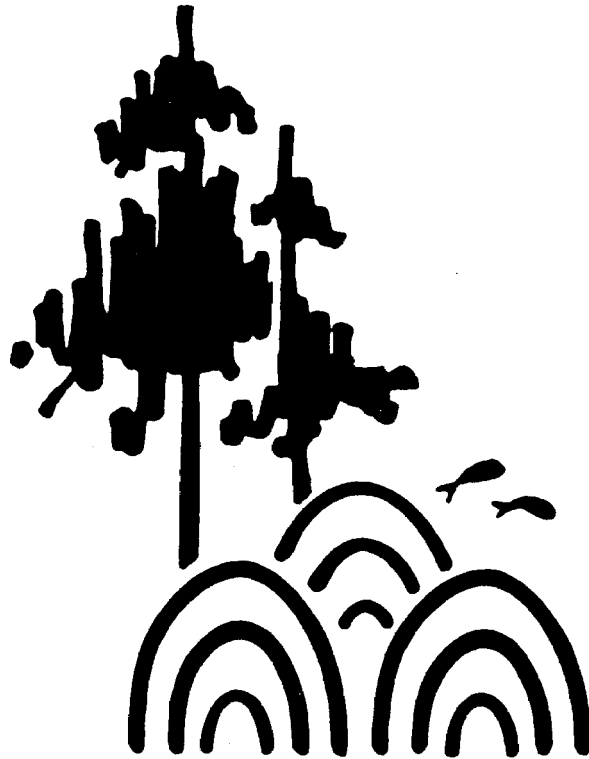


Simulation of Individual Tree Growth and Stand Development in Loblolly Pine Plantations on Cutover, Site-Prepared Areas



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Department of Forestry
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SIMULATION OF INDIVIDUAL TREE GROWTH AND STAND
DEVELOPMENT IN LOBLOLLY PINE PLANTATIONS
ON CUTOVER, SITE-PREPARED AREAS

by

Harold E. Burkhart
Kenneth D. Farrar
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PREFACE

This bulletin presents a model to simulate individual tree growth and stand development in loblolly pine plantations on cutover, site-prepared areas. Those wishing to obtain the Windows software should contact the authors at:

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To defer the costs of development a charge of \$95.00 will be made for the computer program. Checks should be made payable to "Treasurer, Virginia Tech".

Although the software presented here has been extensively tested and checked for accuracy and, to the best of our knowledge, contains no errors, neither Virginia Tech nor the authors claim any responsibility for any errors that do arise.

ABSTRACT

A forest stand simulator, PTAEDA2, was developed to model growth in loblolly pine (*Pinus taeda* L.) plantations on cutover, site-prepared areas. Individual trees were used as the basic growth units. In PTAEDA2, trees are assigned coordinate locations in a stand and 'grown' annually as a function of their size, the site quality, and competition from neighbors. Growth increments are adjusted by stochastic elements representing genetic and microsite variability. Mortality is generated stochastically through Bernoulli trials. Subroutines were developed to simulate the effects of hardwood competition, several thinning options, fertilization and pruning on tree and stand development. Options for varying the spatial location of trees to mimic randomness in machine and hand planting operations are also included. A number of output options allow the user to specify total and merchantable yields.

AUTHORS

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INTRODUCTION

Loblolly pine (*Pinus taeda* L.) is an important commercial species and much effort has been devoted to developing growth and yield models for various types of loblolly pine stands. Most of the past studies have been concerned with pure, even-aged natural stands or with plantations on abandoned agricultural land (old fields). The loblolly pine stand models developed to date have typically been of the 'whole stand' or 'diameter distribution' type (Burkhart et al. 1981).

The objective of the study reported here was to develop a stand model for loblolly pine plantations on cutover, site-prepared areas by using individual trees as the basic modeling unit. When developing this simulator, the basic model structure of Daniels and Burkhart (1975) was used. Components of the Daniels and Burkhart model (PTAEDA) for old-field loblolly pine plantations were estimated using a large data set from cutover, site-prepared plantations. This model, completed in 1987 as an MS-DOS simulator, was termed PTAEDA2. Subsequently, ancillary work on modeling midrotation fertilizer and pruning treatments has been incorporated into the simulator and new software (PTAEDA2.1) written for Windows operating systems. This bulletin contains information about data sources, modeling methodology and software for model implementation.

DATA

Data were available from 186 plot locations established in cutover, site-prepared plantations throughout much of the natural range of loblolly pine. (For a more complete description of these sites, see Burkhart et al. 1985.) At each location, three plots were established. The three plots were required to be similar in site index, number of planted pine surviving and basal area to insure similar initial conditions. Then, no thin (control), light thin (approximately 30 percent of the basal area removed) and heavy thin (approximately 50 percent of the basal area removed) treatments were randomly assigned to the plots.

Prior to thinning, all trees were tagged, measured and their locations mapped. Tree measurements included dbh, total height and height to base of live crown. Besides the planted pine component, volunteer pines and hardwoods competing with the planted pines in the main canopy were also tagged, measured and mapped.

The thinning treatments applied to the lightly thinned and heavily thinned plots were primarily a low thinning such as might be accomplished under operational conditions. In some cases, occasional rows were removed to provide access to remaining trees. Tree removal was primarily based on size; however, larger diseased or poorly formed trees were also removed and spatial distribution of the residual stand was considered. Hardwoods were removed only when they would be removed operationally to provide access to a pine. That is, an effort was made to avoid confounding release from hardwood competition with thinning.

The three plots at each location were remeasured three years after establishment. Remeasurement data included dbh, total height and height to base of live crown. Mortality and ingrowth were also recorded. Thus, growth data for the unthinned condition as well as for the first three years after thinning were available for analyses. Table 1 summarizes the tree and stand characteristics for the unthinned control at time of plot establishment and at remeasurement.

It was decided to use only the unthinned data for developing the growth relationships in PTAEDA2 for several reasons. First, with only one three year remeasurement period immediately after thinning it was difficult to determine what the longer term growth relationships for trees in thinned stands would be. Second, the growth equations fitted to the unthinned trees did not greatly underpredict tree growth on the thinned plots for the first three years after thinning. Finally, the predicted growth relationships exhibited by PTAEDA2 for thinned stands appear logical even though all coefficients were estimated using tree data from unthinned plots. This general procedure is the same as that followed by Daniels and Burkhart (1975) in the original version of PTAEDA. That is, estimates of response to thinning follow from the inherent structure and dynamics of the model even though all coefficients have been estimated using data from unthinned plots.

MODEL CONSTRUCTION

The stand model for loblolly pine plantations on cutover sites is similar in logic and structure to its predecessor PTAEDA (Daniels and Burkhart 1975). The two main subsystems in PTAEDA2 deal with the generation of an initial, pre-competitive stand and the growth and dynamics of that stand. Management subroutines were added to this framework to adjust model parameters for simulation of treated stands. The input and output routines add flexibility to the practical use of the simulator. Figure 1 is a schematic diagram showing the relevant entities in the model.

