SIMULATION OF INDIVIDUAL TREE GROWTH
AND STAND DEVELOPMENT
IN MANAGED LOBLOLLY PINE PLANTATIONS
TABLE OF CONTENTS

INTRODUCTION ......................................................... 1
LITERATURE REVIEW ..................................................... 2
  Stand Level Models ................................................. 2
  Individual Tree Models ............................................. 3
  Competition Indices ............................................... 5
  Modeling Considerations ......................................... 7
TECHNIQUES AND PROCEDURES ........................................ 7
  Preliminary Considerations ....................................... 7
  Data Collection .................................................... 9
  Model Construction ................................................ 9
    Initial Stand Generation ....................................... 9
  The Competition Index ............................................ 12
  Growth Relationships ............................................. 16
  Mortality .......................................................... 19
  Management Routines .............................................. 20
    Site preparation ................................................ 20
    Fertilization ................................................... 20
    Thinning ......................................................... 21
  Yield Estimates ................................................... 21
  Random Number Generation ....................................... 22
  Testing and Validation Procedures ............................... 23
RESULTS AND DISCUSSION ............................................ 23
  Initial Tests and Refinements ................................... 24
  Unmanaged Old-Field Plantations ................................ 24
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We gratefully acknowledge Jack Gregy and Fred Trew of the Westvaco Corporation and Jim Willis and Jim Bowman of the Chesapeake Corporation for their help in data acquisition.

ABSTRACT

A FORTRAN based simulator, PTAEDA, was developed to model growth in managed loblolly pine (Pinus taeda L.) plantations, using individual trees as the basic growth units. In PTAEDA, trees are assigned coordinate locations in a stand and "grown" annually as a function of their size, the site quality, and the competition from neighbors. Growth increments are adjusted by stochastic elements representing genetic and microsite variability. Mortality is generated stochastically through Bernoulli trials. Subroutines were developed to simulate the effects of site preparation, thinning, and fertilization on tree and stand development. Comparisons with published yields showed close agreement for thinned and unthinned old-field plantations. Results indicated that, compared to stand-level models used in the past, the simulator is more flexible in terms of growth and yield estimation and evaluation of alternatives under a wide range of management regimes.

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SIMULATION OF INDIVIDUAL TREE GROWTH AND STAND DEVELOPMENT
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Richard F. Daniels and Harold E. Burkhart 1/

INTRODUCTION

Loblolly pine (Pinus taeda L.) is a fast growing species especially suited to intensive management and is considered among the most important commercial tree species throughout the Southeastern U.S. As demand for forest products increases and acreage available for timber growth decreases, the need for efficient management of this valuable resource becomes acute. Thus, the ability to accurately predict growth and yield under various management alternatives is important.

The objectives of this study were 1) to develop a computer simulation model of tree and stand growth in managed loblolly pine plantations for use in growth and yield estimation and 2) to adapt the model to conversational mode for use as a teaching tool in forestry education.

Most yield data in the Southeast were obtained from pure, even-aged stands having no intermediate cultural treatments. Yield tables for plantations are almost exclusively for old-field conditions. But Southern pine management has reached a point of intensity where the manager is likely to select from among several site preparation alternatives, plant genetically improved stock, and employ thinnings and fertilizer applications during the life of the stand. Today, there exists no method of accurately predicting yield under such intensive management systems.

A yield prediction system incorporating flexibility from the standpoint of land management and utilization alternatives is badly needed in the Southeast. These considerations prompted the development of PTAEDA, a computer simulation model with individual trees as the basic growth units. An individual-tree-based model should offer this flexibility in growth and yield prediction in managed loblolly pine plantations.

Since the unit of biological growth in the forest system is the tree, a model based on individual trees has obvious advantages. Growth in the individual tree model can be more directly related to the biological processes of growth and development than is possible in stand-level models. The tree-level approach allows incorporation of knowledge from tree and plot studies of genetics, nutrient requirements, physiology, water relations, biomass, and other factors.

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Stand dynamics and unit area yield can be viewed in the simulation system, as they are in the underlying biological system, by the response and interactions of individual trees. Such a simulation model is more adaptable to predictions for treated stands. Silvicultural treatments can be represented in the simulation program as subroutines which adjust growth parameters and probabilities according to individual tree responses. If logically constructed, a simulation model which predicts well for stands for which there is information can be used with some confidence for predictions under circumstances for which no data are available.

A computer simulation model of tree growth offers the further advantage that it may be probabilistic in nature. That is, it reflects the variability in natural systems by representing major growth functions as stochastic processes. Thus, variability due to unexplainable factors is dealt with in a logical and natural fashion rather than ignored as in deterministic models.

Besides its practical use in growth and yield estimation, an individual tree simulation model has particular application to forestry education and training. A simulation model can be used to demonstrate the effects of silvicultural treatments as they relate to forest management objectives. Other uses would be in studying sampling and inventory systems and in ecological studies.

Although not a primary justification for this endeavor, a logically developed simulation model would be useful in studying many biological problems where exact spatial distributions, size, and vigor of individual trees must be known. Also, such models indicate where there are voids in knowledge of biological response and, in so doing, help in ordering research priorities.

In short, a well constructed individual tree growth simulation model for loblolly pine should play an important role in 1) growth and yield determinations, 2) evaluation of management alternatives, 3) forestry education, and 4) further research.

LITERATURE REVIEW

Stand Level Models

Yield predictions in the Southeast began with the same methodology as in other parts of the country. Temporary sample plots were established in natural stands of "normal density" and classical normal yield tables were constructed using graphical techniques (Anon. 1929). Yield tables constructed in this manner are still being applied to a limited extent in the Southeast.
A multiple regression approach to variable-density yield estimation was suggested by MacKinney, Schumacher, and Chaiken (1937) and subsequently used to construct a yield prediction equation for loblolly pine stands (MacKinney and Chaiken 1939). Since that time, several studies have utilized multiple regression to predict yield (Bennet, McGee and Clutter 1959, Goebel and Shipman 1964, Dierauf and Marler 1965, Burkhart et al. 1972, and others).

In several recent studies, yields per acre for even-aged stands have been predicted by using a diameter distribution analysis procedure (Bennett and Clutter 1968, Lenhart and Clutter 1971, Lenhart 1972, Smalley and Bailey 1974a, Smalley and Bailey 1974b). In this approach, the number of trees in each 1-inch diameter class is estimated, total heights are predicted for trees of given diameters and stand conditions, and volume is calculated by substituting into tree volume equations. Unit area estimates are made by summing over diameter classes of interest.

**Individual Tree Models**

An alternative method of growth and yield prediction which is receiving considerable attention today is the use of individual tree computer simulation models. In these models, "individual trees" in a "stand" are assigned certain initial size and spatial distributions. The trees are then "grown" according to some function of their size, the site, their competitive status, and a random component representing microsite and/or genetic variability. Competitive status for each tree is quantified in terms of a competition index which is a function of the tree's size and the size of and distance to its neighbors. Mortality is regulated as a function of competition index and/or growth. Volume estimates can be made periodically by applying known volume equations to the dimensions of the trees (Curtis 1972).

Newnham (1964) presented what appears to be the first stand model based on individual tree simulation. He considered diameter increment for trees in plantations of Douglas-fir to be equal to open-grown diameter growth as reduced by a measure of competition. Competition was described for each tree by the sum of the "angles of intersection" of crowns of neighboring trees. Height growth was not considered. In his model, growth was incremented and stand statistics were tabulated every five years from age 10 to 100. Mortality was assigned both as a function of diameter increment and as specified in initial parameters to simulate thinnings and infection centers of mortality. Total heights were obtained through a regression equation in terms of DBH, DBH², and stand basal area. The model was tested and refined and was found to produce reasonable diameter distributions for all but the most dense initial spacings (3.3 X 3.3 ft.). Newnham and Smith (1964) reported on the model's behavior for Douglas-fir and lodgepole pine. Their study included predictions of height and volume per acre throughout the simulation. Later, Lee (1967) improved the model for lodgepole pine.
Since Newnham's work a number of other individual tree models have been developed. Mitchell (1969) developed a simulator for white spruce in which he based growth on branch elongation and crown expansion of individual trees. His model allowed for unequal crown expansion in different directions depending on growing space available for each tree. Bole size was then predicted from regression relationships to crown size and height. Subsequent models have been more similar to Newnham's model, however.

Because of a desire to simulate natural and direct seeded stands, the ability to create variable spatial patterns in simulation studies was explored by Newnham (1968) and Newnham and Maloley (1970). The facility for generating random, uniform, and clumped spatial patterns was included in Bella's (1970) aspen model and Hatch's (1971) red pine model. Also included in these models was the capacity to stochastically generate height growth and to carry heights and other tree dimensions throughout the duration of simulation. These advancements resulted in more realistic tree growth and improved volume estimates.

As discussed by Clutter (1963) and reiterated by Curtis (1972), a well developed growth and yield prediction system should have the relationship that yield is the integral of growth. In practice this may turn out to be a sum of periodic growth. This compatibility of growth and yield is demonstrated in most individual tree simulation models, not only by stand, but on an individual tree basis as well. However, there are difficulties in approximating the continuous growth of trees with discrete growth intervals. This consideration prompted Arney (1972), in his Douglas-fir model, to adopt a growth interval of one year rather than the five years used in previous models.

Arney also included an extension of growth-competition relationships previously developed. He calculated competitive stress for each crown layer and used this to estimate diameter increment at each whorl down the bole and to determine crown layer mortality. This led to considerable control over form and size of simulated trees. He suggested that volume could then be computed directly for each section of the tree.

Other developments have included the ability to simulate even- or uneven-aged stands of mixed species composition (Botkin et al. 1972a, Ek and Monserud 1974). Thinnings were studied with all models discussed thus far, since the authors felt that response followed directly from the competition relationships developed. Response to fertilizer applications was also included in the simulation studies of Hegyi (1974) and Ek and Monserud (1974).

Applications of individual tree simulation models have been varied. Such models are currently being used by industry in the Northwest to aid in decision making (Honig 1972). Mitchell (1975) described a highly detailed management system in which data from low-level aerial photos are used as input to a tree growth simulator. Projections of growth and yield from the simulator are then used in management planning which ultimately influences field applications.
Because of their detail and flexibility, individual tree models have promise in analyzing and perhaps optimizing silvicultural alternatives (Adams and Ek 1974). Other researchers have indicated that they are most useful in studying ecological interactions (Botkin et al. 1972b, Hatch, Gerrard and Tappeiner 1975).

**Competition Indices**

Central to all individual tree models is a competition index which is used in determining growth and mortality during the simulation. This index quantifies competitive stress (or competitive ability, depending on the author) experienced by individual trees, and in most cases is assumed to represent the total effect of competition for scarce resources (e.g. light, water, nutrients, and physical growing space). Stand density measures such as stems per acre, basal area per acre, and crown competition factor have been thought to reflect competition. However, these do not apply to individual trees and cannot be used to reflect variable effects on individual trees in a simulation model.

Probably the first measure of individual tree competitive stress was Staebler's competition index, developed around 1950 (Gerrard 1969). Staebler assumed that total competitive ability for all resources can be represented by an influence or competition circle around each tree with radius $r = a + b$ (DBH). He reasoned that the competition exerted on a tree is directly proportional to the area overlap of its competition circle by those of its neighbors. However, since at the time manual calculation of area overlap was difficult, he settled for linear overlap and applied a set of weighting factors. Most subsequent indices have been based almost entirely on Staebler's work with changes in definition of the competition radius and the measure of overlap.

Newnham (1964) based competition radius on crown radius and considered the subtended angles of overlapping crowns for construction of his index. Gerrard (1969) considered area overlap but divided the sum of overlapped areas by the competition area of the subject tree for an index he called Competition Quotient (CQ) so that $0 \leq CQ \leq 1$. Keister (1971) used the same methodology as Gerrard but defined his competition radius as crown radius X (total height/height to base of live crown). Bella (1971), in his Competitive Influence-zone Overlap (CIO), defined competition radius as crown radius times a species dependent multiplier. He also weighted the overlap by the ratio between the diameters of the subject and competitor trees, raised to an exponent. Both the crown width multiplier and the exponent were determined through an iterative search based on the model's ability to predict diameter growth.

Some attempts to quantify individual tree competition have been adapted from stand density measures. Spurr's (1962) point density is an extension of point sampling methodology to apply a stand measure, basal area per acre, to individual trees. Opie (1968) also concerned himself with "competing basal area." Brown (1965) introduced an index called Area Potentially Available (APA) which is essentially the inverse
of trees per acre. He calculated APA by bisecting inter-tree distances to form a polygon of available growth area. This index was modified by Moore and Budelsky (1973) who weighted division of distance between trees by a ratio of their sizes. Mitchell (1969) used a similar technique for unequal crown expansion in his model.

An interesting index is the Growing Space Index (GSI) developed by Lin (1969). He based his calculations on the largest angle extended by a stem in each quadrant surrounding a subject tree. These angles were weighted and summed by quadrant to produce GSI, distributed from 0 to 100 for each tree.

Hatch's (1971) index considers competitive ability as a function of competition for light only and is based on the proportion of live crown surface area exposed to direct sunlight per unit of height. Thus, input to his simulation must include solar altitudes for each simulated stand of trees. Recently Hatch, Gerrard, and Tappeiner (1975) described a modification of this index in which competitive ability is weighted by the ratio of basal areas of the subject and competitor trees. They reported that the index compared favorably with Bella's C10 in accounting for variation in 5-year DBH growth in red pine.

In an effort to avoid the complex calculations (and thus excessive computer time) involved in calculation of previously mentioned indices, Hegyi (1974) developed a more compact index. He calculated competition between trees as the ratio of their diameters divided by their separation distance. Although strictly an empirical model, Hegyi's index performed well in his jack pine simulator.

The use of competition indices in growth prediction has followed at least three paths. Diameter increment was considered by some authors to be a function of open-grown tree diameter growth as reduced by competition (Newnham 1964, Lee 1967, Arney 1972). Others have used the competition index in regression equations, along with other independent variables, to predict diameter increment (Bella 1971, Gerrard 1969, Keister 1971, Moore and Budelsky 1973). This method provides reliability estimates (e.g. R² and standard errors) which are useful in assessing predictions, determining the nature of unexplained variability, and applying a random component to growth predictions. However, failure of an index to predict growth of individual trees may be more a function of the regression model chosen than the competition model itself.

A third method, employed by Hatch (1971), was to stochastically generate diameter increment from a theoretical distribution. He used the Von Bertalanffy distribution for generating diameter increment with parameters expressed as a function of DBH, competition index, and site index.
Modeling Considerations

Other considerations in individual tree simulation deal mainly with problems related to sampling and model logic. For example, the question of simulated plot size has not been directly answered; Newham (1964) used a plot containing 225 trees while Arney (1972) simulated only 30.

Related to this is the problem of edge bias in simulated plots due to the lack of competitors for border trees. Monsrud and Ek (1974) suggested that this problem needs attention since, even where buffer strips of "non-measured" trees surrounded the plot, the effect of this bias will, in time, creep into the main plot through indirect effects of competition. The inclusion of buffer strips also involves a large number of calculations (for data which will be discarded) on a geometrically increasing number of trees as buffer size increases. They suggested either a "reflection" of plot edges so that border trees compete with mirror images of the plot or a "translation" so that border trees compete with opposite sides of the plot. Even with these apparent solutions there is the problem that spatial periodicities which are considered rare in forest stands may be created.

