SIMULATION OF INDIVIDUAL TREE GROWTH
AND STAND DEVELOPMENT
IN MANAGED LOBLOLLY PINE PLANTATIONS
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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.
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.
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, DBH^2, 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 (Honer 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 CIO 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. $R^2$ 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; Newnham (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. Monserud 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><strong>DBH (inches)</strong></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><em><em>Height</em>(feet)</em>*</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><strong>Age (years)</strong></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><strong>Density (trees/acre)</strong></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:
\[ F(y) = 1 - e^{-ay^b} \quad 0 < y < \infty \]

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

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 2. Equations used in the juvenile growth subroutine (JUV) of PTAEDA, a tree and stand growth simulator of loblolly pine.

<table>
<thead>
<tr>
<th>Equation *</th>
<th>$R^2$</th>
<th>$S_{y\cdot x}$</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCF = 180.89 - 1012.6/A + 0.00347 HD·TS</td>
<td>0.8393</td>
<td>23.22</td>
<td>Strub et al. in press</td>
</tr>
<tr>
<td>$\log_{10} HD = \log_{10} \text{SI} - 5.86537 (1/A - 1/25)$</td>
<td>---</td>
<td>---</td>
<td>Burkhart et al. 1972</td>
</tr>
<tr>
<td>$\log_{10} (TP/TS) = A(0.0130 \log_{10} TP + 0.0009HD - 0.0109 \sqrt{HD})$</td>
<td>0.8400</td>
<td>0.0042</td>
<td>Smalley and Bailey 1974a</td>
</tr>
<tr>
<td>$\text{DMIN} = 0.13291 + 0.04465HD - 0.00001876 A·TS + 17.2761 HD/TS$</td>
<td>0.7662</td>
<td>0.5645</td>
<td>Plantation Data</td>
</tr>
<tr>
<td>$\text{DAVE} = 2.95995 + 0.05406HD - 0.00005217 A·TS + 18.4654 HD/TS$</td>
<td>0.9206</td>
<td>0.3470</td>
<td>Plantation Data</td>
</tr>
<tr>
<td>$\ln H = 1.51205 + 0.7057 \ln HD + (0.2623/D) \ln TS - 2.44501/A - 3.70999/D + 2.95155/(D·A)$</td>
<td>0.9514</td>
<td>0.0697</td>
<td>Plantation Data</td>
</tr>
<tr>
<td>$\ln \text{CBL} = -2.68766 + 1.61229 \ln H + (0.45740/D) \ln TS - (8.95807/A) \ln D + 12.74273/A - 1.64638/D - 21.74093/(D·A)$</td>
<td>0.9142</td>
<td>0.1576</td>
<td>Plantation Data</td>
</tr>
</tbody>
</table>

*Where, CCF = crown competition factor, HD = height of dominant stand (feet), TP = trees planted per acre, TS = trees surviving per acre, SI = site index (feet at base age 25), DMIN = minimum DBH (inches), DAVE = average DBH (inches), H = total tree height (feet), CBL = clear bole 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

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

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

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) DIN</th>
<th>HIN*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weighted Area</td>
<td>all overlapping influence zones (Ek and Monserud 1974)</td>
<td>-0.424</td>
<td>-0.432</td>
</tr>
<tr>
<td>Overlap</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Weighted Size</td>
<td>10 foot radius (Hegyi 1974)</td>
<td>-0.236</td>
<td>-0.276</td>
</tr>
<tr>
<td>Ratio</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(\frac{D_j}{D_i})/DIST_ij</td>
<td>BAF 20</td>
<td>-0.401</td>
<td>-0.447</td>
</tr>
<tr>
<td></td>
<td>BAF 10</td>
<td>-0.415</td>
<td>-0.456</td>
</tr>
<tr>
<td>(\frac{D^2_j}{D^2_i})/DIST_ij</td>
<td>BAF 20</td>
<td>-0.240</td>
<td>-0.286</td>
</tr>
<tr>
<td></td>
<td>BAF 10</td>
<td>-0.258</td>
<td>-0.339</td>
</tr>
<tr>
<td>(\frac{D_j}{D_i})/DIST_ij</td>
<td>BAF 20</td>
<td>-0.207</td>
<td>-0.258</td>
</tr>
<tr>
<td></td>
<td>BAF 10</td>
<td>-0.219</td>
<td>-0.313</td>
</tr>
</tbody>
</table>

*Where DIN = observed DBH increment, HIN = observed total height increment, D = DBH, DIST = distance between trees 1 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
- HD = average height of dominant stand (feet)
- 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
where CR = crown ratio
CI = competition index
\( b_1 \) = 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:

\[
PDIN = 0.286583 HIN + 0.209472
\]

where PDIN = potential diameter increment (inches)
HIN = observed height increment (feet)

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

\[
\frac{b_3 - b_4 CI}{b_1 + b_2 CI + 3 e^{b_4 CI}}
\]

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.

<table>
<thead>
<tr>
<th>Equation *</th>
<th>$r^2$</th>
<th>$S_{Y\cdot X}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$HIN = PHIN (0.54631 + 124.8635 CR 1.6625 e^{-1.15083 CI} - 6.66226 CR)$</td>
<td>0.3406</td>
<td>0.7709</td>
</tr>
<tr>
<td>$DIN = PDIN (0.08652 + 0.20178 CI 1.79998 e^{-1.32061 CI})$</td>
<td>0.2968</td>
<td>0.0850</td>
</tr>
<tr>
<td>$PLIVE = 1.08635 CR 0.07028 e^{-0.02817 CI} 1.17781$</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>

* 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

\[ PLIVE = b_1 CR - b_2 CI + b_3 e^{b_4} \]

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 ARLSE, 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 ARLSE, where it is assumed that only loblolly stems remain. CAF is calculated annually from SPREP and ARLSE, 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 $K_{FERT} + LMR$. From that time, SAF decreases linearly until site quality at age $K_{FERT} + LR$ 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 $i$th 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

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

\[ r^2 = 0.98998 \quad s_{y\cdot x} = 6.2186 \]

