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 Bernouli trials. Subroutines were developed to simulate the effects of site preparation, thinning, and fertilization on tree and stand development. Comparisons with published yields showed close agreement for thinned and unthinned old-field plantations. Results indicated that, compared to stand-level models used in the past, the simulator is more flexible in terms of growth and yield estimation and evaluation of alternatives under a wide range of management regimes.

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INTRODUCTION

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

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

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

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

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

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

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

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

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

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

LITERATURE REVIEW

Stand Level Models

Yield predictions in the Southeast began with the same methodology as in other parts of the country. Temporary sample plots were established in natural stands of "normal density" and classical normal yield tables were constructed using graphical techniques (Anon. 1929). Yield tables constructed in this manner are still being applied to a limited extent in the Southeast.

A multiple regression approach to variable-density yield estimation was suggested by MacKinney, Schumacher, and Chaiken (1937) and subsequently used to construct a yield prediction equation for loblolly pine stands (MacKinney and Chaiken 1939). Since that time, several studies have utilized multiple regression to predict yield (Bennet, McGee and Clutter 1959, Goebel and Shipman 1964, Dierauf and Marler 1965, Burkhart et al. 1972, and others).

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

Individual Tree Models

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

Newnham (1964) presented what appears to be the first stand model based on individual tree simulation. He considered diameter increment for trees in plantations of Douglas-fir to be equal to open-grown diameter growth as reduced by a measure of competition. Competition was described for each tree by the sum of the "angles of intersection" of crowns of neighboring trees. Height growth was not considered. In his model, growth was incremented and stand statistics were tabulated every five years from age 10 to 100. Mortality was assigned both as a function of diameter increment and as specified in initial parameters to simulate thinnings and infection centers of mortality. Total heights were obtained through a regression equation in terms of DBH, 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 indivudal 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

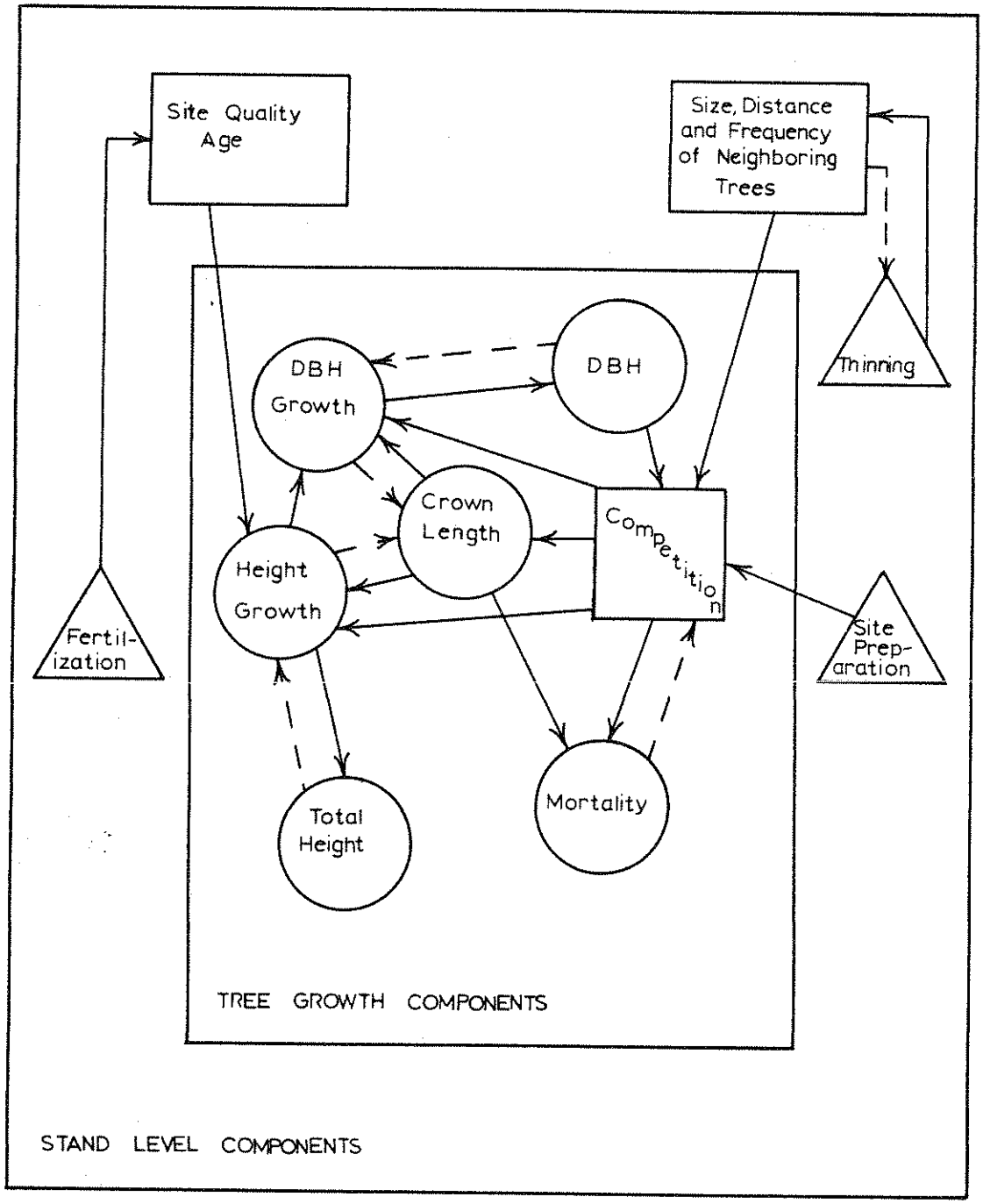
Participants in a recent tree growth simulation workshop agreed that individual tree simulation models will play an essential role in estimating yield and evaluating intensive management alternatives (Honer 1972). They suggested that, at least for now, individual tree modeling efforts should be aimed 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 Burkhart *et al.* (1972). These data consisted of 240, one-tenth acre plots randomly chosen from selected loblolly pine plantations in piedmont and coastal plain Virginia and from coastal plain Delaware, Maryland, and North Carolina. One hundred and eighty-nine of these plots were from old-field origin, while 51 were from site-prepared cutover lands. Data from 81 open grown loblolly pine trees from the same geographic range were also available.

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

Model Construction

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

Initial Stand Generation

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

Table 1. Summary of data used in constructing the loblolly pine tree and stand growth simulator PTAEDA.