Table 1. Summary statistics for the 186 control plots at time of plot establishment and at time of remeasurement.

| | At Plot Establishment | | | At Remeasurement | | |
|---|--------------------------|--------|--------|---------------------|--------|--------|
| | Min. | Mean | Max. | Min. | Mean | Max. |
| <u>Stand Variables</u> | | | | | | |
| Age | 8 | 15.2 | 25 | 11 | 18.2 | 28 |
| Number of planted loblolly surviving (trees/ac.) | 270 | 570 | 1000 | 270 | 544 | 1000 |
| Arithmetic mean dbh of planted loblolly (in.) | 2.7 | 5.7 | 9.9 | 4.0 | 6.4 | 10.6 |
| Total overstory basal area (sq. ft./ac.-all tagged trees) | 24.3 | 112.1 | 234.5 | 50.9 | 130.0 | 236.0 |
| Planted loblolly basal area (sq. ft./ac.) | 21.7 | 107.3 | 232.5 | 45.6 | 124.3 | 233.9 |
| Volume planted loblolly (cu. ft./ac. outside bark) | 215.7 | 2168.0 | 7765.4 | 556.2 | 2851.0 | 8596.3 |
| Site index | 37.9 | 61.8 | 90.4 | | | |
| <u>Tree Variables</u> | | | | | | |
| DBH (in.) | 0.5 | 5.6 | 14.1 | 0.7 | 6.2 | 14.9 |
| Total height (ft.) | 5.0 | 37.5 | 80.0 | 8.0 | 43.2 | 86.0 |
| Crown ratio | 0.0 | 0.44 | 0.94 | 0.0 | 0.40 | 0.93 |

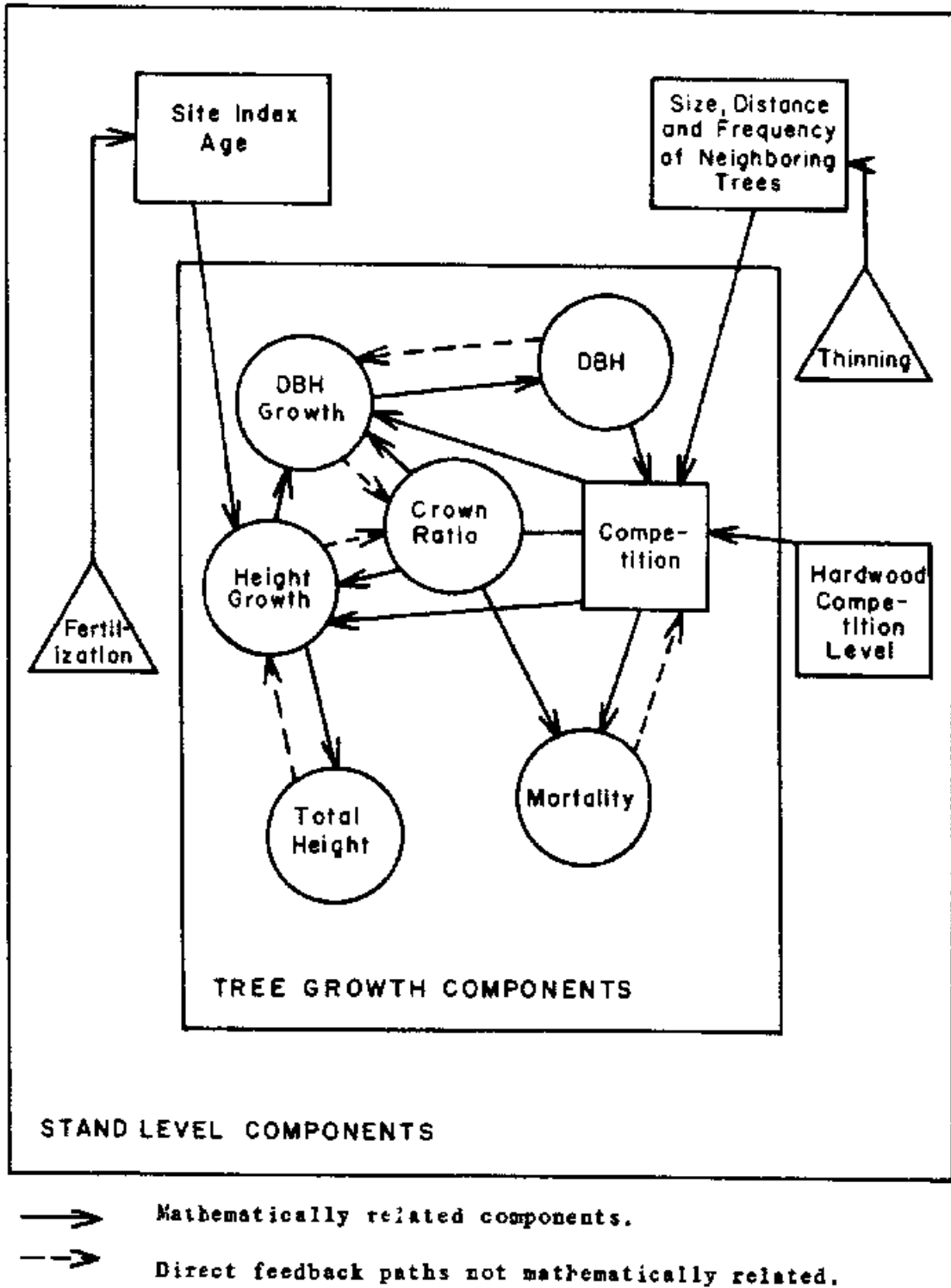


Figure 1. Schematic diagram showing relationships between tree and stand components for a simulation model (PTAEDA2) of loblolly pine growth.

Additional subprograms (not shown) generate uniform, standard normal, and Weibull distributed random variates.

Initial Stand Generation

Rectangular spatial patterns in PTAEDA2 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 planted 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.

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 provision was accomplished by solving for trees planted in the loblolly pine survival function presented by Feduccia et al. (1979) for cutover sites:

$$\log(TP/TS) - A(0.0135 \log TP + 0.0006HD - 0.0084 HD^{1/2})$$

where TP = number of trees planted
 TS = number of trees surviving
 A = stand age (years)
 HD = average height of the dominant stand (ft.)
 log = logarithm base 10.

Another option when beginning a simulation with an existing stand is to directly input a dbh distribution. This option gives the user the opportunity to refine projections of specific existing stands by beginning the simulation with more precise initial conditions.

From this information a plot of n x n dimension is generated. A fixed number of trees was chosen rather than a fixed plot size so that, in effect, plot size would increase with decreasing density. The user can specify any n x n dimension from 5 x 5 to 20 x 20.

From this point, subroutine JUV advances the juvenile stand 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, and, 2) intraspecific competition in such young stands is believed to be negligible.

The age at which intraspecific competition begins was investigated by equating a diameter equation for open-grown trees and one for stand-grown trees fitted to the cutover-site data. This method, which is essentially the same as that used in the original version of PTAEDA, produced reasonable results (typical estimates of the age of onset of intraspecific competition were 6-8 years). However, subsequent investigations showed that there was no improvement in estimating plot yields when the age for switching from the juvenile to the stand dynamics subsystems was used as opposed to changing at an arbitrary age of 8 years (the youngest age in the tree growth data set). Thus, because it is simpler and more straightforward to use a fixed age, the juvenile phase always ends at age 8; the ninth growing season and beyond are predicted using growth and dynamics equations estimated from the cutover-site data.