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

$H_{\text{MAX}} = b_0 + b_1 \text{HD} + b_2 A$

where $H_{\text{MAX}}$ = 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 (number/acre)</td>
<td>729.9</td>
<td>211.5</td>
<td>228</td>
<td>2028</td>
</tr>
<tr>
<td>(ft²/acre)</td>
<td>(742.2)</td>
<td>(234.7)</td>
<td>(300)</td>
<td>(2410)</td>
</tr>
<tr>
<td>Basal Area (ft²/acre)</td>
<td>143.2*</td>
<td>31.3</td>
<td>70.7</td>
<td>200.5</td>
</tr>
<tr>
<td>Cubic-foot Volume (ft³/acre)</td>
<td>2902.7*</td>
<td>1003.7</td>
<td>1036</td>
<td>5615</td>
</tr>
<tr>
<td>(ft³/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 (α = 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><strong>Absolute Deviation</strong></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 (ft$^2$/acre)</td>
<td>7.6</td>
<td>27.4</td>
<td>-56.6</td>
<td>96.3</td>
</tr>
<tr>
<td>Cubic-foot Volume (ft$^3$/acre)</td>
<td>236.9</td>
<td>567.3</td>
<td>-1215</td>
<td>2473</td>
</tr>
<tr>
<td><strong>Percent Deviation</strong></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 (ft$^2$/acre)</td>
<td>3.32</td>
<td>17.16</td>
<td>-49.35</td>
<td>57.66</td>
</tr>
<tr>
<td>Cubic-foot Volume (ft$^3$/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>total</td>
<td>187</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</th>
<th>Volume (cords)**</th>
<th>Average DBH (inches)</th>
<th>Residual Stand at Age 30</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Basal area (feet²)</td>
<td>Volume (cords)</td>
<td>Production (cords)</td>
<td></td>
</tr>
<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) 170(153) 43.7(42.9) 57.7</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) 43.2(57.3) 62.3</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) 47.1(47.2) 65.1</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) 41.3(50.6) 63.7</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) 196(191) 60.6(63.4) 84.6</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) 58.9(63.6) 89.9</td>
</tr>
<tr>
<td>800</td>
<td>15, 20</td>
<td>C&amp;S</td>
<td>43, 47, 51</td>
<td>7, 10, 13</td>
<td>14.7(9.3)</td>
<td>189(448)</td>
<td>222(211) 68.2(70.0) 98.2</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) 56.4(71.4) 94.4</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>Cubic-foot Volume/Acre</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(feet)</td>
<td>(years)</td>
<td>Basal Area Limit (feet)</td>
</tr>
<tr>
<td>51</td>
<td>6 X 7</td>
<td>13,18,20</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25,36</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>100</td>
</tr>
<tr>
<td></td>
<td>unthinned</td>
<td></td>
<td></td>
</tr>
<tr>
<td>55</td>
<td>6 X 6</td>
<td>17,20,24</td>
<td>85</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30</td>
<td>110</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>135</td>
</tr>
<tr>
<td></td>
<td>unthinned</td>
<td></td>
<td></td>
</tr>
</tbody>
</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 over-predict 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


## APPENDICES

<table>
<thead>
<tr>
<th>Appendix</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
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<tr>
<td>II</td>
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<td>IV</td>
<td>50</td>
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<tr>
<td>V</td>
<td>52</td>
</tr>
<tr>
<td>VI</td>
<td>54</td>
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### 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>
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<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>IX</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>
<tr>
<td></td>
<td>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.</td>
</tr>
<tr>
<td></td>
<td>If TP is omitted, PX and PY are the actual distances in feet between trees and between rows, respectively.</td>
</tr>
<tr>
<td>TS</td>
<td>Trees surviving per acre</td>
</tr>
<tr>
<td>AGE</td>
<td>Age of TS for existing stands</td>
</tr>
<tr>
<td>SPREP</td>
<td>Additional number of (loblolly equivalent) competing stems per acre for cutover sites</td>
</tr>
<tr>
<td>ARLSE</td>
<td>Age at which a cutover site will be released from additional competing stems</td>
</tr>
<tr>
<td>KIN</td>
<td>Age at next decision period or age of next input</td>
</tr>
</tbody>
</table>
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\textsuperscript{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.

```plaintext
ptaeda
CMD:
run

--------- PTAEDA ---------

SIMULATION OF TREE AND STAND GROWTH IN LOROLLY 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

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<tr>
<th>DIMENSION</th>
<th>MEAN</th>
<th>ST.DEV.</th>
<th>MIN</th>
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<td>1.47</td>
<td>5.80</td>
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<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>
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<td>0.3570</td>
<td>0.2407</td>
<td>2.5303</td>
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ACRES SIMULATED 0.12500
TREES PLANTED PER ACRE 800.
TREES SURVIVING PER ACRE 664.
HEIGHT OF DOMINANT STAND 17.5

PRODUCT

<table>
<thead>
<tr>
<th>YIELD</th>
<th>INCREM</th>
<th>PAI</th>
<th>MAI</th>
</tr>
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<tbody>
<tr>
<td>BASAL AREA</td>
<td>57.3</td>
<td>*****</td>
<td>*****</td>
</tr>
<tr>
<td>CUBIC FEET</td>
<td>651.</td>
<td>*****</td>
<td>*****</td>
</tr>
<tr>
<td>BIOMASS</td>
<td>11005.</td>
<td>*****</td>
<td>*****</td>
</tr>
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</table>

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. | 136. | 0 | 0.00 | 0 | 0.00 |
```
Appendix II. Example run of the interactive version of simulation model PTAEDA (continued).

INPUT BEFORE 8 TH GROWING SEASON
STAND SUMMARY?
no
ENTER: AGE AT NEXT DECISION PERIOD
15

INPUT BEFORE 15 TH 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

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<th>MAX</th>
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<td>9.96</td>
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<td>HT</td>
<td>43.0</td>
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<td>28.5</td>
<td>51.1</td>
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<td>CI</td>
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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 | 152.5 10.98 12.38 10.15
CUBIC FEET | 3124. 382.5 358.4 208.3
BIOMASS | 57214. 7164.6 6697.7 3814.3

<table>
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<th>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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<td>0.00</td>
</tr>
<tr>
<td>4</td>
<td>88</td>
<td>38.51</td>
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<td>35.86</td>
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<td>0.00</td>
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<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>
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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

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<td>53.5</td>
<td>65.4</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  PAIL  MAI
BASAL AREA 153.3  10.58  0.19  7.66
CUBIC FEET 3937.  398.6  162.5  196.8
BIOMASS 72999.  7437.0  3157.1  3650.0

VOLUME THINNED 1085.

<table>
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<tr>
<th>D CLASS</th>
<th>#LIVE</th>
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<th>#MORT</th>
<th>MEAN H</th>
<th>#THIN</th>
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Appendix II. Example run of the interactive version of simulation model PTAEDA (continued).

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<table>
<thead>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
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<td>TOT</td>
<td>264.</td>
<td>168.</td>
<td>368.</td>
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<td></td>
</tr>
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</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**

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<th>ST.DEV.</th>
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<th>MAX</th>
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ACRES SIMULATED 0.12500

TREES PLANTED PER ACRE 800.

TREES SURVIVING PER ACRE 144.

HEIGHT OF DOMINANT STAND 63.0

**PRODUCT**

<table>
<thead>
<tr>
<th>YIELD</th>
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<th>PAI</th>
<th>MAI</th>
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<td>5.25</td>
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<tr>
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<td>152.1</td>
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<td>BIOMASS 70708.</td>
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VOLUME THINNED 2446.

**D CLASS #LIVE MEAN H #MORT MEAN H #THIN MEAN H**

2 0 0.00 8 22.63 16 28.54
Appendix II. Example run of the interactive version of simulation model PTAEDA (continued).

<table>
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TRIAL RUN SHOWING THE USE OF ALL MANAGEMENT ROUTINES

STAND SUMMARY - AGE 30

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<tr>
<th>DIMENSION</th>
<th>MEAN</th>
<th>ST. DEV.</th>
<th>MIN</th>
<th>MAX</th>
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<tbody>
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ACRES SIMULATED | 0.12500
TREES PLANTED PER ACRE | 800.
TREES SURVIVING PER ACRE | 144.
HEIGHT OF DOMINANT STAND | 65.7

PRODUCT | YIELD | INCREM | PAIN | MAI |
<table>
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VOLUME THINNED | 2446.

