#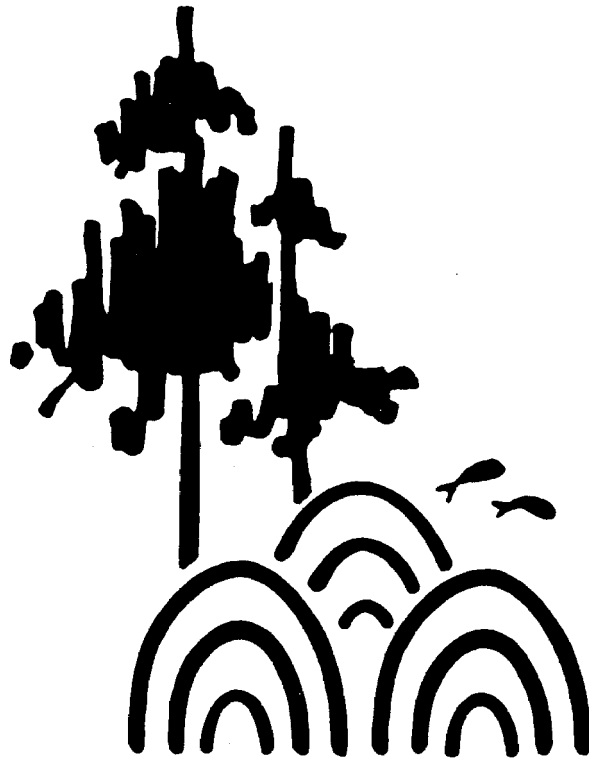 PTAEDA4.0: Simulation of Individual Tree Growth, Stand Development and Economic Evaluation in Loblolly Pine Plantations

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November, 2008

PTAEDA4.0: SIMULATION OF INDIVIDUAL TREE GROWTH, STAND DEVELOPMENT AND ECONOMIC EVALUATION IN LOBLOLLY PINE PLANTATIONS

by

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PREFACE

This bulletin presents a model to simulate individual tree growth and stand development in loblolly pine plantations and perform basic economic analyses on the simulated output. Those wishing to obtain the Windows-based software should contact the authors at:

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To defer the costs of development a charge of $200.00 will be made for the computer program. Checks should be made payable to "Department of Forestry, 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, PTAEDA4.0, was developed to model growth in loblolly pine (*Pinus taeda* L.) plantations on cutover, site-prepared areas. Individual trees were used as the basic modeling units. In PTAEDA4.0, 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 site preparation treatments, hardwood competition, thinning, fertilization and pruning on tree and stand development. A number of output options allow the user to specify total and merchantable yields. Costs of management activities and prices of products determined by the user allow the economic evaluation, in terms of net present value, of various management regimes. PTAEDA4.0 has several enhancements over previous versions including graphical thinning capability, linkage with the Stand Visualization System developed by the Forest Service, the ability to input an existing stand diameter distribution, and the inclusion of percent of trees that are defective by diameter class. These enhancements expand the utility of the model for simulating new plantations and existing stands.

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ACKNOWLEDGMENTS

Version 4.0 differs from version 3.1 with the linkage to the Stand Visualization System developed by the USDA Forest Service.

TABLE OF CONTENTS

PTAEDA4.0: SIMULATION OF INDIVIDUAL TREE GROWTH, STAND

DEVELOPMENT AND ECONOMIC EVALUATION IN LOBLOLLY PINE PLANTATIONS

Harold E. Burkhart, Ralph L. Amateis, James A Westfall and Richard F. Daniels

INTRODUCTION

Loblolly pine (*Pinus taeda* L.) is in important commercial species and much effort has been devoted to modeling its stand development, growth and yield. Many 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 this study 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 plantations on cutover, site-prepared areas. This model, completed in 1987 as an MS-DOS simulator, was termed PTAEDA2 (Burkhart et al. 1987). Subsequent work on modeling midrotation fertilizer and pruning treatments was incorporated into the simulator and new software (PTAEDA2.1) written for Windows operating systems was developed and released in 2001.

The evolution of this modeling methodology has led to the development of growth equations for young trees growing in plantations that have not reached crown closure (Westfall et al., *in press*). These equations allow the simulation of individual tree growth and stand development from time of planting to final harvest. Young trees can be especially sensitive to local growing conditions and some of these factors have been accounted for in this version of PTAEDA. In addition, new crown ratio and diameter increment equations for older trees have been fitted to tree data from thinned and unthinned plots to more adequately predict tree growth for both conditions. Enhanced output options and economic analysis capabilities allow users to evaluate the effects of a number of management treatments on the profitability of growing loblolly pine trees. Linkage with the Stand Visualization System (SVS) developed by the Forest Service allows the user to visualize stand development processes through a rotation. This bulletin contains information about data sources, modeling methodology and software implementation for PTAEDA4.0.