TECHNIQUES AND PROCEDURES

Participants in a recent tree growth simulation workshop agreed that individual tree simulation models will play an essential role in estimating yield and evaluating intensive management alternatives (Honer 1972). They suggested that, at least for now, individual tree modeling efforts should be aimed at highly productive species in areas where intensive management will be practiced.

Because of its importance in the intensively managed Southeastern forests, an individual tree simulation model, PTAEDA, was developed for loblolly pine in managed plantations. The simulator was written in FORTRAN for use in both conversational and batch mode on the IBM/370 system at the Virginia Tech Computing Center.

Preliminary Considerations

The initial step in constructing a simulation model is to identify all relevant entities of the system and to define their attributes and logical relationships. At the same time one should keep in mind that the simulator need not be as complicated as the real world system for adequate description (Fishman 1973). After relevant entities of the loblolly pine growth system were identified, a schematic diagram (Fig. 1) was developed showing logical and functional paths for a simulation model.

The two main subsystems in PTAEDA deal with the generation of an initial, pre-competitive stand (subroutine PLANT, subroutine JUV) and the growth and dynamics of that stand (MAIN, subroutine COMP). Management subroutines were added to this framework to adjust program parameters for simulation of treated stands (PREP, THIN, FERT). The input and
Fig. 1. Schematic diagram showing relationships between tree and stand components for a simulation model of loblolly pine growth.
output routines add flexibility to the practical use of the simulator (INPUT, OUTPUT, TREES). Additional subprograms (not shown) generate uniform, standard normal, and Weibull distributed random variates. A flowchart showing the logic structure and sequence of operations of the model is presented in the appendix.

Data Collection

Plot data were available from the yield studies of Burkhart et al. (1972). These data consisted of 240, one-tenth acre plots randomly chosen from selected loblolly pine plantations in piedmont and coastal plain Virginia and from coastal plain Delaware, Maryland, and North Carolina. One hundred and eighty-nine of these plots were from old-field origin, while 51 were from site-prepared cutover lands. Data from 81 open grown loblolly pine trees from the same geographic range were also available.

In addition to these tree and plot data, a limited amount of individual tree growth data for mapped stands was needed to initially calibrate the size/distance dependent competition index. Growth data were obtained from annually remeasured experimental check plots maintained by the Westvaco Company, the Continental Can Company, and the Chesapeake Corporation. These plots, located in piedmont and coastal plain Virginia, are part of the North Carolina State Forest Fertilization Cooperative Study. Inter-tree distances were then measured in the Westvaco and Chesapeake plots and stand maps were generated. A summary of all three data sets is shown in Table 1.

Model Construction

PTAEDA was initially constructed, debugged, and executed using the interactive WATFIV compiler under CMS (Conversational Monitoring System). The conversational mode was chosen for model development because of its convenience and the excellent interactive debugging facilities offered by this version of WATFIV. After refinement of the interactive model, a second version was adapted for use in batch mode. The two versions of the model are identical except for subroutines INPUT and OUTPUT which handle all input and output functions.

Initial Stand Generation

Rectangular spatial patterns in PTAEDA are controlled by subroutine PLANT in which a number of planting options were incorporated. A user may specify the distance between trees and between rows in a conventional manner (e.g. 6' X 8', 6' X 12') allowing the program to compute the planted number of trees. Alternatively, the number of trees may be specified along with the ratio of planting distance to row width (e.g. 3:4, 1:2). If this ratio is omitted, square spacing is assumed.
Table 1. Summary of data used in constructing the loblolly pine tree and stand growth simulator PTAEDA.

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Mean</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>DBH (inches)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plantation</td>
<td>6.0</td>
<td>2.5 - 16.7</td>
</tr>
<tr>
<td>Open-grown</td>
<td>10.2</td>
<td>1.1 - 37.0</td>
</tr>
<tr>
<td>Mapped stand</td>
<td>6.3</td>
<td>1.7 - 11.7</td>
</tr>
<tr>
<td>Height*(feet)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plantation</td>
<td>43.0</td>
<td>20.7 - 87.5</td>
</tr>
<tr>
<td>Open-grown</td>
<td>30.2</td>
<td>8.0 - 74.0</td>
</tr>
<tr>
<td>Mapped stand</td>
<td>47.7</td>
<td>27.7 - 59.0</td>
</tr>
<tr>
<td>Age (years)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plantation</td>
<td>15</td>
<td>8 - 35</td>
</tr>
<tr>
<td>Open-grown</td>
<td>19</td>
<td>4 - 60</td>
</tr>
<tr>
<td>Mapped stand</td>
<td>17</td>
<td>11 - 19</td>
</tr>
<tr>
<td>Density (trees/acre)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plantation</td>
<td>744</td>
<td>300 - 2900</td>
</tr>
<tr>
<td>Mapped stand</td>
<td>873</td>
<td>430 - 1590</td>
</tr>
</tbody>
</table>

* Average height of the dominant and codominant trees for plantation and mapped stand data. Total height for open-grown trees.
In addition, a provision was included which computes initial planting parameters from the surviving number of trees, age, and spacing ratios of existing stands. This was accomplished by solving for trees planted in the loblolly pine survival function described by Smalley and Bailey (1974a).

From this information a plot of 100 trees is generated with ten rows of ten trees each. A fixed number of trees was chosen rather than a fixed plot size so that, in effect, plot size would increase with decreasing density.

Computational efficiency may have been gained for rectangular spatial patterns by tabulating tree attributes in a 10 by 10 matrix. However, considerations for future inclusions of variable spatial patterns precluded this option and trees were placed in a 100 X 1 vector, numbered from 1 to 100 in a serpentine fashion, and assigned X and Y coordinates.

From this point, subroutine JUV advances the juvenile stands to an age where intraspecific competition begins. It was desired to bypass annual growth calculations in this juvenile period since 1) there are little data available with which to model growth in young stands; 2) intraspecific competition in such young stands was believed to be negligible; and 3) added calculations and computer time could not be justified by more reliable estimates.

The problem of determining an age where intraspecific competition starts to affect growth has recently been confronted by Strub et al. (in press). They found that, over a wide range of sites and planting densities, the age at which average diameter in plantations first differs from that of open-grown trees is consistently one year after Crown Competition Factor (CCF) (Krajicek et al. 1961) reaches 100.

This relationship is used in subroutine JUV to compute the end of the pre-competitive growth stage. CCF is predicted as a function of surviving number of trees per acre (TS), height of the dominant stand (HD) (average height of dominant and codominant trees), and age using the equation developed by Strub et al. (in press). This equation is evaluated each year after age five until CCF is greater than or equal to 100. HD is predicted using the site index curves of Burkhart et al. (1972) while TS is estimated from the survival function of Smalley and Bailey (1974a).

At this point the predicted juvenile mortality is assigned at random. Individual tree dimensions are then generated for the residual stand.

Diameter at breast height is generated from a two parameter Weibull distribution with a cumulative distribution function (CDF) as follows:
\[ P(y) = 1 - e^{-ay^b} \quad 0 < y < \infty \]

The inversion technique was used for generating random variates from this distribution. Parameters \(a\) and \(b\) are estimated from minimum and average DBH as follows (Strub and Burkhart 1974):

\[
b = \frac{\ln(TS/10)}{\ln DAVE - \ln DMIN} \\
a = \left[ \frac{\Gamma(1 + 1/b)}{DAVE} \right]^b
\]

where \(DMIN\) = minimum DBH (inches)  
\(DAVE\) = average DBH (inches)  
\(TS\) = surviving number of trees per acre  

\(DMIN\) and \(DAVE\) are predicted from stand age, HD, and TS.

Height is generated for each tree based on a prediction equation involving DBH, HD, TS, and age. Crown length is then calculated as total height minus clear bole length, where clear bole length is a function of total height, DBH, TS, and age.

Table 2 provides a summary of all equations used in generating the initial stand.

**The Competition Index**

As previously stated, the competition index plays a key role in determining mortality and annual height and diameter growth. Thus, it was considered important to develop an index which demonstrated high correlations with growth. This criterion, coupled with computational efficiency, was used as the basis for selection of a competition index for use in PTAEDA. A number of different indices were calculated and analyzed using the mapped stand data described earlier.

Of the overlap-type indices, the weighted area overlap index used by Ek and Monserud (1974) seemed to be the most desirable because of its logical construction and its successful use in their FOREST model. Competition radius was defined by Ek and Monserud as open-grown crown radius while influence zone overlap was weighted by the ratio of total height times crown radius for competing trees.
<table>
<thead>
<tr>
<th>Equation</th>
<th>( R^2 )</th>
<th>( s_y )</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>( CCF = 180.89 - 101.76/A + 0.0634/HD \cdot TS )</td>
<td>0.8993</td>
<td>0.0034</td>
<td>Strub et al., in press</td>
</tr>
<tr>
<td>( \log_{10}(HD) = \log_{10}(A) + 0.0138 \cdot \log_{10}(P) - 0.0023 \cdot A - 0.0199 \cdot \sqrt{TD} )</td>
<td>—</td>
<td>—</td>
<td>Burkhaart et al., 1972</td>
</tr>
<tr>
<td>( \log_{10}(CT/TS) = A \cdot 0.0138 \cdot \log_{10}(P) + 0.0069 \cdot A - 0.0109 \cdot \sqrt{TD} )</td>
<td>0.9000</td>
<td>0.0042</td>
<td>Smalley and Bailey, 1974a</td>
</tr>
<tr>
<td>( \frac{DNCN}{A} = 0.1291 + 0.0445 \cdot HD - 0.00001876 \cdot A \cdot TS + 0.0726 \cdot HD \cdot TS )</td>
<td>0.7662</td>
<td>0.5645</td>
<td>Plantation Data</td>
</tr>
<tr>
<td>( \frac{DAVE}{A} = 2.9599 + 0.0546 \cdot HD - 0.0005217 \cdot A \cdot TS + 1.84 \cdot HD \cdot TS )</td>
<td>0.9206</td>
<td>0.3470</td>
<td>Plantation Data</td>
</tr>
<tr>
<td>( \ln(H) = 1.5120 + 0.7097 \ln(D) + 0.0005217 \ln(A) - 0.0199 \ln(D) + 1.063 \ln(TS) - 2.445 \ln(A) )</td>
<td>0.9514</td>
<td>0.0697</td>
<td>Plantation Data</td>
</tr>
<tr>
<td>( \ln(CIR) = -2.6876 + 1.662_{-1} + 0.644_{-2} + 0.051_{-2} - 0.019_{-2} \ln(TS) - 2.445 \ln(A) )</td>
<td>0.9303</td>
<td>0.1576</td>
<td>Plantation Data</td>
</tr>
</tbody>
</table>

*Where: CCF = crown competition factor, HD = height of dominant stand (ft), IF = trees planted per acre, TS = trees surviving per acre, SI = site index (ft at age 50), DMIN = minimum DBH (inches), DAVE = average DBH (inches), H = total tree height (feet), GHL = clear hole length (feet), A = age (years).*
Hegyi (1974) showed that in jack pine a much less complicated index was more desirable in terms of both computational efficiency and correlation with growth than a similar weighted area overlap index. The competitive effect of neighboring trees was calculated

\[ CI_i = \sum_{j=1}^{n} \frac{(D_j/D_i)}{DIST_{ij}} \]

where
- \( D = \text{DBH} \)
- \( \text{DIST} = \text{distance between subject tree } i \text{ and } j^{th} \text{ competitor} \)
- \( CI_i = \text{Competition Index of the } i^{th} \text{ tree} \)
- \( n_i = \text{the number of neighbors within a 10 ft. competition radius} \)

In the original application of Hegyi's index, a fixed 10 ft. search radius for competitors was used. Logically, a tree's competitive influence zone will increase as its size increases, causing the competitive stress on neighboring trees to increase over time. On the other hand, some competitors die, causing a decreasing effect on competitive stress. Thus, an index should have roughly the same magnitude for a given tree over time (Hatch 1971). Area overlap indices have these properties built in while Hegyi's index will, in general, decrease over time.

Hegyi's index was modified to account for the above mentioned considerations by choosing competitors based on both their size and distance. Point sampling methodology was employed by multiplying a potential competitor's DBH by a constant to obtain a radius of influence. If this radius intersected the subject tree, then it (the potential competitor) was included as a competitor. Plot radius factors for both 10 and 20 basal area factor (BAF) angle gauges were tried.

Further modifications of Hegyi's index were investigated by expressing competitive effect as the ratio of basal areas of competing trees. Another trial involved weighting the ratio of tree diameters inversely proportional to the square of the distance between the trees rather than simply distance.

From the summary of these trials (Table 3), it is clear that Hegyi's original index modified by using a 10 BAF angle gauge to find competitors is as highly correlated with DBH growth as the area overlap index. In addition, the more simplified calculation of competitive effect employed by Hegyi is considerably more efficient computationally than area overlap calculations which necessitate the use of LOG and ARCSIN functions in computer calculations, both of which are rather costly.

This modified Hegyi index was incorporated into subroutine COMP which evaluates competitive stress for each tree. COMP and HOWFAR, which calculates inter-tree distances, were adapted from similar routines.
Table 3. Correlation of various competition indices with annual growth of loblolly pine.

<table>
<thead>
<tr>
<th>Competition Index</th>
<th>Competition Search Technique</th>
<th>Correlation Coefficient (r)</th>
<th>DIN</th>
<th>HIN*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weighted Area Overlap</td>
<td>all overlapping influence zones (Ek and Monserud 1974)</td>
<td>-0.424</td>
<td>-0.432</td>
<td></td>
</tr>
<tr>
<td>Weighted Size Ratio</td>
<td>10 foot radius (Hegyi 1974)</td>
<td>-0.236</td>
<td>-0.276</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BAF 20</td>
<td>-0.401</td>
<td>-0.447</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BAF 10</td>
<td>-0.415</td>
<td>-0.456</td>
<td></td>
</tr>
<tr>
<td>(\frac{D_j}{D_i}/\text{DIST}_{ij})</td>
<td>BAF 20</td>
<td>-0.240</td>
<td>-0.286</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BAF 10</td>
<td>-0.258</td>
<td>-0.339</td>
<td></td>
</tr>
<tr>
<td>(\frac{D_j^2}{D_i^2}/\text{DIST}_{ij})</td>
<td>BAF 20</td>
<td>-0.207</td>
<td>-0.258</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BAF 10</td>
<td>-0.219</td>
<td>-0.313</td>
<td></td>
</tr>
</tbody>
</table>

*Where DIN = observed DBH increment, HIN = observed total height increment, D = DBH, DIST = distance between trees i and j.*
developed by Ek and Monserud (1974) and together represent a very efficient means of evaluating competition. Competitive stress on border trees is calculated through a translation of plot borders so that, in effect, border trees compete with border trees on the opposite side of the plot.

Growth Relationships

After generation of the pre-competitive stand, competition is evaluated and trees are grown individually on an annual basis. In general, growth in height and diameter is assumed to follow some theoretical growth potential. An adjustment or reduction factor is applied to this potential increment based on a tree's competitive status and vigor, and a random component is then added representing microsite and/or genetic variability.

