

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.

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

INTRODUCTION

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

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

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

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

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

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<sup>1/</sup>The authors are Research Associate and Associate Professor, respectively, in the Division of Forestry and Wildlife Resources, VPI & SU, Blacksburg, Va. 24061.

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

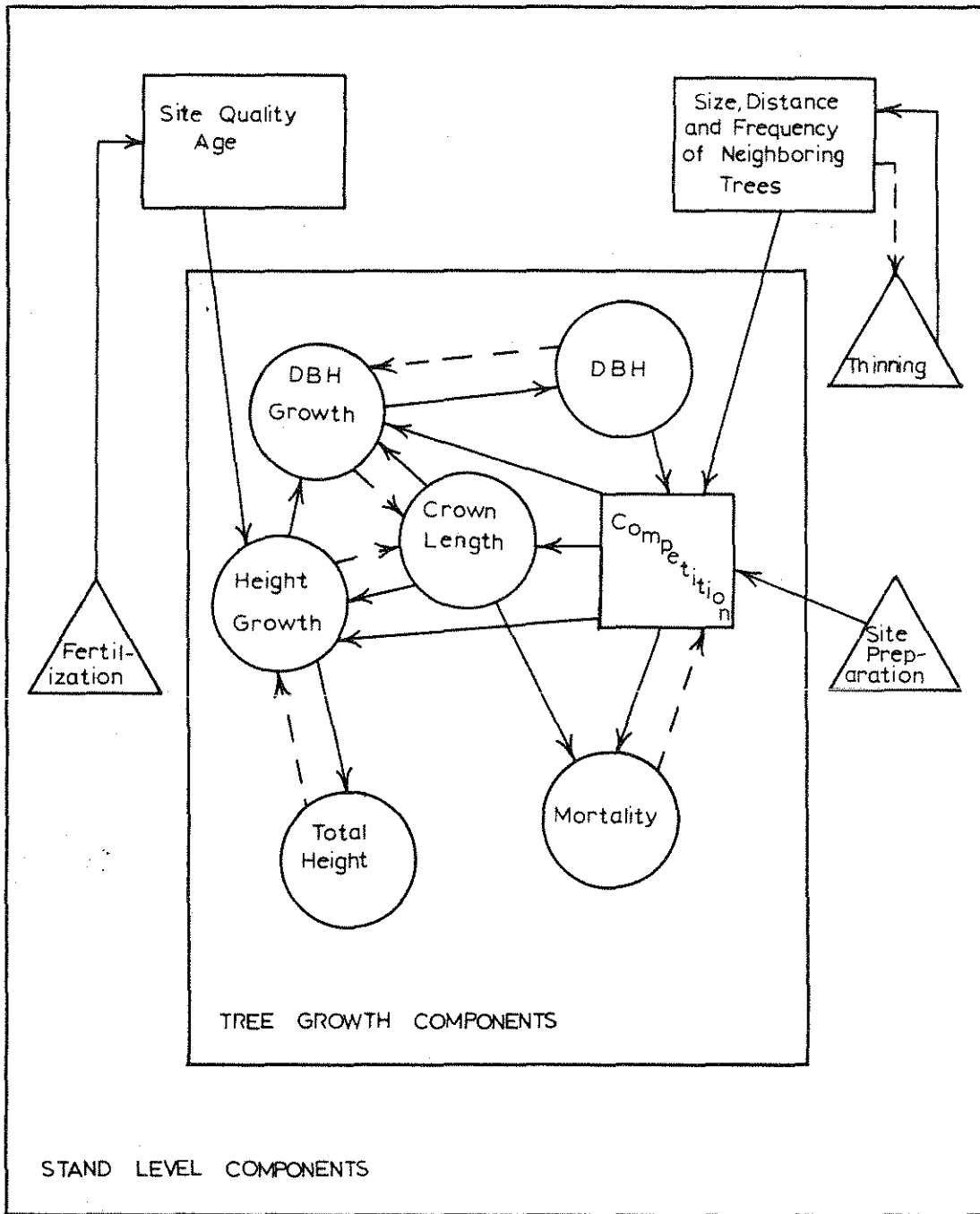
Participants in a recent tree growth simulation workshop agreed that individual tree simulation models will play an essential role in estimating yield and evaluating intensive management alternatives (Honer 1972). They suggested that, at least for now, individual tree modeling efforts should be aimed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



- > Mathematically related components
- -> Direct feedback paths not mathematically related

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 Burkhardt 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.

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

\* 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

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

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

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

### The Competition Index

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

Of the overlap-type indices, the weighted area overlap index used by Ek and Monserud (1974) seemed to be the most desirable because of its logical construction and its successful use in their FOREST model. Competition radius was defined by Ek and Monserud as open-grown crown radius while influence zone overlap was weighted by the ratio of total height times crown radius for competing trees.



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

Equation *	R <sup>2</sup>	S <sub>y·x</sub>	Source
CCF = 180.89 - 1012.6/A + 0.00347 HD·TS	0.8393	23.22	Strub <u>et al.</u> in press
log <sub>10</sub> HD = log <sub>10</sub> SI - 5.86537 (1/A - 1/25)	----	---	Burkhart <u>et al.</u> 1972
log <sub>10</sub> (TP/TS) = A(0.0130 log <sub>10</sub> TP + 0.0009HD - 0.0109√HD)	0.8400	0.0042	Smalley and Bailey 1974a
DMIN = 0.13291 + 0.04465HD - 0.00001876 A·TS + 17.2761 HD/TS	0.7662	0.5645	Plantation Data
DAVE = 2.95995 + 0.05406HD - 0.00005217 A·TS + 18.4654 HD/TS	0.9206	0.3470	Plantation Data
ln H = 1.51205 + 0.7057 ln HD + (0.26231/D) ln TS - 2.44501/A - 3.70999/D + 2.95155/(D·A)	0.9514	0.0697	Plantation Data
ln CBL = -2.68768 + 1.61229 ln H + (0.45740/D) ln TS - (8.95807/A) ln D + 12.74273/A - 1.64638/D - 21.74093/(D·A)	0.9142	0.1576	Plantation Data

\* 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

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

where  $D$  = DBH  
 $DIST$  = distance between subject tree  $i$  and  $j^{th}$  competitor  
 $CI_i$  = Competition Index of the  $i^{th}$  tree  
 $n$  = 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.

Competition Index	Competition Search Technique	Correlation Coefficient (r)	
		DIN	HIN*
Weighted Area Overlap	all overlapping influence zones (Ek and Monserud 1974)	-0.424	-0.432
Weighted Size Ratio			
$(D_j/D_i)/DIST_{ij}$	10 foot radius (Hegyí 1974)	-0.236	-0.276
	BAF 20	-0.401	-0.447
	BAF 10	-0.415	-0.456
$(D_j^2/D_i^2)/DIST_{ij}$	BAF 20	-0.240	-0.286
	BAF 10	-0.258	-0.339
$(D_j/D_i)/DIST_{ij}^2$	BAF 20	-0.207	-0.258
	BAF 10	-0.219	-0.313

\*Where DIN = observed DBH increment, HIN = observed total height increment, D = DBH, DIST = distance between trees i and j.

developed by Ek and Monserud (1974) and together represent a very efficient means of evaluating competition. Competitive stress on border trees is calculated through a translation of plot borders so that, in effect, border trees compete with border trees on the opposite side of the plot.

### Growth Relationships

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

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

$$HD = SI 10^{-5.86537(1/A - 1/25)}$$

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

$$(b_1 + b_2 CR^{b_3} e^{-b_4 CI - b_5 CR})$$

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

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

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

$$D_0 = -2.422297 + 0.286583 H + 0.209472 A$$

$$R^2 = 0.9197 \quad S_{y \cdot x} = 2.14023$$

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

$$(b_1 + b_2 CL^{b_3} e^{-b_4 CI})$$

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.

Equation *	R <sup>2</sup>	S <sub>y·x</sub>
HIN = PHIN (0.54631 + 124.8635 CR <sup>1.66254</sup> e <sup>-1.15083 CI -6.66226 CR</sup> )	0.3406	0.7709
DIN = PDIN (0.08652 + 0.20178 CL <sup>1.79998</sup> e <sup>-1.32061 CI</sup> )	0.2968	0.0850
PLIVE = 1.08635 CR <sup>0.07028</sup> e <sup>-0.02817 CI<sup>1.17781</sup></sup>	--	--

\* 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

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

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 Bernouli 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 <sup>1/</sup> 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

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<sup>1/</sup> Primarily with Dr. Wayne Haynes, Director of the N.C. State Forest Fertilization Cooperative Study, Raleigh, N.C.



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

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

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

A user may thin by rows, from below, or by a combination of these methods by specifying the thinning type in parameter ITHIN. Thinning from below includes two options specified by parameter ILOW; thinning to an upper diameter limit or thinning to a specified basal area. Depending on the value of ILOW, the upper diameter or basal area limit is specified in parameter TLIM. In either case, a lower diameter limit may be specified, DLOW, below which trees will not be removed. If the row thinning option is chosen the  $i^{\text{th}}$  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 Burkhardt 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 (Burkhardt 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 Burkhardt 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

$$HMAX = b_0 + b_1HD + b_2A$$

where HMAX = maximum height (feet)

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

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

### Unmanaged Old-Field Plantations

In general, plot yields predicted by PTAEDA were in close agreement with those observed by Burkhardt *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.

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

() indicates observed yields

\* indicates significant difference ( $\alpha = 0.05$ )  
between observed and predicted means

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

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

The precision of PTAEDA also compared favorably with that shown by diameter distribution models. For cubic-foot volume, 25 percent of predicted values were within  $\pm 5$  percent of the observed, 50 percent were within  $\pm 10$  percent, and over two-thirds were within  $\pm 15$  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.

Product	Mean	Std. Dev.	Low	High
Absolute Deviation				
Trees				
( <u>number/acre</u> )	12.4	51.5	-84	382
Basal Area				
( <u>ft<sup>2</sup>/acre</u> )	7.6	27.4	-56.6	96.3
Cubic-foot Volume				
( <u>ft<sup>3</sup>/acre</u> )	236.9	567.3	-1215	2473
Percent Deviation				
Trees				
( <u>number/acre</u> )	1.16	5.98	-12.35	26.67
Basal Area				
( <u>ft<sup>2</sup>/acre</u> )	3.32	17.16	-49.35	57.66
Cubic-foot Volume				
( <u>ft<sup>3</sup>/acre</u> )	5.45	15.22	-46.12	48.37

Table 7. Distribution of percent deviation of predicted from observed cubic-foot yields.