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<th># MORT</th>
<th>MEAN H</th>
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</table>

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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<td>RUN</td>
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<tr>
<td></td>
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<td>SITE</td>
<td>F</td>
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<td>F</td>
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<td></td>
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<td>TS</td>
<td>F</td>
</tr>
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<td></td>
<td>36 - 40</td>
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<td>F</td>
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<td>F</td>
</tr>
<tr>
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<td>ARLSE</td>
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<td>RESP</td>
<td>F</td>
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<td></td>
<td>56 - 60</td>
<td>LR</td>
<td>I</td>
</tr>
<tr>
<td></td>
<td>61 - 65</td>
<td>QJUV</td>
<td>A</td>
</tr>
<tr>
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<td>I</td>
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<td>NCARDS</td>
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<tr>
<td></td>
<td>78 - 80</td>
<td>QAGAIN</td>
<td>A</td>
</tr>
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</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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</tr>
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<td>I</td>
</tr>
<tr>
<td></td>
<td>11 - 15</td>
<td>ITHIN</td>
<td>I</td>
</tr>
<tr>
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<td>ILOW</td>
<td>I</td>
</tr>
<tr>
<td></td>
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<td>DLOW</td>
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</tr>
<tr>
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<td>TLIM</td>
<td>F</td>
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<td>IROW</td>
<td>I</td>
</tr>
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<td>KFERT</td>
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<td>LMR</td>
<td>I</td>
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<td>51 - 55</td>
<td>LR</td>
<td>I</td>
</tr>
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<td>A</td>
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<td>QTREE</td>
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</tr>
<tr>
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<td>66 - 70</td>
<td>KIN</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>CODE</td>
<td>User supplied 2-digit code or name</td>
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<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>
</tr>
<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>
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</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>Fertilized¹</th>
<th>Fertilized and Thinned²</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cubic-foot Volume per Acre</td>
<td>Residual</td>
<td>Thinned (total)</td>
</tr>
<tr>
<td>Old-field</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>1219 ± 53</td>
<td>1130 to 1307</td>
<td>2536 ± 64</td>
</tr>
<tr>
<td>20</td>
<td>3844 to 3952</td>
<td>3644 to 3878</td>
<td>2927 to 3064</td>
</tr>
<tr>
<td>25</td>
<td>4884 ± 123</td>
<td>5320 ± 141</td>
<td>3215 ± 54</td>
</tr>
<tr>
<td>30</td>
<td>5355 ± 204</td>
<td>5368 ± 245</td>
<td>4462 ± 130</td>
</tr>
</tbody>
</table>

¹Site index 60 (base age 25), 800 trees planted per acre
²$K_{FERT} = 20$, $RESP = 5$, $LMR = 3$, $LR = 7$
³$K_{THIN} = 15$, 20; low thinning to $90 \text{ft}^2$ of basal area per acre; $D_{LOW} = 0$
⁴Mean ± 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>Fertilized²/</th>
<th>Cubic-foot Volume per Acre</th>
<th>Fertilized and Thinned³/</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Residual</td>
<td>Thinned (total)</td>
<td>Residual</td>
</tr>
<tr>
<td>Cutover</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>
</tr>
<tr>
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<td>883 to 957</td>
<td>3040 to 3282</td>
<td>2780 to 3083</td>
<td>2780 to 3083</td>
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<tr>
<td>20</td>
<td>1960 ± 39</td>
<td>3198 ± 75</td>
<td>2970 ± 87</td>
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<td>1883 to 2018</td>
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<tr>
<td>25</td>
<td>3222 ± 65</td>
<td>3320 ± 59</td>
<td>1302 ± 176</td>
<td>3810 to 4031</td>
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<tr>
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<td>4200 ± 152</td>
<td>4324 to 5131</td>
<td>3242 to 3411</td>
<td>1040 to 1420</td>
</tr>
<tr>
<td>30</td>
<td>5020 ± 190</td>
<td>4489 ± 184</td>
<td>4489 ± 184</td>
<td>4536 ± 176</td>
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<tr>
<td>4769 to 5350</td>
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</table>