At age 8 (i.e., after 8 growing seasons) 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:

$$F(y) = 1 - \exp(-ay^b) \quad 0 < y < 1$$

The inversion technique was used for generating random variates from this distribution. Parameters a and b are estimated from minimum and average DBH equations fitted to the younger aged (less than 13 years) cutover-site data (Strub and Burkhart 1974):

$$b = \left[\frac{\ln(TS/10)}{\ln DAVE - \ln DMIN} \right]$$

$$a = \left[\frac{(1 + 1/b)}{DAVE} \right]^b$$

where DMIN = minimum DBH (inches)
 DAVE = average DBH (inches)
 TS = surviving number of trees per acre
 ln = logarithm base e.

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 computed from total height and a crown ratio equation developed by Dyer and Burkhart (1987). Table 2 provides a summary of all equations used in generating the initial stand.

The juvenile stand and stock table at age eight can be obtained as optional output from PTAEDA2.

Competition Index

The competition index used in PTAEDA2 is the same as that applied by Daniels and Burkhart (1975):

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

where D = DBH
 DIST = distance between subject tree i and jth competitor
 CI = Competition Index of the ith tree
 n = the number of neighbors with a BAF 10 'sweep' centered at the subject tree.

Table 2. Equations used in the juvenile growth subroutine (JUV) of PTAEDA2, a tree and stand growth simulator of loblolly pine.

| Equation* | R ² | S _{y,x} | Source |
|--|----------------|------------------|------------------------|
| $D_0 = -2.422297 + 0.286583HD + 0.209472A$ | 0.92 | 2.14 | Strub et al. 1975 |
| $\ln(HD) = \ln(SI)(25/A)^{-0.02205} \exp(-2.83285(1/A - 1/25))$ | 0.82 | 4.66 | Cutover-site data |
| $\log(TP/TS) = A(0.0135 \log TP + 0.0006HD - 0.0084 (HD)^{1/2})$ | 0.81 | 0.076 | Feduccia et al. 1979 |
| $DMIN = -0.19744 + 0.02735HD + 14.5622 HD/TS$ | 0.38 | 0.541 | Cutover-site data |
| $DMIN_{HW} = -0.175362 + 0.026328HD + 15.3232 HD/TS - 0.970907 PHDWD$ | 0.39 | 0.544 | Cutover-site data |
| $DAVE = 1.2951 + 0.10168HD - 0.0000294 A*TS + 11.4659 HD/TS$ | 0.82 | 0.389 | Cutover-site data |
| $DAVE_{HW} = 1.2262 + 0.09203HD + 0.0000019 A*TS + 15.6843 HD/TS - 1.6757PHDWD$ | 0.83 | 0.382 | Cutover-site data |
| $DMAX = 2.1753 + 0.14703HD + 19.7457 HD/TS$ | 0.83 | 0.557 | Cutover-site data |
| $DMAX_{HW} = 2.2180 + 0.14504HD + 21.2174 HD/TS - 1.6844PHDWD$ | 0.84 | 0.554 | Cutover-site data |
| $\log(HD/H) = -0.0400 + (D^{-1} - DMAX^{-1})(0.4284 - 0.4975\log(TS) + 0.3638A + 1.0954 \log(HD))$ | 0.65 | 0.041 | Cutover-site data |
| $CR = 1 - \exp((-1.35243 - 37.02600/A)D/H)$ | 0.61 | 0.083 | Dyer and Burkhart 1987 |
| $CR_{HW} = 1 - \exp((-1.43593 - 38.31743/A)(D/H)(1 - PHDWD))$ | 0.59 | 0.084 | Cutover-site data |

*Where HD = average height of dominant and codominant 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), A = stand age (years), PHDWD = percent basal area of hardwoods, D = DBH, CR = crown ratio, DMAX = maximum DBH (inches) D₀ = dbh of an open-grown tree, DMIN_{HW} = minimum DBH (inches) when percent basal area of hardwoods is specified, DAVE_{HW} = average DBH (inches) when percent basal area of hardwoods is specified, DMAX_{HW} = maximum DBH (inches) when percent basal area of hardwoods is specified, CR_{HW} = crown ratio when percent basal area of hardwoods is specified.

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. The site index model presented by Amateis and Burkhart (1985) was fitted to the remeasurement data from the permanent plots in cutover, site prepared plantations to produce the following equation (Table 2):

$$\ln(\text{HD}) = \ln(\text{SI}) (25/\text{A})^{-0.02205} \exp(-2.83285(1/\text{A}-1/25))$$

where HD = average height of dominant and codominant 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 dominant stand height is not strongly influenced 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 using the mapped stand data; accordingly, it was included in the adjustment factor for height growth.

Hatch (1971) pointed out the desirability of an index which reflects a tree's vigor as opposed to its competitive disadvantage. Crown ratio was considered to be a natural expression of a tree's photosynthetic potential and was used in the adjustment factor as an attribute positively related to realization of potential growth. But in construction of the adjustment factor it was found that crown ratio was also negatively related to tree growth in cases where it approached that of open grown trees. This is presumably related to the fairly well established phenomenon that on comparable sites height growth is generally somewhat less for open grown trees than for stand grown trees (Spurr 1952). Thus, the final equation form selected for the height increment when percent basal area of the hardwoods (PHDWD) is not specified was:

$$\text{HIN} = \text{PHIN} (b_1 + b_2 \text{CR}^{b_3} \exp(-b_4 \text{CI}_p - b_5 \text{CR}))$$

where HIN = height increment (ft.)
 PHIN = potential height increment (ft.)
 CR = crown ratio
 CI_p = pine competition index
 b₁-b₅ = parameters estimated from the data.

The final equation form selected for the height increment when PHDWD is specified was:

$$\text{HIN} = \text{PHIN} (b_1 + b_2 \text{CR}^{b_3} \exp(-b_4 \text{CI}_p - b_5 \text{MCI}_{\text{HW}} - b_6 \text{CR}))$$

where MCI_{HW} = mean competition index of hardwoods and all other variables are as previously defined.

The two equations for predicting HIN were fitted to the data using nonlinear least squares (Table 3). As competition increases (of the pines and/or the hardwoods), the realization of potential height growth decreases. Holding the competition indexes constant, HIN gradually increases with increasing crown ratio, reaching a maximum when crown ratio is approximately 60 percent. 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. The equation used to describe this relationship in PTAEDA2 was the same as that applied by Daniels and Burkhardt (1975) and is shown below:

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

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

where D₀ = open-grown tree DBH (in.)
 H = total tree height (ft.)
 A = age from seed (years)

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

$$\text{PDIN} = 0.286583\text{HIN} + 0.209472$$

where PDIN = potential diameter increment (in.)
 HIN = height increment (ft.)