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Percent deviation	Number of plots
-45.1 to -55.0	1
-35.1 to -45.0	0
-25.1 to -35.0	2
-15.1 to -25.0	17
- 5.1 to -15.0	26
- 5.0 to 5.0	46
5.1 to 15.0	53
15.1 to 25.0	26
25.1 to 35.0	10
35.1 to 45.0	5
45.1 to 55.0	1
total	187

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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.

Site* Index (feet)	Trees at age 5 (number)	Ages when Thinned (years)	Source	Amount of Thinnings		Average DBH (inches)	Residual Stand at Age 30			Total Production (cords)
				Basal area (feet <sup>2</sup> )	Volume (cords)**		Trees per acre (number)	Basal area (feet <sup>2</sup> )	Volume (cords)	
60	600	17, 22	C&S	45, 36	7, 7	13.6(8.8)	168(365)	170(153)	43.7(42.9)	57.7
			PTAEDA		10, 9	13.4(9.6)	152(370)	151(204)	43.2(57.3)	62.3
	800	17, 22	C&S	58, 47	9, 9	14.6(8.3)	159(448)	185(169)	47.1(47.2)	65.1
			PTAEDA		10, 12	13.6(8.6)	142(427)	147(185)	41.3(50.6)	63.7
70	600	15, 20 25	C&S	37, 37, 39	6, 8, 10	15.1(9.8)	158(365)	196(191)	60.6(63.4)	84.6
			PTAEDA		8, 10, 13	14.9(9.7)	139(370)	171(204)	58.9(63.6)	89.9
	800	15, 20 25	C&S	43, 47, 51	7, 10, 13	14.7(9.3)	189(448)	222(211)	68.2(70.0)	98.2
			PTAEDA		9, 13, 16	14.0(9.0)	140(418)	157(208)	56.4(71.4)	94.4

\* Site index at base age 25.

\*\* Cord-wood volume to a 4-inch top. Values for PTAEDA were converted using ratios calculated from Burkhardt, 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.

Site Index (feet)	Original Spacing (feet)	Thinning Schedule (years)	Basal Area Limit (feet)	Cubic-foot Volume/Acre					
				Residual		Thinned		Total	
				Predicted	Observed	Predicted	Observed	Predicted	Observed
51	6 X 7	13,18,20 25,34	80	2100	2065	3164	2261	5264	4326
			90	2311	2436	3161	2431	5472	4867
			100	2623	2934	2878	2707	5501	5641
			unthinned	4195	4726	--	--	4195	4726
55	6 X 6	17,20,24 30	85	2854	2107	3096	2401	5950	4508
			110	3603	2854	2454	2192	6057	5046
			135	4141	3232	1403	1896	5544	5128
			unthinned	4245	4525	--	--	4245	4525

\*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.

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APPENDICES

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

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Variable Name	Definition
TITLE	A descriptive title up to 80 characters long
NYEARS	Length of simulation in years
SITE	Site index (base age 25)
IX	Random number seed, any odd integer
PX	X parameter for planting
PY	Y parameter for planting
TP	<p>Trees planted per acre</p> <p>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.</p> <p>If TP is omitted, PX and PY are the actual distances in feet between trees and between rows, respectively.</p>
TS	Trees surviving per acre
AGE	Age of TS for existing stands
SPREP	Additional number of (loblolly equivalent) competing stems per acre for cutover sites
ARLSE	Age at which a cutover site will be released from additional competing stems
KIN	Age at next decision period or age of next input

---

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

Variable Name	Definition
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 <sup>th</sup> row to be thinned
ILOW	Low thinning type 1 = diameter limit 2 = residual basal area limit
DLOW	Lower diameter limit below which trees will not be removed (low thinning option only)
TLIM	Thinning limit: If ILOW = 1, upper diameter limit above which trees will not be removed ILOW = 2, residual basal to be left after thinning
KFERT	Age of growing season immediately after treatment
RESP	Maximum site index increase (feet) due to fertilization
LMR	Length of time (years) to attain RESP after initially fertilizing
LR	Total length of fertilization response
QAGAIN	To simulate another stand QAGAIN = YES

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

ptaeda  
CMD:  
run

----- PTAEDA -----

SIMULATION OF TREE AND STAND GROWTH IN LOBLOLLY 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

DIMENSION	MEAN	ST.DEV.	MIN	MAX
DBH	3.83	1.07	1.47	5.80
HT	16.2	2.1	9.3	18.9
CL	11.6	2.2	5.8	15.0
CI	0.7051	0.3570	0.2407	2.5303

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

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

D CLASS	#LIVE	MEAN H	#MORT	MEAN H	#THIN	MEAN H
1	16	9.32	0	0.00	0	0.00
2	72	12.87	0	0.00	0	0.00
3	168	15.14	0	0.00	0	0.00
4	240	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.	

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

DIMENSION	MEAN	ST.DEV.	MIN	MAX
DBH	6.36	1.95	2.18	9.96
HT	43.0	4.4	28.5	51.1
CL	20.3	4.8	7.8	27.7
CI	1.4739	0.6816	0.6756	4.2570

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

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

D CLASS	#LIVE	MEAN H	#MORT	MEAN H	#THIN	MEAN H
2	16	28.54	8	22.63	0	0.00
3	24	34.92	16	32.56	0	0.00
4	88	38.51	8	35.86	0	0.00
5	104	42.64	0	0.00	0	0.00
6	88	42.36	0	0.00	0	0.00
7	128	45.06	0	0.00	0	0.00
8	80	45.52	0	0.00	0	0.00
9	64	47.00	0	0.00	0	0.00
10	40	47.12	0	0.00	0	0.00
TOT	632.		168.		0.	

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

DIMENSION	MEAN	ST.DEV.	MIN	MAX
DBH	10.23	1.36	8.32	13.14
HT	58.7	2.9	53.5	65.4
CL	26.9	1.9	23.9	30.6
CI	0.8759	0.1536	0.4553	1.1984

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

PRODUCT	YIELD	INCREM	PAI	MAI
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.

D CLASS	#LIVE	MEAN H	#MORT	MEAN H	#THIN	MEAN H
2	0	0.00	8	22.63	16	28.54
3	0	0.00	16	32.56	24	34.92
4	0	0.00	8	35.86	88	38.51
5	0	0.00	0	0.00	104	42.64
6	0	0.00	0	0.00	88	42.36
7	0	0.00	0	0.00	48	43.97
8	24	56.42	0	0.00	0	0.00
9	72	58.70	0	0.00	0	0.00
10	64	58.59	0	0.00	0	0.00
11	48	58.51	0	0.00	0	0.00



Appendix II. Example run of the interactive version of simulation model PTAEDA (continued).

---

12	40	60.19	0	0.00	0	0.00
13	16	60.23	0	0.00	0	0.00
TOT	264.		168.		368.	

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

DIMENSION	MEAN	ST.DEV.	MIN	MAX
DBH	12.88	1.18	11.10	15.15
HT	67.0	3.2	60.3	72.4
CL	27.8	1.3	25.8	30.1
CI	0.6333	0.1012	0.4826	0.8600

ACRES SIMULATED	0.12500
TREES PLANTED PER ACRE	800.
TREES SURVIVING PER ACRE	144.
HEIGHT OF DOMINANT STAND	63.0

PRODUCT	YIELD	INCREM	PAI	MAI
BASAL AREA	131.3	4.91	-4.39	5.25
CUBIC FEET	3803.	196.1	-26.8	152.1
BIOMASS	70708.	3659.3	-458.3	2828.3

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).

---

3	0	0.00	16	32.56	24	34.92
4	0	0.00	8	35.86	88	38.51
5	0	0.00	0	0.00	104	42.64
6	0	0.00	0	0.00	88	42.36
7	0	0.00	0	0.00	48	43.97
8	0	0.00	0	0.00	24	56.42
9	0	0.00	0	0.00	72	58.70
10	0	0.00	0	0.00	24	57.81
11	24	65.70	0	0.00	0	0.00
12	40	65.86	0	0.00	0	0.00
13	40	67.61	0	0.00	0	0.00
14	24	69.07	0	0.00	0	0.00
15	16	67.54	0	0.00	0	0.00
TOT	144.		168.		488.	

TRIAL RUN SHOWING THE USE OF ALL MANAGEMENT ROUTINES

STAND SUMMARY - AGE 30

DIMENSION	MEAN	ST.DEV.	MIN	MAX
DBH	13.79	1.39	11.63	16.58
HT	70.4	3.8	64.4	76.2
CL	25.4	1.3	23.4	27.8
CI	0.6886	0.1218	0.4924	0.9094

ACRES SIMULATED	0.12500
TREES PLANTED PER ACRE	800.
TREES SURVIVING PER ACRE	144.
HEIGHT OF DOMINANT STAND	65.7

PRODUCT	YIELD	INCREM	PAI	MAI
BASAL AREA	150.8	5.40	3.90	5.03
CUBIC FEET	4583.	233.0	156.0	152.8
BIOMASS	85265.	4348.1	2911.3	2842.2

VOLUME THINNED 2446.

D CLASS	#LIVE	MEAN H	#MORT	MEAN H	#THIN	MEAN H
2	0	0.00	8	22.63	16	28.54
3	0	0.00	16	32.56	24	34.92
4	0	0.00	8	35.86	88	38.51
5	0	0.00	0	0.00	104	42.64
6	0	0.00	0	0.00	88	42.36
7	0	0.00	0	0.00	48	43.97
8	0	0.00	0	0.00	24	56.42
9	0	0.00	0	0.00	72	58.70
10	0	0.00	0	0.00	24	57.81
11	0	0.00	0	0.00	0	0.00
12	24	68.84	0	0.00	0	0.00
13	56	68.80	0	0.00	0	0.00
14	16	70.68	0	0.00	0	0.00
15	32	72.73	0	0.00	0	0.00
16	8	73.26	0	0.00	0	0.00
17	8	72.75	0	0.00	0	0.00
TOT	144.		168.		488.	