²/SPREP = 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.

```
$JOB    WATFIV
C
C
C PTAEDA
C PTAEDA IS A SIMULATION MODEL OF TREE AND STAND GROWTH
C IN MANAGED LODOLLY PINE (PINUS TALDA L.) PLANTATIONS.
C
C DEVELOPED BY RICHARD F. DANIELS, VPI&SU, 1975.
C
COMMON /VGL(3),S(2)
COMMON /BLOK1/X(100),Y(100),LMORT(100),KMT(100),D(100),
1 H(100),CL(100),CI(100),LID(100),LEDGE(9),ACRES
COMMON /BLOK2/DIR(4),DIST(9),XDIST,YDIST
COMMON /BLOK3/YCUFT(50,3),YDRT(50,3),BA(50),KJ,K,KNLIVE,
1 NTHIN,HD
COMMON /BLOK4/TITLE(20),NYEARS,SITE,EXIST,EXAGE,EXTS,
1 PX,PY,TP,KOUT,KI,KTREE,WJUV,WAGAIN
COMMON /BLOK5/SPREP,CAF,ARLF,CGUTO
COMMON /BLOK6/KEFT,LMH,LR,RESP,SAP,WEFT
COMMON /BLOK7/KTHI,RETH,ILH,DILW,DLW,ILIN
COMMON /BLOK8/PLIX,PLX,DIF,DELX,NRCX,WRXW,WRXW1
REAL YES,'YES','NO','NO'
COMMON /LWUK/N
DATA S/G,17093,0.7129/1
C
C INPUT INITIAL SIMULATION CRITERIA
C
1 CALL INPUT(I)
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 YDRT(K,L)=0.
DO 60 L=1,N
0(1)=0.
H(1)=0.
CL(1)=0.
C(1)=0.
KMRT(1)=NYEARS
60 LMRT(1)=1
KTHI=0
KOUT=0
KUNG=0
QFRT=NO
C
C GENERATE INITIAL STAND
C
CALL PLANT
CALL JUV(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 COMMENCE ANNUAL TREE GROWTH

65 KC=KJ+1
A=KC
DO 200 K=KC,NYEARS
A*K

C INPUT MANAGEMENT CRITERIA

C IF(GCUTU.EQ.YES) CALL PREPA
C IF(KIN.EQ.KJ) CALL INPUT2
C IF(KTHIN.EQ.K1) CALL THIN(A)
C IF(QFERT.EQ.YES) CALL FERT(A)
PHIN=POTH-HD
DO 100 I=1,N
IF(LMORT(I-1).LT.10C,10,90
10 CR=CL(I)/H(I)

C DETERMINE TREE MORTALITY

C
PLIVE=1.086*CK**.C102826*EXP(-.0281694*(CI(I)*CAF)
1 **1.177809)
P=U(I)
IF(P.LT.PLIVE) GOTO 80
NLIVE=NLIVE-1
LMORT(I-1)=2
KMORT(I)=K
GOTO 90

C COMPUTE H AND D INCREMENT ON ALL TREES

80 HKRU=.54631*CR**1.66254*EXP(4.2722-1.15063*CI(I)
1 *CAF-4.66226*CR
R=STNORM(I)
HIN=PHIN*HRED
HINMAX=1.00206*PHIN+.1346206
IF(HIN.GT.HINMAX) HIN=HINMAX
PDIN=.2658336*HIN+.209478
HIN=HIN+R*S(I)
IF(HIN.LT.0.) HIN=0.
DRED=.06524+.020178*CI(I)**1.179986*EXP(-1.320610
1 *CI(I)*CAF)
DIN=PDIN*DRED+R*S(2)
IF(DIN.LT.0.) DIN=0.

C CALCULATE PRODUCTS

C
D(I)=D(I)+DIN
H(I)=H(I)+HIN
90 L=LMORT(I)
DSQ=D(I)+D(I)
Appendix VI. Source listing of tree and stand growth simulation program PTAEDA (continued).

IF(L+U.1) HA(K)=4A(K)+DG
YCUFT(K,L)=YCUFT(K,L)+DG*(H(I)**.00232+34864
YORWT(K,L)=YORWT(K,L)+DG*(H(I)**.0432865+.798337
100 CONTINUE
HA(K)=HA(K)*.005454/ACRES
DO 150 L=1,3
YCUFT(K,L)=YCUFT(K,L)/ACRES
YORWT(K,L)=YORWT(K,L)/ACRES
150 CONTINUE

C DETERMINE GROWN LENGTH
C
C T=NLIVE/ACRES
DO 101 I=1,N
CL(I)=0.
IF(LMURTH(I).NE.1) GO TO 101
CBL(K(I))=1.61228/E**((.157396/D(I))*D(I)**
1 (-8.958067/A)*EXP(-2.687682+12.74273/A
2 +21.74093/IA))
CL(I)=CL(I)-CBL
IF(CL(I).GT.HI) CBL=CL(I)-HI
CL(I)=CL(I)-CBL
IF(CL(I).LT.0) CL(I)=0.
101 CONTINUE
HO=POTH
CALL COMP
C OUTPUT STAND SUMMARY
C IF(CL(K).EQ.K) CALL OUTPUT
IF(KTKEQ(K).NE.K) CALL TREE
200 CONTINUE
C Hulse keeping
C CALL INPUT3
IF(JAGAIN.EQ.NO) GO TO 1
STOP
END

SUBROUTINE INPUT(I)
C
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),YEARS,SITE,EXIST,EXAGE,EXTS,
LP,XP,YP,KOUT,KIN,KTREE,QJUV,QAGAIN
COMMON /BLOK5/SPREP,CAF,ARLSE,QCUTO
COMMON /BLOK6/KFERT,LMR,LR,RESP,SAF,QFERT
COMMON /BLOK7/KTHIN,IIN,IRW,ILCW,IBM,LLOW,LLOW,TLM
REAL YES/YES/,NO/NO/
C
C READ INITIAL SIMULATION CRITERIA

PTAO1110
PTAO1112
PTAO1113
PTAO1114
PTAO1115
PTAO1116
PTAO1117
PTAO1118
PTAO1119
PTAO1200
PTAO1210
PTAO1220
PTAO1230
PTAO1240
PTAO1250
PTAO1260
PTAO1270
PTAO1280
PTAO1290
PTAO1300
PTAO1310
PTAO1320
PTAO1330
PTAO1340
PTAO1350
PTAO1360
PTAO1370
PTAO1380
PTAO1390
PTAO1400
PTAO1410
PTAO1420
PTAO1430
PTAO1440
PTAO1450
PTAO1460
PTAO1470
PTAO1480
PTAO1490
PTAO1500
PTAO1510
PTAO1520
PTAO1530
PTAO1540
PTAO1550
PTAO1560
PTAO1570
PTAO1580
PTAO1590
PTAO1600
PTAO1610
PTAO1620
PTAO1630
PTAO1640
PTAO1650
Appendix VI. Source listing of tree and stand growth simulation program
PTAEDA (continued).

C

WRITE(6,6001)
6001 FORMAT(/15x,LO(4,''),5x,'PTAEDA',5X,10(*-1)/*
1 ' SIMULATION OF TREE AND STAND GROWTH IN,'
2 ' LUMULY PINE PLANTATIONS '*/
3 ' ENTER: TITLE'
READ(9,5001) (TITLE(L),L=1,20)

5001 FORMAT(20A4)
WRITE(6,6002)
6002 FORMAT(' ENTER: YEAR,SITE,IX*)
READ(9,*),N YEARS,SITE,IX
10 WRITE(6,6003)
6003 FORMAT(' ENTER SPATIAL PARAMETERS: PX,PY,TS,AGE*)
READ(9,5002) PX,PY,TS,AGE
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(' ENTER SITE PREP PARAMETERS: SPREP,ARLSE*)
READ(9,5002) SPREP,ARLSE
35 CA0=SPREP+1
WRITE(6,6106)
6106 FORMAT(' ENTER FERTILIZE AT PLANTING TIME?*)
READ(9,5002) QFERT
IF(QFERT.EQ.NO) GO TO 36
IF(QFERT.EQ.YES) GO TO 35
WRITE(6,6107)
6107 FORMAT(' ENTER FERT PARAMETERS: RESP, LR*)
READ(9,*), RESP, LR
KFR=0
L4R=0
SAF=SITE+RESP/SITE
WRITE(6,6008)
6008 FORMAT(' ENTER 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.NYEARS) GO TO 39
   WRITE(6,601G) KIN
   601 FORMATTF/* INPUT BEFORE 12TH GROWING SEASON*/
   39 KTHIN=0