The potential height increment for each tree is considered to be the change in average height of the dominant and codominant trees, obtained as the first difference with respect to age of the following expression, transformed from the site index equation presented by Burkhart et al. (1972) (Table 2):

\[
\text{HD} = \text{SI} 10^{-5.86537(1/A - 1/25)}
\]

where

- \( \text{HD} \) = average height of dominant stand (feet)
- \( \text{SI} \) = site index base 25 (feet)
- \( A \) = stand age (years)

A tree may grow more or less than this potential, depending on its individual attributes.

Past work has shown that, except in extreme cases, average stand height is influenced very little by density. However, on an individual tree basis, competition from neighboring trees seems to affect a tree's realization of potential height increment. The competition index showed a significant correlation with observed height increment (\( r = -0.46 \)) using the mapped stand data, and so was included in the adjustment factor for height growth.

Hatch (1971) pointed out the desirability of an index which reflects a tree's vigor as opposed to its competitive disadvantage. Crown ratio was considered to be a natural expression of a tree's photosynthetic potential and was used in the adjustment factor as an attribute positively related to realization of potential growth. But in construction of the adjustment factor it was found that crown ratio was also negatively related to tree growth in cases where it approached that of open grown trees. This is presumably related to the fairly well established phenomenon that on comparable sites height growth is generally somewhat less for open grown trees than for stand grown trees (Spurr 1952). Thus, the final form chosen for the height growth adjustment was
\[
\begin{align*}
&b_3 - b_4 \text{CI} - b_5 \text{CR} \\
&\left( b_1 + b_2 \text{CR} e^{b_3} \right)
\end{align*}
\]

where

CR = crown ratio  \\
CI = competition index  \\
b_i = constants to be estimated from data

Using the mapped stand data, an equation relating actual and potential height increment by this factor was fitted by non-linear least squares (Table 4). It can be seen that as competition increases, the realization of potential height growth decreases. Holding competition index constant, the adjustment factor has a maximum value when crown ratio is roughly 0.25. It gradually decreases with increasing crown ratio, but decreases rapidly as crown ratio approaches zero. It should be noted that the height growth adjustment factor may attain values greater than one so that, under favorable conditions, individual tree height growth may be greater than the change in average dominant stand height. Assuming residual variability in height growth is normally distributed, a random component is added to the final growth determinations with variance equal to the residual mean square from the fitted regression.

The maximum DBH attainable for an individual tree of given height and age was considered to be equal to that when open-grown. An equation describing this relationship was developed from the open-grown tree data described earlier and is shown below:

\[
D_0 = -2.422297 + 0.286583 H + 0.209472 A
\]

\[
R^2 = 0.9197 \quad s_{y'x} = 2.14023
\]

where

\( D_0 \) = open-grown tree DBH (inches)  \\
\( H \) = total tree height (feet)  \\
\( A \) = age from seed (years)

The first difference of this equation with respect to age was thought to represent a maximum potential diameter increment:

\[
\text{PDIN} = 0.286583 \text{ HIN} + 0.209472
\]

where

\( \text{PDIN} \) = potential diameter increment (inches)  \\
\( \text{HIN} \) = observed height increment (feet)

This potential diameter increment is reduced by a reduction factor of the form

\[
\frac{b_3 - b_4 \text{CI}}{b_1 + b_2 \text{CI} e^{b_3}}
\]

where CI represents competitive effects and CL (crown length in feet) is a measure of photosynthetic potential. The multiplier decreases with
Table 4. Growth and mortality equations used in the tree and stand growth simulation program PTAEDA.

| Equation * | $r^2$ | $s_{y|x}$ |
|------------|-------|-----------|
| HIN = PHIN (0.54631 + 124.8635 CR $1.66254 e^{-1.15083 CI -6.66226 CR}$) | 0.3406 | 0.7709 |
| DIN = PDIN (0.08652 + 0.20178 CL $1.79998 e^{-1.32061 CI}$) | 0.2968 | 0.0850 |
| PLIVE = 1.08635 CR $0.07028 e^{-0.02817 CI 1.17781}$ | -- | -- |

* Where, PHIN = potential height increment, HIN = actual height increment, PDIN = potential DBH increment, DIN = actual DBH increment, CI = competition index, CR = crown ratio, CL = crown length, PLIVE = survival probability.
increasing competition and increases with increasing crown length. An equation relating actual and potential diameter growth by this factor was developed using non-linear least squares (Table 4). A normally distributed random component is added to growth determinations with variance equal to the residual mean square from the fitted regression.

The inclusion of measures of photosynthetic potential in the above models play a key role in determining thinning response. Others have included only competitive effects in such adjustment factors. However, when a tree is released by removing neighboring trees its response will depend not only on the reduction in competition for resources, but the potential it has for using those resources. Both crown length and crown ratio reflect this potential.

Crown length is incremented each year as the difference between height increment and change in clear bole length. Clear bole length is predicted annually as a function of height, DBH, age, and number of trees per acre (Table 2).

**Mortality**

The probability that a tree remains alive in a given year was assumed to be a function of its competitive stress and individual vigor as measured by photosynthetic potential. An equation describing that probability was developed using non-linear least squares and methodology proposed by Hamilton (1974) for fitting probabilities to dichotomous (0, 1) data (Table 4). The probability of survival equation took the form

$$PLIVE = b_1 CR^b_2 - b_3 CI^4 e^{-b_4}$$

where $PLIVE = $ probability that a tree remains alive

$PLIVE$ increases with increasing crown ratio and decreases with increasing competition. When crown ratio is one and competition index is zero, $PLIVE$ takes on its maximum value, $b_1 (1.08635)$. That this "probability" is greater than one is of no practical concern in predicting $PLIVE$ under stand conditions.

In PTAEDA, survival probability is calculated for each tree and used in Bernoulli trials to stochastically determine annual mortality. The calculated $PLIVE$ is compared to a uniform random variate between zero and one. If $PLIVE$ is less than this generated threshold, the tree is considered to have died.
Management Routines

After PTAEDA was initially developed for old-field, unmanaged plantations, management subroutines were added to simulate the effects of site preparation, fertilization, and thinning.

Site preparation. The efficiency of a site preparation program was considered to be the degree to which a cutover site approaches old-field conditions. Growth reductions on cutover land were assumed to be due solely to competing vegetation since degradation in site quality caused by past management practices could be described by initially specifying a lower site index. Under these assumptions, subroutine PREP was developed including a competition adjustment factor (CAF) which is multiplied times both competition index and trees per acre to reflect the increased number of stems on cutover land.

Initial attempts were made to relate CAF values to actual site preparation treatments on cutover sites. However, a lack of quantitative data and the high variability in site preparation treatments and treatment response precluded this option. Instead, two parameters, SPREP and ARLESE, are specified in the initial input list which dictate the original proportion of competing stems and the age at which the stand will be released to old-field conditions, respectively. Thus, if SPREP is set equal to one the number of additional (loblolly equivalent) competing stems is equal to the planted number of stems. These additional competitors are reduced in number linearly until ARLESE, where it is assumed that only loblolly stems remain. CAF is calculated annually from SPREP and ARLESE, when the cutover option is specified, to obtain a multiplier for competitive relationships. A manager in close contact with a specific area should have a feel for proper values of the above parameters.

Fertilization. From past simulation work (Ek and Monserud 1974, Hegyi 1974) and personal communications 1/ it was concluded that response to fertilizer treatments could be described by increases in site quality. Therefore, subroutine FERT was developed with a site adjustment factor (SAF) which acts as a multiplier on site index for fertilized stands.

Of course, the true nature of fertilizer response depends on many factors such as the element applied, the application rate, mode of application, time of year of application, physiographic province, soil texture, soil origin, soil fertility, and drainage. Sufficient data

1/ Primarily with Dr. Wayne Haynes, Director of the N.C. State Forest Fertilization Cooperative Study, Raleigh, N.C.
were not available to aggregate these effects and others and their interactions into a reliable model of fertilization response. Thus, it was not possible to calibrate SAF values with actual fertilizer treatments. Instead, three parameters, RESP, LMR, and LR, were included which specify, respectively, the maximum response in site quality, the length of time (from application) in years to attain this maximum response, and the total length of time of the response. SAF increases linearly from the age of fertilization (KFERT) until RESP is reached at age KFERT + LMR. From that time, SAF decreases linearly until site quality at age KFERT + LR is the same as the original site quality prior to fertilization. Linear functions were chosen as initial approximations in the absence of actual data. In fertilizing at planting time, LMR is assumed to be zero and only RESP and LR are specified. As with site preparation, it was thought that managers in close contact with fertilized stands would have a knowledge of proper values for these parameters.

It has recently been suggested that tree form improves as a result of fertilizer treatment. It should be pointed out that volume estimates in PTAEDA for fertilized stands do not reflect this form change, but are made using the same volume equations used for untreated stands. Thus, fertilizer yields estimated by the model may be conservative.

**Thinning.** Due to the nature of the competition relationships developed in a model such as PTAEDA, response to thinning should follow directly from the decrease in competition due to removal of neighbors. As pointed out earlier, this response is moderated somewhat by a tree's own potential for growth as measured in PTAEDA by some function of crown size.

A user may thin by rows, from below, or by a combination of these methods by specifying the thinning type in parameter ITHIN. Thinning from below includes two options specified by parameter ILOW; thinning to an upper diameter limit or thinning to a specified basal area. Depending on the value of ILOW, the upper diameter or basal area limit is specified in parameter TLIM. In either case, a lower diameter limit may be specified, DLOW, below which trees will not be removed. If the row thinning option is chosen the ith row to be thinned is specified by parameter IROW. When a combination of thinning types is used, the row thinning occurs first and the residual stand is then thinned from below as specified. Output includes the size distribution of thinned trees and an estimate of total cubic-foot volume removed for thinned stands. As with fertilization, no attempt was made to account for changes in form due to thinning treatments.

**Yield Estimates**

Estimates of production in PTAEDA are restricted to basal area per acre, trees per acre, total stem cubic-foot volume (outside bark), and
total above ground biomass. Total stem cubic-foot volume for each tree is determined by the following equation developed by Burkhart et al. (1972):

\[ V = 0.34864 + 0.00232 \, D^2 H \]

where
- \( V \) = total stem cubic-foot volume (o.b.)
- \( D \) = DBH (inches)
- \( H \) = total height (feet)

An equation for total above ground dry weight per tree was developed from the published data of Metz and Wells (1965) who determined biomass by component for 10 plantation-grown loblolly pine trees. This equation took the form

\[ W = 4.798337 + 0.043286 \, D^2 H \]

\[ r^2 = 0.98998 \quad S_{y|x} = 6.2186 \]

where
- \( W \) = total above ground dry weight per tree (pounds)

These equations are applied to tree dimensions (DBH and total height) and estimates are summed over all trees and expanded for per acre values. In addition to these estimates, the current annual increment, five-year periodic annual increment, and mean annual increment are calculated and displayed to characterize stand growth.

Growth and yield estimates were limited to these few products for simplicity. Users may apply conversion factors and ratios to obtain other products of interest to them (Burkhart 1974). To facilitate conversions and to further describe stand conditions, the mean, standard deviation and range of relevant tree dimensions, and the stand diameter distribution and average height of each diameter class for live trees, trees removed in thinning, and trees lost due to mortality are included in the output summary.

Random Number Generation

Pseudo-random numbers from various distributions were needed for the stochastic components of PTAEDA. Uniform random variates on the interval \((0, 1)\) are generated by function \(U\) which employs the multiplicative congruential technique and is based on the simple one line generator described by Marsaglia and Bray (1968). In all of a series of tests for uniformity and randomness, this function performed at least as well as the IBM supplied RANDU.

The uniform generator provides the basis for generating pseudo-random numbers from other distributions. Standard normal variates are generated by function STNORM which employs the log-sin transformation
of uniform variates described by Fishman (1973). Weibull random variates are generated in line by inverting the Weibull CDF and substituting uniform variates for values of the cumulative probabilities.

Testing and Validation Procedures

Validation of a simulation model is a difficult problem due to the many practical, theoretical, and even philosophical complexities involved (Naylor et al. 1966). Indeed, many hold the view that simulation models can never be validated, but only invalidated over time. Such models do not lend themselves to statistical tests of precision. Thus, testing and validation of PTAEDA was restricted to empirical comparisons and analysis of residuals with published and historical data.

From the 240 yield plots of Burkhart et al. (Table 1) a subset of 187 plots of old-field origin was selected for testing the predictive ability of PTAEDA. Although not an independent data set, these plots were included only in determining functional relationships used in initial stand generation (Table 2); growth functions including competitive effects were based on the mapped stand data.

Each of the 187 old-field plots was simulated by one stochastic run of PTAEDA using the existing stand feature described earlier. Deviation of observed minus predicted values, and percent deviation from observed values of trees, basal area, and total cubic-foot volume per acre were analyzed for trends with age, site, density, and their interactions. In addition, differences between mean values of these products were tested for significance.

Data were not available for either calibration or testing of the site preparation and fertilization routines. Thinning comparisons were conducted by simulating initial stands and thinning schedules described by Coile and Schumacher (1964) and Goebel et al. (1974) for stands similar to those used in model construction.

A well-known concept in ecology is that a given site will maintain a fixed amount of total biomass. The behavior of the model with respect to biomass predictions was another area of testing and validation that was examined.

RESULTS AND DISCUSSION

Preliminary trials with PTAEDA demonstrated its versatility and reliability as a prediction tool for loblolly pine growth and yield. The model proved to be moderate in terms of computer costs, requiring roughly one minute of execution time to simulate a 30-year rotation.
However, costs accumulated rapidly when making multiple runs. A complete description of input variables, example runs, and a source listing of the program for the interactive version can be found in the appendix. Card format for the batch mode version is also presented.

Initial Tests and Refinements

PTAEDA was used to generate and grow stands over a wide range of stand conditions and silvicultural treatments. These trials indicated that the model produced results which were not improbable, suggesting that logical and functional relationships were generally in good order.

One area of refinement became obvious when testing the thinning options. Past work has shown that there is little, if any, height response due to thinning (Goebel et al. 1974)---a phenomenon related to height-density independence. However, due to the construction of height growth components, the model did not behave in this way. Height growth increased rapidly due to the decreased competition resulting from thinning. Since potential diameter growth is based on attained height growth, diameter, too, increased much more rapidly than would be expected.

To correct for the above flaws, a prediction equation for maximum height, given average height of the dominant stand and age, was developed using the plantation data. This equation

\[ \text{HMAX} = b_0 + b_1 \text{HD} + b_2 \text{A} \]

where \( \text{HMAX} = \) maximum height (feet)

was differenced with respect to age to obtain an expression for maximum attainable height growth. Thus, a check on "runaway" height growth was included in the model. Subsequent thinning trials produced much more reasonable height and diameter response.

The above refinement was the only change made to the basic model as originally developed. The practice of fitting dimensional relationships and growth equations by least squares has been overlooked by many researchers in tree simulation, but clearly minimizes the amount of "fine tuning" necessary in subsequent calibration (Ek and Monserud 1974).

Unmanaged Old-Field Plantations

In general, plot yields predicted by PTAEDA were in close agreement with those observed by Burkhart et al. (1972) (Table 5). However, it can be seen that mean basal area and mean cubic-foot volume per acre were underestimated by the model and in fact differences between means of observed and predicted values were significant using a
Table 5. Mean, standard deviation, and range of predicted and observed yields on 187 old-field loblolly pine sample plots.