ANOTHER STAND ?

no

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

Card	Columns	Variable	Format * type
1	1 - 80	TITLE	A
2	1 - 3	RUN	--
	4 - 5	CODE	A
	6 - 10	NYEARS	I
	11 - 15	SITE	F
	16 - 20	IX	I
	21 - 25	PX	F
	26 - 30	PY	F
	31 - 35	TS	F
	36 - 40	AGE	F
	41 - 45	SPREP	F
	46 - 50	ARLSE	F
	51 - 53	RESP	F
	56 - 60	LR	I
	61 - 65	QJUV	A
	66 - 70	KIN	I
	71 - 75	KFREQ	I
	76 - 77	NCARDS	I
	78 - 80	QAGAIN	A

\*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).

Card	Columns	Variable	Format * type
3 - NCARDS	1 - 5	MANAG	--
	6 - 10	KTHIN	I
	11 - 15	ITHIN	I
	16 - 20	ILOW	I
	21 - 25	DLOW	F
	26 - 30	TLIM	F
	31 - 35	IROW	I
	36 - 40	KFERI	I
	41 - 45	RESP	F
	46 - 50	LMR	I
	51 - 55	LR	I
	56 - 58	QOUT	A
	61 - 63	QTREE	A
	66 - 70	KIN	I

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

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---

Variable Name	Definition
RUN	Card 2 identification, to be punched on card
CODE	User supplied 2-digit code or name
QJUV	If output describing the juvenile stand is desired QJUV = YES
KFREQ	Frequency of output summaries after KIN (years)
NCARDS	Number of management cards (MANAG)
MANAG	Card 3 - NCARDS identification, to be punched on card
QOUT	If stand output is desired after this growing season QOUT = YES
QTREE	If individual tree output is desired after this growing season QTREE = YES

---

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.

Age (years)	Unmanaged	Fertilized <sup>2/</sup>	Cubic-foot Volume per Acre		Fertilized and Thinned	
			Residual	Thinned <sup>3/</sup> (total)	Residual	Thinned (total)
Old-field 10	1219 ± 53 <sup>4/</sup>					
	1130 to 1307					
15	2536 ± 64					
	2410 to 2641					
20	3902 ± 38	3792 ± 86	2992 ± 40	940 ± 53	2995 ± 47	907 ± 69
	3844 to 3952	3644 to 3878	2927 to 3064	873 to 1023	2901 to 3058	869 to 1022
25	4884 ± 123	5320 ± 141	3215 ± 54	940 ± 68	3794 ± 79	1893 ± 64
	4723 to 5076	5064 to 5512	3040 to 3278	1870 to 2058	3692 to 3903	1771 to 1981
30	5355 ± 204	5368 ± 245	4462 ± 130		4524 ± 202	
	4912 to 5539	4884 to 5662	4219 to 4631		4281 to 4668	

<sup>1/</sup> Site index 60 (base age 25), 800 trees planted per acre

<sup>2/</sup> KFERT = 20, RESP = 5, LMR = 3, LR = 7

<sup>3/</sup> KTHIN = 15, 20; low thinning to 90 ft<sup>2</sup> of basal area per acre; DLOW = 0

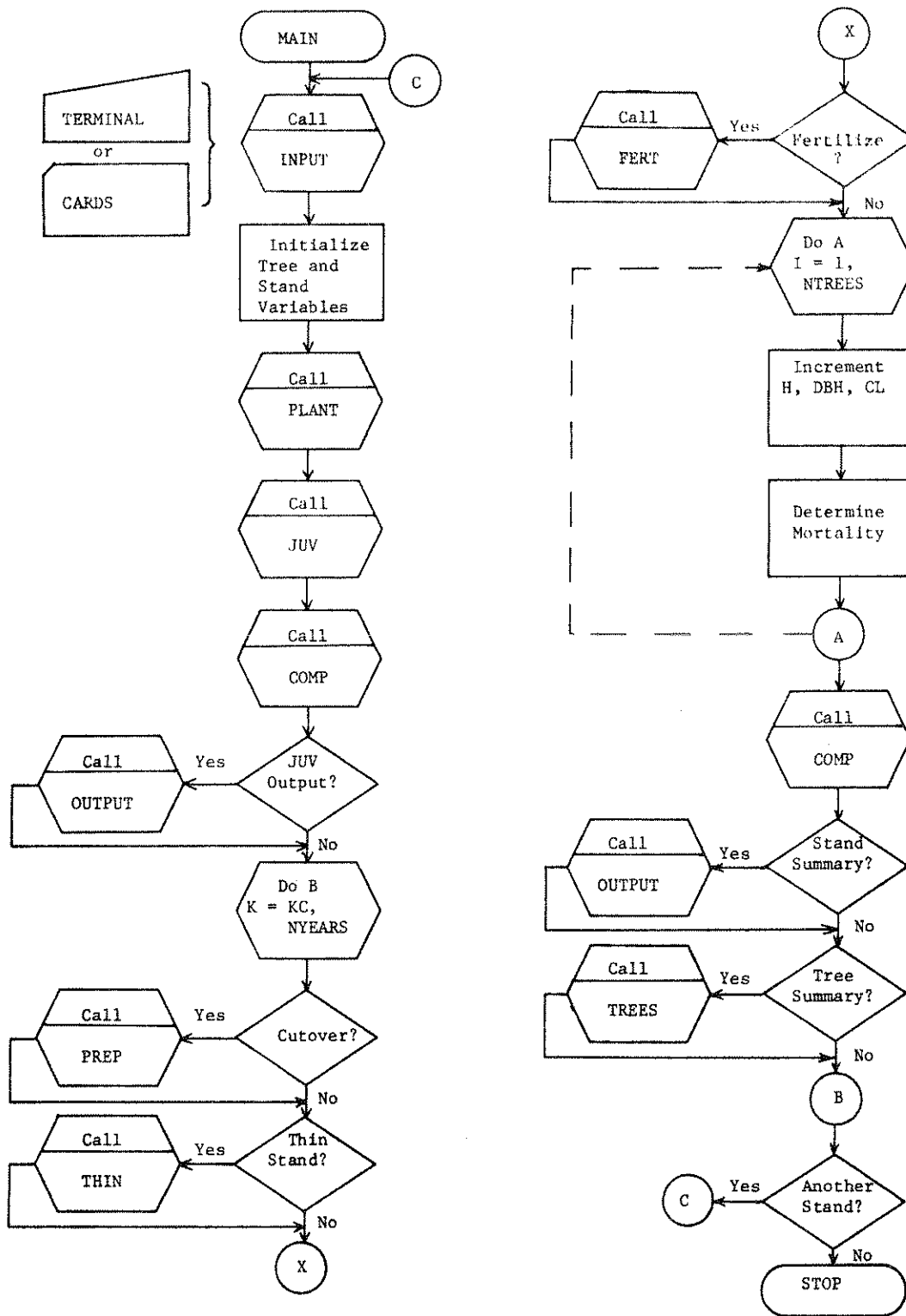
<sup>4/</sup> Mean ± standard deviation  
Low to High

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

Age (years)	Unmanaged	Fertilized <sup>2/</sup>	Cubic-foot Volume per Acre		Fertilized and Thinned	
			Residual	Thinned <sup>3/</sup> (total)	Residual	Thinned (total)
Cutover <sup>5/</sup> 10	920 ± 26					
	883 to 957					
15	1960 ± 39					
	1883 to 2018					
20	3222 ± 65	3198 ± 75	2970 ± 87	340 ± 66	2970 ± 87	340 ± 65
	3111 to 3209	3040 to 3282	2780 to 3083	245 to 428	2780 to 3083	245 to 428
25	4300 ± 152	4826 ± 134	3320 ± 59	1302 ± 176	3901 ± 69	1274 ± 111
	4047 to 4621	4649 to 5131	3242 to 3411	1040 to 1420	3810 to 4031	1040 to 1420
30	5020 ± 190	4867 ± 189	4489 ± 184		4536 ± 176	
	4769 to 5350	4636 to 5115	4118 to 4748		4197 to 4804	

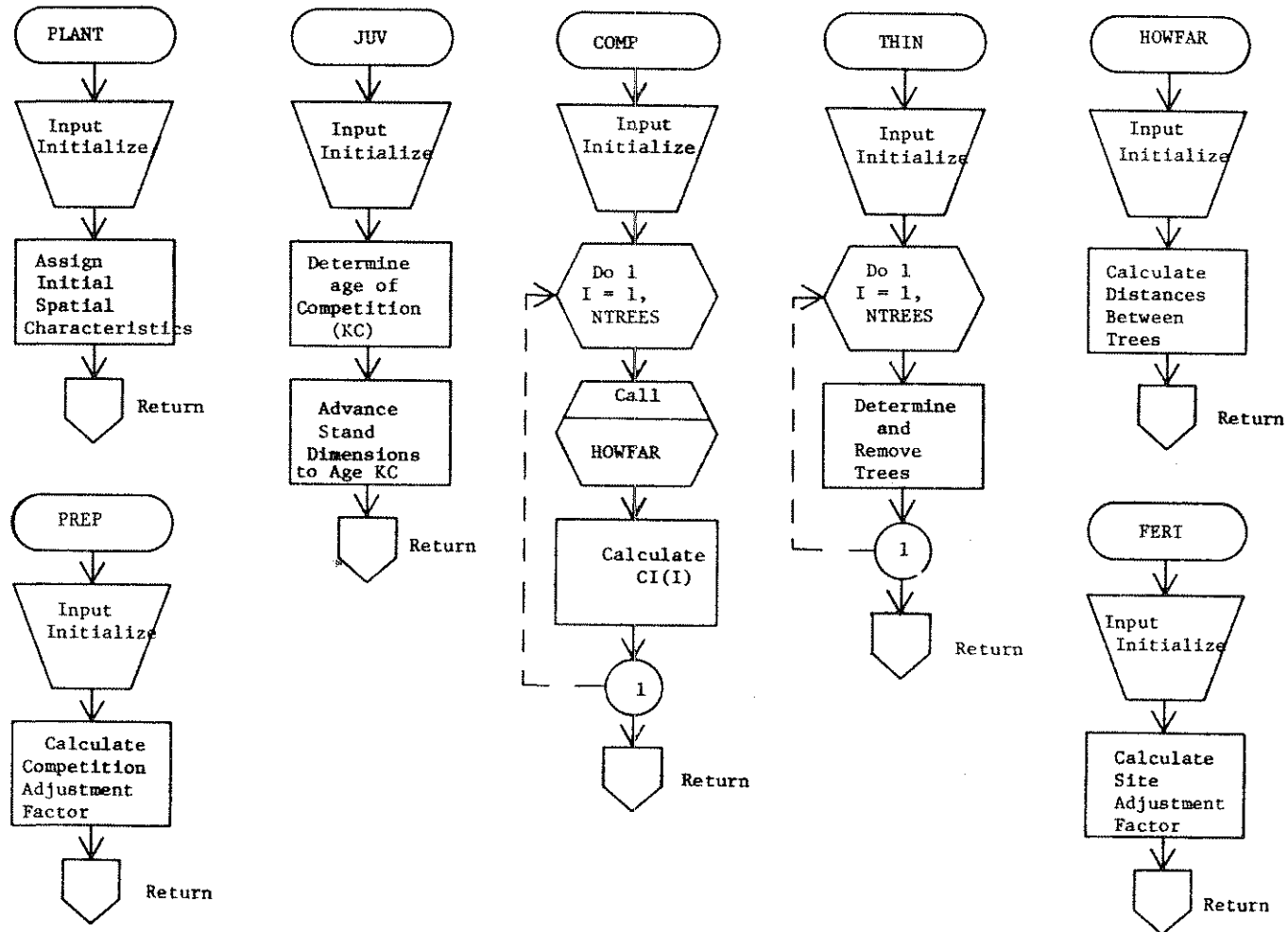
<sup>5/</sup> SPREP = 1., ARISE = 20.