   IF(KIN.EQ.NYEARS.OR.KIN.LE.10) GO TO 60
   WRITE(6,6011)
6011 FORMATT/ THIN STAND?*/
   READ(9,5002) QTHIN
   IF(QTHIN.EQ.NO) GO TO 60
   IF(QTHIN.EQ.YES) GC TO 40
   WRITE(6,6012)
6012 FORMATT/* ENTER THINNING TYPE, AGE: ITHIN,KTHIN*/
   READ(9,*) ITHIN,KTHIN
   GO TO (50,55,50), ITHIN
50 WRITE(6,6013)
6013 FORMATT/* ENTER ROw THIN PARAMETER: IROW*/
   READ(9,*) ITHIN,EQ+1) GO TO 60
55 WRITE(6,6014)
6014 FORMATT/* ENTER LOW THIN PARAMETERS: ILOW,DLOW,TLIM*/
   READ(9,*) ILOW,DLOW,TLIM
60 IF(KIN.EQ.NYEARS.OR.KIN.LE.15.OR.QFERT.EQ.YES) GC TO 70
   QFERT=NO
   WRITE(6,6015)
6015 FORMATT/ FERTILIZE STAND?*/
   READ(9,5002) QFERT
   IF(QFERT.EQ.NO) GC TO 70
   IF(QFERT.EQ.YES) GC TO 40
   WRITE(6,6016)
6016 FORMATT/* ENTER FERT PARAMETERS: RESP,LR,LMR,KFERT*/
   READ(9,*) RESP,LR,LMR,KFERT
70 KOUT=0
   IF(KIN.EQ.NYEARS) GO TO 75
   WRITE(6,6017)
6017 FORMATT/* STAND SUMMARY*/
   READ(9,5002) QSTAND
   IF(QSTAND.EQ.NO) GO TO 80
   IF(QSTAND.EQ.YES) GC TO 70
75 KOUT=KIN
80 KTREE=0
   IF(KTREE.EQ.0) GO TO 90
   WRITE(6,6018)
6018 FORMATT/* TREE SUMMARY*/
   READ(9,5002) QTREE
   IF(QTREE.EQ.NO) GO TO 90
   IF(QTREE.EQ.YES) GC TO 80
   KTREE=KIN
90 IF(KIN.EQ.NYEARS) GO TO 95
   WRITE(6,6019)
6019 FORMATT/* ENTER: AGE AT NEXT DECISION PERIOD*/
   READ(9,*) KIN
95 RETURN
```
Appendix VI. Source listing of tree and stand growth simulation program
PTAEDA (continued).

```plaintext
ENTRY INPUT
WRITE(6,6020)
6020 FORMAT('DO ANOTHER STAND ?')
READ(9,5002) QAGAIN
RETURN
END

SUBROUTINE JUV(IK)

SUBROUTINE JUV DETERMINES THE AGE AT WHICH
COMPETITION BEGINS AND ADVANCES THE JUVENILE STAND
TO THAT POINT IN TIME.

COMMON /BLUK1/X(100),Y(100),LMORT(100),KMUHT(100),C(100),
           HI(100),CI(100),CII(100),MID(100),LEDGE(9),ACRES
COMMON /BLUKJ/YCUTF(50,3),VCRWT(50,3),BA(50),KJ,K,NLIVE,
           NTHIN,HQ
COMMON /BLKD4/TITLE,J,NYEAR,SITE,QUEST,EXAGE,EXTS,
              PX,PY,PKUT,PKH,KTREE,QJUV,QAGAIN
COMMON /BLKD5/SPREP,CAF,ARLSE,QAUTO
COMMON /BLKD6/KFERT,LHR,LR,RESP,SAF,QFERT
COMMON /BLKD7/N
REAL YES/1,NC/1,

DO 100 KJ=5,15
   A=KJ
   HD=(SITE*SAF)*10*(196537+(1./A-1./25.))
   SPROP=(TP*CAF)**(-A*.013)**10**(-A*(.0009*HD-.0109*SQRT(HD)))
   TS=SPROP*TP
   IF(CCF.1100.) GO TO 10
  10 NLIVE=TS*ACRES+.5
   NMORT=N-NLIVE
   NTHIN=0
  CONTINUE

DISTRIBUTE MORTALITY AMONG TREES AT RANDOM

DO 200 IM=1,NMORT
   IMORT(U(IK))=IMORT(U(IK))+1.
   IF(LMORT(IMORT),NE.1) GO TO 20
   LMORT(IMORT)=0
   KMORT(IMORT)=0
   CONTINUE

ADVANCE STAND DIMENSIONS

DMIN=13+.044449*HD-.18764*4*A*(TS*CAF)
  +17.27608*HD/(TS*CAF)
```

```markdown
<table>
<thead>
<tr>
<th>Line</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-10</td>
<td>ENTRY INPUT</td>
</tr>
<tr>
<td>11</td>
<td>WRITE(6,6020)</td>
</tr>
<tr>
<td>12</td>
<td>6020 FORMAT('DO ANOTHER STAND ?')</td>
</tr>
<tr>
<td>13</td>
<td>READ(9,5002) QAGAIN</td>
</tr>
<tr>
<td>14</td>
<td>RETURN</td>
</tr>
<tr>
<td>15</td>
<td>END</td>
</tr>
<tr>
<td>25</td>
<td>SUBROUTINE JUV(IK)</td>
</tr>
<tr>
<td>30</td>
<td>COMMON /BLUK1/X(100),Y(100),LMORT(100),KMUHT(100),C(100),</td>
</tr>
<tr>
<td>31</td>
<td>HI(100),CI(100),CII(100),MID(100),LEDGE(9),ACRES</td>
</tr>
<tr>
<td>32</td>
<td>COMMON /BLUKJ/YCUTF(50,3),VCRWT(50,3),BA(50),KJ,K,NLIVE,</td>
</tr>
<tr>
<td>33</td>
<td>NTHIN,HQ</td>
</tr>
<tr>
<td>34</td>
<td>COMMON /BLKD4/TITLE,J,NYEAR,SITE,QUEST,EXAGE,EXTS,</td>
</tr>
<tr>
<td>35</td>
<td>PX,PY,PKUT,PKH,KTREE,QJUV,QAGAIN</td>
</tr>
<tr>
<td>36</td>
<td>COMMON /BLKD5/SPREP,CAF,ARLSE,QAUTO</td>
</tr>
<tr>
<td>37</td>
<td>COMMON /BLKD6/KFERT,LHR,LR,RESP,SAF,QFERT</td>
</tr>
<tr>
<td>38</td>
<td>COMMON /BLKD7/N</td>
</tr>
<tr>
<td>39</td>
<td>REAL YES/1,NC/1,</td>
</tr>
<tr>
<td>40</td>
<td>DO 100 KJ=5,15</td>
</tr>
<tr>
<td>41</td>
<td>A=KJ</td>
</tr>
<tr>
<td>42</td>
<td>HD=(SITE*SAF)<em>10</em>(196537+(1./A-1./25.))</td>
</tr>
<tr>
<td>43</td>
<td>SPROP=(TP<em>CAF)**(-A</em>.013)<strong>10</strong>(-A*(.0009<em>HD-.0109</em>SQRT(HD)))</td>
</tr>
<tr>
<td>44</td>
<td>TS=SPROP*TP</td>
</tr>
<tr>
<td>46</td>
<td>IF(CCF.1100.) GO TO 10</td>
</tr>
<tr>
<td>47</td>
<td>NLIVE=TS*ACRES+.5</td>
</tr>
<tr>
<td>48</td>
<td>NMORT=N-NLIVE</td>
</tr>
<tr>
<td>49</td>
<td>NTHIN=0</td>
</tr>
<tr>
<td>50</td>
<td>CONTINUE</td>
</tr>
<tr>
<td>55</td>
<td>DO 200 IM=1,NMORT</td>
</tr>
<tr>
<td>56</td>
<td>IMORT(U(IK))=IMORT(U(IK))+1.</td>
</tr>
<tr>
<td>57</td>
<td>IF(LMORT(IMORT),NE.1) GO TO 20</td>
</tr>
<tr>
<td>58</td>
<td>LMORT(IMORT)=0</td>
</tr>
<tr>
<td>59</td>
<td>KMORT(IMORT)=0</td>
</tr>
<tr>
<td>60</td>
<td>CONTINUE</td>
</tr>
<tr>
<td>65</td>
<td>DMIN=13+.044449<em>HD-.18764</em>4<em>A</em>(TS*CAF)</td>
</tr>
<tr>
<td>66</td>
<td>+17.27608<em>HD/(TS</em>CAF)</td>
</tr>
</tbody>
</table>
```
Appendix VI. Source listing of tree and stand growth simulation program PTAEDA (continued).