<table>
<thead>
<tr>
<th>Product</th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>Low</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trees</td>
<td>729.9</td>
<td>211.5</td>
<td>228</td>
<td>2028</td>
</tr>
<tr>
<td>(number/acre)</td>
<td>(742.2)</td>
<td>(234.7)</td>
<td>(300)</td>
<td>(2410)</td>
</tr>
<tr>
<td>Basal Area</td>
<td>143.2*</td>
<td>31.3</td>
<td>70.7</td>
<td>200.5</td>
</tr>
<tr>
<td>(ft^2/acre)</td>
<td>(150.7)</td>
<td>(32.7)</td>
<td>(72.0)</td>
<td>(217.2)</td>
</tr>
<tr>
<td>Cubic-foot Volume</td>
<td>2902.7*</td>
<td>1003.7</td>
<td>1036</td>
<td>5615</td>
</tr>
<tr>
<td>(ft^3/acre)</td>
<td>(3139.7)</td>
<td>(1123.7)</td>
<td>(941)</td>
<td>(6275)</td>
</tr>
</tbody>
</table>

() indicates observed yields
* indicates significant difference ($\alpha = 0.05$) between observed and predicted means
two-tailed t-test ($\alpha = 0.05$). Observed and predicted number of trees were much closer. The summary of deviations and percent deviations of predicted from observed values (Table 6) helps to quantify the relative agreement for various stand components.

Even considering the 5 percent under-prediction observed for total cubic-foot volume, this level of bias is comparable to that found in studies utilizing the diameter distribution approach to loblolly pine yield estimation. Smalley and Bailey (1974a) reported a 4 percent over-prediction while Lenhart and Clutter (1971) showed a 6 percent over-prediction.

The precision of PTAEDA also compared favorably with that shown by diameter distribution models. For cubic-foot volume, 25 percent of predicted values were within ± 5 percent of the observed, 50 percent were within ± 10 percent, and over two-thirds were within ± 15 percent. The distribution of percent deviation of predicted from observed cubic-foot yields is shown in Table 7. It can be seen that positive and negative deviations are fairly well balanced, at least about the mean deviation of 5 percent. Both Burkhart (1971) and Smalley and Bailey (1974a) reported broader distributions of percent deviation.

Percent deviation of predicted from observed values of trees, basal area, and cubic-foot volume per acre were plotted over age, site, density and all two-way interactions. In addition, percent deviations were regressed on these stand variables and interactions using multiple linear regression. From these analyses it was found that percent deviation of trees per acre increased with increasing age and decreased with increasing values of the age x site interaction. Cubic-foot volume per acre tended to be under-predicted at high values of the age x density interaction. No trends were observed in percent deviation of basal area per acre.

It should be remembered that the data set used in the above tests was not independent of all components of PTAEDA. Thus, comparisons with previous yield estimation efforts using totally independent data are somewhat inconclusive, but do aid in evaluating the model's limitations.

Thinning Trials

Considering the variability in published thinning yields, comparisons of observed and predicted thinning response showed close agreement. Coile and Schumacher (1964) presented a series of thinning schedules which would result in residual stands at age 30 having roughly the same volume as unthinned stands. In simulating these stands with PTAEDA (Table 8), this phenomenon could not be reproduced. However, using their
Table 6. Absolute deviation and percent deviation of simulated from observed yields on 187 old-field loblolly pine sample plots.

<table>
<thead>
<tr>
<th>Product</th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>Low</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absolute Deviation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trees (number/acre)</td>
<td>12.4</td>
<td>51.5</td>
<td>-84</td>
<td>382</td>
</tr>
<tr>
<td>Basal Area (ft²/acre)</td>
<td>7.6</td>
<td>27.4</td>
<td>-56.6</td>
<td>96.3</td>
</tr>
<tr>
<td>Cubic-foot Volume (ft³/acre)</td>
<td>236.9</td>
<td>567.3</td>
<td>-1215</td>
<td>2473</td>
</tr>
<tr>
<td>Percent Deviation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trees (number/acre)</td>
<td>1.16</td>
<td>5.98</td>
<td>-12.35</td>
<td>26.67</td>
</tr>
<tr>
<td>Basal Area (ft²/acre)</td>
<td>3.32</td>
<td>17.16</td>
<td>-49.35</td>
<td>57.66</td>
</tr>
<tr>
<td>Cubic-foot Volume (ft³/acre)</td>
<td>5.45</td>
<td>15.22</td>
<td>-46.12</td>
<td>48.37</td>
</tr>
</tbody>
</table>
Table 7. Distribution of percent deviation of predicted from observed cubic-foot yields.

<table>
<thead>
<tr>
<th>Percent deviation</th>
<th>Number of plots</th>
</tr>
</thead>
<tbody>
<tr>
<td>-45.1 to -55.0</td>
<td>1</td>
</tr>
<tr>
<td>-35.1 to -45.0</td>
<td>0</td>
</tr>
<tr>
<td>-25.1 to -35.0</td>
<td>2</td>
</tr>
<tr>
<td>-15.1 to -25.0</td>
<td>17</td>
</tr>
<tr>
<td>-5.1 to -15.0</td>
<td>26</td>
</tr>
<tr>
<td>-5.0 to 5.0</td>
<td>46</td>
</tr>
<tr>
<td>5.1 to 15.0</td>
<td>53</td>
</tr>
<tr>
<td>15.1 to 25.0</td>
<td>26</td>
</tr>
<tr>
<td>25.1 to 35.0</td>
<td>10</td>
</tr>
<tr>
<td>35.1 to 45.0</td>
<td>5</td>
</tr>
<tr>
<td>45.1 to 55.0</td>
<td>1</td>
</tr>
<tr>
<td><strong>total</strong></td>
<td><strong>187</strong></td>
</tr>
</tbody>
</table>
Table 8. Comparison of yield values simulated by program PTAEDA and those of Coile and Schumacher (1964) for thinned and unthinned loblolly pine plantations at age 30.

<table>
<thead>
<tr>
<th>Site Index (feet)</th>
<th>Trees at age 5 (number)</th>
<th>Ages when Thinned (years)</th>
<th>Source</th>
<th>Amount of Thinnings Basal area (feet²)</th>
<th>Average Volume (cords)**</th>
<th>Average DBH (inches)</th>
<th>Residual Stand at Age 30</th>
<th>Total Production (cords)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>600</td>
<td>17, 22</td>
<td>C&amp;S</td>
<td>45, 36</td>
<td>7, 7</td>
<td>13.6(8.8)</td>
<td>168(365)</td>
<td>170(153)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>PTAEDA</td>
<td>10, 9</td>
<td>13.4(9.6)</td>
<td>152(370)</td>
<td>151(204)</td>
<td>43.2(57.3)</td>
</tr>
<tr>
<td>800</td>
<td>17, 22</td>
<td>C&amp;S</td>
<td>58, 47</td>
<td>9, 9</td>
<td>14.6(8.3)</td>
<td>159(448)</td>
<td>185(169)</td>
<td>47.1(47.2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>PTAEDA</td>
<td>10, 12</td>
<td>13.6(8.6)</td>
<td>142(427)</td>
<td>147(185)</td>
<td>41.3(50.6)</td>
</tr>
<tr>
<td>70</td>
<td>600</td>
<td>15, 20</td>
<td>C&amp;S</td>
<td>37, 37, 39</td>
<td>6, 8, 10</td>
<td>15.1(9.8)</td>
<td>158(365)</td>
<td>196(191)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>PTAEDA</td>
<td>8, 10, 13</td>
<td>14.9(9.7)</td>
<td>139(370)</td>
<td>171(204)</td>
<td>58.9(63.6)</td>
</tr>
<tr>
<td>800</td>
<td>15, 20</td>
<td>C&amp;S</td>
<td>43, 47</td>
<td>7, 10, 13</td>
<td>14.7(9.3)</td>
<td>189(448)</td>
<td>222(211)</td>
<td>68.2(70.0)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>PTAEDA</td>
<td>9, 13, 16</td>
<td>14.0(9.0)</td>
<td>140(418)</td>
<td>157(208)</td>
<td>56.4(71.4)</td>
</tr>
</tbody>
</table>

*Site index at base age 25.

**Cord-wood volume to a 4-inch top. Values for PTAEDA were converted using ratios calculated from Burkhart, et al. 1972.

()Indicates data for unthinned stands.
guidelines for basal area removal, a greater volume of pulpwood was harvested in thinnings by PTAEDA, resulting in roughly equivalent estimates of total production. Coile and Schumacher reported much greater diameter response than was reproduced by PTAEDA, while diameter estimates for unthinned stands were comparable. A striking trend is that volume was consistently over-predicted at low densities and under-predicted for higher densities. This was true for a number of other site index values and densities not shown in Table 8. Conceivably, this may be related to the trend found for unmanaged stands in which the age and density interaction was found significant in explaining volume prediction bias. Low densities resulting from thinning accentuate this effect.

Goebel et al. (1974), working with loblolly pine, reported very little increase in total production due to thinning, and observed marked decreases in residual stand volume on thinned plots. Simulation of their thinning schedules produced similar results, although somewhat higher total production was found at more intense thinnings. Again, volume was over-predicted at lower densities (Table 9).

Average DBH on unthinned plots was comparable, although Goebel et al. (1974) observed extremely high survival (80 to 100 percent at the age of first thinning). This high survival explains the somewhat higher yields observed on unthinned plots. DBH response was much greater in the simulated plots than the observed. Again, this was probably due to the high density in the observed plots caused by the high survival rate.

In general, the thinning trials with PTAEDA demonstrated a number of concepts which are well established in the literature (Andrulot, Blackwell, and Burns 1972, Coile and Schumacher 1964, Goebel et al. 1974, Wakeley 1969). First, it was shown that no gain in residual stand volume can be expected due to thinning. Second, gains in total volume are possible, especially with frequent light to moderate thinnings, due to the anticipation of mortality. Finally, response to thinning is concentrated in diameter growth with little, if any, height growth increase.

Biomass Relations

The concept that a stand will maintain a fixed amount of total biomass was not generally reflected in PTAEDA. There was a definite tendency for stands to "break up" both in terms of volume and total biomass after age 35. Considering that both mortality and growth relationships were estimated from data for mapped stands no older than 20 years, this should not be surprising. The implicit assumption that the effects of competition and, particularly, crown ratio on growth and mortality remain the same over time is not justified. Apparently, crown ratio may become relatively small for old plantation-grown trees and yet they will remain vigorous.
Table 9. Comparison of simulated yields from PTAEDA and observed yields of Goebel et al. (1974) at age 34.

<table>
<thead>
<tr>
<th>Site Index</th>
<th>Original Spacing</th>
<th>Thinning Schedule</th>
<th>Basal Area Limit (feet)</th>
<th>Residual</th>
<th>Cubic-foot Volume/Acre</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Predicted</td>
<td>Observed</td>
</tr>
<tr>
<td>51</td>
<td>6 X 7</td>
<td>13,18,20,25,34</td>
<td>80</td>
<td>2100</td>
<td>2065</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>90</td>
<td>2311</td>
<td>2436</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>100</td>
<td>2623</td>
<td>2934</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>unthinned</td>
<td>4195</td>
<td>4726</td>
</tr>
<tr>
<td>55</td>
<td>6 X 6</td>
<td>17,20,24,30</td>
<td>85</td>
<td>2854</td>
<td>2107</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>110</td>
<td>3603</td>
<td>2854</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>135</td>
<td>4141</td>
<td>3232</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>unthinned</td>
<td>4265</td>
<td>4525</td>
</tr>
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</table>

*Site index at base age 25
CONCLUSIONS AND RECOMMENDATIONS

Despite a limited data base and the difficulty in realistically quantifying biological relationships, PTAEDA produced reasonable values in simulating unmanaged and thinned old-field plantations of loblolly pine. However, tests and comparisons indicated a number of areas where further refinement and testing are needed.

The bias observed in cubic foot yield and basal area prediction is of primary concern. Since number of trees per acre is predicted fairly closely, the bias in basal area may be attributed to an under-prediction of diameter growth. This, too, would explain bias in cubic-foot volume. A clue to the root of this bias was provided by the importance of the age x density interaction in comparisons of percent deviation from observed yields. This comparison indicated that perhaps competitive relationships over time are ill-defined, especially in relation to diameter growth. Although thinning trials were inconclusive in validating the model's diameter response, the consistent tendency to overpredict volume in heavily thinned stands is further evidence of the need for model refinement in diameter growth prediction at extreme (high and low) densities.

Mortality relationships also need to be better defined. The apparent, however slight, under-prediction of trees per acre, the premature "break-up" of older stands, and the importance of age and the age x site interaction in explaining variability of deviations from observed values of trees per acre all point to the need for refinement in this area.

It is suggested that a broader base of mapped stand data coupled with judicious construction of biologically rational growth and mortality models would considerably diminish the aforementioned limitations. Attempts to simulate unfamiliar stand conditions may be futile until these spatially dependent components are at least bracketed by data from existing stands.

It is hoped that data will become available for calibration and testing of the fertilization and site preparation routines. Only then will it be possible to test the ideas hypothesized for their effect on tree and stand growth. Trials of these management routines, along with trials of unmanaged stands, thinned stands and their combinations are tabulated in the appendix. In addition, estimates of the standard deviation and range for 10 replications of each treatment combination are presented.

Although the major justification for this study was growth and yield estimation in loblolly pine plantations, there are many other possible uses for PTAEDA. Such a model may serve to increase knowledge of growth and yield response surfaces which can later be satisfactorily described by using a more simplistic approach.

Expansion of the model to different southern pine species is a distinct possibility, as is the inclusion of variable spatial patterns for natural and direct seeded stands.
Finally, because the size and location of individual trees are known, the model lends itself directly to many tree and stand studies where spatial input is important. Understory relationships and energy flows could be reproduced by adding a solar component. Also of interest is the possibility of studying various spatial patterns of insect and disease attack and the effectiveness of various control programs.
LITERATURE CITED


<table>
<thead>
<tr>
<th>Appendix</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>40</td>
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<tr>
<td>II</td>
<td>42</td>
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<tr>
<td>III</td>
<td>47</td>
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<td>IV</td>
<td>50</td>
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<td>V</td>
<td>52</td>
</tr>
<tr>
<td>VI</td>
<td>54</td>
</tr>
</tbody>
</table>

Appendix I: Input variable definitions for both interactive and batch modes of simulation model PTAEDA.

Appendix II: Example run of the interactive version of simulation model PTAEDA.

Appendix III: Card formats and additional variable descriptions for the batch version of simulation model PTAEDA.

Appendix IV: Total cubic-foot volume of loblolly pine under various management regimes, estimated by 10 stochastic runs of tree and stand growth simulator PTAEDA.

Appendix V: Flowchart of tree and stand growth simulation program PTAEDA.

Appendix VI: Source listing of tree and stand growth simulation program PTAEDA.
Appendix I. Input variable definitions for both interactive and batch modes of simulation model PTAEDA.

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>TITLE</td>
<td>A descriptive title up to 80 characters long</td>
</tr>
<tr>
<td>NYEARS</td>
<td>Length of simulation in years</td>
</tr>
<tr>
<td>SITE</td>
<td>Site index (base age 25)</td>
</tr>
<tr>
<td>LX</td>
<td>Random number seed, any odd integer</td>
</tr>
<tr>
<td>PX</td>
<td>X parameter for planting</td>
</tr>
<tr>
<td>PY</td>
<td>Y parameter for planting</td>
</tr>
<tr>
<td>TP</td>
<td>Trees planted per acre</td>
</tr>
</tbody>
</table>

If TP is given, PX and PY are the ratio of planting distance between trees to row width, respectively. If PX and PY are omitted, square spacing is assumed.