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.

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$JOB      WATFIV
C
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C          PTAEDA
C
C          PTAEDA IS A SIMULATION MODEL OF TREE AND STAND GROWTH
C          IN MANAGED LOBLOLLY PINE (PINUS TAEDA L.) PLANTATIONS.
C
C          DEVELOPED BY RICHARD F. DANIELS, VPI&SU, 1975.
C
C          DIMENSION VOL(3),S(2)
C          COMMON /BLOK1/X(100),Y(100),LMORT(100),KMORT(100),D(100),
C          1 H(100),CL(100),CI(100),MID(100),LEDGE(9),ACRES
C          COMMON /BLOK2/IDIS(4),DIST(9),XDIST,YDIST
C          COMMON /BLOK3/YCUFT(50,3),YDRWT(50,3),BA(50),KJ,K,NLIVE,
C          1 NTHIN,HD
C          COMMON /BLOK4/TITLE(20),NYEARS,SITE,QEXIST,EXAGE,EXTS,
C          1 PX,PY,TP,KOUT,KIN,KTREE,QJUV,QAGAIN
C          COMMON /BLOK5/SPREP,CAF,ARLSE,CCUTO
C          COMMON /BLOK6/KFERT,LMR,LR,RESP,SAF,QFERT
C          COMMON /BLOK7/KTHIN,I THIN,IRDW,ILOW,DLOW,TLIM
C          COMMON /BLOK8/PLOTX,PLOTY,DELX,DELY,NROX,NRCY,YRCW(10)
C          REAL YES,'YES',,NC,'NU'
C          COMMON /BLOK0/N
C          DATA S/O.77093,O.C7729/
C
C          INPUT INITIAL SIMULATION CRITERIA
C
C          1 CALL INPUT(IX)
C
C          INITIALIZE TREE AND STAND VARIABLES
C
C          DO 50 K=1,50
C          BA(K)=0.
C          DO 50 L=1,3
C          YCUFT(K,L)=0.
C          50 YDRWT(K,L)=0.
C          DO 60 I=1,N
C          D(I)=0.
C          H(I)=0.
C          CL(I)=0.
C          CI(I)=0.
C          KMORT(I)=NYEARS
C          60 LMORT(I)=1
C          KTHIN=0
C          KOUT=0
C          KTREE=0
C          QFERT=NU
C
C          GENERATE INITIAL STAND
C
C          CALL PLANT
C          CALL JUV(IX)
C          CALL COMP
C          IF(QJUV.EQ.NO) GO TO 65

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PTA00010
PTA00020
PTA00030
PTA00040
PTA00050
PTA00060
PTA00070
PTA00080
PTA00090
PTA00100
PTA00110
PTA00120
PTA00130
PTA00140
PTA00150
PTA00160
PTA00170
PTA00180
PTA00190
PTA00200
PTA00210
PTA00220
PTA00230
PTA00240
PTA00250
PTA00260
PTA00270
PTA00280
PTA00290
PTA00300
PTA00310
PTA00320
PTA00330
PTA00340
PTA00350
PTA00360
PTA00370
PTA00380
PTA00390
PTA00400
PTA00410
PTA00420
PTA00430
PTA00440
PTA00450
PTA00460
PTA00470
PTA00480
PTA00490
PTA00500
PTA00510
PTA00520
PTA00530
PTA00540
PTA00550

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

	CALL OUTPUT	PTA00560
	KIN=KJ+1	PTA00570
C		PTA00580
C	COMMENCE ANNUAL TREE GROWTH	PTA00590
C		PTA00600
	65 KC=KJ+1	PTA00610
	A=KC	PTA00620
	DO 200 K=KC,NYEARS	PTA00630
	A=K	PTA00640
C		PTA00650
C	INPUT MANAGEMENT CRITERIA	PTA00660
C		PTA00670
	IF(QCUTO.EQ.YES) CALL PREP(A)	PTA00680
	IF(KIN .EQ.K) CALL INPUT2	PTA00690
	IF(KTHIN.EQ.K) CALL THIN(A)	PTA00700
	IF(QFERT.EQ.YES) CALL FERT(A)	PTA00710
	POTH=(SITE*SAF)*10**(-5.86537*(1./A-1./25.))	PTA00720
	PHIN=POTH-HD	PTA00730
	DO 100 I=1,N	PTA00740
	IF(LMORT(I)-1) 10C,10,90	PTA00750
	10 CR=CL(I)/H(I)	PTA00760
C		PTA00770
C	DETERMINE TREE MORTALITY	PTA00780
C		PTA00790
	PLIVE=1.086*CR**.C702826*EXP(-.0281694*(CI(I)*CAF)	PTA00800
	1 **1.177809)	PTA00810
	P=U(IX)	PTA00820
	IF(P.LT.PLIVE) GO TO 80	PTA00830
	NLIVE=NLIVE-1	PTA00840
	LMORT(I)=2	PTA00850
	KMORT(I)=K	PTA00860
	GO TO 90	PTA00870
C		PTA00880
C	COMPUTE H AND D INCREMENT ON ALL TREES	PTA00890
C		PTA00900
	80 HRED=.54631+CR**1.66254*EXP(4.82722-1.15083*CI(I)	PTA00910
	1 *CAF-6.66226*CR)	PTA00920
	R=STNORM(IX)	PTA00930
	HIN=PHIN*HRED	PTA00940
	HINMAX=1.00206*PHIN+.13462026	PTA00950
	IF(HIN.GT.HINMAX) HIN=HINMAX	PTA00960
	PDIN=.28658336*HIN +.2094718	PTA00970
	HIN=HIN+R*S(1)	PTA00980
	IF(HIN.LT.0.) HIN = 0.	PTA00990
	DRED=.086524+.020178*CL(I)**1.179986*EXP(-1.320610	PTA01000
	1 *CI(I)*CAF)	PTA01010
	DIN=PDIN*DRED+R*S(2)	PTA01020
	IF(DIN.LT.0.) DIN=0.	PTA01030
C		PTA01040
C	CALCULATE PRODUCTS	PTA01050
C		PTA01060
	D(I)=C(I)+DIN	PTA01070
	H(I)=H(I)+HIN	PTA01080
	90 L=LMORT(I)	PTA01090
	DSQ=D(I)*C(I)	PTA01100

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

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IF(L.EQ.1) BA(K)*FA(K)+DSQ PTA01110
YCUFT(K,L)=YCUFT(K,L)+DSQ*H(I)*.00232+.34864 PTA01120
YDRWT(K,L)=YDRWT(K,L)+DSQ*H(I)*.0432865+.798337 PTA01130
100 CONTINUE PTA01140
BA(K)=BA(K)+.005454/ACRES PTA01150
DO 150 L=1,3 PTA01160
YCUFT(K,L)=YCUFT(K,L)/ACRES PTA01170
YDRWT(K,L)=YDRWT(K,L)/ACRES PTA01180
150 CONTINUE PTA01190
C PTA01200
C DETERMINE CROWN LENGTH PTA01210
C PTA01220
T=NLIVE/ACRES PTA01230
DO 101 I=1,N PTA01240
CI(I)=0. PTA01250
IF(LMURT(I).NE.1) GO TO 101 PTA01260
CBL=F(I)**1.612287*(T*CAF)**(.457396/D(I))*D(I)** PTA01270
1 (-8.958067/A)*EXP(-2.687682+12.74273/A PTA01280
2 -21.74093/(A*C(I))-1.646384/D(I)) PTA01290
IF(H(I)-CBL-CL(I).GT.HIN) CBL=H(I)-CL(I)-HIN PTA01300
CL(I)=H(I)-CBL PTA01310
IF(CL(I).LT.0) CL(I)=0. PTA01320
101 CONTINUE PTA01330
HD=POTH PTA01340
CALL COMP PTA01350
C PTA01360
C OUTPUT STAND SUMMARY PTA01370
C PTA01380
IF(KOUT.EQ.K) CALL OUTPUT PTA01390
IF(KTREE.EQ.K) CALL TREE PTA01400
200 CONTINUE PTA01410
C PTA01420
C HOUSE KEEPING PTA01430
C PTA01440
CALL INPUT3 PTA01450
IF(QAGAIN.EQ.YES) GO TO 1 PTA01460
STOP PTA01470
END PTA01480
PTA01490
SUBROUTINE INPUT(IX) PTA01500
C PTA01510
C SUBROUTINE INPUT IS DIVIDED INTO 3 MAIN SUB-SECTIONS PTA01520
C DESIGNED TO PROMPT THE USER FOR AND READ INITIAL SIMULATION PTA01530
C CRITERIA, MANAGEMENT CRITERIA, AND PROGRAM CONTINUATION PTA01540
C CRITERIA. THIS SUBROUTINE IS THE ONLY ONE WHICH NEED PTA01550
C BE CHANGED FOR BATCH MODE OPERATION. PTA01560
C PTA01570
COMMON /BLOK4/TITLE(20),NYEARS,SITE,QEXIST,EXAGE,EXTS, PTA01580
L PX,PY,TP,KOUT,KIN,KTREE,QJUV,QAGAIN PTA01590
COMMON /BLOK5/SPREP,CAF,ARLSE,QCUTO PTA01600
COMMON /BLOK6/KFERT,LMR,LR,RESP,SAF,QFERT PTA01610
COMMON /BLOK7/KTHIN,ITHIN,IROW,ILOW,DLOW,TLIM PTA01620
REAL YES/'YES'/,NC/'NO'/ PTA01630
C PTA01640
C READ INITIAL SIMULATION CRITERIA PTA01650