The final equation selected for the diameter increment when PHDWD is not specified as in input was:

$$\text{DIN} = \text{PDIN} (b_1 \text{CR}^{b_2} \exp(-b_3 \text{CI}_p))$$

Table 3. Growth and mortality equations used in the tree and stand growth simulation program PTAEDA2.

| Equations used without specifying percent hardwoods | R ₂ | S _{y,x} |
|---|----------------|------------------|
| HIN = PHIN(0.26325 + 2.11119CR ^{0.56188} exp(-0.26375CI _p -1.03076CR)) | 0.46 | 0.751 |
| DIN = PDIN(0.72511188CR ^{0.98014576} exp(-0.37397613CI _p)) | 0.66 | 0.085 |
| PLIVE = 1.02797 CR ^{0.03790} exp(-0.00230CI _p ^{2.65206}) | --- | --- |
| Equations used when specifying percent hardwoods | | |
| HIN = PHIN(0.27861 + 2.2506CR _{HW} ^{0.58852} exp(-0.27575CI _p -0.24289MCI _{HW} -1.12339CR)) | 0.46 | 0.751 |
| DIN = PDIN(0.726022 CR _{HW} ^{0.9653866} exp(-0.3778245CI _p -0.1894939MCI _{HW})) | 0.66 | 0.085 |
| PLIVE = 1.02788 CR _{HW} ^{0.03778} exp(-0.00230CI _p ^{2.65114} + MCI _{HW} ^{2.65114}) | --- | --- |
| MCI _{HW} = MCI _p ((1-PHDWD) ^{-1.0909} -1) | 0.94 | 0.019 |

where: PHIN = potential height increment, HIN = actual height increment, PDIN = potential DBH increment, DIN = actual DBH increment, CI = pine competition index, MCI_{HW} = mean competition index of hardwoods, MCI_p = mean competition index of pine, CR = crown ratio, CR_{HW} = crown ratio when percent basal area of hardwoods is specified, PLIVE = survival probability, PHDWD = percent basal area of hardwoods, exp = base of the natural logarithm.

where DIN = diameter increment (in.)
 CR = crown ratio
 and all other variables are as previously defined.

When the optional PHDWD is specified, the diameter increment equation used in the model is:

$$DIN = PDIN (b_1 + CR_{HW}^{b_2} \exp(-b_3 CI_p - b_4 MCI_{HW}))$$

where all variables are as previously defined.

The two equations for predicting DIN were fitted to the data using nonlinear least squares (Table 3). DIN decreases with increasing competition and increases with increasing crown ratio. 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 crown ratio as a measure of photosynthetic potential in the above models plays a key role in determining thinning response. 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. Crown ratio reflects this potential.

Crown ratio is predicted annually as a function of height, DBH, age and, when specified, percent hardwood basal area (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 or 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 3). The probability of survival equation when PHDWD is not specified is:

$$PLIVE = b_1 CR^{b_2} \exp(-b_3 CI_p^{b_4})$$

where PLIVE = probability that a tree remains alive and all other variables are as previously defined.

When PHDWD is specified the PLIVE equation is:

$$PLIVE = b_1 CR_{HW}^{b_2} \exp(-b_3 CI_p^{b_4} + MCI_{HW}^{b_4})$$

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 . That this 'probability' is greater than one is of no practical concern in predicting PLIVE under stand conditions.

In PTAEDA2, survival probability is calculated for each tree and used in Bernoulli trials to stochastically determine annual mortality. The calculated PLIVE is compared to a uniform random variate between zero and one. If PLIVE is less than this generated threshold, the tree is considered to have died.

Varying Hardwood Competition Level

Besides competitive pressures exerted by neighboring pines, tree growth on cutover sites is often affected by competition from neighboring hardwoods. The competition exerted by a hardwood depends on its relative size and proximity to pines as well as certain species specific attributes which are difficult to quantify. Two methods are available in PTAEDA2 for accounting for the effects of hardwood competition on the pines. In the first method, the competition index of each pine is determined by its size and the sizes and proximity of neighboring pines only. This method is the default method in the model and reflects the mean level of hardwoods in the data set (approximately 5 percent of the basal area in the main canopy in hardwood).

The second method assumes that the crown ratio of all pines in the stand will be affected by the level of hardwood competition according to the equation:

$$CR_{HW} = 1 - \exp(-1.43593 - 38.32743A^{-1}) (D/H) (1 - PHDWD))$$

where all variables are as previously defined. This method also assumes that, for a given size and distance to a subject pine, the competition index for a hardwood regardless of species would be the same as for a pine of the same size and distance. Moreover, since hardwoods are not grown in the simulator on an annual basis along with the pines, the effect of the hardwoods is applied as an average to all pines in the stand according to the equation:

$$MCI_{HW} = MCI_p((1 - PHDWD)^{-1.0909} - 1)$$

where MCI_{HW} = mean competition index of the hardwoods
 MCI_p = mean competition index of the pines
 PHDWD = percent overstory basal area in hardwoods.

Using this second method requires specifying PHDWD as an input to the model either initially or at some point during the rotation. Burkhart and Sprinz (1984) showed that the level of PHDWD remains relatively constant over rotation lengths of usual interest. Therefore, for many purposes, it may be useful to specify a desired level of PHDWD initially and retain this level throughout the rotation. However, the simulator accommodates changing levels of PHDWD which might more accurately reflect specific stand conditions. For example, a thinning and hardwood release regime can be simulated where PHDWD is initially specified at a particular level, say 10 percent, and remains at this level until the age of thinning. Then, at the age of thinning, the stand can be simultaneously thinned and released from hardwood competition (PHDWD set to 0). This capability offers the user the opportunity to evaluate the impact of thinning, hardwood release or hardwood ingrowth on stand development. Levels of PHDWD from 0 to 90 percent can be inputted to the model by the user.

Stock-Table Options

There are three stock-table output options in PTAEDA2: (1) cubic-foot, (2) cords-board feet and (3) user-specified coefficients for combined-variable equation forms. At the beginning of each run the user may select an output option. If option (1) is selected a stand and stock table consisting of numbers of trees, average height, basal area, cubic-foot volume (ob) of the total stem for all trees 1-inch dbh and greater, and cubic-foot volume (ob) to a 4-inch top diameter (ob) for all stems in the 5-inch dbh class and above. will be generated by 1-inch dbh classes. A final volume column may be 'customized' according to the user's specifications. First, the user indicates whether cubic-foot volume is to be computed (1) inside bark, or (2) outside bark. Second, a threshold dbh class is specified (i.e., minimum dbh class to be included in stock table and must be entered as an integer, e.g., 4, 5, 6, etc.). Third, the user specifies the top diameter limit (ob) (this can be any real number that is less than the threshold dbh specified).

The second stock-table option gives a stand and stock table consisting of numbers of trees, average height, basal area, cubic-foot volume (ob) of the total stem for all trees 1-inch dbh and greater, standard cords to a 4-inch top diameter (ob) for all trees in the 5-inch dbh class and above, and board-foot volume. Board-foot volumes shown vary according to user specified inputs. First the user chooses a log rule: (1) International 1/4-inch, (2) Doyle, or (3) Scribner. Second, the user specifies the threshold dbh class for board-foot computation; this must be an integer greater than or equal to 8. All board-foot volumes are computed to a 6-inch top diameter limit (ib). Any tree with a D^2H value (D = dbh in inches, H = total height in feet) less than 3800 is assumed not to qualify for sawtimber and its board-foot volume is set equal to zero.

In the third stock-table option, the user can specify a title for the volume or weight units chosen, the threshold dbh for stock table computations, and the intercept (a) and slope (b) value for the combined-variable equation

$$V = a + bD^2H$$

where D = dbh in inches
 H = total tree height in feet

for up to three columns of output. This feature allows users to specify any desired volume or weight units and to use equations that are applicable to their particular geographic area and utilization practices.

Additional information about the tree volume equations used in PTAEDA2 can be found in the following section.