If TP is omitted, PX and PY are the actual distances in feet between trees and between rows, respectively.

| TS            | Trees surviving per acre |
| AGE           | Age of TS for existing stands |
| SPREP         | Additional number of (loblolly equivalent) competing stems per acre for cutover sites |
| ARLSE         | Age at which a cutover site will be released from additional competing stems |
| KIN           | Age at next decision period or age of next input |
Appendix I. Input variable definitions for both interactive and batch modes of simulation model PTAEDA (continued).

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>Definition</th>
</tr>
</thead>
</table>
| ITHIN         | Thinning type:  
                1 = row thinning  
                2 = low thinning  
                3 = combination of 1 and 2 |
| KTHIN         | Age of growing season immediately after thinning |
| IROW          | \( I^{th} \) row to be thinned |
| ILOW          | Low thinning type  
                1 = diameter limit  
                2 = residual basal area limit |
| DLOW          | Lower diameter limit below which trees will  
                not be removed (low thinning option only) |
| TLIM          | Thinning limit: If  
                \( ILOW = 1 \), upper diameter limit above  
                which trees will not be removed  
                \( ILOW = 2 \), residual basal to be left  
                after thinning |
| KFERT         | Age of growing season immediately after treatment |
| RESP          | Maximum site index increase (feet) due to fertilization |
| LMR           | Length of time (years) to attain RESP  
                after initially fertilizing |
| LR            | Total length of fertilization response |
| QAGAIN        | To simulate another stand QAGAIN = YES |
Appendix II. Example run of the interactive version of simulation model PTAEDA.

```
ptaeda
CMD: run

----------- PTAEDA -----------
SIMULATION OF TREE AND STAND GROWTH IN LORLLOLY PINE PLANTATIONS

ENTER: TITLE
trial run showing the use of all management routines
ENTER: NYEARS, SITE, IX
30, 60, 571
EXISTING STAND? ENTER: YES OR NO
no
ENTER PLANTING PARAMETERS: PX, PY, TP
1, 1, 800
CUTOVER SITE?
yes
ENTER SITE PREP PARAMETERS: SPREP, ARLSE
1.10
FERTILIZE AT PLANTING TIME?
yes
ENTER FERT PARAMETERS: RESP, LR
10, 10
JUVENILE STAND OUTPUT?
yes

TRIAL RUN SHOWING THE USE OF ALL MANAGEMENT Routines

STAND SUMMARY - AGE 7

<table>
<thead>
<tr>
<th>DIMENSION</th>
<th>MEAN</th>
<th>ST. DEV.</th>
<th>MIN</th>
<th>MAX</th>
</tr>
</thead>
<tbody>
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<td>3.83</td>
<td>1.07</td>
<td>1.47</td>
<td>5.80</td>
</tr>
<tr>
<td>HT</td>
<td>16.2</td>
<td>2.1</td>
<td>9.3</td>
<td>18.9</td>
</tr>
<tr>
<td>CL</td>
<td>11.6</td>
<td>2.2</td>
<td>5.8</td>
<td>15.0</td>
</tr>
<tr>
<td>CI</td>
<td>0.7051</td>
<td>0.3570</td>
<td>0.2407</td>
<td>2.5303</td>
</tr>
</tbody>
</table>

ACRES SIMULATED 0.12500
TREES PLANTED PER ACRE 800.
TREES SURVIVING PER ACRE 664.
HEIGHT OF DOMINANT STAND 17.5

PRODUCT
YIELD  INCREM  PAI  MAI
BASEAL AREA  57.3  *****  *****  8.18
CUBIC FEET  651.  *****  *****  92.9
BIOMASS    11005. *****  *****  1572.2

D CLASS #LIVE  MEAN H  #MORT  MEAN H  #THIN  MEAN H
1     16   9.32    0  0.00    0  0.00
2     72  12.87    0  0.00    0  0.00
3   168  15.14    0  0.00    0  0.00
4   280  17.02    0  0.00    0  0.00
5   112  18.07    0  0.00    0  0.00
6    56  18.81    0  0.00    0  0.00
TOT 664.   116.  0.00    0  0.00    0  0.00
```
Appendix II. Example run of the interactive version of simulation model PTAEDA (continued).

INPUT BEFORE 8TH GROWING SEASON
STAND SUMMARY?
o
ENTER: AGE AT NEXT DECISION PERIOD
15

INPUT BEFORE 15TH GROWING SEASON
THIN STAND?
no
FERTILIZE STAND?
no
STAND SUMMARY?
yes
ENTER: AGE AT NEXT DECISION PERIOD
16

TRIAL RUN SHOWING THE USE OF ALL MANAGEMENT ROUTINES

STAND SUMMARY - AGE 15

<table>
<thead>
<tr>
<th>DIMENSION</th>
<th>MEAN</th>
<th>ST.DEV.</th>
<th>MIN</th>
<th>MAX</th>
</tr>
</thead>
<tbody>
<tr>
<td>DBH</td>
<td>6.36</td>
<td>1.95</td>
<td>2.18</td>
<td>9.96</td>
</tr>
<tr>
<td>HT</td>
<td>43.0</td>
<td>4.4</td>
<td>28.5</td>
<td>51.1</td>
</tr>
<tr>
<td>CL</td>
<td>20.3</td>
<td>4.3</td>
<td>7.8</td>
<td>27.7</td>
</tr>
<tr>
<td>CI</td>
<td>1.4739</td>
<td>0.6816</td>
<td>0.6756</td>
<td>4.2570</td>
</tr>
</tbody>
</table>

ACRES SIMULATED 0.12500
TREES PLANTED PER ACRE 800.
TREES SURVIVING PER ACRE 632.
HEIGHT OF DOMINANT STAND 48.8

PRODUCT YIELD INCREM PAI MAI
BASAL AREA 152.3 10.98 12.38 10.15
CUBIC FEET 3124. 382.5 358.4 208.3
BIOMASS 57214. 7164.6 6697.7 3814.3

<table>
<thead>
<tr>
<th>D CLASS</th>
<th># LIVE</th>
<th>MEAN H</th>
<th># MORT</th>
<th>MEAN H</th>
<th># THIN</th>
<th>MEAN H</th>
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<tbody>
<tr>
<td>2</td>
<td>16</td>
<td>28.54</td>
<td>8</td>
<td>22.63</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>3</td>
<td>24</td>
<td>34.92</td>
<td>16</td>
<td>32.56</td>
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<td>0.00</td>
</tr>
<tr>
<td>4</td>
<td>88</td>
<td>38.51</td>
<td>8</td>
<td>35.86</td>
<td>0</td>
<td>0.00</td>
</tr>
<tr>
<td>5</td>
<td>104</td>
<td>42.64</td>
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<td>0.00</td>
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<td>0.00</td>
</tr>
<tr>
<td>6</td>
<td>88</td>
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<tr>
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<td>0.00</td>
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<td>0.00</td>
</tr>
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<td>8</td>
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<td>0.00</td>
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<td>40</td>
<td>47.12</td>
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<td>TOT</td>
<td>632</td>
<td>168</td>
<td>168</td>
<td>0</td>
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</tr>
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</table>
Appendix II. Example run of the interactive version of simulation model PTAEDA (continued).

INPUT BEFORE 16 TH GROWING SEASON
THIN STAND?
yes
ENTER THINNING TYPE, AGE: ITHIN,KTHIN
2,16
ENTER LOW THIN PARAMETERS: ILOW,DLOW,TLIM
2,0,100
FERTILIZE STAND?
no
STAND SUMMARY?
no
ENTER: AGE AT NEXT DECISION PERIOD
20

INPUT BEFORE 20 TH GROWING SEASON
THIN STAND?
no
FERTILIZE STAND?
no
STAND SUMMARY?
yes
ENTER: AGE AT NEXT DECISION PERIOD
21

TRIAL RUN SHOWING THE USE OF ALL MANAGEMENT ROUTINES

STAND SUMMARY - AGE 20

<table>
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<tr>
<th>DIMENSION</th>
<th>MEAN</th>
<th>ST.DEV.</th>
<th>MIN</th>
<th>MAX</th>
</tr>
</thead>
<tbody>
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<td>1.36</td>
<td>8.32</td>
<td>13.14</td>
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<td>1.1984</td>
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</table>

ACRES SIMULATED: 0.12500
TREES PLANTED PER ACRE: 800.
TREES SURVIVING PER ACRE: 264.
HEIGHT OF DOMINANT STAND: 61.2

PRODUCT | YIELD | INCREM | PAI | MAI |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>BASAL AREA</td>
<td>153.3</td>
<td>10.58</td>
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<td>7.66</td>
</tr>
<tr>
<td>CUBIC FEET</td>
<td>3937.</td>
<td>3986.6</td>
<td>162.5</td>
<td>196.8</td>
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<tr>
<td>BIOMASS</td>
<td>72999.</td>
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VOLUME THINNED: 1085.

<table>
<thead>
<tr>
<th>D CLASS</th>
<th>#LIVE</th>
<th>MEAN H</th>
<th>#MORT</th>
<th>MEAN H</th>
<th>#THIN</th>
<th>MEAN H</th>
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<tbody>
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<td>2</td>
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<td>22.63</td>
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</tr>
<tr>
<td>4</td>
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<td>0.00</td>
<td>8</td>
<td>35.86</td>
<td>88</td>
<td>38.51</td>
</tr>
<tr>
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Appendix II. Example run of the interactive version of simulation model PTAEDA (continued).

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</tr>
<tr>
<td>16</td>
<td>60.23</td>
<td>0</td>
<td>0.00</td>
</tr>
</tbody>
</table>

INPUT BEFORE 21 TH GROWING SEASON
THIN STAND?
yes
ENTER THINNING TYPE, AGE: ITHIN,KTHIN
2,21
ENTER LOW THIN PARAMETERS: ILOW,DLow,TLIM
2,0,100
FERTILIZE STAND?
yes
ENTER FERT PARAMETERS: RESP,LR,LMR,KFERT
5,7,2,21
STAND SUMMARY?
no
ENTER: AGE AT NEXT DECISION PERIOD
25

INPUT BEFORE 25 TH GROWING SEASON
THIN STAND?
no
STAND SUMMARY?
yes
ENTER: AGE AT NEXT DECISION PERIOD
30

TRIAL RUN SHOWING THE USE OF ALL MANAGEMENT Routines

STAND SUMMARY - AGE 25

<table>
<thead>
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<th>DIMENSION</th>
<th>MEAN</th>
<th>ST.DEV.</th>
<th>MIN</th>
<th>MAX</th>
</tr>
</thead>
<tbody>
<tr>
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<td>12.88</td>
<td>1.18</td>
<td>11.10</td>
<td>15.15</td>
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<td>HT</td>
<td>67.0</td>
<td>3.2</td>
<td>60.3</td>
<td>72.4</td>
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<tr>
<td>CL</td>
<td>27.8</td>
<td>1.3</td>
<td>25.8</td>
<td>30.1</td>
</tr>
<tr>
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<td>0.6333</td>
<td>0.1012</td>
<td>0.4826</td>
<td>0.8600</td>
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<tr>
<td>ACRES SIMULATED</td>
<td>0.12500</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TREES PLANTED PER ACRE</td>
<td>800.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TREES SURVIVING PER ACRE</td>
<td>144.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HEIGHT OF DOMINANT STAND</td>
<td>63.0</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>PRODUCT</td>
<td>YIELD</td>
<td>INCREM</td>
<td>PA1</td>
<td>MA1</td>
</tr>
<tr>
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<td>-4.39</td>
<td>5.25</td>
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<td>3803.</td>
<td>196.1</td>
<td>-26.8</td>
<td>152.1</td>
</tr>
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<td>BIOMASS</td>
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<td>3659.3</td>
<td>-458.3</td>
<td>2828.3</td>
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<td>VOLUME THINNED</td>
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<td></td>
<td></td>
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<tr>
<td>D CLASS</td>
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<td>MEAN H</td>
<td>#MORT</td>
<td>MEAN H</td>
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<td>8</td>
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Appendix II. Example run of the interactive version of simulation model PTAEDA (continued).

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<table>
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</table>

**Trial Run Showing the Use of All Management Routines**

**Stand Summary - Age 30**

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<th>Dimension</th>
<th>Mean</th>
<th>Std. Dev.</th>
<th>Min</th>
<th>Max</th>
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<tbody>
<tr>
<td>DBH</td>
<td>13.79</td>
<td>1.39</td>
<td>11.63</td>
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<td>HT</td>
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<td>3.8</td>
<td>64.4</td>
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<tr>
<td>CL</td>
<td>25.4</td>
<td>1.3</td>
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<tr>
<td>CI</td>
<td>0.6886</td>
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<td>0.4924</td>
<td>0.9094</td>
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</table>

**Acres Simulated** 0.12500
**Trees Planted Per Acre** 800.
**Trees Surviving Per Acre** 144.
**Height of Dominant Stand** 65.7

**Product** YIELD INCREM PAI MAI
**Basal Area** 150.8 5.40  5.80  5.03
**Cubic Feet** 4583. 233.0 156.0 152.8
**Biomass** 85265. 4346.1 29113. 2842.2

**Volume Thinned** 2446.

<table>
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<tr>
<th>Class</th>
<th># Live</th>
<th>Mean H</th>
<th># Hort</th>
<th>Mean H</th>
<th># Thin</th>
<th>Mean H</th>
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**Another Stand?** No
Appendix III. Card formats and additional variable descriptions for the batch version of simulation model PTAEDA.

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<th>Columns</th>
<th>Variable</th>
<th>Format Type</th>
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</tr>
<tr>
<td>2</td>
<td>1 - 3</td>
<td>RUN</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>4 - 5</td>
<td>CODE</td>
<td>A</td>
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<td>NYEARS</td>
<td>I</td>
</tr>
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<td></td>
<td>11 - 15</td>
<td>SITE</td>
<td>F</td>
</tr>
<tr>
<td></td>
<td>16 - 20</td>
<td>IX</td>
<td>I</td>
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<td>21 - 25</td>
<td>PX</td>
<td>F</td>
</tr>
<tr>
<td></td>
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<td>PY</td>
<td>F</td>
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<tr>
<td></td>
<td>31 - 35</td>
<td>TS</td>
<td>F</td>
</tr>
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<td>AGE</td>
<td>F</td>
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<td>41 - 45</td>
<td>SPREP</td>
<td>F</td>
</tr>
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<td>46 - 50</td>
<td>ARLSE</td>
<td>F</td>
</tr>
<tr>
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<td>51 - 53</td>
<td>RESP</td>
<td>F</td>
</tr>
<tr>
<td></td>
<td>56 - 60</td>
<td>LR</td>
<td>I</td>
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<td>QJUV</td>
<td>A</td>
</tr>
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<td>KIN</td>
<td>I</td>
</tr>
<tr>
<td></td>
<td>71 - 75</td>
<td>KFREQ</td>
<td>I</td>
</tr>
<tr>
<td></td>
<td>76 - 77</td>
<td>NCARDS</td>
<td>I</td>
</tr>
<tr>
<td>78</td>
<td>78 - 80</td>
<td>QAGAIN</td>
<td>A</td>
</tr>
</tbody>
</table>

*Where, A = alpha-numeric, I = integer, F = floating-point, and -- indicates a name to be punched on card.
Appendix III. Card formats and additional variable descriptions for the batch version of simulation model PTAEDA (continued).