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

$$F(y) = 1 - e^{-ay^b} \qquad 0 < y < \infty$$

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^2	$S_{y \cdot x}$	Source
$CCF = 180.89 - 1012.6/A + 0.00347\ HD \cdot TS$	0.8393	23.22	Strub *et al*. in press
$\log_{10}HD = \log_{10}SI - 5.86537\ (1/A - 1/25)$	----	---	Burkhart *et al*. 1972
$\log_{10}(TP/TS) = A(0.0130\ \log_{10}TP + 0.0009HD - 0.0109\sqrt{HD})$	0.8400	0.0042	Smalley and Bailey 1974a
$DMIN = 0.13291 + 0.04465HD - 0.00001876\ A \cdot TS + 17.2761\ HD/TS$	0.7662	0.5645	Plantation Data
$DAVE = 2.95995 + 0.05406HD - 0.00005217\ A \cdot TS + 18.4654\ HD/TS$	0.9206	0.3470	Plantation Data
$\ln H = 1.51205 + 0.7057 \ln HD + (0.26231/D) \ln TS - 2.44501/A - 3.70999/D + 2.95155/(D \cdot A)$	0.9514	0.0697	Plantation Data
$\ln CBL = -2.68768 + 1.61229 \ln H + (0.45740/D) \ln TS - (8.95807/A) \ln D + 12.74273/A - 1.64638/D - 21.74093/(D \cdot A)$	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 ith 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 competitiors 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 (Hegyi 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 Burkhart *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 presumeably 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:

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

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

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

* Where, PHIN = potential height increment, HIN = actual height increment, PDIN = potential DBH increment, DIN = actual DBH increment, CI = competition index, CR = crown ratio, CL = crown length, PLIVE = survival probability.

increasing competition and increases with increasing crown length. An equation relating actual and potential diameter growth by this factor was developed using non-linear least squares (Table 4). A normally distributed random component is added to growth determinations with variance equal to the residual mean square from the fitted regression.

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

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

Mortality

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

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

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 pratical 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 [1/] it was concluded that response to fertilizer treatments could be described by increases in site quality. Therefore, subroutine FERT was developed with a site adjustment factor (SAF) which acts as a multiplier on site index for fertilized stands.

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

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

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

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

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

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

Yield Estimates

Estimates of production in PTAEDA are restricted to basal area per acre, trees per acre, total stem cubic-foot volume (outside bark), and

total above ground biomass. Total stem cubic-foot volume for each tree is determined by the following equation developed by Burkhart et al. (1972):

$$V = 0.34864 + 0.00232\ D^2H$$

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

$$W = 4.798337 + 0.043286\ D^2H$$

$$r^2 = 0.98998 \quad S_{y \cdot x} = 6.2186$$

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

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

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

Random Number Generation

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

The uniform generator provides the basis for generating pseudo-random numbers from other distributions. Standard normal variates are generated by function STNORM which employs the log-sin transformation

of uniform variates described by Fishman (1973). Weibull random variates are generated in line by inverting the Weibull CDF and substituting uniform variates for values of the cumulative probabilities.

Testing and Validation Procedures

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

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

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

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

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

RESULTS AND DISCUSSION

Preliminary trials with PTAEDA demonstrated its versatility and reliability as a prediction tool for loblolly pine growth and yield. The model proved to be moderate in terms of computer costs, requiring roughly one minute of execution time to simulate a 30-year rotation.

However, costs accumulated rapidly when making multiple runs. A complete description of input variables, example runs, and a source listing of the program for the interactive version can be found in the appendix. Card format for the batch mode version is also presented.

Initial Tests and Refinements

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

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

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

$$HMAX = b_0 + b_1 HD + b_2 A$$

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 Burkhart et al. (1972) (Table 5). However, it can be seen that mean basal area and mean cubic-foot volume per acre were underestimated by the model and in fact differences between means of observed and predicted values were significant using a

Table 5. Mean, standard deviation, and range of predicted and observed yields on 187 old-field loblolly pine sample plots.

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

() indicates observed yields

* indicates significant difference (α =0.05) between observed and predicted means

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

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

The precision of PTAEDA also compared favorably with that shown by diameter distribution models. For cubic-foot volume, 25 percent of predicted values were within $\pm$ 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 (number/acre)	12.4	51.5	-84	382
Basal Area (ft^2/acre)	7.6	27.4	-56.6	96.3
Cubic-foot Volume (ft^3/acre)	236.9	567.3	-1215	2473
	Percent Deviation			
Trees (number/acre)	1.16	5.98	-12.35	26.67
Basal Area (ft^2/acre)	3.32	17.16	-49.35	57.66
Cubic-foot Volume (ft^3/acre)	5.45	15.22	-46.12	48.37

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

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

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: Basal area (feet^2)	Amount of Thinnings: Volume (cords)**	Average DBH (inches)	Residual Stand at Age 30: Trees per acre (number)	Residual Stand at Age 30: Basal area (feet^2)	Residual Stand at Age 30: Volume (cords)	Total Production (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 Burkhart, et al. 1972.

()Indicates data for unthinned stands.

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

LITERATURE CITED

Adams, D.M. and A.R. Ek. 1974. Optimizing the management of uneven-aged forest stands. Can. J. For. Res. 4:274-287.

Andrulot, E.R., L.P. Blackwell, and P.Y. Burns. 1972. Effects of thinning on yield of loblolly pine in central Louisiana. Louisiana Tech Univ. School of Forestry, Bull. 6., 145 p.

Anon. 1929. Volume yield and stand tables for second growth Southern pines. USDA Forest Service. USDA Misc. Publ. 50, 202 p.

Arney, J.D. 1972. Computer simulation of Douglas-fir tree and stand growth. Unpublished Ph.D. Thesis, Oregon State Univ., 79 p.

Bella, I.E. 1970. Simulation of growth, yield and management of aspen. Unpublished Ph.D. Thesis, Univ. of British Columbia, 190 p.

Bella, I.E. 1971. A new competition model for individual trees. Forest Sci. 17:364-372.

Bennett, F.A. and J.L. Clutter. 1968. Multiple-product yield estimates for unthinned slash pine plantations--pulpwood, sawtimber, gum. USDA Forest Service Res. Pap. SE-35, 21 p.

Bennett, F.A., C.E. McGee, and J.L. Clutter. 1959. Yield of old-field slash pine plantations. USDA Forest Service Station Pap. 107, 19 p.

Botkin, D.B., J.F. Janak, and J.R. Wallis. 1972a. Rationale, limitations, and assumptions of a Northeastern forest growth simulator. IBM J. Res. Develop. 16:101-116.

Botkin, D.B., J.F. Janak, and J.R. Wallis. 1972b. Some ecological consequences of a computer model of forest growth. J. Ecol. 60:849-872.

Brown, G.S. 1965. Point density in stems per acre. Forest Res. Inst., N.Z. Forest Service, Forest Res. Notes No. 38, 11 p.

Burkhart, H.E. 1971. Slash pine yield estimates based on diameter distribution: An evaluation. Forest Sci. 17:452-453.

Burkhart, H.E. 1974. Prediction of cubic-foot volume for plantation-grown loblolly pine trees. Report to the Chesapeake Corporation of Virginia. (Mimeo), 5 p.

Burkhart, H.E., R.C. Parker, M.R. Strub, and R.G. Oderwald. 1972. Yields of old-field loblolly pine plantations. Div. Forestry and Wildlife Resources, V.P.I. & S.U., FWS-3-72, 51 p.