\[ \text{DAVE} = 2.459949 + 0.054063 \times \text{HD} - 0.5168 \times \text{IT} \times \text{CAF} \]

\[ \text{BHA} = \text{ALOG}((\text{IT} \times \text{ACRES} \times \text{CAF}) / \text{ALOG}((\text{DAVE} / \text{DMIN})) \times \text{BHA} \]

\[ \text{DO 30 \text{I} = 1, \text{N}} \]

\[ \text{IF}((\text{LMCLT} \times 1) - 300) \geq 300 \]

\[ \text{R} = \text{UI}(\text{X}) \]

\[ \text{D} \text{I} = (-\text{ALOG}(\text{R}) / \text{BHA}) \times \text{I} / \text{BHA} \]

\[ \text{H} \text{I} = \text{H} \text{D} \times \text{I} + 0.262307 \times \text{D} \times \text{I} \times \text{EXP}(1.52047) \]

\[ \text{I} = -2.44507 / \text{A} + 2.551552 / (\text{A} \times \text{D} \times \text{I}) - 3.70999 / (\text{D} \times \text{I}) \]

\[ \text{CBI} = (\text{I} \times 1.61223 \times \text{I} \times \text{CAF}) \times \text{EXP}(-1.130999 / \text{D} \times \text{I}) \]

\[ \text{C} \text{ALCUB} = \text{C} \text{ALCUB} + \text{A} \times \text{K} \times \text{ACRES} / \text{ACRES} \]

\[ \text{YORH} = \text{YORH} + \text{A} \times \text{K} \times \text{ACRES} / \text{ACRES} \]

\[ \text{RETURN} \]

\[ \text{END} \]

SUBROUTINE PLANT

SUBROUTINE PLANT CONTROLS ASSIGNMENT OF INITIAL RECTANGULAR SPACING.

COMMON /BLOK/: X(100), Y(100), LMORT(100), KMORT(100), D(100),

H(100), CL(100), CT(100), MID(100), LEDGE(9), ACRES

COMMON /BLOK/: ID(10), DIST(9), XDIST, YDIST

COMMON /BLOK/: TITLE(20), YEARS, SITE, QEXIST, EXAGE, EXSTS

PX, PY, TX, OUT, X, K, TREE, QJUV, QAGAIN

COMMON /BLOK/: PLOTS, PLOTS, DELX, DELY, NRCK, NROW, YROW(10)

REAL YES/YES, NC/NC/

IF(QEXIST .NE. YES) GO TO 5

EXISTING STAND

\[ \text{HD} = \text{SITE} \times \text{D} \times \text{I} \times (5.81537 - \text{EXAGE} - 0.25) \]

\[ \text{TP} = 10 \times (1.1 - 0.01 \times \text{EXAGE}) \times \text{ALOG}((\text{EXST}) \times \text{H} \times 0.009 + \text{HD} - 0.109 \times \text{SQRT}(\text{HD})) \]

GIVEN ONLY SPACING IN FEET

\[ \text{IF}((\text{TP} - 300) \geq 10) \]

\[ \text{DELX} = \text{PX} \]

\[ \text{DELY} = \text{PY} \]
Appendix VI. Source listing of tree and stand growth simulation program PTAEDA (continued).

APT=DELX*DELY
TP=43560./APT
GO TO 30
C
GIVEN ONLY PLANTED TREES PER ACRE.
C
10 IF (PX.NE.0.) GO TO 20
PX=1.
PY=1.
C
GIVEN PLANTED TREES PER ACRE AND SPACING RATIO.
C
20 APT=43560./TP
DEL=SQR(APT/(PX*PY))
DELX=DEL*PX
DELY=DEL*PY
30 ACRES=N/TP
NROWS=SQR(FLUAT(N)+.5)
PLOTX=NROWS*DELX
PLOTY=NROWS*DELY
C
ASSIGN TREE COORDINATES.
C
X(I)=DELX/2.
Y(I)=DELY/2.
YROW(I)=Y(I)
QX=1.
QY=0.
DO 200 I=2,N
DO 100 J=NROWS,N,NROWS
IF (I.NE.J) GG TO 100
QX=QX*(-1.)
QY=QY+.1
X(I)=X(I-1)-QX/2
Y(I)=Y(I-1)+QY/2
GO TO 200
100 CONTINUE
X(I)=X(I-1)+QX*DELX
Y(I)=Y(I-1)+QY*DELY
NCG=NROWS
NGY=NROWS
RETURN
END

SUBROUTINE THIN(A)
C
SURROUTINE THIN REMOVES TREES EITHER BY ROWS OR FROM
BETWEEN. THINNING FROM BELOW MAY BE ACCOMPLISHED BY REMOVING
TREES BELOW A SPECIFIED DBH OR BY THINNING TO A SPECIFIED
RESIDUAL BASAL AREA.
C
COMMON /BLK1/(X(1CO0),Y(1CO0),LMORT(100),KMORT(100),D(100),
I(100),CL(100),CI(100),MID(100),LEDGE(9),ACRES
COMMON /BLK3/YCUFT(50,3),YDRWT(50,3),BA(150),KJ,K,NLIVE,
C
PTA03860
PTA03870
PTA03880
PTA03890
PTA03900
PTA03910
PTA03920
PTA03930
PTA03940
PTA03950
PTA03960
PTA03970
PTA03980
PTA03990
PTA04000
PTA04010
PTA04020
PTA04030
PTA04040
PTA04050
PTA04060
PTA04070
PTA04080
PTA04090
PTA04100
PTA04110
PTA04120
PTA04130
PTA04140
PTA04150
PTA04160
PTA04170
PTA04180
PTA04190
PTA04200
PTA04210
PTA04220
PTA04230
PTA04240
PTA04250
PTA04260
PTA04270
PTA04280
PTA04290
PTA04300
PTA04310
PTA04320
PTA04330
PTA04340
PTA04350
PTA04360
PTA04370
PTA04380
PTA04390
PTA04400
Appendix VI. Source listing of tree and stand growth simulation program PTAEDA (continued).

```
1 KTHIN:HD
COMMON/BLCK4/TITLE(20),NYEARS,SITE,EXIST,EXAGE,EXTS,
1 PX,PY,TP,KUUT,KTREE,WTREE,WTREE,WTREE,
COMMON /BLCK7/KTHIN,ITHIN,IFR,ITHIN,IFR,IFR,ITHIN,IFR,ITHIN,IFR
COMMON/BLCK8/PLGTX,PLGTY,DELX,DELY,NDL_NM,NDL_NM,NDL_NM,
COMMON/BLKD/N
GO TO (1,Z,Y),ITHIN
C
C ROW THINNING
C
1 NRNDUMP=NGD(NRGY,IPRW)
IF(NRNDUMP.LE.0) GO TO 11
N=N-NRNDUMP*NRGX
NRGY=NRGY-NRNDUMP
PLGTX=PLGTX-NRNDUMP*DELY
ACRES=PLGTX*PLGTY/43560.
11 CONTINUE
DO 100 I=1,N
IF homic(1).NE.1) GO TO 100
DO 99 IR=1,NRGY,IPRW
IF(Y(I).NE.YROW(IR)) GO TO 99
NTHIN=NTHIN+1
NLIVE=NLIVE-1
LMORT(I)=1
200 CONTINUE
GO TO 3
C
C LOW THINNING
C
2 IF(LOW.EQ.2) GO TO 22
C
DIAMETER LIMIT OPTION
C
DO 300 I=1,N
IF(IRMORT(I).NE.1) GO TO 300
IF(Y(I).LT.OLW. OR. Y(I).GE.TLIM) GO TO 300
NTHIN=NTHIN+1
NLIVE=NLIVE-1
LMORT(I)=3
200 CONTINUE
GO TO 3
C
BA LIMIT OPTION
C
22 BATH=(BA(K-1)-TLIV)*ACRES/.005494
BATHN=0.
DO 400 I=1,N
IF(BATHN.GE.BATH) GO TO 3
DLMN=9.E6
DO 400 I=1,N
IF(LMORT(I).NE.1) GO TO 300
IF(Y(I).GE.DLMN. OR. Y(I).LT.OLW) GO TO 300
```