<table>
<thead>
<tr>
<th>Card</th>
<th>Columns</th>
<th>Variable</th>
<th>Format type</th>
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</thead>
<tbody>
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<td>I</td>
</tr>
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<td>I</td>
</tr>
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<td>DLOW</td>
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<td>TLIM</td>
<td>F</td>
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<td>IROW</td>
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</table>
Appendix III. Card formats and additional variable descriptions for the batch version of simulation model PTAEDA (continued).

<table>
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<tr>
<th>Variable Name</th>
<th>Definition</th>
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<td>Card 2 identification, to be punched on card</td>
</tr>
<tr>
<td>CODE</td>
<td>User supplied 2-digit code or name</td>
</tr>
<tr>
<td>QJUV</td>
<td>If output describing the juvenile stand is desired QJUV = YES</td>
</tr>
<tr>
<td>KFREQ</td>
<td>Frequency of output summaries after KIN (years)</td>
</tr>
<tr>
<td>NCARDS</td>
<td>Number of management cards (MANAG)</td>
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<tr>
<td>MANAG</td>
<td>Card 3 - NCARDS identification, to be punched on card</td>
</tr>
<tr>
<td>QOUT</td>
<td>If stand output is desired after this growing season QOUT = YES</td>
</tr>
<tr>
<td>QTREE</td>
<td>If individual tree output is desired after this growing season QTREE = YES</td>
</tr>
</tbody>
</table>
Appendix IV. Total cubic-foot volume of loblolly pine under various management regimes, estimated by 10 stochastic runs of tree and stand growth simulator PTAEDA.

<table>
<thead>
<tr>
<th>Age (years)</th>
<th>Unmanaged</th>
<th>Fertilized&lt;sup&gt;2/&lt;/sup&gt;</th>
<th>Cubic-foot Volume per Acre</th>
<th>Fertilized and Thinned&lt;sup&gt;3/&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Residual</td>
<td>Thinned&lt;sup&gt;3/&lt;/sup&gt; (total)</td>
<td>Residual</td>
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<tr>
<td>Old-field</td>
<td>10</td>
<td>1219 ± 53</td>
<td>1130 to 1307</td>
<td>2536 ± 64</td>
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<tr>
<td></td>
<td>15</td>
<td>3902 ± 38</td>
<td>3792 ± 86</td>
<td>2992 ± 40</td>
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<tr>
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<td>3844 to 3952</td>
<td>3644 to 3878</td>
<td>2927 to 3064</td>
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<tr>
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<td>25</td>
<td>4084 ± 123</td>
<td>5320 ± 141</td>
<td>3215 ± 54</td>
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<td>4723 to 5076</td>
<td>5064 to 5512</td>
<td>3040 to 3278</td>
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<tr>
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<td>30</td>
<td>5355 ± 204</td>
<td>5368 ± 245</td>
<td>4462 ± 130</td>
</tr>
<tr>
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<td>30</td>
<td>4912 to 5539</td>
<td>4884 to 5662</td>
<td>4219 to 4631</td>
</tr>
</tbody>
</table>

<sup>1/</sup> Site index 60 (base age 25), 800 trees planted per acre
<sup>2/</sup> KFERT = 20, RESP = 5, LMR = 3, LR = 7
<sup>3/</sup> KTHIN = 15, 20; low thinning to 90 ft<sup>2</sup> of basal area per acre; DLOW = 0
<sup>4/</sup> Mean ± standard deviation
  Low to High
Appendix IV. Total cubic-foot volume of loblolly pine under various management regimes, estimated by 10 stochastic runs of tree and stand growth simulator PTAEDA (continued).

<table>
<thead>
<tr>
<th>Age (years)</th>
<th>Unmanaged</th>
<th>Fertilized&lt;sup&gt;2/&lt;/sup&gt;</th>
<th>Cubic-foot Volume per Acre</th>
<th>Fertilized and Thinned&lt;sup&gt;3/&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Residual</td>
<td>Thinned (total)</td>
<td>Residual</td>
</tr>
<tr>
<td>Cutover&lt;sup&gt;5/&lt;/sup&gt;</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>920 ± 26</td>
<td>2970 ± 87</td>
<td>340 ± 66</td>
<td>2970 ± 87</td>
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<tr>
<td></td>
<td>883 to 957</td>
<td>2780 to 3083</td>
<td>245 to 428</td>
<td>2780 to 3083</td>
</tr>
<tr>
<td>15</td>
<td>1960 ± 39</td>
<td>3320 ± 59</td>
<td>1302 ± 176</td>
<td>3901 ± 69</td>
</tr>
<tr>
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<td>1883 to 2018</td>
<td>4649 to 5111</td>
<td>3242 to 3411</td>
<td>3810 to 4031</td>
</tr>
<tr>
<td>20</td>
<td>3222 ± 65</td>
<td>4826 ± 134</td>
<td>1040 to 1420</td>
<td>4536 ± 176</td>
</tr>
<tr>
<td>4300 ± 152</td>
<td>3040 to 3282</td>
<td>4867 ± 189</td>
<td>4489 ± 184</td>
<td>4197 to 4804</td>
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<tr>
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<td>4047 to 4621</td>
<td>4649 to 5115</td>
<td>4118 to 4748</td>
<td></td>
</tr>
<tr>
<td>30</td>
<td>5020 ± 190</td>
<td>4636 to 5115</td>
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</tr>
</tbody>
</table>

<sup>5/</sup>SFREP = 1., ARISE = 20.
Appendix V. Flowchart of tree and stand growth simulation program PTAEDA.
Appendix V. Flowchart of tree and stand growth simulation program PTAEDA (continued).
Appendix VI. Source listing of tree and stand growth simulation program PTAEDA.

```plaintext
$JOB  WATFIV
C
C PTAEDA
C PTAEDA IS A SIMULATION MODEL OF TREE AND STAND GROWTH
C IN MANAGED Loblolly Pine (PINUS TAEDA L.) PLANTATIONS.
C DEVELOPED BY RICHARD F. DANIELS, VP/FSU, 1975.
C
DIMENSION VGL(3),S(2)
COMMON /BLOK1/X(100),Y(100),LMORT(100),KMORT(100),D(100),
1 H(100),CL(100),CI(100),HDI(100),LEDGE(9),ACRES
COMMON /BLOK2/10S(4),DIST(9),XDIST,YDIST
COMMON /BLOK3/YCUFT(50,3),YDRI(50,3),8A(50),KJ,KX,NLIVE,
1 NTIM,H0
COMMON /BLOK4/NAME(20),NYEAR,SITE,SEXIST,EXAGE,EXTS,
1 PX,PY,TP,KOUT,KI,KTREE,QUV,QAAN
COMMON /BLOK5/SPROP,CAF,ARLSE,CLUTO
COMMON /BLOK6/KFERT,LMK,LR,RESP,SAF,WFERT
COMMON /BLOK7/KTHI,ITHI,IKWU,ILW,BLW,ILIM
COMMON /BLOK8/PLUX,PLDFT,DFLX,DELY,NRCX,NRCY,YRCX,YRCY
REAL YES/1YES/,NO/NY/
COMMON /HLK0/N
DATA 5/C.77093,0./7729/
C
C INPUT INITIAL SIMULATION CRITERIA
C
1 CALL INPUT1(X)
C
C INITIALIZE TREE AND STAND VARIABLES
C
DO 50 K=1,50
BA(K)=0.
DO 50 L=1,3
YCUFT(K,L)=0.
50 YDRI(K,L)=0.
DO 60 L=1,N
1(I)=0.
H(I)=0.
CI(I)=0.
KMORT(I)=NYEARS
60 LMORT(I)=1
KTHI=0
KOUT=0
KTREE=0
QFERT=NU
C
C GENERATE INITIAL STAND
C
CALL PLANT
CALL JUV1(X)
CALL COMP
IF(JUV=EQ.NO) GO TO 65
```
Appendix VI.  Source listing of tree and stand growth simulation program
PTAEDA (continued).

CALL OUTPUT
   KIN=KJ+1
C
C   COMMENCE ANNUAL TREE GROWTH
C
   65 KC=KJ+1
   A=KC
   DO 200 K=KC,NYEARS
      A=K
C
C   INPUT MANAGEMENT CRITERIA
C
   IF(I CUTU.EQ.YES) CALL PREP(A)
   IF(KIN .EQ.K) CALL INPUT2
   IF(KTHIN.EQ.K) CALL THIN(A)
   IF(I FERT.EQ.YES) CALL FERT(A)
   POTH=1*(SITE*SAF)*10**(-5.86537*(1./A-1./25.))
   PHIN=POTH-H0
   DO 100 I=1,N
      IF(LMORT(I).EQ.1) 100,10,90
   10 CR=CL(I)/H(I)
C
C   DETERMINE TREE MORTALITY
C
   PLIVE=1.086*C*K**.C102826*EXP(-.0281694*(C11)*CAF)
      **.1.77809)
   P=U(IX)
   IF(P.LT.PLIVE) GO TO 80
   NLIVE=NLIVE-1
   LMGRT(I)=2
   KMRT(I)=K
   GO TO 90
C
C   COMPUTE H AND D INCREMENT ON ALL TREES
C
   80 HKEU=.54631*CR**1.66254*EXP(14.2722-.1.15083*C11)
      1.*CAF-.66226*CR)
   R=STNORM(IX)
   HIN=PHIN*HRED
   HINMAX=1.0020*PHIN+.1346226
   IF(HIN.GT.HINMAX) HIN=HINMAX
   PDIN=.2695836*HIN+.2094718
   HIN=HIN+R*S(I1)
   IF(HIN.LT.0.) HIN = 0.
   DRED=.086524+.020178*CL(I)**1.179986*EXP(-1.320610)
      1.*C11)*CAF)
   DIN=PDIN*DRED+R*S(2)
   IF(DIN.LT.0.) DIN=0.
C
C   CALCULATE PRODUCTS
C
   D(I)=C(I)+DIN
   H11=H(I)+HIN
   90 L=LMGRT(I)
   DSQ=C(I)*C11)
Appendix VI. Source listing of tree and stand growth simulation program PTAEDA (continued).

```plaintext
IF (L+U+1) HA(K)+FA(K)+DSU
YCUFT(K,L)=YCUFT(K,L)+DSU*H(I)*.00232+.34864
YUWRT(K,L)=YUWRT(K,L)+DSU*H(I)*.0432865+.798337
100 CONTINUE
HA(K)=HA(K)*.005434/ACRES
DO 150 I=1,3
YCUFT(K,L)=YCUFT(K,L)/ACRES
YUWRT(K,L)=YUWRT(K,L)/ACRES
150 CONTINUE
C
C DETERMINE GROWN LENGTH
C
T=NLI/V/ACRES
DO 101 I=1,N
C(I)=0.
IF (LMUR(I),NE,1) GO TO 101
CBL=H(I)*1.61248/IT*CAF)**(.457396/D(I))*D(I)**
L =-.958067/A1*EXP(2.687682/D.74273/A
2 =2L.74093/1A1*1(I)-1.546394/D(I)
IF (H(I)-CBL-CL(I),ST,HIN) CBL=H(I)-CL(I)-HIN
CL(I)=H(I)-CBL
IF (CL(I),LT,0) CL(I)=0.
101 CONTINUE
C
C OUTPUT STAND SUMMARY
C
IF (KUUT,EQ,K) CALL OUTPUT
IF (KTREE,EQ,K) CALL TREE
200 CONTINUE
C
C MULSE KEEPING
C
CALL INPUT3
IF (AGAIN,EQ,YES) GOTO 1
STOP
END

SUBROUTINE INPUT(IX)
C SUBROUTINE INPUT IS DIVIDED INTO 3 MAIN SUB-SECTIONS
C DESIGNED TO PROMPT THE USER FOR AND READ INITIAL SIMULATION
C CRITERIA, MANAGEMENT CRITERIA, AND PROGRAM CONTINUATION
C CRITERIA. THIS SUBROUTINE IS THE ONLY ONE WHICH NEED
C BE CHANGED FOR BATCH MODE OPERATION.
C
COMMON /BLOK4/TITLE(20),NYESR,SITE,EXIST,EXAGE,EXTS,
1 PX, PY, TK,DUT,KIR,KTREE,QUV,QAING
COMMON /BLOK5/SPREP,CAF,ARLSE,QURO
COMMON /BLOK6/KFERT,LMR,LR,RESP,SAF,QTERT
COMMON /BLOK7/KTHIK,ITHIN,IROW,ILOW,DLOW,TLIM
REAL YES/YES/,NC/NO/
C
READ INITIAL SIMULATION CRITERIA
```
Appendix VI. Source listing of tree and stand growth simulation program
PTAEDA (continued).

C

WRITE(6,6001)
6001 FORMAT(1X,1X,'1',1X,5X,'PTAEDA',5X,10('=',1X))
1 * SIMULATION OF TREE AND STAND GROWTH IN
2 * Loblolly PINE PLANTATIONS */
3 * ENTER: TITLE*)
READ(9,5001) (TITLE,L), L=1,20

5001 FORMAT(20A4)
WRITE(6,6002)
6002 FORMAT(1X, 'ENTEK: NYEARS; SITE; IX')
READ(9,*) NYEARS; SITE; IX
10 WRITE(6,6003)
6003 FORMAT(1X, 'EXISTING STAND? ENTER: YES OR NO')
READ(9,5002)OEXIST
5002 FORMAT(A3)
IF(OEXIST.EQ.'NO') GO TO 20
IF(OEXIST.NE.'YES') GO TO 10
WRITE(6,6004)
6004 FORMAT('ENTER SPATIAL PARAMETERS: PX, PY, EXTS, EXAGE')
READ(9,*) PX, PY, EXTS, EXAGE
GO TO 30
20 WRITE(6,6005)
6005 FORMAT('ENTER PLANTING PARAMETERS: PX, PY, TP')
READ(9,*) PX, PY, TP
30 SPREP=0.
WRITE(6,6006)
6006 FORMAT('CUTOVER SITE? ')'
READ(9,5002) QCUTC
IF(QCUTC.EQ.'NO') GO TO 35
IF(QCUTC.NE.'YES') GO TO 30
WRITE(6,6007)
6007 FORMAT('ENTER SITE PKREP PARAMETERS: SPREP, ARLOSE')
READ(9,*) SPREP, ARLOSE
35 CAF=SPREP+1.
SAF=1.
WRITE(6,6106)

6106 FORMAT('FERTILIZE AT PLANTING TIME?')
READ(9,5002) QFERT
IF(QFERT.EQ.'NO') GO TO 36
IF(QFERT.NE.'YES') GO TO 35
WRITE(6,6107)
6107 FORMAT('ENTER FERT PARAMETERS: RESP, LR')
READ(9,*) RESP, LR
KERT=0.
LYR=0.
SAF=(SITE+RESP)/SITE
36 WRITE(6,6008)
6008 FORMAT('JUVENILE STAND OUTPUT?')
READ(9,5002) CJUV
IF(CJUV.EQ.'YES') GO TO 33
WRITE(6,6009)
6009 FORMAT('ENTER: AGE AT NEXT DECISION PERIOD')
READ(9,*) KIN
38 RETURN
Appendix VI. Source listing of tree and stand growth simulation program PTAEDA (continued).