Clutter, J.L. 1963. Compatible growth and yield models for loblolly pine. Forest Sci. 9:354-371.

Coile, T.S. and F.X. Schumacher. 1964. Soil-Site Relations, Stand Structure, and Yields of Slash and Loblolly Pine Plantations in the Southern United States. T.S. Coile, Inc. Forest Land Consultants, Durham, N.C. 296 p.

Curtis, R.O. 1972. Yield tables past and present. J. Forestry 70:28-32.

Dierauf, T.A. and R.L. Marler. 1965. Pulpwood yields of planted loblolly pine in Piedmont and Coastal Plain Virginia. Va. Div. Forestry Occas. Rep. 21, 4 p.

Ek, A.R. and R.A. Monserud. 1974. FOREST: A computer model for simulating the growth and reproduction of mixed species forest stands. University of Wisconsin School of Natural Resources Res. Rep. R2635, 13 p.

Fishman, G.S. 1973. Concepts and Methods in Discrete Event Simulation. John Wiley and Sons, Inc. New York, 385 p.

Gerrard, D.J. 1969. Competition quotient: a new measure of the competition affecting individual forest trees. Mich. State Univ. Agric. Exp. Sta., Res. Bull. No. 20, 32 p.

Goebel, N.B. and R.D. Shipman. 1964. Volume yields of loblolly pine plantations for a variety of sites in the South Carolina Piedmont. Clemson Univ. Forest Res. Series No. 13, 23 p. (Revised 1966, Revised 1969).

Goebel, N.B., J.R. Warner, and D.H. VanLear. 1974. Periodic thinnings in loblolly pine stands: growth, yield, and economic analysis. Clemson Univ. Dept. of Forestry, Forest Res. Series No. 28, 11 p.

Hamilton, D.A. 1974. Event probabilities estimated by regression. USDA Forest Service Res. Pap. INT-152, 18 p.

Hatch, C.R. 1971. Simulation of an even-aged red pine stand in northern Minnesota. Unpublished Ph.D. Thesis, Univ. Minn., 120 p.

Hatch, C.R., D.J. Gerrard, and J.C. Tappeiner, II. 1975. Exposed crown surface area: a mathematical index of individual tree growth potential. Can. J. For. Res. 5:224-228.

Hegyi, F. 1974. A simulation model for managing jack-pine stands. In: Growth Models for Tree and Stand Simulation. Royal College of Forestry; Stockholm, Sweden, p. 74-90.

Honer, T.G. 1972. Proceedings: Tree growth simulation workshop. Forest Management Inst., Ottawa, Ont. Canada. Internal Rep. FMR-25, 116 p.

Keister, T.D. 1971. A measure of the intraspecific competition experienced by an individual tree in a planted stand. La. State Univ. Sta. Bull. 447, 109 p.

Krajicek, J.E., K.A. Binkman, and S.F. Gingrich. 1961. Crown competition - a measure of density. Forest Sci. 7:35-42.

Lee, Y. 1967. Stand models for lodgepole pine and limits to their application. Unpublished Ph.D. Thesis, Univ. of British Columbia, 322 p.

Lenhart, J.D. 1972. Cubic volume yields for unthinned old field loblolly pine plantations in the Interior West Gulf Coastal Plain. Texas Forestry Pap. 14, 46 p.

Lenhart, J.D. and J.L. Clutter. 1971. Cubic-foot yield tables for old-field loblolly pine plantations in the Georgia Piedmont. Ga. Forest Res. Coun. Report 22--Series 3, 12 p.

Lin, J.Y. 1969. Growing space index and stand simulation of young western hemlock in Oregon. Unpublished Ph.D. Thesis. Duke Univ., 182 p.

MacKinney, A.L. and L.E. Chaiken. 1939. Volume, yield, and growth of loblolly pine in the mid-Atlantic coastal region. U.S.D.A. Forest Service Tech. Note No. 33, 30 p.

MacKinney, A.L., F.X. Schumacher, and L.E. Chaiken. 1937. Construction of yield tables for non-normal loblolly pine stands. J. Agric. Res. 54:531-545.

Marsaglia, G. and T.A. Bray. 1968. One line random number generators and their use in combinations. Comm. ACM. 11:757-759.

Metz, L.J. and C.G. Wells. 1965. Weight and nutrient content of the above ground parts of some loblolly pines. U.S.D.A. Forest Service Res. Pap. SE-17, 20 p.

Mitchell, K.J. 1969. Simulation of the growth of even-aged stands of white spruce. Yale Univ. School of Forestry Bull. No. 75, 48 p.

Mitchell, K.J. 1975. Stand description and growth simulation from low-level stereo photos of tree crowns. J. Forestry 73:12-16.

Monserud, R.A. and A.R. Ek. 1974. Plot edge bias in forest stand growth simulation models. Can. J. For. Res. 4:419-423.

Moore, J.A. and C.A. Budelsky. 1973. A new index representing individual tree competitive status. Can. J. For. Res. 3:495-500.

Naylor, T.H., J.L. Balintfy, D.S. Burdick, and K. Chu. 1966. Computer Simulation Techniques. John Wiley and Sons, Inc., New York, 352 p.

Newnham, R.M. 1964. The development of a stand model for Douglas-fir Unpublished Ph.D. Thesis, Univ. of British Columbia, 201 p.

Newnham, R.M. 1968. The generation of artificial populations of points (spatial patterns) on a plane. Forest Management Inst., Ottawa, Ont. Canada. Information Rep. FMR-10, 28 p.

Newnham, R.M. and G.T. Maloley. 1970. The generation of hypothetical forest stands for use in simulation studies. Forest Management Inst., Ottawa, Ont. Canada. Information Rep. RMS-X-26, 41 p.

Newnham, R.M. and J.H.G. Smith. 1964. Development and testing of stand models for Douglas-fir and lodgepole pine. Forestry Chron. 40:492-502.

Opie, J.E. 1968. Predictability of individual tree growth using various definitions of competing basal area. Forest Sci. 14:314-323.

Smalley, G.W. and R.L. Bailey. 1974a. Yield tables and stand structure for loblolly pine plantations in Tennessee, Alabama, and Georgia highlands. USDA Forest Service Res. Pap. SO-96, 81 p.

Smalley, G.W. and R.L. Bailey. 1974b. Yield tables and stand structure for shortleaf pine plantations in Tennessee, Alabama, and Georgia highlands. USDA Forest Service Res. Pap. SO-97, 57 p.

Spurr, S.H. 1952. Forest Inventory. Ronald Press Co., New York, 476 p.

Spurr, S.H. 1962. A measure of point density. Forest Sci. 8:85-96.

Strub, M.R. and H.E. Burkhart. 1974. Approximating forest diameter distributions using the Weibull density function. Va. J. Sci. 25:119 (Abstr.).

Strub. M.R., R.B. Vasey, and H.E. Burkhart. A comparison of diameter growth characteristics and crown competition factors in loblolly pine plantations. Forest Sci. (in press).