Appendix VI. Source listing of tree and stand growth simulation program PTAEDA (continued).

```
OMIN=D(I)
IMIN=I
300 CONTINUE
BATHIN=BATHIN+D(IMIN)*D(IMIN)
NTHIN=NTHIN+1
NLIVE=NLIVE-1
LMORT(IMIN)=3
KMORT(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)
BA(I)=BA(I)-DSQ*.05434/ACRES
YCFT=DSQ*H(I)*.00232+.74864
YOWT=DSQ*H(I)*.043284+.79834
YCUFT(K,I)=YCUFT(K,1)-YCFT/ACRES
YCUFT(K,3)=YCUFT(K,3)+YCFT/ACRES
YDRWT(K,1)=YDRWT(K,1)-YOWT/ACRES
YDRWT(K,3)=YDRWT(K,3)+YOWT/ACRES
500 CONTINUE
CALL OUTPUT
K=K+1
4 RETURN
END

SUBROUTINE FERT(A)
C SUBROUTINE FERT SIMULATES THE EFFECTS OF
C FERTILIZATION ON SITE QUALITY BY CALCULATING A SITE
C ADJUSTMENT FACTOR (CAF) WHICH ACTS AS A MULTIPLIER OF
C SITE INDEX.
C
COMMON /6LOK4/TITLE(20),NYEARS,SITE,QEXIST,EXAGE,EXTS,
1 PX,PY,KUT,KIR,KTREE,QJUV,QAGAIN
COMMON /6LOK6/KFEFT,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)
C
SUBROUTINE PREP SIMULATES THE INCREASED
C
COMPETITION ON CUTOVER LAND BY CALCULATING A
C
COMPETITION ADJUSTMENT FACTOR (CAF) WHICH IS USED
C
TO MULTIPLY ALL COMPETITIVE COMPONENTS OF PTAEDA.
C
COMMON /BLOK5/SPREP,CAF,AKLSE,CUTO
REAL N0, N1
IF(A.GE.ARLSE) GO TO 10
CAF=SPREP*(1.-A/ARLSE)*1
GO TO 20
10 CAF=1
QCUTG=N0
20 RETURN
END

SUBROUTINE OUTPUT
C
SUBROUTINE OUTPUT CALCULATES AND DISPLAYS
C
SUMMARY STATISTICS FOR TREE AND STAND CHARACTERISTICS.
C
REAL MAI(3)
DIMENSION NDC(25,3),HDC(25,3),PM(13),YINC(3),PAI(3),
1 BAR(4),DMIN(4),DMAX(4),SD(4)
COMMON /BLOK1/X(100),Y(100),LMC1(100),K1C1(100),D(100),
1 HM1(100),CL1(100),CN1(100),NM1(100),LE(100)*,ACRES
COMMON /BLOK2/YCUT(50,3),YCRM(50,3),BA(50),KJ,K,NLIVE,
1 NTHN,K0
COMMON /BLOK4/TITLE(20),NYES,SITES,SEXIST,EXAGE,EXTS,
1 PX,PY,KU16,KL,KTREE,QJUV,QAGAIN
REAL YES,'YES'/,NC,'NO'/
COMMON /BLOK3/YCUT(50,3),YCRM(50,3),BA(50),KJ,K,NLIVE,
1 NTHN,KO
COMMON /BLOK4/TITLE(20),NYES,SITES,SEXIST,EXAGE,EXTS,
1 PX,PY,KU16,KL,KTREE,QJUV,QAGAIN
REAL YES,'YES'/,NC,'NO'/
COMMON /BLOK3/YCUT(50,3),YCRM(50,3),BA(50),KJ,K,NLIVE,
1 NTHN,KO
IF(QJUV.EQ.NO) GO TO 1
K=K
INDEX=1
1 INDEX=1

CALL STAT(0,N,LMC1,BAR(1),DMIN(1),DMAX(1),SD(1),INDEX)
CALL STAT(0,N,LMC1,BAR(2),DMIN(2),DMAX(2),SD(2),INDEX)
CALL STAT(0,N,LMC1,BAR(3),DMIN(3),DMAX(3),SD(3),INDEX)
INDEX=2
CALL STAT(0,N,LMC1,BAR(4),DMIN(4),DMAX(4),SD(4),INDEX)
INDEX=3
CALL STAT(0,N,LMC1,DUMP1,DIN2,DMAX2,DUMP2,INDEX)
MAXDC=DMAX2+.45
MINDC=DIN2+.45
IF(MINDC.LT.1) MINDC=1

DO 100 ID=MINDC,MAXDC
Appendix VI. Source listing of tree and stand growth simulation program PTAEDA (continued).