C READ MANAGEMENT CRITERIA
C
ENTRY INPUT2
IF(KIN.EQ.0) GO TO 39
WRITE(6,6010) KIN
39 KTHIN=0
IF(KIN.EQ.NYEARS.CR.KIN.LT.10) GO TO 40
40 WRITE(6,6011)
6011 FORMAT('THIN STAND?')
READ(9,5002) QTHIN
IF(QTHIN.EQ.NO) GO TO 60
IF(QTHIN.EQ.YES) GC TO 40
WRITE(6,6012)
6012 FORMAT('ENTER THINNING TYPE, AGE: THIN,KTHIN')
READ(9,*) ITHIN,KTHIN
GO TO (150,55,56), ITHIN
50 WRITE(6,6013)
6013 FORMAT('ENTER ROW THIN PARAMETER: IROW')
READ(9,*) IROW
IF(IROW.EQ.1) GO TO 60
WRITE(6,6014)
6014 FORMAT('ENTER LOW THIN PARAMETERS: ILOW,DLGW,TLIM')
READ(9,*) ILOW,DLGW,TLIM
60 IF(KIN.EQ.NYEARS.CR.KIN.LT.15.OR.QFERT.EQ.YES) GC TO 70
QFERT=NO
WRITE(6,6015)
6015 FORMAT('FERTILIZE STAND?')
READ(9,5002) QFERT
IF(QFERT.EQ.NO) GC TO 70
IF(QFERT.EQ.YES) GC TO 60
WRITE(6,6016)
6016 FORMAT('ENTER FERT PARAMETER: RESP,LR,LMR,KFERT')
READ(9,*) RESP,LR,LMR,KFERT
70 KOUT=0
IF(KIN.EQ.NYEARS) GO TO 75
WRITE(6,6017)
6017 FORMAT('STAND SUMMARY?')
READ(9,5002) QSTAND
IF(QSTAND.EQ.NO) GO TO 80
IF(QSTAND.EQ.YES) GO TO 70
75 KOUT=KIN
80 KTREE=0
IF(KTREE.EQ.0) GO TO 90
WRITE(6,6018)
6018 FORMAT('TREE SUMMARY?')
READ(9,5002) QTREE
IF(QTREE.EQ.NO) GO TO 90
IF(QTREE.EQ.YES) GO TO 80
KTREE=KIN
90 IF(KIN.EQ.NYEARS) GO TO 95
WRITE(6,6019)
6019 FORMAT('ENTER: AGE AT NEXT DECISION PERIOD')
READ(9,*) KIN
95 RETURN

PTA02210
PTA02220
PTA02230
PTA02240
PTA02250
PTA02260
PTA02270
PTA02280
PTA02290
PTA02300
PTA02310
PTA02320
PTA02330
PTA02340
PTA02350
PTA02360
PTA02370
PTA02380
PTA02390
PTA02400
PTA02410
PTA02420
PTA02430
PTA02440
PTA02450
PTA02460
PTA02470
PTA02480
PTA02490
PTA02500
PTA02510
PTA02520
PTA02530
PTA02540
PTA02550
PTA02560
PTA02570
PTA02580
PTA02590
PTA02600
PTA02610
PTA02620
PTA02630
PTA02640
PTA02650
PTA02660
PTA02670
PTA02680
PTA02690
PTA02700
PTA02710
PTA02720
PTA02730
PTA02740
PTA02750
Appendix VI. Source listing of tree and stand growth simulation program
PTAEDA (continued).

```
C
C ENTRY INPUT3
WRITE(6,6020)
6020 FORMAT('GANOTHER STAND ??')
KEAC(9,5002) QAGAIN
RETURN
END

SUBROUTINE JUV1X
C
C SUBROUTINE JLV DETERMINES THE AGE AT WHICH
C COMPETITION BEGINS AND ADVANCES THE JUVENILE STAND
C TO THAT POINT IN TIME.
C
C COMMON /BLUK1/Y(100),Y(10U),LMORT(100),KMUPT(100),D(100),
1 HI(100),CL1I10U),C1110U),MID(100),LEDGE(9),ACRES
C COMMON /BLUK2/YCUFT(50+3),YDRT(50+3),BA(50+3),KJ,R,L,NC,LIVE,
1 NTHIN,HD
C COMMON /BLUK5/THET(20),NYEARS,SITE,EXIST,EXAGE,EXTS,
1 PX,PY,PT,KOU,T,KITHREE,KJUV,QAGAIN
C COMMON /BLUK6/SPRED,CAF,ARLSE,GCUTO
C COMMON /BLUK7/KFERT,LMR,LR,RESP,SAF,QFERT
C COMMON /BLK0D/N
C REAL YES/'YES'/,NC,'NO'
C
C DETERMINE COMPETITION AGE
C
DO 100 KJ=5,15
A=KJ
HD=(SFAF)*10**(-5.66537*(1./A-1./25.))
SPRD=TP*CAF**(-A*U1.3)*10**(-A*(1.009*HD-.0109*SQRT(HD)))
TS=SPRDP*TP
CCF=189.84-1012.6/A+.00347*HD*TS*CAF
IF(CCF<100.) GO TO 100
100 CONTINUE
10 NLIVE=TS*ACRES+.5
NMORT=N-NLIVE
NTHIN=0
C
C DISTRIBUTE MORTALITY AMONG TREES AT RANDOM
C
0U 200 IM=1,NMORT
20 IMORT=U(IMRT)*NMRT.
IF(LMORT(IMORT)<.001) GO TO 20
LMORT(IMORT)=0
KMORT(IMORT)=0
200 CONTINUE
C
C ADVANCE STAND DIMENSIONS
C
DMIN=-.13+.044649*IM+.18764E-4*AT(S*CAF)
DMIN=-.13+.044649*IM+.18764E-4*AT(S*CAF)
1 +17.7608*HD/(TS*CAF)
```
Appendix VI. Source listing of tree and stand growth simulation program PTAEDA (continued).

```
DAVE=2.959949+.0540637*MD-.52168E-4*A*(TS*CAF)
1 +18.4654*HD/(TS*CAF)
BHTAT=ALOGITS*ACRES*CAF)/ALOG(DAVE/DMIN)
4HTAT=(GAMMA(L+1/BHTAT)/DAVE)**BHTAT
DO 30 I=1,N
IF(LM(i)=1) 30,30,300
30 R=UI(I)
DO(J)=(-ALOG(R)/4HTAT)**(1/BHTAT)
H(I)=MD+.705702*(TS*CAF)**(1.262307/D(I))**EXP1.512047
1 -2.445067/A+2.581352/(A*D(I))-.3709999/D(I)**
C(n)=(1)*1.612287*(TS*CAF)**(1.457396/D(I))**D(I)**
2 -21.74093/(A*C(I))-.646384/D(I)
CL(I)=H(I)-CBL
IF(CL(I)<LT.0) CL(I)=0.
C
CALCULATE PRODUCTS
C
DSQ=D(I)*D(I)
BA(KJ)=BA(KJ)*DSQ
YDFRT(KJ,1)=YDFRT(KJ,1)+.479337+.8432865*DSQ*H(I)
YCUT(KJ,1)=YCUT(KJ,1)+.34864+.00323*DSQ*H(I)
300 CONTINUE
BA(KJ)=BA(KJ)*.05454/ACRES
YDFRT(KJ,1)=YDFRT(KJ,1)/ACRES
YCUT(KJ,1)=YCUT(KJ,1)/ACRES
RETURN
END
SUBROUTINE PLANT
C
SUBROUTINE PLANT CONTROLS ASSIGNMENT OF
C INITIAL RECTANGULAR SPACING
C
COMMON /BLOK1/X(100),Y(100),LMCRT(100),KMRT(100),D(100),
1 H(100),CL(100),CT(100),MDI(100),LEDGE(9),ACRES
COMMON /BLOK2/IOS(IS),DOS(IS),XS(IS),YS(IS)
COMMON /BLOK4/TITLE(20),NYEARS,SEXIST,EXAGE,EXTS,
1 PX,PY,KP,KIN,KTREE,QJUV,QAGAIN
COMMON /BLOK8/PLOT,PLOTY,DELX,DELY,NRCX,NRCY,YROW(10)
COMMON /BLOK9/REAL,Y/YES*,/NC/NG*/
IF(SEXIST.NE.YES) GO TO 5
C
EXISTING STAND
C
MD=SITE*10**(-.58537*(L-/EXAGE-1.2/25.))
TP=10**((1-1./.03#EXAGE)**2+ALOG(10*EXTS)+
1 EXAGE**(.0099*HD-.0109)*SQRT(MD))
C
GIVEN ONLY SPACING IN FEET
C
5 IF(TP.GT.300) GO TO 10
DELX=PX
DELY=PY
```
Appendix VI. Source listing of tree and stand growth simulation program PTAEDA (continued).

APT=DELY*DELY
TP=+3600.*APT
G=10.30

C GIVEN ONLY PLANTED TREES PER ACRE

10 IF(PX.NE.0.) GO TO 20
PX=1.
PY=1.

C GIVEN PLANTED TREES PER ACRE AND SPACING RATIO

20 APT=43560./TP
DEL=SQRT(APT/(PX*PY))
DELY=DEL*PY
ACRES=N/TP
NROWS=SQRT(FLUAT(N))+.5
PLOTX=NROWS*DELY
PLOTY=NROWS*DELY

C ASSIGN TREE COORDINATES

X(I)=DELY/2.
Y(I)=DELY/2.
YROW(I)=Y(I)
XQ=1.
YQ=0.
DO 200 I=2,N
DO 100 J=NROWS,N,NROWS
IF(I,NJ,1) GC TC 100
XQ=XQ*(-1.)
YQ=YQ+1.
X(I)=X(I-1)
JJ=J/NROWS
IF(JJ,NJ,1) YROW(JJ)=YROW(JJ-1)+DELY
GO TO 200
100 CONTINUE
X(I)=X(I-1)+XQ*DELY
GO TO 200
Y(I)=Y(I)+YQ*DELY
NQX=NROWS
NQY=NROWS
RETURN
END

SUBROUTINE THIN(A)

SURROOUTINE THIN REMOVES TREES EITHER BY ROWS OR FROM
BELOW. THINNING FROM BELOW MAY BE ACCOMPLISHED BY REMOVING
TREES BELOW A SPECIFIED DBH OR BY THINNINg TO A SPECIFIED
RESIDUAL BASAL AREA.

COMMON /BLK1/X(100),Y(100),LMORT(100),KMORT(100),D(100),
I (100),CL(100),CI(100),MID(100),LEDGE(9),ARES
COMMON /BLK3/YCUFT(50,3),YDRT(50,3),BA(50),KJ,K,NLIVE,
Appendix VI. Source listing of tree and stand growth simulation program PTAEDA (continued).

```plaintext
1 ATMIN. MD
COMMON /BLCK4/ TITLE(20), NYEAR, SITE, QEXIST, EXAGE, EXTS,
1 PX, PY, TP, KuUT, KIN, KTREE, QJUV, QAGAIN
COMMON /BLCK7/KTH, KTHN, ITHIN, IRGW, ILOW, DLOW, TLIM
COMMON /BLCK8/PLOT, PLOTX, DELX, DELY, NROX, NRCY, YROW(10)
COMMON /BLCKD/N
GO TO (1, 2, 1), ITHIN
C
C RUN THINNING
C
1 NRDUMP=MGG(NRCY, IRGW)
IF(NRDUMP.LE.0) GO TO 11
N=N-RDUMP*NROX
NRCY=NRCY-NRDUMP
PLOT=PLOT-NRDUMP*DELY
ACRES=PLOT*X*PLOT/43560.
11 CONTINUE
DO 100 I=1,N
IF(LMORT(I).NE.1) GO TO 100
DO 99 IR=1,NRCY,IRGW
IF(Y(I).NE.YROW(IR)) GO TO 99
NTHIN=NTHIN+1
NLIVE=NLIVE+1
LMORT(I)=3
KMO(I)=KTHIN
99 CONTINUE
100 CONTINUE
IF(IPTHIN.EQ.1) GO TO 3
C
C LOW THINNING
C
2 IF(ILGW.EQ.2) GO TO 22
C
DIA METER LIMIT OPTION
C
DO 200 I=1,N
IF(LMORT(I).NE.1) GO TO 200
IF(D(I).LT.DLOW OR D(I).GE.TLIM) GO TO 200
NTHIN=NTHIN+1
NLIVE=NLIVE+1
LMROT(I)=3
KMO(I)=KTHIN
200 CONTINUE
GO TO 3
C
BA LIMIT OPTION
C
22 BATH=(BA(K-1)-TLIV)*ACRES/.005454
BATHIN=0.
DO 400 I=1,N
IF(BATHIN.GE.BATH) GO TO 3
DMIN=9.56
DO 300 I=1,N
IF(LMORT(I).NE.1) GO TO 300
IF(D(I).GE.DMIN OR D(I).LT.DLOW) GO TO 300
300 CONTINUE
```
Appendix VI. Source listing of tree and stand growth simulation program PTAEDA (continued).

```
DMIN=D(I)
IMIN=I
300  CONTINUE
BATHIN=BATHIN+D(IMIN)*D(IMIN)
MTHIN=MTHIN+1
NLIVE=NLIVE-1
LMKT(IMIN)=3
KMKT(IMIN)=KTHIN
400  CONTINUE
3  IF(KTHIN.NE.NYEARS-1) GO TO 4
   K=K-1
   DO 500  I=1,N
      IF(KMORT(I).NE.K+1) GO TO 500
      DSQ=D(I)*D(I)
      BAK=BAK+DSQ*.CO5494/ACRES
      YCFT=DSQ*H(I)*.00232+.34864
      YDMT=DSQ*H(I)*.043287+.79834
      YCUFT(K,1)=YCUFT(K,1)-YCFT/ACRES
      YCUFT(K,3)=YCUFT(K,3)+YCFT/ACRES
      YDRWT(K,1)=YDRWT(K,1)-YDMT/ACRES
      YDRWT(K,3)=YDRWT(K,3)+YDMT/ACRES
   500  CONTINUE
   CALL OUTPUT
   K=K+1
   4  RETURN
END

SUBROUTINE FERT(A)

SUBROUTINE FERT SIMULATES THE EFFECTS OF
FERTILIZATION ON SITE QUALITY BY CALCULATING A SITE
ADJUSTMENT FACTOR (CAF) WHICH ACTS AS A MULTIPLIER OF
SITE INDEX.

COMMON /BLK4/TITLE(20),NYEARS,SITE,QEXIST,EXAGE,EXTS,
PX,PY,TF,KCUT,KTH,KTREE,QJUV,QAGAIN
COMMON /BLK6/KFERT,LMR,LR,RESP,SAF,QFERT
REAL NO/*NU*/
IF(A-KFERT.LE.0) GO TO 50
IF(A-KFERT.GT.LMR) GO TO 20

C    AGE LE AGE OF MAX RESPONSE (LMR)
C
SAF=RESP*(1-(KFERT+LMR-A)/LMR)
GO TO 30
20    IF(A-KFERT.GE.LR) GO TO 40

C    AGE GT AGE OF MAX RESPONSE (LMR)
C
SAF=RESP*(1+(KFERT+LMR-A)/(LR-LMR))
30    SAF=(SAF*SITE)/SITE
GO TO 50
40    SAF=1
QFERT=NU
50    RETURN
```
Appendix VI. Source listing of tree and stand growth simulation program PTAEDA (continued).