Tree Volume Equations

The cubic-foot volume equations used in PTAEDA2 were derived using stem analysis data from 445 dominant, codominant or intermediate crown class trees grown in cutover, site-prepared loblolly pine plantations (Amateis and Burkhart 1987). Total stem volume is predicted by:

$$V_{\text{tob}} = 0.18658 + 0.00250D^2H$$

$$V_{\text{tib}} = -0.09653 + 0.00210D^2H$$

where V_{tob} = stem cubic-foot volume, outside bark, stump to tip
 V_{tib} = total stem cubic-foot volume, inside bark, stump to tip
 D = dbh in inches
 H = total tree height in feet

Merchantable volumes to specified top diameters (ob) are predicted from:

$$V_{\text{ob}} = V_{\text{tob}}(1 - 0.54583d^{3.22011}/D^{3.03262})$$

$$V_{\text{ib}} = V_{\text{tib}}(1 - 0.60828d^{3.14961}/D^{2.99580})$$

where V_{ob} = merchantable cubic-foot volume (ob) to top diameter limit $d(\text{ob})$
 V_{ib} = merchantable cubic-foot volume (ib) to top diameter limit $d(\text{ob})$
 d = top diameter limit (ob)

and other symbols remain as previously defined.

The board-foot volume equations were derived from sample trees felled in plantations in Piedmont and Coastal Plain Virginia, North Carolina, South Carolina and Coastal Plain Delaware and Maryland. Sample trees had to be greater than or equal to 7.6 inches dbh and have at least one 16-foot log to a 5.6-inch inside bark top limit. After the first 16-foot log, 8-foot increments were used until a 5.6-inch top was reached. International 1/4-inch volumes were computed using appropriate formulas (for additional information on log rules, see Avery and Burkhart, 1994). Doyle volumes were computed using the Doyle formula and inside bark diameter plus one-half bark thickness. If computed Doyle volume was less than log length in feet, volume was set equal to length. Scribner-volumes for 16-foot logs were computed using a table in Belyea (1931). For log lengths other than 16-feet, the ratio length/16 was used to adjust the volume.

The following equations were estimated from the data.¹

$$V_I = -24.3816 + 0.005816(D^2H)^{1.0835}$$

$$V_D = 3.2492 + 0.00003386(D^2H)^{1.5651}$$

$$V_S = -29.7455 + 0.01888(D^2H)^{0.9521}$$

where V_I = International 1/4-inch board-foot volume to a 6-inch top diameter (ib)
 V_D = Doyle board-foot volume to a 6-inch top diameter (ib)
 V_S = Scribner board-foot volume to a 6-inch top diameter (ib)
 D = dbh in inches (ob)
 H = total tree height in feet

Cordwood volumes were computed from the 1-inch dbh class conversion factors presented by Burkhart et al . (1972). These conversion factors range from 84 cubic feet outside bark per standard cord for the 5-inch dbh class to 95 for the 13-inch class and above.

¹ Burk, T. E. 1984. Unpublished research report.

Fertilization

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

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 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, four parameters were included which specify, respectively, the maximum response in site quality, the length of time (from application) in years to attain this maximum response, the length of maximum response and the total length of time of the response. SAF increases linearly from the fertilization until the maximum response is reached at some age. SAF is then maintained at this response level for a time equal to the length of maximum response. From that time, SAF decreases linearly until site quality at some later age is the same as the original site quality prior to fertilization. Linear functions were chosen as initial approximations because of the absence of actual data. When fertilizing at planting time, the length of time to maximum response is assumed to be zero and only the remaining three parameters are specified. It was thought that managers in close contact with fertilized stands would have a knowledge of proper values for these parameters.

When fertilization occurs as a midrotation treatment, the fertilizer response functions of Hynynen et al. (1998) are used in PTAEDA2.1 These equations were developed using data from midrotation loblolly pine plantations across the southeastern United States. Information about dose, nutrient elements (nitrogen and/or phosphorus) and time of fertilization are provided by the user.

It has been suggested that tree form improves as a result of fertilizer treatment. It should be pointed out that, when output options 1 and 2 are used, volume estimates in PTAEDA2 for fertilized stands do not include form change, but are computed using the same volume equations used for untreated stands. Thus, fertilized yield estimates from the model may be conservative.

Thinning

Due to the nature of the competition relationships in a model such as PTAEDA2, response to thinning should follow directly from the decrease in competition due to removal of neighbors. This response is moderated somewhat by a tree's own potential for growth as measured in PTAEDA2 by crown ratio.

A user may thin by rows, from below, or by a combination of these methods. A fourth thinning option allows the user to selectively thin from a graphical representation of the trees as they appear on the screen. Thinning from below includes two options: thinning to an upper diameter limit or thinning to a specified basal area. Depending on which option is chosen, the proper diameter or basal area limit is then specified. In either case, a lower diameter limit may be specified below which trees will not be removed. If the row thinning option is chosen the i^{th} row to be thinned is specified. Due to the algorithm used for row thinning and to the reduced number of trees being simulated, a row thinning may be prescribed in PTAEDA2 at most one time in any simulation run. When a combination of thinning types is used, the row thinning occurs first and the residual stand is then thinned from below as specified.

Graphical thinning using the Treescap display presents a top-down view of the stand with the relative tree sizes (crown projections) presented on an x-y grid. Actual data for a given tree can be seen to the left of the Treescap display when the mouse is moved across the tree. Right clicking the mouse button removes a tree; holding the shift key down and clicking the right mouse button restores the tree. Clicking the 3D button on the toolbar displays a "pseudo" three dimensional view of the stand. Graphical thinning may be useful to users who wish to evaluate removal methods such as those that may occur from patch cuts, insect attacks, blow-downs or thinning from above.

Stand and stock tables of trees removed during thinning operations can be obtained as optional output from PTAEDA2. When this option is selected, the simulator will produce a stand and stock table after each thinning which displays the trees removed at that particular thinning. At rotation age, PTAEDA2 produces a cumulative stand and stock table of all trees removed during the rotation. Thus, the amount of wood removed at each thinning can be evaluated as well as the cumulative effect of multiple thinnings. As with fertilization, no attempt was made to account for changes in tree form due to thinning treatments.

Pruning

Pruning may be accomplished in PTAEDA2 by specifying one of three pruning scenarios: prune to a specified height, prune to a specified crown ratio or prune a certain percent of the live crown. Pruning results in a decrease of live crown which feeds back through the model as a change in crown ratio. As with fertilization and thinning, no attempt was made to account for changes in tree form due to pruning.

TESTING AND VALIDATION PROCEDURES

The approach taken to validate and test PTAEDA2 was two-fold. First, the individual growth and survival components were validated using the tree growth data from the 186 light thin and 186 heavy thin plots from the sample plots in cutover, site-prepared plantations. Second, overall model performance was evaluated for logical trends and relationships.

Validation Data

Since PTAEDA2 was developed using the tree data from the unthinned control plots, the thinned plot data provided a semi-independent validation data set for testing the model. There were 13,739 loblolly pine trees from the light thin plots and 10,457 trees from the heavy thin plots available for testing PTAEDA2. Because the thinned plots came from the same stands as the unthinned controls and were screened to have similar initial conditions, the range of ages, site indexes and stand densities were essentially the same for the model development (unthinned) and validation (thinned) data.