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

C		PTA01660
	WRITE(6,6001)	PTA01670
6001	FORMAT(/13X,10('-',),5X,'PTAEDA',5X,10('-',)//	PTA01680
	1 ' SIMULATION OF TREE AND STAND GROWTH IN',	PTA01690
	2 ' LOBLULLY PINE PLANTATIONS '//	PTA01700
	3 ' ENTER: TITLE')	PTA01710
	READ(9,5001) (TITLE(L),L=1,20)	PTA01720
5001	FORMAT(20A4)	PTA01730
	WRITE(6,6002)	PTA01740
6002	FORMAT(' ENTER: NYEARS,SITE,IX')	PTA01750
	READ(9,*) NYEARS,SITE,IX	PTA01760
	10 WRITE(6,6003)	PTA01770
6003	FORMAT(' EXISTING STAND ? ENTER: YES OR NO')	PTA01780
	READ(9,5002)QEXIST	PTA01790
5002	FORMAT(A3)	PTA01800
	IF(QEXIST.EQ.NO) GO TO 20	PTA01810
	IF(QEXIST.NE.YES) GO TO 10	PTA01820
	WRITE(6,6004)	PTA01830
6004	FORMAT(' ENTER SPATIAL PARAMETERS: PX,PY,TS,AGE')	PTA01840
	READ(9,*) PX,PY,EXTS,EXAGE	PTA01850
	GO TO 30	PTA01860
	20 WRITE(6,6005)	PTA01870
6005	FORMAT(' ENTER PLANTING PARAMETERS: PX,PY,TP')	PTA01880
	READ(9,*) PX,PY,TP	PTA01890
	30 SPREP=0.	PTA01900
	WRITE(6,6006)	PTA01910
6006	FORMAT(' CUTOVER SITE ?')	PTA01920
	READ(9,5002) QCUTC	PTA01930
	IF(QCUTO.EQ.NO) GO TO 35	PTA01940
	IF(QCUTO.NE.YES) GO TO 30	PTA01950
	WRITE(6,6007)	PTA01960
6007	FORMAT(' ENTER SITE PREP PARAMETERS: SPREP,ARLSE')	PTA01970
	READ(9,*) SPREP,ARLSE	PTA01980
	35 CAF=SPREP+1	PTA01990
	SAF=1.	PTA02000
	WRITE(6,6106)	PTA02010
6106	FORMAT(' FERTILIZE AT PLANTING TIME ?')	PTA02020
	READ(9,5002) QFERT	PTA02030
	IF(QFERT.EQ.NO) GO TO 36	PTA02040
	IF(QFERT.NE.YES) GO TO 35	PTA02050
	WRITE(6,6107)	PTA02060
6107	FORMAT(' ENTER FERT PARAMETERS : RESP, LR')	PTA02070
	READ(9,*) RESP,LR	PTA02080
	KFERT=0	PTA02090
	LXR=0	PTA02100
	SAF=(SITE+RESP)/SITE	PTA02110
	36 WRITE(6,6008)	PTA02120
6008	FORMAT(' JUVENILE STAND OUTPUT?')	PTA02130
	READ(9,5002) QJUV	PTA02140
	IF(QJUV.EQ.YES) GO TO 33	PTA02150
	WRITE(6,6009)	PTA02160
6009	FORMAT(' ENTER: AGE AT NEXT DECISION PERIOD')	PTA02170
	READ(9,*) KIN	PTA02180
	38 RETURN	PTA02190
C		PTA02200

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

C	READ MANAGEMENT CRITERIA	PTA02210
C	ENTRY INPUT2	PTA02220
	IF(KIN.EQ.NYEARS) GO TO 39	PTA02230
	WRITE(6,6010) KIN	PTA02240
6010	FORMAT('/', ' INPUT BEFORE ', I2, ' TH GROWING SEASON')	PTA02250
39	KTHIN=0	PTA02260
	IF(KIN.EQ.NYEARS.GR.KIN.LT.10) GO TO 60	PTA02270
40	WRITE(6,6011)	PTA02280
6011	FORMAT(' THIN STAAD?')	PTA02290
	READ(9,5002) QTHIN	PTA02300
	IF(QTHIN.EQ.NO) GC TO 60	PTA02310
	IF(QTHIN.NE.YES)GC TO 40	PTA02320
	WRITE(6,6012)	PTA02330
6012	FORMAT(' ENTER THINNING TYPE, AGE: ITHIN,KTHIN')	PTA02340
	READ(9,*) ITHIN,KTHIN	PTA02350
	GO TO (50,55,50), ITHIN	PTA02360
50	WRITE(6,6013)	PTA02370
6013	FORMAT(' ENTER ROW THIN PARAMETER: IROW')	PTA02380
	READ(9,*) IROW	PTA02390
	IF(IITHIN.EQ.1) GO TO 60	PTA02400
55	WRITE(6,6014)	PTA02410
6014	FORMAT(' ENTER LOW THIN PARAMETERS: ILOW,DLOW,TLIM')	PTA02420
	READ(9,*) ILOW,DLOW,TLIM	PTA02430
60	IF(KIN.EQ.NYEARS.CR.KIN.LT.15.OR.QFERT.EQ.YES) GC TO 70	PTA02440
	QFERT=NO	PTA02450
	WRITE(6,6015)	PTA02460
6015	FORMAT(' FERTILIZE STAND?')	PTA02470
	READ(9,5002) QFERT	PTA02480
	IF(QFERT.EQ.NO) GC TO 70	PTA02490
	IF(QFERT.NE.YES)GC TO 60	PTA02500
	WRITE(6,6016)	PTA02510
6016	FORMAT(' ENTER FERT PARAMETERS: RESP,LR,LMR,KFERT')	PTA02520
	READ(9,*) RESP,LR,LMR,KFERT	PTA02530
70	KOUT=0	PTA02540
	IF(KIN.EQ.NYEARS) GO TO 75	PTA02550
	WRITE(6,6017)	PTA02560
6017	FORMAT(' STAND SUMMARY?')	PTA02570
	READ(9,5002) QSTAND	PTA02580
	IF(QSTAND.EQ.NO) GO TO 80	PTA02590
	IF(QSTAND.NE.YES)GO TO 70	PTA02600
75	KOUT=KIN	PTA02610
80	KTREE=0	PTA02620
	IF(KTREE.EQ.0) GO TO 90	PTA02630
	WRITE(6,6018)	PTA02640
6018	FORMAT(' TREE SUMMARY?')	PTA02650
	READ(9,5002) QTREE	PTA02660
	IF(QTREE.EQ.NO) GO TO 90	PTA02670
	IF(QTREE.NE.YES) GO TO 80	PTA02680
	KTREE=KIN	PTA02690
90	IF(KIN.EQ.NYEARS) GO TO 95	PTA02700
	WRITE (6,6019)	PTA02710
6019	FORMAT(' ENTER: AGE AT NEXT DECISION PERIOD')	PTA02720
	READ(9,*) KIN	PTA02730
95	RETURN	PTA02740
		PTA02750

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

C		PTA02760
C		PTA02770
C		PTA02780
	ENRY INPUT3	PTA02790
	WRITE(6,6020)	PTA02800
6020	FORMAT('QANOTHER STAND ?')	PTA02810
	READ(9,5002) QAGAIN	PTA02820
	RETURN	PTA02830
	END	PTA02840
		PTA02850
	SUBROUTINE JUV(IX)	PTA02860
C		PTA02870
C		PTA02880
C	SUBROUTINE JLV DETERMINES THE AGE AT WHICH	PTA02890
C	COMPETITION BEGINS AND ADVANCES THE JUVENILE STAND	PTA02900
C	TO THAT POINT IN TIME.	PTA02910
C		PTA02920
	COMMON /BLUK1/X(100),Y(100),LMORT(100),KMORT(100),D(100),	PTA02930
	I H(100),CL(100),CI(100),MID(100),LEDGE(9),ACRES	PTA02940
	COMMON /BLUK3/YCUFT(50,3),YDRWT(50,3),BA(50),KJ,K,NLIVE,	PTA02950
	I NTHIN,ND	PTA02960
	COMMON /BLUK4/TITLE(20),NYEARS,SITE,QEXIST,EXAGE,EXTS,	PTA02970
	I PX,PY,TP,KOUT,KIN,KTREE,QJUV,QAGAIN	PTA02980
	COMMON /BLUK5/SPREP,CAF,ARLSE,QCUTO	PTA02990
	COMMON /BLUK6/KFERT,LHR,LR,RESP,SAF,QFERT	PTA03000
	COMMON /BLUKD/N	PTA03010
	REAL YES/'YES'/,NC/'NO'/	PTA03020
C		PTA03030
C	DETERMINE COMPETITION AGE	PTA03040
C		PTA03050
	DO 100 KJ=5,15	PTA03060
	A=KJ	PTA03070
	HD=(SITE*SAF)*10**(-5.86537*(1./A-1./25.))	PTA03080
	SPROP=(TP*CAF)**(-A*.013)*10**(-A*(.0009*HD-.0109*SQRT(HD)))	PTA03090
	TS=SPROP*TP	PTA03100
	CCF = 189.89-1012.6/A+.00347*HD*TS*CAF	PTA03110
	IF(CCF.GT.100.) GO TO 10	PTA03120
100	CONTINUE	PTA03130
	10 NLIVE=TS*ACRES+.5	PTA03140
	NMORT=N-NLIVE	PTA03150
	NTHIN=0	PTA03160
C		PTA03170
C	DISTRIBUTE MORTALITY AMONG TREES AT RANDOM	PTA03180
C		PTA03190
	DO 200 IM=1,NMORT	PTA03200
20	IMORT=(U(IX))*N+1.	PTA03210
	IF(LMORT(IMORT).NE.1) GO TO 20	PTA03220
	LMORT(IMORT) = 0	PTA03230
	KMORT(IMORT)=0	PTA03240
200	CONTINUE	PTA03250
C		PTA03260
C	ADVANCE STAND DIMENSIONS	PTA03270
C		PTA03280
	DMIN=.13+.044649*TD-.18764E-4*A*(TS*CAF)	PTA03290
1	+17.27608*HD/(TS*CAF)	PTA03300