Wakeley, P.C. 1969. Single commercial thinnings in variously spaced slash and loblolly pine plantations. USDA Forest Service. Res. Pap. SO-48, 12 p.

APPENDICES

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

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	Trees planted per acre If TP is given, PX and PY are the ratio of planting distance between trees to row width, respectively. If PX and PY are omitted, square spacing is assumed. If TP is omitted, PX and PY are the actual distances in feet between trees and between rows, respectively.
TS	Trees surviving per acre
AGE	Age of TS for existing stands
SPREP	Additional number of (loblolly equivalent) competing stems per acre for cutover sites
ARLSE	Age at which a cutover site will be released from additional competing stems
KIN	Age at next decision period or age of next input

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

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

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

```
ptaeda
 CMD:
run

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

SIMULATION OF TREE AND STAND GROWTH IN 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	KFERT	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).

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)	Cubic-foot Volume per Acre					
		Unmanaged	Fertilized[2/]	Thinned[3/]		Fertilized and Thinned	
				Residual	Thinned (total)	Residual	Thinned (total)
Old-field	10	1219 ± 53 [4/]					
		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	

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

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

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

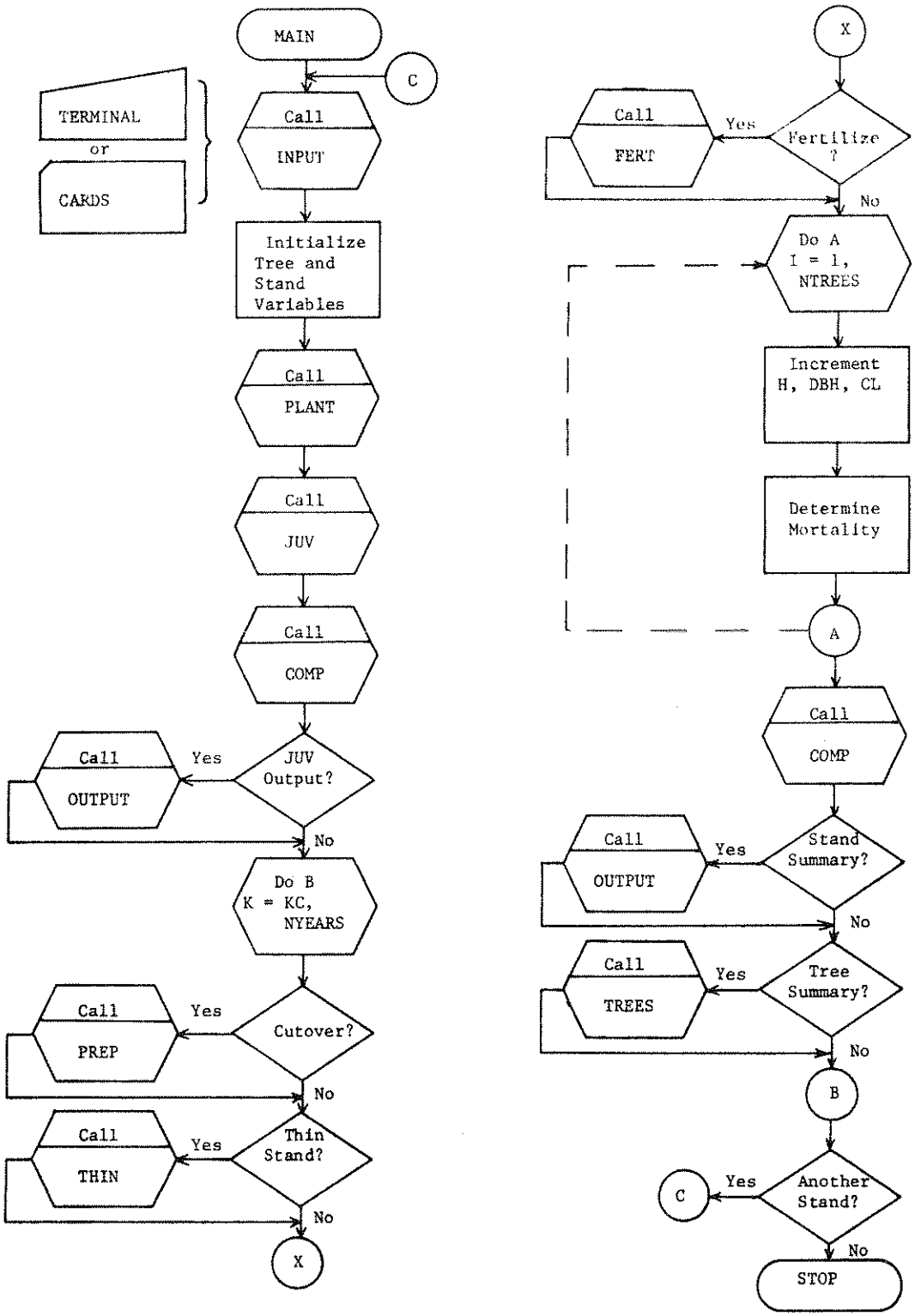
4/ Mean ± standard deviation
Low to High

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).

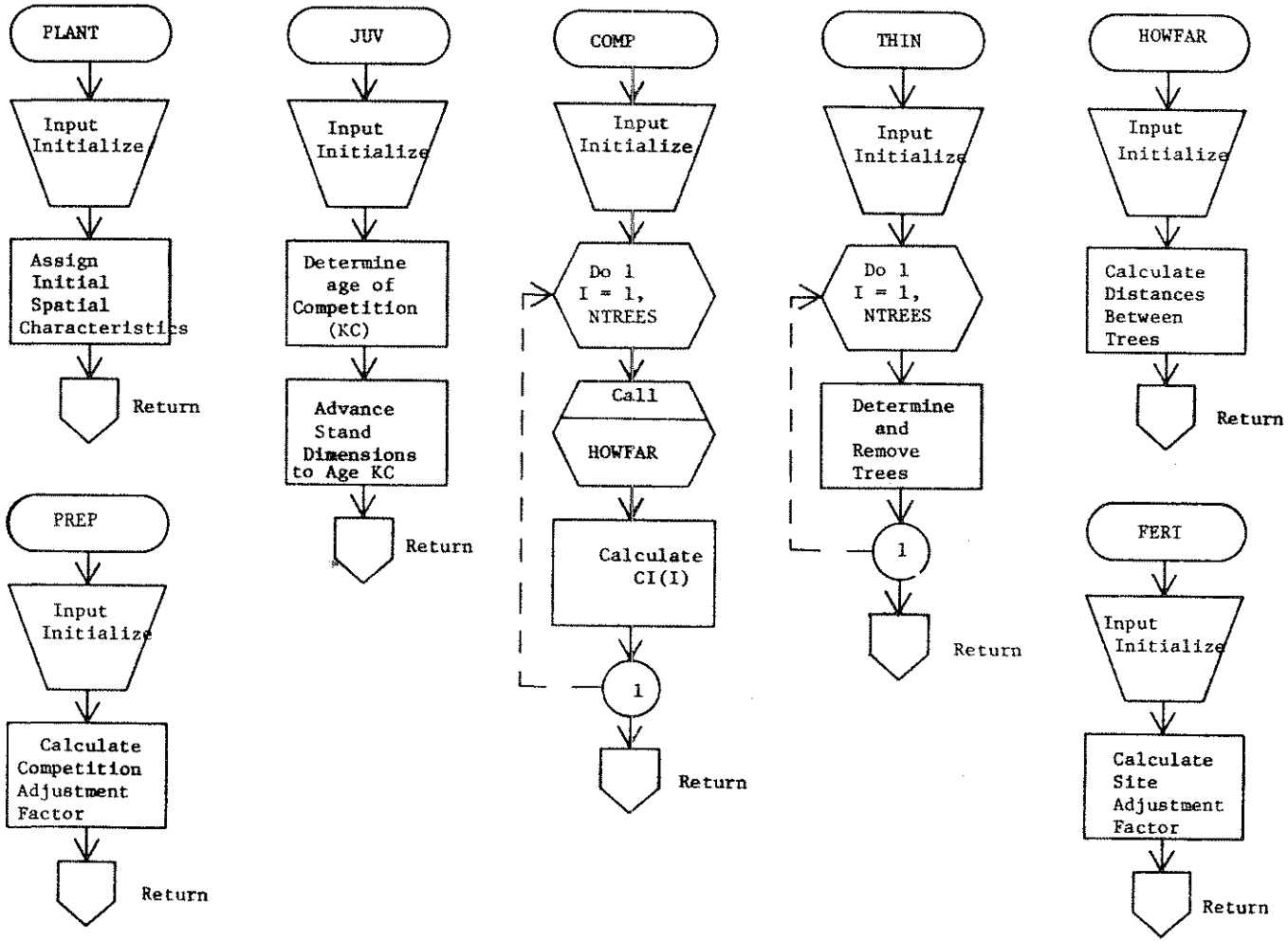
	Age (years)	Unmanaged	Fertilized[2/]	Cubic-foot Volume per Acre			
				Thinned[3/]		Fertilized and Thinned	
				Residual	Thinned (total)	Residual	Thinned (total)
Cutover [5/]	10	920 ± 26					
		883 to 957					
	15	1960 ± 39					
		1883 to 2018					
	20	3222 ± 65	3198 ± 75	2970 ± 87	340 ± 66	2970 ± 87	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	

[5/] SPREP = 1., ARISE = 20.

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



Appendix V. Flowchart of tree and stand growth simulation program PTAEDA (continued).



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