Testing Growth and Survival Equations

The height increment, diameter increment and survival equations in PTAEDA2 were used to predict the height growth, diameter growth and survival for the thinned plot trees over the three year remeasurement period. Predicted growth and survival were compared to observed by computing residuals. Table 4 summarizes these residuals for the three equations with and without hardwood competition index as part of the modifier.

It can be seen from the residuals in Table 4 that the height and diameter increment equations in PTAEDA2 that were developed from the unthinned plot trees slightly underpredict the growth on the thinned plot trees for the first three year period after thinning. This underprediction bias is larger for the heavily thinned plots than for the lightly thinned plots. The magnitude of these biases is not large, however, and the residual plots show no significant trends across crown ratio or competition index.

The PLIVE residuals in Table 4 show a slight overprediction bias for the survival equations in PTAEDA2. It is reasonable to expect mortality in unthinned stands to be greater than for similar stands immediately after thinning (given that the removals were 'research' rather than 'operational' thinnings). Again, however, these residuals are not large and should not present problems when applying the unthinned-based PLIVE equations to survival after thinning.

It can be seen from Table 4 that including the mean level of hardwoods on each plot in the growth and survival equations does not have much impact on the predictive ability of the equations. It appears that, for the range of these data, knowing the mean level of hardwoods in a stand does not greatly improve predictions on an individual tree basis.

Growth and Yield Relationships

PTAEDA2 was evaluated with regard to certain growth and yield relationships that have been well established. Three simulation runs using different random number seeds were averaged over a range of site indexes and number of planted loblolly pine at ages through 50 years. Figures 2a-b show mean annual increment (MAI) projections for 600 and 1200 trees per acre planted, respectively, at site indexes 50, 60, 70 and 80. It can be seen that MAI culminates sooner and declines faster on higher quality sites at greater densities. Figures 3a-b show relationships for basal area development on site index 50 and 70 land for planting densities of 400, 800 and 1200 trees per acre. For a given density, high site land achieves greater basal areas faster than low site land and for a specified site index, greater planting densities produce more total basal area at least up to some point. Figures 4a-b show survival trends for various combinations of site index and initial density. Competition induced mortality is greater on higher sites planted at higher densities. Mean crown ratio development follows that of survival with smaller crown ratios for higher site-density combinations (Figures 5a-b).

The growth and yield relationships shown in Figures 2-5 indicate that simulation results from PIAEDA2 predict reasonable trends over typical age, site index and initial density combinations.

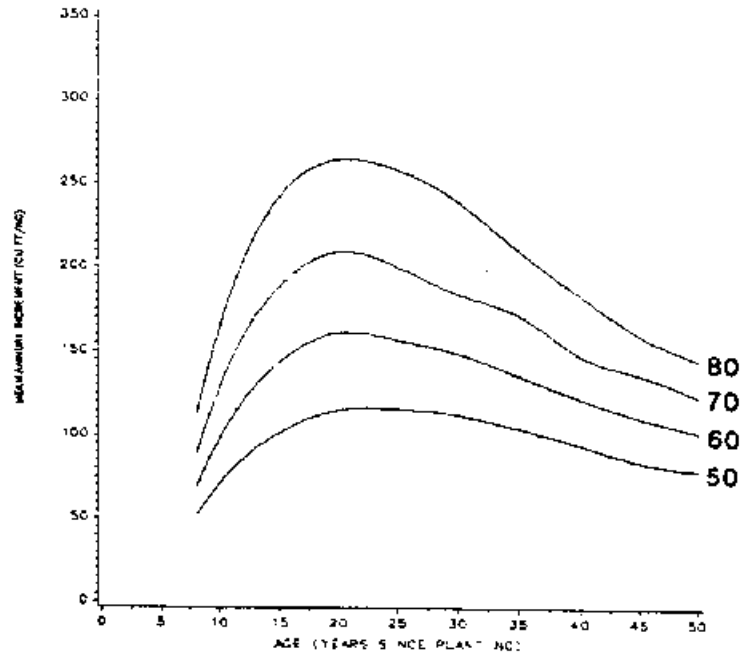


Figure 2a. Projected mean annual increment for 600 trees planted on site index land 50, 60, 70 and 80.

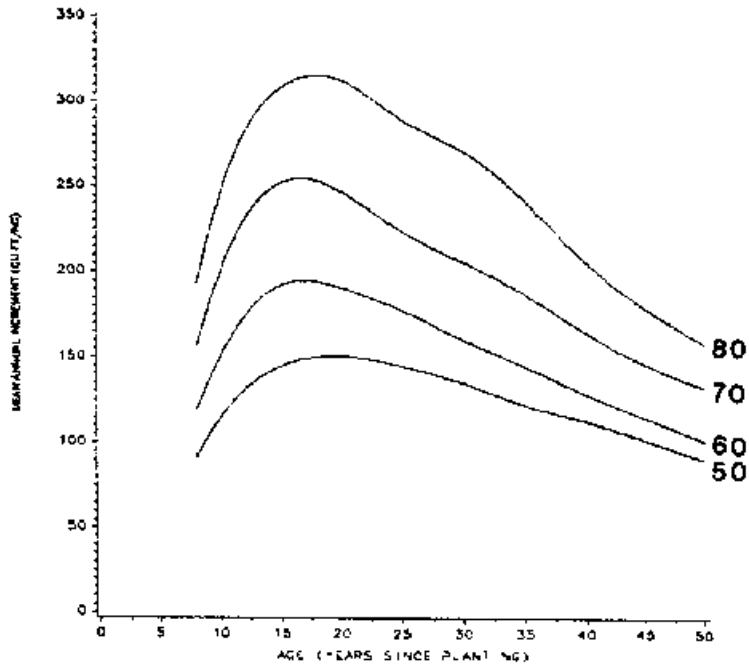


Figure 2b. Projected mean annual increment for 1200 trees planted on site index land 50, 60, 70 and 80.

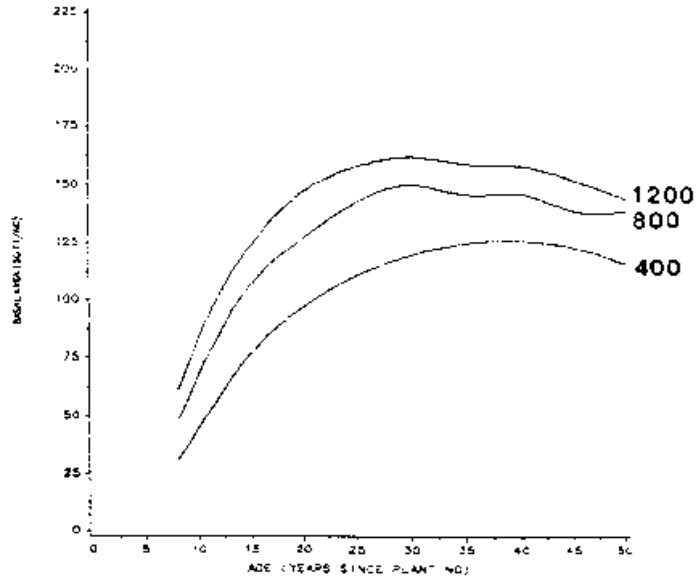


Figure 3a. Basal area projections for site index 50 land and 400, 800, and 1200 trees per acre planted.