```
DO 100 L=1,3
NCC(10,L)=0
100 HOC(10,L)=0
DO 150 M=1,3
YINC(M)=9.69
150 PAI(M)=9.69
IF(KJ.EQ.K) GO TO 3
YINC(1)=EA(K)-EA(K-1)
YINC(2)=YCUT(K,1)-YCUT(K-1,1)
YINC(3)=YDRW(K,1)-YDRW(K-1,1)
IF(KJ.KJ.GT.5) GO TO 3
PAI(1)=(BA(K)-BA(K-5))/5.
PAI(2)=(YCUT(K,1)-YCUT(K-5,1))/5.
PAI(3)=(YDRW(K,1)-YDRW(K-5,1))/5.
3 MALL1=BA(K)/K
MALL2=YCUT(K,1)/K
MALL3=YDRW(K,1)/K
PROD11=BA(K)
PROD21=YCUT(K,1)
PROD31=YDRW(K,1)
TS=NLI/ACRES
NMORT=N-A/ACRES
TM=NMT/ACRES
TS=NTHIN/ACRES
C CALCULATE DISTRIBUTION OF SIZES
C DO 200 I=1,N
L=MCRE(1)
IF(L.EQ.0) GO TO 200
ID=ID+65
IF(ID.LE.1) ID=1
NOC(ID,L)=NCC(ID,L)+1
HOC(ID,L)=HOC(ID,L)+M(1)
200 CONTINUE
DO 300 L=1,3
DO 300 ID=MINDC,MINDC
IF(MINDC(ID,L).LE.0) GO TO 300
HOC(ID,L)=HOC(ID,L)/NDC(ID,L)
NDC(ID,L)=NDC(ID,L)/ACRES*4
300 CONTINUE
C DISPLAY TREE AND STAND CHARACTERISTICS
C WRITE(6,6100)(TITLE(M),M=1,20)
6100 FORMAT(1/"','",20A4/)
WRITE(6,6101) K
6101 FORMAT(1/20A4) 1 MEAN ST.DEV. MIN MAX)
WRITE(6,6102)(BAR(M),SD(M),DMIN(M),DMAX(M), M=1,4)
6102 FORMAT(1/DBH*,6X,4(3X,F5.2)/' HT',5X,4(3X,F5.1)/')
1 C1',6X,4(3X,F6.4)/')
WRITE(6,6103) ACRES,TP,TS,H0
6103 FORMAT(40A4,1/"ACRES SIMULATED",1/"F10.0",1/"PER ACRE")
```
Appendix VI. Source Listing of Tree and Stand Growth Simulation Program

PTAEDA (continued).

2. HEIGHT OF DOMINANT STAND*,F11.1/
WRITE(6,61041) (PROD(M),YINC(M),PAI(M),MAI(M),H=1,3)
6104 FORMAT('PRODUCT YIELD INCREMENTS PAI  MAI /
1  * BASEL AREA*,4X,F6.1,3(2X,F6.2)/* CUBIC FEET*,3X,F6.0*
2 3(2X,F6.1)/* BIOMASS *,2X,F7.0,3(1X,F7.1) 
IF(INTHIN.LE.0) GO TO 57
WRITE(6,65011) YCUFT(K,3)
6501 FORMAT(' VOLUME THINNED ',F6.0/
57 CONTINUE
WRITE(6,6105)
6105 FORMAT(' OD CLASS #LIVE MEAN H  #MORT MEAN H ,
1  WITHIN MEAN H ')
DO 400 I=INDTH,MAXOCT
400 WRITE(6,61061) I,INDC,lO,HDCIIO,l0,LIC,l0,31
6106 FORMAT(13,3(4X,15,3X,F6.2))
WRITE(6,6107) IS,IM,TT
6107 FORMAT(' TOT ',3(4X,F5.0,9X)/)
RETURN
END

SUBROUTINE COMP
C
C SUBROUTINE COMP CALCULATES A MODIFIED
C HEGYI COMPETITION INDEX ON ALL LIVE TREES IN
C A STAND. COMPETITORS ARE FOUND BY SAMPLING
C NEIGHBORS BASED ON THEIR SIZE AND DISTANCE AWAY
C BY ESSENTIALLY TAKING A POINT SAMPLE AT EACH
C SUBJECT TREE WITH A 8Af-l0 PLOT.
C
DIMENSION JDIS(5)
COMMON /BLOK1/X1(100),Y1(100),LMORT(100),KMBRT(100),D(100),
1 H1(100),CL1(100),C1(100),MID(100),LEDGE(9),ACRES
COMMON /BLOK2/IDIS4(1),DIST(1),XDIST,YDIST
COMMON /BLOKB/PLTX,PLOTY,DELX,DELY,NRCX,NRCY,TRC1(10)
COMMON /BLOK2/N
DATA PLOTX/2.15/,PL1/3.14159/,JOIS/1.964765,965,4,3,2/
IDIS1=1
DMAX=0
DO 100 I=1,N
100 IF(P1(I).LT.DMAX) DMAX=P1(I)
DISMAX=PLOTX*DMAX-DELX/2.
DISMAY=PLOTY*DMAX-DELY/2.
DO 200 I=1,N
200 IF(X(I).LT.DISMAX.AND.X(I).LT.(PLOTX-DISMAX)) .AND.
1 Y(I).LT.DISMAY.AND.Y(I).LT.(PLOTY-DISMAY)) MID(I)=1
MLESS1=N-1
DO 500 I=1,MLESS1
IF(LMORT(I).NE.1) GO TO 500
500 IPLUS1=I+1
DO 400 J=IPLUS1,N
IF(LMORT(J).NE.1) GO TO 400
INTOR=MID(I)*MID(J)
XDST=X(J)-X(I)
YDIST=Y(J)-Y(I)
Appendix VI. Source listing of tree and stand growth simulation program

PTAEDA (continued).

C SUPLPULUH HCWFAR CALCULATES DISTANCES BETWEEN C TREES ON MAIN AND 'BORDER' PLOTS FOR USE IN CALCULATING C COMPETITION FOR NON-INTERIOR TREES.

COMMON /BLUK2/DIST(9),XDIST,YDIST,
COMMON /BLUK8/PLOTX,PLOTY,DELX,DELY,NRCX,NRCY,YRCW(10),
IF (IDIST) = 6,5,5
5 DIST(5) = SQRT((XDIST-PLOTX)*(XDIST-PLOTX)+
1 (YDIST )*(YDIST ))
IDIS(2)=5
GO TO 10
6 DIST(6) = SQRT((XDIST+PLOTX)*(XDIST+PLOTX)+
1 (YDIST )*(YDIST ))
IDIS(2)=6
10 IF (YDIST ) = 3,8,6
3 DIST(3) = SQRT((XDIST )*(XDIST )+
1 (YDIST+PLOTY)*(YDIST+PLOTY))
IDIS(3)=3
ICGOE=IDIS(2)+IDIS(3)–7
GO TO (2,4,11,11,11,11,7,9),ICGDE
4 DIST(8) = SQRT((XDIST )*(XDIST )+
1 (YDIST–PLOTY)*(YDIST–PLOTY))
IDIS(3)=8
ICGOE=IDIS(2)+IDIS(3)–7
GO TO (2,4,11,11,11,11,11,7,9),ICGDE
2 DIST(2) = SQRT((XDIST–PLOTX)*(XDIST–PLOTX)+
1 (YDIST+PLOTY)*(YDIST+PLOTY))
IDIS(4)=2
RETURN
4 DIST(4) = SQRT((XDIST+PLOTX)*(XDIST+PLOTX)+
1 (YDIST+PLOTY)*(YDIST+PLOTY))
IDIS(4)=4
RETURN
END
Appendix VI. Source listing of tree and stand growth simulation program PTAEDA (continued).

```
RETURN
7 DIST(5)=SQRT((XDIST-PLOTX)*(XDIST-PLOTX)+
1   (YDIST-PLOTY)*(YDIST-PLOTY))
9 DIST(9)=SQRT((XDIST+PLOTX)*(XDIST+PLOTX)+
1   (YDIST+PLOTY)*(YDIST+PLOTY))
11 RETURN
END

SUBROUTINE STAT(X,N,FLAG,XBAR,MIN,MAX,S,INDEX)
C
C SUBROUTINE STAT CALCULATES THE MEAN, STANDARD
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.AND.INDEX.EQ.1) GO TO 100
IF(X(I)*GT.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
VAR=(SUMXSQ-SUMX*SUMX/M)/(M-1)
S=SQRT(VAR)
XBAR=SUMX/M
RETURN
END

FUNCTION U(I)
C
C GENERATES A UNIFORM(0,1) RANDOM VARIATE
C
I=X*65535
U=.5*I*.23283C6E-9
RETURN
END

FUNCTION UNORM(I)
C
C GENERATES A STANDARD NORMAL RANDOM VARIATE
C
STNUM=1-2*ALOG(U(I))***.5*COS(6.283*I)
RETURN
END
```
Appendix VI. Source listing of tree and stand growth simulation program PTAEDA (continued).

```
SUBROUTINE TREE
RETURN
END

DATA       ,100/
COMMON /BLKD/ N
INTEGER N/100/
END
ENTRY
```

\[ \text{PTA08260} \]
\[ \text{PTA08270} \]
\[ \text{PTA08280} \]
\[ \text{PTA08290} \]
\[ \text{PTA08300} \]
\[ \text{PTA08310} \]
\[ \text{PTA08320} \]
\[ \text{PTA08330} \]
\[ \text{PTA08340} \]
\[ \text{PTA08250} \]