```
$JOB     WATFIV                                                          PTA00010
C                                                                        PTA00020
C                                                                        PTA00030
C                              PTAEDA                                    PTA00040
C                                                                        PTA00050
C            PTAEDA IS A SIMULATION MODEL OF TREE AND STAND GROWTH       PTA00060
C      IN MANAGED LOBLOLLY PINE (PINUS TAEDA L.) PLANTATIONS.            PTA00070
C                                                                        PTA00080
C      DEVOLPED BY RICHARD F. DANIELS, VPI&SU, 1975.                     PTA00090
C                                                                        PTA00100
       DIMENSION VOL(3),S(2)                                             PTA00110
       COMMON /BLOK1/X(100),Y(100),LMORT(100),KMORT(100),D(100),         PTA00120
      1 H(100),CL(100),CI(100),MID(100),LEDGE(9),ACRES                   PTA00130
       COMMON /BLOK2/IDIS(4),DIST(9),XDIST,YDIST                         PTA00140
       COMMON /BLOK3/YCUFT(50,3),YDRWT(50,3),BA(50),KJ,K,NLIVE,          PTA00150
      1 NTHIN,HD                                                         PTA00160
       COMMON /BLOK4/TITLE(20),NYEARS,SITE,QEXIST,EXAGE,EXTS,            PTA00170
      1 PX,PY,TP,KOUT,KIN,KTREE,QJUV,QAGAIN                              PTA00180
       COMMON /BLOK5/SPREP,CAF,ARLSE,CCUTO                               PTA00190
       COMMON /BLOK6/KFERT,LMR,LR,RESP,SAF,QFERT                         PTA00200
       COMMON /BLOK7/KTHIN,ITHIN,IROW,ILOW,DLOW,TLIM                     PTA00210
       COMMON /BLOK8/PLOTX,PLOTY,DELX,DELY,NROX,NRCY,YRCW(10)            PTA00220
       REAL YES/'YES'/,NO/'NO'/                                          PTA00230
       COMMON /BLOKD/N                                                   PTA00240
       DATA S/0.77093,0.07729/                                           PTA00250
C                                                                        PTA00260
C      INPUT INITIAL SIMULATION CRITERIA                                 PTA00270
C                                                                        PTA00280
     1 CALL INPUT(IX)                                                    PTA00290
C                                                                        PTA00300
C      INITIALIZE TREE AND STAND VARIABLES                               PTA00310
C                                                                        PTA00320
       DO 50 K=1,50                                                      PTA00330
       BA(K)=0.                                                          PTA00340
       DO 50 L=1,3                                                       PTA00350
       YCUFT(K,L)=0.                                                     PTA00360
    50 YDRWT(K,L)=0.                                                     PTA00370
       DO 60 I=1,N                                                       PTA00380
       D(I)=0.                                                           PTA00390
       H(I)=0.                                                           PTA00400
       CL(I)=0.                                                          PTA00410
       CI(I)=0.                                                          PTA00420
       KMORT(I)=NYEARS                                                   PTA00430
    60 LMORT(I)=1                                                        PTA00440
       KTHIN=0                                                           PTA00450
       KOUT=0                                                            PTA00460
       KTREE=0                                                           PTA00470
       QFERT=NO                                                          PTA00480
C                                                                        PTA00490
C      GENERATE INITIAL STAND                                            PTA00500
C                                                                        PTA00510
       CALL PLANT                                                        PTA00520
       CALL JUV(IX)                                                      PTA00530
       CALL COMP                                                         PTA00540
       IF(QJUV.EQ.NO) GO TO 65                                           PTA00550
```

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-HO                                                      PTA00730
      DO 100 I=1,N                                                      PTA00740
      IF(LMORT(I)-1) 100,10,90                                          PTA00750
   10 CR=CL(I)/H(I)                                                     PTA00760
C                                                                       PTA00770
C     DETERMINE TREE MORTALITY                                          PTA00780
C                                                                       PTA00790
      PLIVE=1.086*CR**.0702826*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)=D(I)+DIN                                                     PTA01070
      H(I)=H(I)+HIN                                                     PTA01080
   90 L=LMORT(I)                                                        PTA01090
      DSQ=D(I)*D(I)                                                     PTA01100
```