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

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DAVE=2.959949+.0540637*HD-.52168E-4*A*(TS*CAF)
1 +18.4654*HD/(TS*CAF)
BHAT=ALOG(TS*ACRES*CAF)/ALOG(DAVE/DMIN)
AHAT=(GAMMA(1+1/BHAT)/DAVE)**BHAT
DO 300 I=1,N
IF(LMORT(I)-1) 300,30,300
30 R=U(IX)
D(I)=(-ALOG(R)/AHAT)**(1/BHAT)
H(I)=HD**(.705702*(TS*CAF)**(.262307/D(I))*EXP(1.512047
1 -2.445067/A+2.551552/(A*D(I))-3.709999/D(I))
CBL=+(I)**1.612287*(TS*CAF)**(.457396/D(I))*D(I)**
1 (-8.958067/A)*EXP(-2.687682+12.74273/A
2 -21.74093/(A*C(I))-1.646384/D(I))
CL(I)=H(I)-CBL
IF(CL(I).LT.0) CL(I)=0.
C
C CALCULATE PRODUCTS
C
DSQ=D(I)*O(I)
BA(KJ)=BA(KJ)+DSQ
YDRWT(KJ,1)=YDRWT(KJ,1)+4.798337+.0432865*DSQ*H(I)
YCUFT(KJ,1)=YCUFT(KJ,1)+.34864+.00232*DSQ*H(I)
300 CONTINUE
BA(KJ)=BA(KJ)*.005454/ACRES
YDRWT(KJ,1)=YDRWT(KJ,1)/ACRES
YCUFT(KJ,1)=YCUFT(KJ,1)/ACRES
RETURN
END

