forest Service North Central Forest Experiment Station. 10p.

Smith, W. Brad. 1983. Adjusting the STEMS regional forest growth model to improve local predictions. Res. Note NC-297. USDA Forest Service, North Central Forest Experiment Station. 5p.

Smith, W. Brad and S.R. Shifley. 1984. Diameter growth, survival, and volume estimates for trees in Indiana and Illinois. Research Paper NC-257. USDA Forest Service, North Central Forest Experiment Station 9p.

Smith, W. Brad and J. T. Hahn 1986. Michigan's Forest Statistics, 1987: An Inventory Update. Gen Tech. Rep. NC-112. USDA Forest Service, North Central Forest Experiment Station. 44p.

Smith, Donald. 1986. The Practice of Silviculture, Eighth Edition. John Wiley and Sons, Inc. 527p.

Snee, Ronald D. 1977. Validation of Regression Models; Methods and Examples. Technometrics 4(15): 415-427.

Spurr S.H., and B.V. Barnes. 1980. Forest Ecology. John Wiley and Sons, Inc. New York. 687p.

Tubbs C.H., and D.R. Houston. 1990. *Fagus grandifolia* Ehrh. American Beech. In: Silvics of North America, volume 2. Hardwoods. U.S.D.A. Forest Service Ag. Handbook 654, pp.325-332.

USDA Forest Service. 1979. A generalized forest growth projection system applied to the Lake States region. Gen. Tech. Rep. NC-49. St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station. 96 p.

Walters R.S., and H.W. Yawney. 1990. *Acer rubrum* L. Red Maple. In: Silvics of North America, volume 2. Hardwoods. U.S.D.A. Forest Service Ag. Handbook 654, pp.60-69.

West, P.W. 1981. Simulation of diameter growth and mortality in regrowth eucalypt forest of southern Tasmania. Forest Science. 27(3):603-616.

Wykoff, W.R., N.L. Crookston, and A.R. Stage. 1982. Users' guide to the stand prognosis model. Gen. Tech. Rep. INT-133. Ogden, UT: USDA Forest Service Intermountain Forest and Range Experiment Station. 112p.

Wykoff, W.R. 1990. A basal area increment model for individual conifers in the northern Rocky Mountains. Forest Sceince. 36(4)1077-1104.

Zeide, Boris. 1989. Accuracy of equations describing diameter growth. Canadian Journal of Forest Research 19: 1283-1286.

Zeide, Boris. 1992. Has pine growth declined in the southeastern United States? Conservation Biology 6(2): 185-195.