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

```
      IF(L.EQ.1) BA(K)=BA(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+4.798337                  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
      CT(I)=0.                                                          PTA01250
      IF(LMORT(I).NE.1) GO TO 101                                       PTA01260
      CBL=H(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*D(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
     1 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'/,NO/'NO'/                                          PTA01630
C                                                                       PTA01640
C     READ INITIAL SIMULATION CRITERIA                                  PTA01650
```

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

```
C
      WRITE(6,6001)
 6001 FORMAT(//13X,10('-'),5X,'PTAEDA',5X,10('-')//
     1 ' SIMULATION OF TREE AND STAND GROWTH IN',
     2 ' LOBLOLLY PINE PLANTATIONS '//
     3 ' ENTER: TITLE')
      READ(9,5001) (TITLE(L),L=1,20)
 5001 FORMAT(20A4)
      WRITE(6,6002)
 6002 FORMAT(' ENTER: NYEARS,SITE,IX')
      READ(9,*) NYEARS,SITE,IX
   10 WRITE(6,6003)
 6003 FORMAT(' EXISTING STAND ?  ENTER: YES OR NO')
      READ(9,5002)QEXIST
 5002 FORMAT(A3)
      IF(QEXIST.EQ.NO)  GO TO 20
      IF(QEXIST.NE.YES) GO TO 10
      WRITE(6,6004)
 6004 FORMAT(' ENTER SPATIAL PARAMETERS: PX,PY,TS,AGE')
      READ(9,*) PX,PY,EXTS,EXAGE
      GO TO 30
   20 WRITE(6,6005)
 6005 FORMAT(' ENTER PLANTING PARAMETERS: PX,PY,TP')
      READ(9,*) PX,PY,TP
   30 SPREP=0.
      WRITE(6,6006)
 6006 FORMAT(' CUTOVER SITE ? ')
      READ(9,5002) QCUTO
      IF(QCUTO.EQ.NO)  GO TO 35
      IF(QCUTO.NE.YES) GO TO 30
      WRITE(6,6007)
 6007 FORMAT(' ENTER SITE PREP PARAMETERS: SPREP,ARLSE')
      READ(9,*)  SPREP,ARLSE
   35 CAF=SPREP+1
      SAF=1.
      WRITE(6,6106)
 6106 FORMAT(' FERTILIZE AT PLANTING TIME ?')
      READ(9,5002) QFERT
      IF(QFERT.EQ.NO) GO TO 36
      IF(QFERT.NE.YES) GO TO 35
      WRITE(6,6107)
 6107 FORMAT(' ENTER FERT PARAMETERS : RESP, LR')
      READ(9,*) RESP,LR
      KFERT=0
      LMR=0
      SAF=(SITE+RESP)/SITE
   36 WRITE(6,6008)
 6008 FORMAT(' JUVENILE STAND OUTPUT?')
      READ (9,5002) QJUV
      IF(QJUV.EQ.YES) GO TO 38
      WRITE(6,6009)
 6009 FORMAT(' ENTER: AGE AT NEXT DECISION PERIOD')
      READ(9,*) KIN
   38 RETURN
C
```

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

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

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

```
C
C
C
      ENTRY INPUT3
      WRITE(6,6020)
 6020 FORMAT('0ANOTHER STAND ?')
      READ(9,5002) QAGAIN
      RETURN
      END

      SUBROUTINE JUV(IX)
C
C
C          SUBROUTINE JUV DETERMINES THE AGE AT WHICH
C     COMPETITION BEGINS AND ADVANCES THE JUVENILE STAND
C     TO THAT POINT IN TIME.
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 /BLOK3/YCUFT(50,3),YDRWT(50,3),BA(50),KJ,K,NLIVE,
     1 NTHIN,HD
      COMMON /BLOK4/TITLE(20),NYEARS,SITE,QEXIST,EXAGE,EXTS,
     1 PX,PY,TP,KOUT,KIN,KTREE,QJUV,QAGAIN
      COMMON /BLOK5/SPREP,CAF,ARLSE,QCUTO
      COMMON /BLOK6/KFERT,LMR,LR,RESP,SAF,QFERT
      COMMON /BLOKD/N
      REAL YES/'YES'/,NO/'NO'/
C
C     DETERMINE COMPETITION AGE
C
      DO 100 KJ=5,15
      A=KJ
      HD=(SITE*SAF)*10**(-5.86537*(1./A-1./25.))
      SPROP=(TP*CAF)**(-A*.013)*10**(-A*(.0009*HD-.0109*SQRT(HD)))
      TS=SPROP*TP
      CCF = 189.89-1012.6/A+.00347*HD*TS*CAF
      IF(CCF.GT.100.) GO TO 10
  100 CONTINUE
   10 NLIVE=TS*ACRES+.5
      NMORT=N-NLIVE
      NTHIN=0
C
C     DISTRIBUTE MORTALITY AMONG TREES AT RANDOM
C
      DO 200 IM=1,NMORT
   20 IMORT=(U(IX))*N+1.
      IF(LMORT(IMORT).NE.1) GO TO 20
      LMORT(IMORT) = 0
      KMORT(IMORT)=0
  200 CONTINUE
C
C     ADVANCE STAND DIMENSIONS
C
      DMIN=.13+.044649*HD-.18764E-4*A*(TS*CAF)
     1      +17.27608*HD/(TS*CAF)
```

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

```
      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     -2.445007/A+2.951552/(A*D(I))-3.709999/D(I))
      CBL=H(I)**1.612287*(TS*CAF)**(.457396/D(I))*D(I)**
     1     (-8.958067/A)*EXP(-2.687682+12.74273/A
     2     -21.74093/(A*D(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)*D(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 /BLOK2/IDIS(4),DIST(9),XDIST,YDIST
      COMMON /BLOK4/TITLE(20),NYEARS,SITE,QEXIST,EXAGE,EXTS,
     1 PX,PY,TP,KOUT,KIN,KTREE,QJUV,QAGAIN
      COMMON /BLOK8/PLOTX,PLOTY,DELX,DELY,NROX,NROY,YROW(10)
      COMMON /BLOKD/N
      REAL YES/'YES'/,NO/'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
```