SUBROUTINE PLANT
C
C SUBROUTINE PLANT CONTROLS ASSIGNMENT OF
C INITIAL RECTANGULAR SPACING.
C
COMMON /BLOK1/X(100),Y(100),LMORT(100),KMORT(100),D(100),
1 H(100),CL(100),CI(100),MID(100),LEDGE(9),ACRES
COMMON /BLEK2/IDIS(4),DIST(9),XDIST,YDIST
COMMON /BLOK4/TITLE(20),NYEARS,SITE,QEXIST,EXAGE,EXTS,
1 PX,PY,TP,KOUT,KIA,KTREE,QJUV,QAGAIN
COMMON /BLOK8/PLOTX,PLOTY,DELX,DELY,NRCX,NROY,YROW(10)
COMMON /BLOK0/N
REAL YES/'YES'/,NC/'NO'/
IF(QEXIST.NE.YES) GO TO 5
C
C EXISTING STAND
C
HD=SITE*10**(-5.86537*(1./EXAGE-1./25.))
TP=10**((1./(1.-.013*EXAGE))*(ALOG10(EXTS)+
1 EXAGE*(.0009*HD-.0109*SQRT(HD))))
C
C GIVEN ONLY SPACING IN FEET
C
5 IF(TP.GT.300) GO TO 10
DELX=PX
DELY=PY

```

PTA03310  
PTA03320  
PTA03330  
PTA03340  
PTA03350  
PTA03360  
PTA03370  
PTA03380  
PTA03390  
PTA03400  
PTA03410  
PTA03420  
PTA03430  
PTA03440  
PTA03450  
PTA03460  
PTA03470  
PTA03480  
PTA03490  
PTA03500  
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PTA03700  
PTA03710  
PTA03720  
PTA03730  
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PTA03750  
PTA03760  
PTA03770  
PTA03780  
PTA03790  
PTA03800  
PTA03810  
PTA03820  
PTA03830  
PTA03840  
PTA03850



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

	APT=DELX*DELY	PTA03860
	TP=43560./APT	PTA03870
	GO TO 30	PTA03880
C		PTA03890
C	GIVEN ONLY PLANTED TREES PER ACRE	PTA03900
C		PTA03910
	10 IF(PX.NE.0.) GO TO 20	PTA03920
	PX=1.	PTA03930
	PY=1.	PTA03940
C		PTA03950
C	GIVEN PLANTED TREES PER ACRE AND SPACING RATIO	PTA03960
C		PTA03970
	20 APT=43560./TP	PTA03980
	DEL=SQRT(APT/(PX*PY))	PTA03990
	DELX=DEL*PX	PTA04000
	DELY=DEL*PY	PTA04010
	30 ACRES=N/TP	PTA04020
	NROWS=SQRT(FLOAT(N))+.5	PTA04030
	PLOTX=NROWS*DELX	PTA04040
	PLOTY=NROWS*DELY	PTA04050
C		PTA04060
C	ASSIGN TREE COORDINATES	PTA04070
C		PTA04080
	X(1)=DELX/2.	PTA04090
	Y(1)=DELY/2.	PTA04100
	YROW(1)=Y(1)	PTA04110
	QX=1.	PTA04120
	QY=0.	PTA04130
	DO 200 I=2,N	PTA04140
	DO 100 J=NROWS,N,NROWS	PTA04150
	IF(I.NE.J+1) GO TO 100	PTA04160
	QX=QX*(-1.)	PTA04170
	QY=QY+1.	PTA04180
	X(I)=X(I-1)	PTA04190
	JJ=J/NROWS	PTA04200
	IF(JJ.GT.1) YROW(JJ)=YROW(JJ-1)+DELY	PTA04210
	GO TO 200	PTA04220
	100 CONTINUE	PTA04230
	X(I)=X(I-1)+QX*DELX	PTA04240
	200 Y(I)=Y(1)+QY*DELY	PTA04250
	NROX=NROWS	PTA04260
	NROY=NROWS	PTA04270
	RETURN	PTA04280
	END	PTA04290
		PTA04300
	SUBROUTINE THIN(A)	PTA04310
C		PTA04320
C	SUBROUTINE THIN REMOVES TREES EITHER BY ROWS OR FROM	PTA04330
C	BELOW. THINNING FROM BELOW MAY BE ACCOMPLISHED BY REMOVING	PTA04340
C	TREES BELOW A SPECIFIED DBH OR BY THINNING TO A SPECIFIED	PTA04350
C	RESIDUAL BASAL AREA.	PTA04360
C		PTA04370
	COMMON /BLK1/X(100),Y(100),LMORT(100),KMORT(100),D(100),	PTA04380
	1 H(100),CL(100),CI(100),MID(100),LEDGE(9),ACRES	PTA04390
	COMMON /BLK3/YCUFT(50,3),YDRWT(50,3),BA(50),KJ,K,NLIVE,	PTA04400

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

	1 NTHIN,HD	PTA04410
	COMMON/BLOCK4/TITLE(20),NYEARS,SITE,QEXIST,EXAGE,EXTS.	PTA04420
	1 PX,PY,TP,KOUT,KIN,KTREE,QJUV,QAGAIN	PTA04430
	COMMON /BLOK7/KTHIN,ITHIN,IROW,ILOW,DLQW,TLIM	PTA04440
	COMMON /BLOK8/PLOTX,PLOTY,DELX,DELY,NROX,NROY,YROW(10)	PTA04450
	COMMON /BLOK0/N	PTA04460
	GO TO (1,2,1),ITHIN	PTA04470
C		PTA04480
C	ROW THINNING	PTA04490
C		PTA04500
	1 NRDUMP=MOD(NROY,IROW)	PTA04510
	IF(NRDUMP.LE.0) GO TO 11	PTA04520
	N=N-NRDUMP*NROX	PTA04530
	NROY=NROY-NRDUMP	PTA04540
	PLOTY=PLOTY-NRDUMP*DELY	PTA04550
	ACRES=PLOTX*PLOTY/43560.	PTA04560
	11 CONTINUE	PTA04570
	DO 100 I=1,N	PTA04580
	IF(LMORT(I).NE.1) GO TO 100	PTA04590
	DO 99 IR=1,NROY,IROW	PTA04600
	IF(Y(IR).NE.YROW(IR)) GO TO 99	PTA04610
	NTHIN=NTHIN+1	PTA04620
	NLIVE=NLIVE-1	PTA04630
	LMORT(I)=3	PTA04640
	KMORT(I)=KTHIN	PTA04650
	99 CONTINUE	PTA04660
	100 CONTINUE	PTA04670
	IF(ITHIN.EQ.1) GO TO 3	PTA04680
C		PTA04690
C	LOW THINNING	PTA04700
C		PTA04710
	2 IF(ILOW.EQ.2) GO TO 22	PTA04720
C		PTA04730
C	DIAMETER LIMIT OPTICN	PTA04740
C		PTA04750
	DO 200 I=1,N	PTA04760
	IF(LMORT(I).NE.1) GO TO 200	PTA04770
	IF(D(I).LT.DLUW.OR.D(I).GE.TLIM) GO TO 200	PTA04780
	NTHIN=NTHIN+1	PTA04790
	NLIVE=NLIVE-1	PTA04800
	LMORT(I)=3	PTA04810
	KMORT(I)=KTHIN	PTA04820
	200 CONTINUE	PTA04830
	GO TO 3	PTA04840
C		PTA04850
C	BA LIMIT OPTICN	PTA04860
C		PTA04870
	22 BATH=(BA(K-1)-TLIM)*ACRES/.005454	PTA04880
	BATHIN=0.	PTA04890
	DO 400 IT=1,N	PTA04900
	IF(BATHIN.GE.BATH) GO TO 3	PTA04910
	DMIN=9.E6	PTA04920
	DO 300 I=1,N	PTA04930
	IF(LMORT(I).NE.1) GO TO 300	PTA04940
	IF(D(I).GE.DMIN.OR.D(I).LT.DLUW) GO TO 300	PTA04950

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

	DMIN=D(I)	PTA04960
	IMIN=I	PTA04970
300	CONTINUE	PTA04980
	BATHIN =BATHIN+D(IMIN)*D(IMIN)	PTA04990
	NTHIN=NTHIN+1	PTA05000
	NLIVE=NLIVE-1	PTA05010
	LMORT(IMIN)=3	PTA05020
	KMORT(IMIN)=KTHIN	PTA05030
400	CONTINUE	PTA05040
	3 IF(KTHIN.NE.NYEARS-1) GO TO 4	PTA05050
	K=K-1	PTA05060
	DO 500 I=1,N	PTA05070
	IF(KMORT(I).NE.K+1) GO TO 500	PTA05080
	DSQ=D(I)*D(I)	PTA05090
	BA(K)=BA(K)-DSQ*.005454/ACRES	PTA05100
	YCFT=DSQ*H(I)*.00232 + .34864	PTA05110
	YDWT=DSQ*H(I)*.043287+4.79834	PTA05120
	YCUFT(K,1)=YCUFT(K,1)-YCFT/ACRES	PTA05130
	YCUFT(K,3)=YCUFT(K,3)+YCFT/ACRES	PTA05140
	YDRWT(K,1)=YDRWT(K,1)-YDWT/ACRES	PTA05150
	YDRWT(K,3)=YDRWT(K,3)+YDWT/ACRES	PTA05160
500	CONTINUE	PTA05170
	CALL OUTPUT	PTA05180
	K=K+1	PTA05190
	4 RETURN	PTA05200
	END	PTA05210
	SUBROUTINE FERT(A)	PTA05220
C		PTA05230
C		PTA05240
C	SUBROUTINE FERT SIMULATES THE EFFECTS OF	PTA05250
C	FERTILIZATION ON SITE QUALITY BY CALCULATING A SITE	PTA05260
C	ADJUSTMENT FACTOR (CAF) WHICH ACTS AS A MULTIPLIER OF	PTA05270
C	SITE INDEX.	PTA05280
C		PTA05290
	COMMON /BLOK4/TITLE(20),NYEARS,SITE,QEXIST,EXAGE,EXTS,	PTA05300
	1 PX,PY,TP,KOUT,KIN,KTREE,QJUV,QAGAIN	PTA05310
	COMMON /BLOK6/KFERT,LMR,LR,RESP,SAF,QFERT	PTA05320
	REAL NO/'NU'/	PTA05330
	IF(A-KFERT.LE.0) GO TO 50	PTA05340
	IF(A-KFERT.GT.LMR) GO TO 20	PTA05350
C		PTA05360
C	AGE LE AGE OF MAX RESPONSE (LMR)	PTA05370
C		PTA05380
	SAF=RESP*(1.-(KFERT+LMR-A)/LMR)	PTA05390
	GO TO 30	PTA05400
	20 IF(A-KFERT.GE.LR) GO TO 40	PTA05410
C		PTA05420
C	AGE GT AGE OF MAX RESPONSE (LMR)	PTA05430
C		PTA05440
	SAF=RESP*(1.+(KFERT+LMR-A)/(LR-LMR))	PTA05450
	30 SAF=(SAF+SITE)/SITE	PTA05460
	GO TO 50	PTA05470
	40 SAF=1	PTA05480
	QFERT=NO	PTA05490
	50 RETURN	PTA05500

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

	END	PTA05510
	SUBROUTINE PREP(A)	PTA05520
C		PTA05530
C	SUBROUTINE PREP SIMULATES THE INCREASED	PTA05540
C	COMPETITION ON CUTOVER LAND BY CALCULATING A	PTA05550
C	COMPETITION ADJUSTMENT FACTOR (CAF) WHICH IS USED	PTA05560
C	TO MULTIPLY ALL COMPETITIVE COMPONENTS OF PTAEDA.	PTA05570
C		PTA05580
	COMMON /BLOK5/SPREP,CAF,ARLSE,CCUTO	PTA05590
	REAL NO/'NO'/	PTA05600
	IF(A.GE.ARLSE) GO TO 10	PTA05610
	CAF=SPREP*(1.-A/ARLSE)+1	PTAC5620
	GO TO 20	PTA05630
10	CAF=1	PTA05640
	QCUTG=NO	PTA05650
20	RETURN	PTA05660
	END	PTA05670
		PTA05680
	SUBROUTINE OUTPUT	PTA05690
C		PTA05700
C	SUBROUTINE OUTPUT CALCULATES AND DISPLAYS	PTA05710
C	SUMMARY STATISTICS FOR TREE AND STAND CHARACTERISTICS.	PTA05720
C		PTA05730
	REAL MAT(3)	PTA05740
	DIMENSION NDC(25,3),HDC(25,3),PROD(3),YINC(3),PAI(3),	PTA05750
	1 BAR(4),DMIN(4),DMAX(4),SD(4)	PTA05760
	COMMON /BLOK1/X(100),Y(100),LMCRT(100),KMURT(100),D(100),	PTA05770
	1 H(100),CL(100),CI(100),MID(100),LEDGE(9),ACRES	PTA05780
	COMMON /BLOK3/YCUFT(50,3),YDRWT(50,3),BA(50),KJ,K,NLIVE,	PTA05790
	1 NTHIN,FD	PTA05800
	COMMON /BLOK4/TITLE(20),NYEARS,SITE,QEXIST,EXAGE,EXTS,	PTA05810
	1 PX,PY,TP,KOUT,KIA,KTREE,QJUV,QAGAIN	PTA05820
	REAL YES/'YES'/,NC/'NO'/	PTA05830
	COMMON /BLOK0/N	PTA05840
	IF(QJUV.EQ.NO) GO TO 1	PTA05850
	K=KJ	PTA05860
	QJUV=NO	PTA05870
	1 INDEX=1	PTA05880
C		PTA05890
C	CALCULATE STAND SUMMARY STATISTICS	PTA05900
C		PTA05910
	CALL STAT(D,N,LMCRT,BAR(1),DMIN(1),DMAX(1),SD(1),INDEX)	PTA05920
	CALL STAT(H,N,LMCRT,BAR(2),DMIN(2),DMAX(2),SD(2),INDEX)	PTAC5930
	CALL STAT(CL,N,LMCRT,BAR(3),DMIN(3),DMAX(3),SD(3),INDEX)	PTA05940
	CALL STAT(CI,N,LMCRT,BAR(4),DMIN(4),DMAX(4),SD(4),INDEX)	PTA05950
	INDEX=2	PTA05960
	CALL STAT(D,N,LMCRT,DUMP1,DMIN2,DMAX2,DUMP2,INDEX)	PTA05970
	MAXDC=DMAX2+.45	PTA05980
	MINDC=DMIN2+.45	PTA05990
	IF(MINDC.LT.1) MINDC=1	PTA06000
C		PTA06010
C	CALCULATE CURRENT, PERIODIC, AND MEAN ANNUAL INCREMENT	PTA06020
C		PTA06030
	DO 100 ID=MINDC,MAXDC	PTA06040
		PTA06050

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

	DO 100 L=1,3	PTA06060
	NDC(ID,L)=0	PTA06070
100	HDC(ID,L)=0	PTA06080
	DO 150 M=1,3	PTA06090
	YINC(M)=9.E9	PTA06100
150	PAI(M)=9.E9	PTA06110
	IF(KJ.EQ.K) GO TO 3	PTA06120
	YINC(1)=BA(K)-BA(K-1)	PTA06130
	YINC(2)=YCUFT(K,1)-YCUFT(K-1,1)	PTA06140
	YINC(3)=YDRWT(K,1)-YDRWT(K-1,1)	PTA06150
	IF(K-KJ.LT.5) GO TO 3	PTA06160
	PAI(1)=(BA(K)-BA(K-5))/5.	PTA06170
	PAI(2)=(YCUFT(K,1)-YCUFT(K-5,1))/5.	PTA06180
	PAI(3)=(YDRWT(K,1)-YDRWT(K-5,1))/5.	PTA06190
3	MAI(1)=BA(K)/K	PTA06200
	MAI(2)=YCUFT(K,1)/K	PTA06210
	MAI(3)=YDRWT(K,1)/K	PTA06220
	PROD(1)=BA(K)	PTA06230
	PROD(2)=YCUFT(K,1)	PTA06240
	PROD(3)=YDRWT(K,1)	PTA06250
	TS=NLIVE/ACRES	PTA06260
	NMORT=N-NLIVE-NTHIN	PTA06270
	TM=NMORT/ACRES	PTA06280
	TT=NTHIN/ACRES	PTA06290
C		PTA06300
C	CALCULATE DISTRIBUTION OF SIZES	PTA06310
C		PTA06320
	DO 200 I=1,N	PTA06330
	L=LMCRT(I)	PTA06340
	IF(L.EQ.0) GO TO 200	PTA06350
	ID=D(I)+.45	PTA06360
	IF(ID.LT.1) ID=1	PTA06370
	NDC(ID,L)=NDC(ID,L)+1	PTA06380
	HDC(ID,L)=HDC(ID,L)+H(I)	PTA06390
200	CONTINUE	PTA06400
	DO 300 L=1,3	PTA06410
	DO 300 ID=MINDC,MAXDC	PTA06420
	IF(NDC(ID,L).LE.0) GO TO 300	PTA06430
	HDC(ID,L)=HDC(ID,L)/NDC(ID,L)	PTA06440
	NDC(ID,L)=NDC(ID,L)/ACRES+.5	PTA06450
300	CONTINUE	PTA06460
C		PTA06470
C	DISPLAY TREE AND STAND CHARACTERISTICS	PTA06480
C		PTA06490
	WRITE(6,6100)(TITLE(M),M=1,20)	PTA06500
6100	FORMAT(//' ',20A4//)	PTA06510
	WRITE(6,6101) K	PTA06520
6101	FORMAT(' STAND SUMMARY - AGE',13//' DIMENSION ',	PTA06530
	1 ' MEAN ST.DEV. MIN MAX')	PTA06540
	WRITE(6,6102)(BAR(M),SD(M),DMIN(M),DMAX(M), M=1,4)	PTA06550
6102	FORMAT(' DBH',6X,4(3X,F5.2)//' HT',5X,4(3X,F5.1)//	PTA06560
	1 ' CL',5X,4(3X,F5.1)//' CI',6X,4(2X,F6.4)//	PTA06570
	WRITE(6,6103) ACRES,TP,TS,HD	PTA06580
6103	FORMAT(' OACRES SIMULATED ',F10.5/' TREES PLANTED',	PTA06590
	1 ' PER ACRE ',F10.0/' TREES SURVIVING PER ACRE',F10.0/	PTA06600

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

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2 * HEIGHT OF DOMINANT STAND',F11.1//                                PTA06610
WRITE(6,6104)(PROC(M),YINC(M),PAI(M),MAI(M),M=1,3)                 PTA06620
6104 FORMAT('OPRODUCT      YIELD  INCREM  PAI    MAI'/          PTA06630
1 * BASAL AREA',4X,F6.1,3(2X,F6.2)/' CUBIC FEET',3X,F6.0,      PTA06640
2 3(2X,F6.1)/' BIOMASS   ',2X,F7.0,3(1X,F7.1)//                PTA06650
IF(NTHIN.LE.0) GO TO 57                                           PTA06660
WRITE(6,6501) YCUFT(K,3)                                          PTA06670
6501 FORMAT(' VOLUME THINNED ',F6.0/)                             PTA06680
57 CONTINUE                                                       PTA06690
WRITE(6,6105)                                                      PTA06700
6105 FORMAT('OD CLASS #LIVE  MEAN H   #MORT  MEAN H',          PTA06710
1 ' #THIN  MEAN H')                                             PTA06720
DO 400 ID=MINDC,MAXDC                                             PTA06730
400 WRITE(6,6106) ID, (NDC(ID,L),HDC(ID,L),L=1,3)              PTA06740
6106 FORMAT(' ',I3,3(4X,I5,3X,F6.2))                             PTA06750
WRITE(6,6107) IS,IM,IT                                           PTA06760
6107 FORMAT(' TOT ',3(4X,F5.0,9X)//                               PTA06770
RETURN                                                            PTA06780
END                                                                PTA06790

SUBROUTINE COMP                                                  PTA06800
C                                                                    PTA06810
C                                                                    PTA06820
C      SUBROUTINE COMP CALCULATES A MODIFIED                     PTA06830
C      HEGYI COMPETITION INDEX ON ALL LIVE TREES IN             PTA06840
C      A STAND.  COMPETITORS ARE FOUND BY SAMPLING              PTA06850
C      NEIGHBORS BASED ON THEIR SIZE AND DISTANCE AWAY         PTA06860
C      BY ESSENTIALLY TAKING A POINT SAMPLE AT EACH           PTA06870
C      SUBJECT TREE WITH A BAF-10 PRISM.                        PTA06880
C                                                                    PTA06890
C                                                                    PTA06900
C                                                                    PTA06910
C                                                                    PTA06920
C                                                                    PTA06930
C                                                                    PTA06940
C                                                                    PTA06950
C                                                                    PTA06960
C                                                                    PTA06970
C                                                                    PTA06980
C                                                                    PTA06990
C                                                                    PTA07000
C                                                                    PTA07010
C                                                                    PTA07020
C                                                                    PTA07030
C                                                                    PTA07040
C                                                                    PTA07050
C                                                                    PTA07060
C                                                                    PTA07070
C                                                                    PTA07080
C                                                                    PTA07090
C                                                                    PTA07100
C                                                                    PTA07110
C                                                                    PTA07120
C                                                                    PTA07130
C                                                                    PTA07140
C                                                                    PTA07150
DIMENSION JDIS(9)
COMMON /BLOK1/X(100),Y(100),LMORT(100),KMORT(100),D(100),
1 H(100),CL(100),CI(100),MID(100),LEDGE(9),ACRES
COMMON /BLOK2/IDIS(4),DIST(9),XDIST,YDIST
COMMON /BLOK8/PLOTX,PLOTY,DELX,DELY,NROX,NRCY,YROW(10)
COMMON /BLOKD/N
DATA PLOTR/2.75/,PI/3.14159/,JDIS/1,9,6,7,6,5,4,3,2/
IDIS(1)=1
DMAX=0
DO 100 I=1,N
100 IF(D(I).GT.DMAX) DMAX=D(I)
DISMAX=PLOTR*DMAX-DELX/2.
DISMAY=PLOTR*DMAX-DELY/2.
DO 200 I=1,N
MID(I)=2
200 IF(X(I).GT.DISMAX.AND.X(I).LT.(PLOTX-DISMAX).AND.
1 Y(I).GT.DISMAY.AND.Y(I).LT.(PLOTY-DISMAY)) MID(I)=1
NLESS1=N-1
DO 500 I=1,NLESS1
IF(LMORT(I).NE.1) GO TO 500
IPLUS1=I+1
DO 400 J=IPLUS1,N
IF(LMORT(J).NE.1) GO TO 400
INTIOR=MID(I)+MID(J)
XDIST=X(J)-X(I)
YDIST=Y(J)-Y(I)

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

DIST(1)=SQRT(XDIST*XDIST+YDIST*YDIST)	PTA07160
IF(INTEIOR.LT.3) GC TO 1	PTA07170
CALL HOWFAR	PTA07180
1 RJI=D(J)/D(I)	PTA07190
RIJ=1/RJI	PTA07200
DO 300 L=1,4	PTA07210
LC=IDIS(L)	PTA07220
LCC=JDIS(LC)	PTA07230
LEDGE(LC)=0	PTA07240
LEDGE(LCC)=0	PTA07250
IF(DIST(LC).GE.D(J)*PLOTX) GO TO 20	PTA07260
IF(LEDGE(LC).EQ.0) CI(I)=CI(I)+RJI/DIST(LC)	PTA07270
20 IF(DIST(LC).GE.D(I)*PLOTX) GO TO 30	PTA07280
IF(LEDGE(LCC).EQ.0) CI(J)=CI(J)+RIJ/DIST(LC)	PTA07290
30 IF(INTEIOR.LE.3) GC TO 400	PTA07300
300 CONTINUE	PTA07310
400 CONTINUE	PTA07320
500 CONTINUE	PTA07330
RETURN	PTA07340
END	PTA07350
PTA07360	
PTA07370	
PTA07380	
PTA07390	
PTA07400	
PTA07410	
PTA07420	
PTA07430	
PTA07440	
PTA07450	
PTA07460	
PTA07470	
PTA07480	
PTA07490	
PTA07500	
PTA07510	
PTA07520	
PTA07530	
PTA07540	
PTA07550	
PTA07560	
PTA07570	
PTA07580	
PTA07590	
PTA07600	
PTA07610	
PTA07620	
PTA07630	
PTA07640	
PTA07650	
PTA07660	
PTA07670	
PTA07680	
PTA07690	
PTA07700	