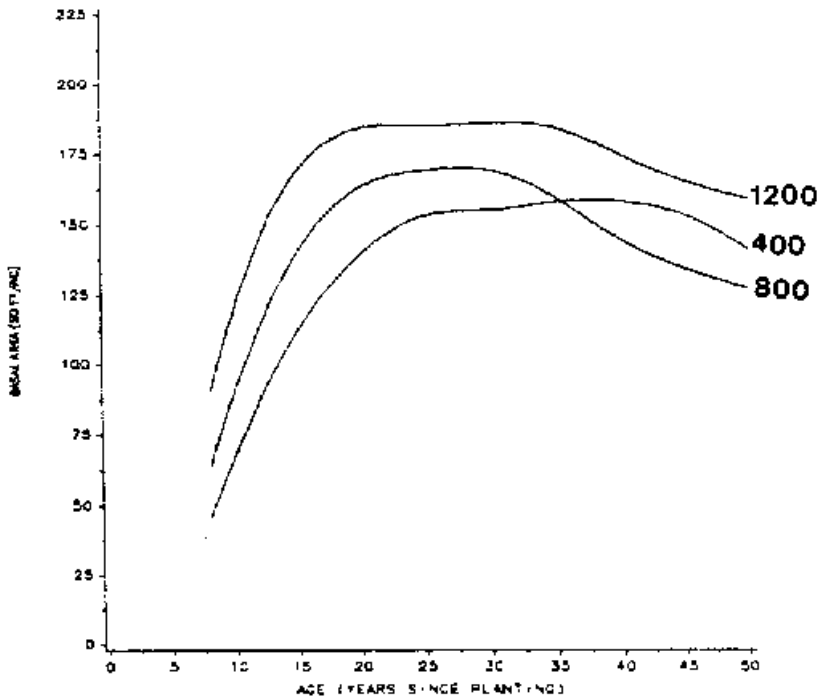


Figure 3b. Basal area projection for site index 70 land and 400, 800, and 1200 trees per acre planted.

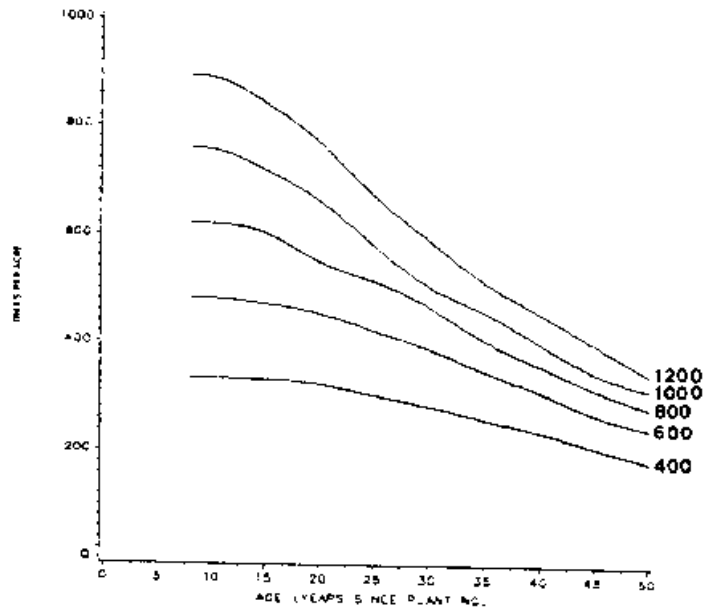


Figure 4a. Projected survival for site index 50 land and 400, 600, 800, 1000, and 1200 trees per acre planted.

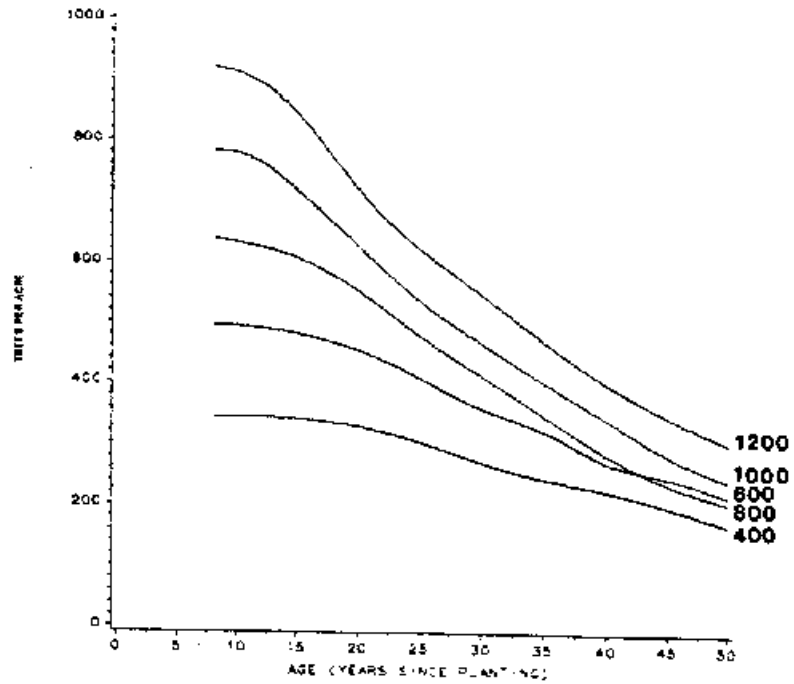


Figure 4b. Projected survival for site index 70 land and 400, 600, 800, 1000, and 1200 trees per acre planted.

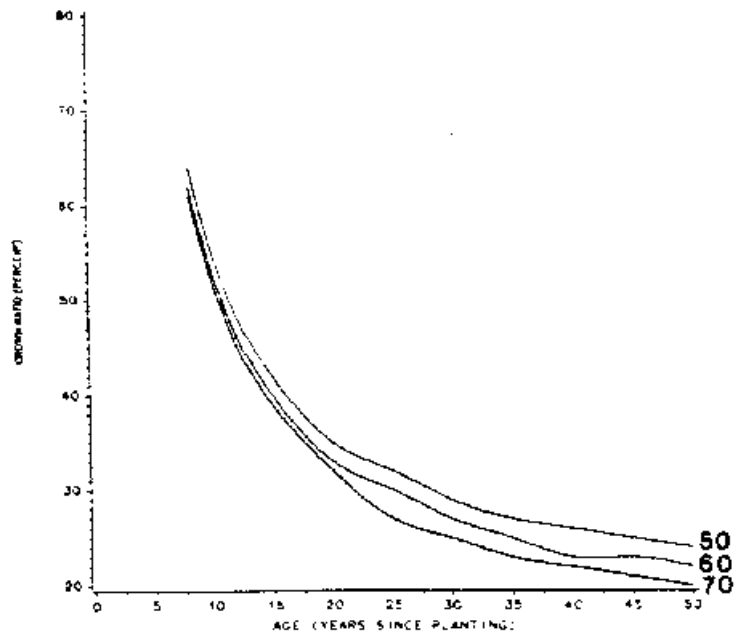


Figure 5a. Projected mean crown ratio for 1200 trees per acre planted and site indexes 50, 60, and 70.