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(I)+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 /BLOK1/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 /BLOK3/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/BLCK4/TITLE(20),NYEARS,SITE,QEXIST,EXAGE,EXTS,            PTA04420
     1 PX,PY,TP,KOUT,KIN,KTREE,QJUV,QAGAIN                              PTA04430
       COMMON /BLOK7/KTHIN,ITHIN,IROW,ILOW,DLOW,TLIM                    PTA04440
       COMMON /BLOK8/PLOTX,PLOTY,DELX,DELY,NROX,NROY,YROW(10)           PTA04450
       COMMON /BLOKD/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(I).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 OPTION                                      PTA04740
C                                                                       PTA04750
       DO 200 I=1,N                                                     PTA04760
       IF(LMORT(I).NE.1) GO TO 200                                      PTA04770
       IF(D(I).LT.DLOW.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 OPTION                                            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.DLOW) 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
                                                                        PTA05220
      SUBROUTINE FERT(A)                                                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/'NO'/                                                     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
                                                                        PTA05520
      SUBROUTINE PREP(A)                                                PTA05530
C                                                                       PTA05540
C          SUBROUTINE PREP SIMULATES THE INCREASED                      PTA05550
C     COMPETITION ON CUTOVER LAND BY CALCULATING A                      PTA05560
C     COMPETITION ADJUSTMENT FACTOR (CAF) WHICH IS USED                 PTA05570
C     TO MULTIPLY ALL COMPETITIVE COMPONENTS OF PTAEDA.                 PTA05580
C                                                                       PTA05590
      COMMON /BLOK5/SPREP,CAF,ARLSE,QCUTO                               PTA05600
      REAL NO/'NO'/                                                     PTA05610
      IF(A.GE.ARLSE) GO TO 10                                           PTA05620
      CAF=SPREP*(1.-A/ARLSE)+1                                          PTA05630
      GO TO 20                                                          PTA05640
   10 CAF=1                                                             PTA05650
      QCUTO=NO                                                          PTA05660
   20 RETURN                                                            PTA05670
      END                                                               PTA05680
                                                                        PTA05690
      SUBROUTINE OUTPUT                                                 PTA05700
C                                                                       PTA05710
C          SUBROUTINE OUTPUT CALCULATES AND DISPLAYS                    PTA05720
C     SUMMARY STATISTICS FOR TREE AND STAND CHARACTERISTICS.            PTA05730
C                                                                       PTA05740
      REAL MAI(3)                                                       PTA05750
      DIMENSION NDC(25,3),HDC(25,3),PROD(3),YINC(3),PAI(3),             PTA05760
     1 BAR(4),DMIN(4),DMAX(4),SD(4)                                     PTA05770
      COMMON /BLOK1/X(100),Y(100),LMCRT(100),KMORT(100),D(100),         PTA05780
     1 H(100),CL(100),CI(100),MID(100),LEDGE(9),ACRES                   PTA05790
      COMMON /BLOK3/YCUFT(50,3),YCRWT(50,3),BA(50),KJ,K,NLIVE,          PTA05800
     1 NTHIN,HD                                                         PTA05810
      COMMON /BLOK4/TITLE(20),NYEARS,SITE,QEXIST,EXAGE,EXTS,            PTA05820
     1 PX,PY,TP,KOUT,KIN,KTREE,QJUV,QAGAIN                              PTA05830
      REAL YES/'YES'/,NO/'NO'/                                          PTA05840
      COMMON /BLOKD/N                                                   PTA05850
      IF(QJUV.EQ.NO) GO TO 1                                            PTA05860
      K=KJ                                                              PTA05870
      QJUV=NO                                                           PTA05880
    1 INDEX=1                                                           PTA05890
C                                                                       PTA05900
C     CALCULATE STAND SUMMARY STATISTICS                                PTA05910
C                                                                       PTA05920
      CALL STAT(D ,N,LMCRT,BAR(1),DMIN(1),DMAX(1),SD(1),INDEX)          PTA05930
      CALL STAT(H ,N,LMCRT,BAR(2),DMIN(2),DMAX(2),SD(2),INDEX)          PTA05940
      CALL STAT(CL,N,LMCRT,BAR(3),DMIN(3),DMAX(3),SD(3),INDEX)          PTA05950
      CALL STAT(CI,N,LMCRT,BAR(4),DMIN(4),DMAX(4),SD(4),INDEX)          PTA05960
      INDEX=2                                                           PTA05970
      CALL STAT(D ,N,LMCRT,DUMP1,DMIN2,DMAX2,DUMP2,INDEX)               PTA05980
      MAXDC=DMAX2+.45                                                   PTA05990
      MINDC=DMIN2+.45                                                   PTA06000
      IF(MINDC.LT.1) MINDC=1                                            PTA06010
C                                                                       PTA06020
C     CALCULATE CURRENT, PERIODIC, AND MEAN ANNUAL INCREMENT            PTA06030
C                                                                       PTA06040
      DO 100 ID=MINDC,MAXDC                                             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=LMORT(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('0STAND SUMMARY  - AGE',I3//' 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('0ACRES 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).

```
     2 ' HEIGHT OF DOMINANT STAND',F11.1/)                              PTA06610
      WRITE(6,6104)(PROD(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) VCUFT(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) TS,TM,TT                                            PTA06760
 6107 FORMAT(' TOT ',3(4X,F5.0,9X)/)                                    PTA06770
      RETURN                                                            PTA06780
      END                                                               PTA06790
                                                                        PTA06800
      SUBROUTINE COMP                                                   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
      DIMENSION JDIS(9)                                                 PTA06900
      COMMON /BLOK1/X(100),Y(100),LMORT(100),KMORT(100),D(100),         PTA06910
     1 H(100),CL(100),CI(100),MID(100),LEDGE(9),ACRES                   PTA06920
      COMMON /BLOK2/IDIS(4),DIST(9),XDIST,YDIST                         PTA06930
      COMMON /BLOK8/PLOTX,PLOTY,DELX,DELY,NROX,NROY,YROW(10)            PTA06940
      COMMON /BLOKD/N                                                   PTA06950
      DATA PLOTR/2.75/,PI/3.14159/,JDIS/1,9,8,7,6,5,4,3,2/              PTA06960
      IDIS(1)=1                                                         PTA06970
      DMAX=0                                                            PTA06980
      DO 100 I=1,N                                                      PTA06990
  100 IF(D(I).GT.DMAX) DMAX=D(I)                                        PTA07000
      DISMAX=PLOTR*DMAX-DELX/2.                                         PTA07010
      DISMAY=PLOTR*DMAX-DELY/2.                                         PTA07020
      DO 200 I=1,N                                                      PTA07030
      MID(I)=2                                                          PTA07040
  200 IF(X(I).GT.DISMAX.AND.X(I).LT.(PLOTX-DISMAX).AND.                 PTA07050
     1   Y(I).GT.DISMAY.AND.Y(I).LT.(PLOTY-DISMAY)) MID(I)=1            PTA07060
      NLESS1=N-1                                                        PTA07070
      DO 500 I=1,NLESS1                                                 PTA07080
      IF(LMORT(I).NE.1) GO TO 500                                       PTA07090
      IPLUS1=I+1                                                        PTA07100
      DO 400 J=IPLUS1,N                                                 PTA07110
      IF(LMORT(J).NE.1) GO TO 400                                       PTA07120
      INTIOR=MID(I)+MID(J)                                              PTA07130
      XDIST=X(J)-X(I)                                                   PTA07140
      YDIST=Y(J)-Y(I)                                                   PTA07150
```