```

SUBROUTINE HOWFAR
C
C     SUBROUTINE HOWFAR CALCULATES DISTANCES BETWEEN
C     TREES ON MAIN AND 'BORDER' PLOTS FOR USE IN CALCULATING
C     COMPETITION FOR NLN-INTERIOR TREES.
C
COMMON /BLOK2/IDIS(4),DIST(9),XDIST,YDIST
COMMON /BLOK8/PLCTX,PLOTX,DELX,DELY,NRCX,NRCY,YRCW(10)
IF(XDIST) 6,5,5
5  DIST(5)=SQRT((XDIST-PLCTX)*(XDIST-PLCTX)+
1  (YDIST      )*(YDIST      ))
  IDIS(2)=5
  GO TO 10
6  DIST(6)=SQRT((XDIST+PLCTX)*(XDIST+PLCTX)+
1  (YDIST      )*(YDIST      ))
  IDIS(2)=6
10 IF(YDIST) 3,8,8
3  DIST(3)=SQRT((XDIST      )*(XDIST      )+
1  (YDIST+PLOTY)*(YDIST+PLOTY))
  IDIS(3)=3
  ICODE=IDIS(2)+IDIS(3)-7
  GO TO (2,4,11,11,11,7,9),ICODE
8  DIST(8)=SQRT((XDIST      )*(XDIST      )+
1  (YDIST-PLOTY)*(YDIST-PLOTY))
  IDIS(3)=8
  ICODE=IDIS(2)+IDIS(3)-7
  GO TO (2,4,11,11,11,7,9),ICODE
2  DIST(2)=SQRT((XDIST-PLCTX)*(XDIST-PLCTX)+
1  (YDIST+PLUTY)*(YDIST+PLUTY))
  IDIS(4)=2
  RETURN
4  DIST(4)=SQRT((XDIST+PLCTX)*(XDIST+PLCTX)+
1  (YDIST+PLOTY)*(YDIST+PLOTY))
  IDIS(4)=4

```

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

```

RETURN
7 DIST(7)=SQRT((XDIST-PLOTX)*(XDIST-PLOTX)+
1 (YDIST-PLOTY)*(YDIST-PLOTY))
IDIS(4)=7
RETURN
9 DIST(9)=SQRT((XDIST+PLOTX)*(XDIST+PLOTX)+
1 (YDIST-PLUTY)*(YDIST-PLUTY))
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(IX)
C
C GENERATES A UNIFORM(0,1) RANDOM VARIATE
C
IX=IX*65535
U=.5+IX*.2328306E-9
RETURN
END

FUNCTION STNORM(IX)
C
C GENERATES A STANDARD NORMAL RANDOM VARIATE
C
STNORM=(-2*ALOG(U(IX)))**.5*COS(6.283*U(IX))
RETURN
END

```

PTA07710  
PTA07720  
PTA07730  
PTA07740  
PTA07750  
PTA07760  
PTA07770  
PTA07780  
PTA07790  
PTA07800  
PTA07810  
PTA07820  
PTA07830  
PTA07840  
PTA07850  
PTA07860  
PTA07870  
PTA07880  
PTA07890  
PTA07900  
PTA07910  
PTA07920  
PTA07930  
PTA07940  
PTA07950  
PTA07960  
PTA07970  
PTA07980  
PTA07990  
PTA08000  
PTA08010  
PTA08020  
PTA08030  
PTA08040  
PTA08050  
PTA08060  
PTA08070  
PTA08080  
PTA08090  
PTA08100  
PTA08110  
PTA08120  
PTA08130  
PTA08140  
PTA08150  
PTA08160  
PTA08170  
PTA08180  
PTA08190  
PTA08200  
PTA08210  
PTA08220  
PTA08230  
PTA08240  
PTA08250



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

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SUBROUTINE TREE	PTA08260
RETURN	PTA08270
END	PTA08280
	PTA08290
BLOCK DATA	PTA08300
COMMON /BLGKD/ N	PTA08310
INTEGER N/100/	PTA08320
END	PTA08330
	PTA08340
\$ENTRY	PTA08350