END

SUBROUTINE PREP(A)

SUBROUTINE PREP SIMULATES THE INCREASED
COMPETITION ON CUTOVER LAND BY CALCULATING A
COMPETITION ADJUSTMENT FACTOR (CAF) WHICH IS USED
TO MULTIPLY ALL COMPETITIVE COMPONENTS OF PTAEDA.

COMMON /BLOKS/SPREP,CAF,ARLSE,GCUTO
REAL NO/N1/N2/
1 IF(A.GE.ARSLSE) GO TO 10
CAF=SPREP*(1.4/ARLSE)+1
GO TO 20
10 CAF=1
QCUTO=NO
20 RETURN
ENDD

SUBROUTINE OUTPUT

SUBROUTINE OUTPUT CALCULATES AND DISPLAYS
SUMMARY STATISTICS FOR TREE AND STAND CHARACTERISTICS.

REAL MAI(3)
DIMENSION NOC(25,3),HDC(25,3),PRUD(3),YINC(3),PAI(3),
1 BAR(4),DMIN(4),DMAX(4),SD(4)
COMMON /BLK1/1(100),Y(100),LMCRT(100),KMUR(100),D(100),
1 HI(100),CL100),C(100),MG(100),LEDGE(100),ACRES
COMMON /BLK4/YCFUT(50,5),YCFUL(50,3),C(50),KJ,KJL,HIL,
1 NTHIN,H0
COMMON /BLOK5/TITLE(20),NYES,SITE,EXIST,IER,ACME,INDEX,
1 KF,PY,TP,KOUT,KIN,KTREE,JJUV,AGAIN
REAL YES/YES/,NC/NO/NC
COMMON /BLOK6/N
IF(QJUV.EQ.NO) GO TO 1
K=KJ
JJUV=NG
1 INDEX=1

CALL CALCULATE STAND SUMMARY STATISTICS

CALL STAT1(N,LMCRT,BAR1),DMIN(1),DMAX(1),SD(1),INDEX)
CALL STAT1(N,LMCRT,BAR2),DMIN(2),DMAX(2),SD(2),INDEX)
CALL STAT1(N,LMCRT,BAR3),DMIN(3),DMAX(3),SD(3),INDEX)
CALL STAT1(N,LMCRT,BAR4),DMIN(4),DMAX(4),SD(4),INDEX)
INDEX=2
CALL STAT1(N,LMCRT,DUMP1),DMIN2,DMAX2,INDEX)
MAXDC=DMAX2+.45
MINDC=DMIN2+.45
IF(MINDC.LT.1) MINDC=1

CALL CALCULATE CURRENT, PERIODIC, AND MEAN ANNUAL INCREMENT

DO 100 ID=MINDC,MAXDC

PTA05510
PTA05520
PTA05530
PTA05540
PTA05550
PTA05560
PTA05570
PTA05580
PTA05590
PTA05600
PTA05610
PTA05620
PTA05630
PTA05640
PTA05650
PTA05660
PTA05670
PTA05680
PTA05690
PTA05700
PTA05710
PTA05720
PTA05730
PTA05740
PTA05750
PTA05760
PTA05770
PTA05780
PTA05790
PTA05800
PTA05810
PTA05820
PTA05830
PTA05840
PTA05850
PTA05860
PTA05870
PTA05880
PTA05890
PTA05900
PTA05910
PTA05920
PTA05930
PTA05940
PTA05950
PTA05960
PTA05970
PTA05980
PTA05990
PTA06000
PTA06010
PTA06020
PTA06030
PTA06040
PTA06050
Appendix VI. Source listing of tree and stand growth simulation program PTAEDA (continued).

```
DO 100 L=1,3
NOC(L,L)=0
100 HOC(10,L)=0
DO 150 M=1,3
YINC(M)=9.19
150 PAI(M)=9.19
IF(KJ.EQ.K) GO TO 3
YINC(1)=BA(K)-BA(K-1)
YINC(2)=YCUFT(K-1)-YCUFT(K-1,1)
YINC(3)=YDRWT(K-1,1)-YDRWT(K-1,1)
IF(KJ.LT.5) GO TO 10 3
PAI(1)=$(BA(K)-BA(K-5))/5.
PAI(2)=$(YCUFT(K,1)-YCUFT(K-5,1))/5.
PA1(3)=$(YDRWT(K,1)-YDRWT(K-5,1))/5.
3 MAT(1)=BA(K)/K
MAT(2)=YCUFT(K,1)/K
MAT(3)=YDRWT(K,1)/K
PROD(1)=BA(K)
PROD(2)=YCUFT(K,1)
PROD(3)=YDRWT(K,1)
TS=NLI/ACRES
NMORT=NAL/NTHIN
TM=NMORT/ACRES
TT=NTHIN/ACRES

C CALCULATE DISTRIBUTION OF SIZES
C
DO 200 I=1,N
L=NCRT(I)
IF(L.EQ.0) GO TO 200
ID=DI(I)+45
IF(ID.LT.1) ID=1
NOC(I,1)=NOC(I,1)+1
HOC(I,1)=HOC(I,1)+H(I)
200 CONTINUE
DO 300 ID=MINDC,MAXDC
300 CONTINUE

C DISPLAY TREE AND STAND CHARACTERISTICS
C
WRITE(6,6100)TITLE(M),M=1,20
6100 FORMAT(1X'TREE AND STAND CHARACTERISTICS')
WRITE(6,6101)K
6101 FORMAT(1X',SUMMARY - AGE*',1/1 DIMENSION ',1'MEAN STD. DEV. MIN MAX')
WRITE(6,6102)(BAR(M),STD(M),C7(H(M),DFR(M),M=1,4)
6102 FORMAT('AGE',6X,6X,*H',5X,4(3X,F5.2)/* FLA',5X,4(3X,F5.2)*/')
WRITE(6,6103)ACRES,TP,TS,HD
6103 FORMAT(1X',ACRES SIMULATED',F10.5/1 TREES PLANTED',F10.5/1 TREES SURVIVING PER ACRE',F10.5/1 PER ACRE ')
Appendix VI. Source listing of tree and stand growth simulation program PTAEDA (continued).

2 * HEIGHT OF DOMINANT STAND, F11, 1/
WRITE (6, 6104) (PROC(N), YINC(M), PAI(M), MAI(M), M=1,3)
PTA06620
6104 FORMAT(*10PRODUCT YIELD INCREMENT PAI MAI/
1 * BASAL AREA*4, F6.1*31(FX,F6.2)1/* CUBIC FEET*, 3X,F6.0,
2 31(FX,F6.1)1/* BDMASS 1,2X,F7.0,3(1X,F7.1)1/
IF(NTHIN.LE.0) GO TO 57
WRITE (6, 6501) YCUFT(K,3)
PTA06630
6501 FORMAT(* VOLUME THINNED *, F6.0/) PT A06640
57 CONTINUE
WRITE (6, 6105)
6105 FORMAT(* OD CLASS # LIVE MEAN H # MORT MEAN H*,
1 * WITHIN MEAN H*)
DU 400 ID=MINDC, MAXDC
400 WRITE (6, 6106) ID, (NOC(ID,L), HDC(ID,L), L=1, 3)
6106 FORMAT(* ID, 3(4X,F15.3, X,F6.2))
WRITE (6, 6107) ID, IM, TT
6107 FORMAT(* TOT *, 3(4X,F5.0, 9X/) RETURN
END
SUBROUTINE COMP

SUBROUTINE COMP CALCULATES A MODIFIED
MEGYI COMETITION INDEX ON ALL LIVE TREES IN
A STAND. COMPETITORS ARE FOUND BY SAMPLING
NEIGHBORS BASED ON THEIR SIZE AND DISTANCE AWAY
BY ESSENTIALLY TAKING A POINT SAMPLE AT EACH
SUBJECT TREE WITH A BAR-10 PRISM.

DIMENSION JCIS(1)
COMMON /BLK1/X(100), Y(100), LMORT(100), KMORT(100), D(100),
1 H(100), CL(100), C1(100), MID(100), LEDGE(9), ACRE
COMMON /BLK2/IDIS(14), DIST(10), XDIST, YDIST, IM
COMMON /BLKB/PLTDX, PLOTY, DFLX, DFLY, NRDX, NRDC, YRC(10)
COMMON /BLOND/N
DATA PLOTX/2, 15/, P1/3, 14159/, JDIS/L, 9, 6, 7, 6, 5, 4, 3, 2/
1 IDIS(1)=1
DMAX=0
DO 100 I=1, N
100 IF (D11 GT DMAX) DMAX=D(11)
DISMXY=PLOTX+DMAX-DELX/2.
200 IF (X(I) GT DSYM) AND (X(I)) LT (PLUTX-DSYM) AND,
1 Y(I) GT DSYM AND (Y(I)) LT (PLUTY-DSYM)) MID(I)=1
MLESS=1
DO 500 I=1, MLESS1
500 IF (LMORT(I)=NE.1) GO TO 500
IPLUS1=1+1
DO 400 J=IPLUS1, N
400 IF (LMORT(J)=NE.1) GO TO 460
INTOR=MID(I)+MID(J)
XDIST=X(J)-X(I)
YDIST=Y(J)-Y(I)
PTA06590
PTA06820
PTA06830
PTA06840
PTA06850
PTA06860
PTA06870
PTA06880
PTA06890
PTA06900
PTA06910
PTA06920
PTA06930
PTA06940
PTA06950
PTA06960
PTA06970
PTA06980
PTA06990
PTA07000
PTA07010
PTA07020
PTA07030
PTA07040
PTA07050
PTA07060
PTA07070
PTA07080
PTA07090
PTA07100
PTA07110
PTA07120
PTA07130
PTA07140
PTA07150
Appendix VI. Source listing of tree and stand growth simulation program PTAEDA (continued).

DIST(1)=SQR(T(XDIST)XDIST*YDIST*YDIST)
IF INTUP.LT.3 GO TO 1
CALL HOWNFAR
1 PJL=I(IJ)/C(I)
I(UJ)=I(UJ)/PJL
DO 30 L=1,4
LC=IDIS(L)
LCG=JDIS(LC)
LEDGE(LC)=0
LEDGE(LC)=L(1)
IF (DIST(LC).GE.D(J)*PLOTX) GO TO 20
IF (LEDGE(LC)==EQ.0) C(I(I)=C(I)+RIJ/DIST(LC)
20 IF (DIST(LC).GE.D(I)*PLOTX) GO TO 30
IF (LEDGE(LC)==EQ.0) C(I(J)=C(I(J)+RIJ/DIST(LC)
30 IF (INTUP.LE.3) GO TO 400
400 CONTINUE
500 CONTINUE
RETURN
END

SUBROUTINE HOWNFAR
SUBROUTINE HOWNFAR CALCULATES DISTANCES BETWEEN TRESS ON MAIN AND "BORDER" PLANS FOR USE IN CALCULATING COMPETITION FOR NON-INTERIOR TREES.

COMM /BLU2/IDIS(4),DIST(9)*YDIST*YDIST
COMM /BLOK/PLIX,PLX,PLTX,DELX,DELY,NCX,YRCX,YRCW(10)
IF (DIST(6)>D) RETURN
5 DIST(5)=SQR((XDIST-PLTX)*(XDIST-PLTX)+1)
(IYDIST+YDIST)
6 DIST(2)=GO TO 10
10 DIST(6)=SQR((XDIST+PLTX)*(XDIST+PLTX)+1)
(IYDIST+YDIST)
10 IDIS(2)=6
10 IF (YDIST) 3,8,6
3 DIST(3)=SQR((XDIST 1)*YDIST)
1 (YDIST+PLTX)*(YDIST+PLTX)
10 IDIS(3)=3
10 IDIX=IDIS(2)+IDIS(3)-7
GO TO (2,4,11,11,7,9),ICCE
4 DIST(8)=SQR((XDIST 1)*YDIST)
1 (YDIST+PLTX)*(YDIST+PLTX)
10 IDIS(3)=8
10 ICOV=IDIS(2)+IDIS(3)-7
GO TO (2,4,11,11,7,9),ICCE
2 DIST(2)=SQR((XDIST+PLTX)*(XDIST+PLTX)+1)
(YDIST+PLTX)*(YDIST+PLTX)
10 IDIS(4)=2
RETURN
4 DIST(4)=SQR((XDIST+PLTX)*(XDIST+PLTX)+1)
(YDIST+PLTX)*(YDIST+PLTX)
10 IDIS(4)=4

PTA07160
PTA07170
PTA07180
PTA07190
PTA07200
PTA07210
PTA07220
PTA07230
PTA07240
PTA07250
PTA07260
PTA07270
PTA07280
PTA07290
PTA07300
PTA07310
PTA07320
PTA07330
PTA07340
PTA07350
PTA07360
PTA07370
PTA07380
PTA07390
PTA07400
PTA07410
PTA07420
PTA07430
PTA07440
PTA07450
PTA07460
PTA07470
PTA07480
PTA07490
PTA07500
PTA07510
PTA07520
PTA07530
PTA07540
PTA07550
PTA07560
PTA07570
PTA07580
PTA07590
PTA07600
PTA07610
PTA07620
PTA07630
PTA07640
PTA07650
PTA07660
PTA07670
PTA07680
PTA07690
PTA07700
Appendix VI. Source listing of tree and stand growth simulation program PTAEDA (continued).

```
RETURN
7 DIST(7)=SQR1((XDIST-PLXT)* (XDIST-PLXT)+
1 (YDIST-PLTET)* (YDIST-PLTET))
1 DIS(4)=7
RETURN
9 DIST(9)=SQR1((XDIST+PLXT)* (XDIST+PLXT)+
1 (YDIST-PLTET)* (YDIST-PLTET))
11 RETURN
END

SUBROUTINE STAT(X,N,FLAG,xbartult,nu,MAX,MIN,INDEX)
C C SUBROUTINE STAT CALCULATES THE MEAN, STANDARD
C C DEVIATION AND RANGE OF INPUT VECTOR.
C
REAL X(N),MIN,MAX
INTEGER FLAG(N)
M=0
SUMX=0.
SUMXSQ=0.
MAX=0.
MIN=1.E10
DO 100 I=1,N
   IF (FLAG(I).EQ.0) GO TO 100
   IF (FLAG(I).NE.1) GO TO 100
   IF (X(I).GE.MAX) MAX=X(I)
   IF (X(I).LT.MIN) MIN=X(I)
   IF (FLAG(I).NE.1) GO TO 100
   M=M+1
   SUMX=SUMX+X(I)
   SUMXSQ=SUMXSQ+X(I)*X(I)
100 CONTINUE
VARI=(SUMXSQ-SUMX*SUMX/M)/(M-1)
XSRT(VARI)
XBAR=SUMX/M
RETURN
END

FUNCTION U(IK)
C C GENERATES A UNIFORM(0,1) RANDOM VARIATE
C
IK=IK*65535
U=.5+IK*.2328366E-9
RETURN
END

FUNCTION SINORM(I)
C C GENERATES A STANDARD NORMAL RANDOM VARIATE
C
STNORM=1-2*ALOG(U(IK))***.5*COS(6.2838*I(IK))
RETURN
END
```
Appendix VI. Source listing of tree and stand growth simulation program
PTAEDA (continued).

SUBROUTINE TREE
RETURN
END

BLOCK DATA
COMMON /BLOCK/ N
INTEGER N/100/
END

ENTRY