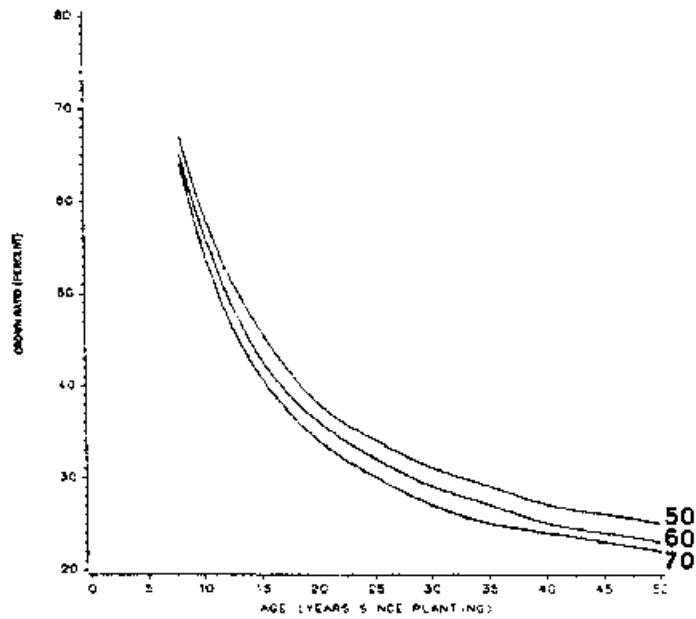


Figure 5b. Projected mean crown ratio for 600 trees per acre planted and site index 30, 60, and 80.

Table 4. Mean residuals (observed minus predicted) and average observed values for the height (HIN) and diameter (DIN) growth equations and the survival equations (PLIVE) found in PTAEDA2.

| | Equation ¹ | | | | | |
|--|--------------------------|--------|---------|--------------------------|--------|---------|
| | Light Thinned Plot Trees | | | Heavy Thinned Plot Trees | | |
| | HIN | DIN | PLIVE | HIN | DIN | PLIVE |
| Average observed | 1.9007 | 0.2562 | 0.9943 | 1.8925 | 0.2940 | 0.9941 |
| Mean residual without hardwood component | -0.1728 | 0.0296 | -0.0011 | -0.1899 | 0.0664 | -0.0022 |
| Mean residual with hardwood component | -0.1672 | 0.0365 | -0.0010 | -0.1838 | 0.0734 | -0.0022 |

¹Equations are in Table 3.

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COMPUTING CONSIDERATIONS

Preface

The equations that comprise PTAEDA2.1 have been programmed into a Windows application for implementation with Windows 95, 98, NT or 2000 operating systems. The PTAEDA2.1 software is available for \$95 by contacting:

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Most of the functionality of the PTAEDA2.1 software follows that of other Windows applications and experienced users of Windows software should have no trouble implementing PTAEDA2.1. There are, however, nuances peculiar to this application for which additional explanation may be helpful.

Saving PTAEDA2.1 runs

Using the “Save” or “Save as..” File menu items archives the current screen plus all Initialize Stand variables. Thus, users can create new simulation scenarios by retrieving archived simulation scenarios and making desired changes to the inputs. This minimizes the time needed to make multiple simulation runs.

Copying output

Stand and stock table output values can be highlighted with the arrow keys or by dragging the mouse and then copied to the Windows clipboard. From the clipboard they can be pasted into other Windows applications such as spreadsheets or graphics packages. This facilitates further analyses of PTAEDA2.1 simulation results.

Terminating a simulation

A PTAEDA2.1 simulation run can be terminated at any time by clicking the Initialize toolbar button (ctrl I). This presents the Initialize Stand screen to the user so that another simulation run can be initiated.

Macro facility

The macro facility in PTAEDA2.1 allows recording and playback of a sequence of user inputs to the initialize and midrotation projection/treatment toolbar buttons. To record a macro, click the record button on the toolbar (or activate the record command from the Macro menu item) and then perform the desired inputs, treatments and projections for a simulation. When completed, click the stop button. The macro may be played from beginning to end by clicking the play button. Alternatively, it may be played one step at a time using the step button. Macros may be saved to disk for playing at a later time from the Macro menu item. **It is important to remember that macros will only play from the point at which recording began.** For example, if a stand is initialized and then the record button is clicked to begin recording a macro, it must only be played back for stands that have already been initialized. If a macro is played improperly and a solution cannot be reached, the macro will quit and PTAEDA2.1 will resume the state it was in before the macro was started.

Macros can be useful when testing different simulation scenarios. For example, suppose a user wishes to test the same fertilizer, thinning, pruning projection sequence on different stands. The first stand would be initialized. Then the macro would be turned on and the particular fertilizer, thinning, pruning and projection sequence recorded. Then another stand can be initialized with a different set of starting conditions. The macro containing the treatment and projection scenarios from the first stand would be played on the second stand (either completely to the end or in a stepwise fashion). Now the two PTAEDA2.1 simulations will contain the results from two stands initialized differently but treated the same. Clearly, using the macro facility can save considerable time when the same set of inputs/treatments must be applied many times to different stands. Macro recording is limited to about 100 steps if the steps are graphical selection thinning and the number of simulated trees is 400. If the steps are not all graphical selection thinning then the macro limit is about 1000 steps.

Reliability of predictions

The reliability of predicted per acre values generated from PTAEDA2.1 simulations will depend on the number of trees simulated. The number of trees simulated is determined from the number of simulated rows entered when the stand is initialized. The user can choose any integer value from 5 to 20. The square of this value is the number of trees simulated (e.g. a simulation of 20 rows results in 20 rows with 20 trees per row or 400 trees simulated). Predictions associated with small numbers of trees, such as a 5-row simulation, can be expected to be much less reliable than those associated with a larger number of trees such as the 20-row simulation. This is especially true when trees are removed in thinnings or lost to mortality over longer rotations. As an example, Table 5 displays the variability in basal area associated with an 8-row (64 trees), 12-row (144 trees) and 18-row (324 trees) simulation using the same initial conditions. Users wishing to obtain information on variability as well as average values may select a smaller simulation plot size and make repeated runs with different random number seeds. Those interested only in estimates of average values will probably find it more efficient to select a larger simulation plot size and make only a single run.

Random number generation

The random number generator used in PTAEDA2 is from Nihram (1972). While this algorithm does not generate completely independent random numbers, this should pose no practical problems for most users. The effect of altering the random number seed for different plot sizes is shown in Table 5. It is evident that when larger plot sizes are simulated, the choice of random number seed has a negligible effect upon predictions.

Table 5. Basal area (sq.ft/ac) for site index 60 at 35 years and 800 trees per acre planted for three simulated plot sizes and selected random number seeds.

| <u>Random Number Seed</u> | No of Rows and Trees Per Row, Plot Size (acres) | | |
|---------------------------|---|-----------------------|-----------------------|
| | 6 <u>(0.0450)</u> | 12 <u>(0.1800)</u> | 18 <u>(0.4050)</u> |
| 68767 | 141 | 158 | 157 |
| 113355 | 147 | 146 | 153 |
| 242622 | 117 | 156 | 155 |
| 925394 | 161 | 151 | 161 |
| 821131 | 147 | 153 | 161 |
| Mean | 142.6 | 152.8 | 157.4 |
| Standard Deviation | 16.1 | 4.7 | 3.6 |