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

```
      DIST(1)=SQRT(XDIST*XDIST+YDIST*YDIST)                              PTA07160
      IF(INTIOR.LT.3) GO 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)*PLOTR) GO TO 20                                PTA07260
      IF(LEDGE(LC ).EQ.0) CI(I)=CI(I)+RJI/DIST(LC)                       PTA07270
   20 IF(DIST(LC).GE.D(I)*PLOTR) GO TO 30                                PTA07280
      IF(LEDGE(LCC).EQ.0) CI(J)=CI(J)+RIJ/DIST(LC)                       PTA07290
   30 IF(INTIOR.LE.3) GO TO 400                                          PTA07300
  300 CONTINUE                                                           PTA07310
  400 CONTINUE                                                           PTA07320
  500 CONTINUE                                                           PTA07330
      RETURN                                                             PTA07340
      END                                                                PTA07350
                                                                         PTA07360
      SUBROUTINE HOWFAR                                                  PTA07370
C                                                                        PTA07380
C          SUBROUTINE HOWFAR CALCULATES DISTANCES BETWEEN                PTA07390
C     TREES ON MAIN AND 'BORDER' PLOTS FOR USE IN CALCULATING            PTA07400
C     COMPETITION FOR NON-INTERIOR TREES.                                PTA07410
C                                                                        PTA07420
      COMMON /BLOK2/IDIS(4),DIST(9),XDIST,YDIST                          PTA07430
      COMMON /BLOK8/PLOTX,PLOTY,DELX,DELY,NRCX,NRCY,YRCW(10)             PTA07440
      IF(XDIST) 6,5,5                                                    PTA07450
    5 DIST(5)=SQRT((XDIST-PLOTX)*(XDIST-PLOTX)+                          PTA07460
     1             (YDIST       )*(YDIST       ))                        PTA07470
      IDIS(2)=5                                                          PTA07480
      GO TO 10                                                           PTA07490
    6 DIST(6)=SQRT((XDIST+PLOTX)*(XDIST+PLOTX)+                          PTA07500
     1             (YDIST       )*(YDIST       ))                        PTA07510
      IDIS(2)=6                                                          PTA07520
   10 IF(YDIST) 3,8,8                                                    PTA07530
    3 DIST(3)=SQRT((XDIST       )*(XDIST       )+                        PTA07540
     1             (YDIST+PLOTY)*(YDIST+PLOTY))                          PTA07550
      IDIS(3)=3                                                          PTA07560
      ICODE=IDIS(2)+IDIS(3)-7                                            PTA07570
      GO TO (2,4,11,11,11,7,9),ICODE                                     PTA07580
    8 DIST(8)=SQRT((XDIST       )*(XDIST       )+                        PTA07590
     1             (YDIST-PLOTY)*(YDIST-PLOTY))                          PTA07600
      IDIS(3)=8                                                          PTA07610
      ICODE=IDIS(2)+IDIS(3)-7                                            PTA07620
      GO TO (2,4,11,11,11,7,9),ICODE                                     PTA07630
    2 DIST(2)=SQRT((XDIST-PLOTX)*(XDIST-PLOTX)+                          PTA07640
     1             (YDIST+PLOTY)*(YDIST+PLOTY))                          PTA07650
      IDIS(4)=2                                                          PTA07660
      RETURN                                                             PTA07670
    4 DIST(4)=SQRT((XDIST+PLOTX)*(XDIST+PLOTX)+                          PTA07680
     1             (YDIST+PLOTY)*(YDIST+PLOTY))                          PTA07690
      IDIS(4)=4                                                          PTA07700
```

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

```
      RETURN                                                            PTA07710
    7 DIST(7)=SQRT((XDIST-PLOTX)*(XDIST-PLOTX)+                         PTA07720
     1              (YDIST-PLOTY)*(YDIST-PLOTY))                        PTA07730
      IDIS(4)=7                                                         PTA07740
      RETURN                                                            PTA07750
    9 DIST(9)=SQRT((XDIST+PLOTX)*(XDIST+PLOTX)+                         PTA07760
     1              (YDIST-PLOTY)*(YDIST-PLOTY))                        PTA07770
   11 RETURN                                                            PTA07780
      END                                                               PTA07790
                                                                        PTA07800
      SUBROUTINE STAT(X,N,FLAG,XBAR,MIN,MAX,S,INDEX)                    PTA07810
C                                                                       PTA07820
C          SUBROUTINE STAT CALCULATES THE MEAN, STANDARD                PTA07830
C     DEVIATION AND RANGE OF INPUT VECTOR.                              PTA07840
C                                                                       PTA07850
      REAL X(N),MIN,MAX                                                 PTA07860
      INTEGER FLAG(N)                                                   PTA07870
      M=0                                                               PTA07880
      SUMX=0.                                                           PTA07890
      SUMXSQ=0.                                                         PTA07900
      MAX=0.                                                            PTA07910
      MIN=1.E10                                                         PTA07920
      DO 100 I=1,N                                                      PTA07930
      IF(FLAG(I).EQ.0) GO TO 100                                        PTA07940
      IF(FLAG(I).NE.1.AND.INDEX.EQ.1) GO TO 100                         PTA07950
      IF(X(I).GT.MAX) MAX=X(I)                                          PTA07960
      IF(X(I).LT.MIN) MIN=X(I)                                          PTA07970
      IF(FLAG(I).NE.1) GO TO 100                                        PTA07980
      M=M+1                                                             PTA07990
      SUMX=SUMX+X(I)                                                    PTA08000
      SUMXSQ=SUMXSQ+X(I)*X(I)                                           PTA08010
  100 CONTINUE                                                          PTA08020
      VAR=(SUMXSQ-SUMX*SUMX/M)/(M-1)                                    PTA08030
      S=SQRT(VAR)                                                       PTA08040
      XBAR=SUMX/M                                                       PTA08050
      RETURN                                                            PTA08060
      END                                                               PTA08070
                                                                        PTA08080
      FUNCTION U(IX)                                                    PTA08090
C                                                                       PTA08100
C     GENERATES A UNIFORM(0,1) RANDOM VARIATE                           PTA08110
C                                                                       PTA08120
      IX=IX*65539                                                       PTA08130
      U=.5+IX*.23283C6E-9                                               PTA08140
      RETURN                                                            PTA08150
      END                                                               PTA08160
                                                                        PTA08170
      FUNCTION STNORM(IX)                                               PTA08180
C                                                                       PTA08190
C     GENERATES A STANDARD NORMAL RANDOM VARIATE                        PTA08200
C                                                                       PTA08210
      STNORM=(-2*ALOG(U(IX)))**.5*COS(6.283*U(IX))                      PTA08220
      RETURN                                                            PTA08230
      END                                                               PTA08240
                                                                        PTA08250
```

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

```
      SUBROUTINE TREE                                                   PTA08260
      RETURN                                                            PTAC8270
      END                                                               PTA08280
                                                                        PTA08290
      BLOCK DATA                                                        PTA08300
      COMMON /BLOKD/ N                                                  PTAC8310
      INTEGER N/100/                                                    PTAC8320
      END                                                               PTA08330
                                                                        PTA08340
$ENTRY                                                                  PTA08350
```