DATA

Pre-crown Closure

Data from a number of sources were obtained to develop equations for predicting early growth of loblolly pine where different silvicultural treatments have been applied. Two data sets were provided by the Auburn University Silvicultural Herbicide Cooperative (AUSHC). The Competition Omission Monitoring Project (COMProject) was established in 1984-85 at 13 locations across the Southeast (Miller et al. 1995). Four competition control treatments were implemented: 1) Control – no treatment, 2) Woody control – hardwoods and woody plants were eliminated for the first 5 years, 3) Herbaceous control – forbs and grasses were eradicated for the first 4 years, and 4) Total control – a combination of treatments 2 and 3 above. Individual tree measurements were taken immediately after planting and annually thereafter through age 11 and again at age 15.

The AUSHC Growth Impact Study was established over a 5-year period to evaluate the effects of herbaceous weed

control treatments. The growth response of loblolly pine was studied at thirteen locations covering a range of physiographic regions (Lauer et al. 1993). Generally, each location included 4 replications of 5 treatments set in a randomized complete-block design: 1) no treatment (control), 2) 1-year herbaceous control, broadcast application, 3) 1-year herbaceous control, banded application, 4) 2-year herbaceous control, broadcast application, and 5) 2-year herbaceous control, banded application. Measurement schedules varied by location, but data exist for ages 1 to 9 inclusive and for most ages from 11 through 20.

Data from the North Carolina State University Forest Nutrition Cooperative (NCSFNC) Regionwide 14 study were also used for this research. This study was established during 1989-2000 at 21 locations, most being situated in the Upper Coastal Plain region. Six fertilization treatments were applied at time of planting at 2/3 of the study locations. Intensity of treatments ranged from control (no fertilization) to application of nitrogen (N), phosphorus (P), and potassium (K). Individual trees were measured for both height and diameter dimensions at time of establishment and at 2-year intervals thereafter (NCSFNC 2000).

The NCSFNC also provided data from their Regionwide 7 study, which was initiated at 12 locations from 1978-81. A 2^3 factorial design was used to apply combinations of fertilization, site-preparation, and herbaceous control treatments. Fertilization treatments were control (no fertilizer) and a banded application of 45N + 50P lbs/ac. Similarly, herbaceous management techniques included control (no herbicide) and 2-years of herbicide applied in bands. Site-preparation treatments varied by location, but were generally matched to soil characteristics (e.g., bedding vs. no bedding on poorly drained sites). A split-plot system was employed with the 2 levels of site-preparation comprising the main plots and combinations of fertilization and herbaceous weed control forming the sub-plots. Measurements of tree DBH and height were taken every second growing season over the entire length of the study (Allen and Lein 1998).

A growth study implemented and maintained by MeadWestvaco Corporation provided additional data for analyzing the effects of various silvicultural practices on early growth of loblolly pine. The study was installed between 1995-2000 in stands covering a wide range of site conditions. Fertilization, mechanical and chemical site-preparation methods, and vegetation control regimes form the basis for many of the treatment combinations found on study plots. Tree diameter at breast height measurements were taken at 3 and 5 years for plots having attained those ages. Height data are generally available through age 3, except for locations established after 1998, while some age-five height records are present for plots installed early in the study.

Additional data for this research came from a set of loblolly pine spacing trials established in 1983 by the Loblolly Pine Growth and Yield Research Cooperative at Virginia Tech. Four locations were established – two in the Coastal Plain and two in the Piedmont physiographic regions (Amateis et al. 1988). Loblolly pine seedlings were planted in all combinations of 4, 6, 8, and 12 feet (1.2, 1.8, 2.4, and 3.7 m) spacings according to the factorial arrangement proposed by Lin and Morse (1975). Herbaceous vegetation was chemically controlled up to age 3. Trees were measured annually for diameter, total height, height-to-crown, and crown width until age 10. Subsequent measurements include annual diameter data and bi-annual height and height-to-crown records.

Post-crown Closure

Data for modeling older tree growth in stands where crown closure has occurred 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 have been remeasured at three year intervals since establishment. Remeasurement data included dbh, total height and height to base of live crown. Mortality and ingrowth were also recorded. Thus, growth data over several remeasurements were available for analyses. Table 1 summarizes the tree and stand characteristics for the unthinned control at time of plot establishment and at remeasurement. Additional data summaries can be found in Westfall and Burkhart (2001).

MODEL CONSTRUCTION

PTAEDA4.0 is similar in logic and structure to its predecessors PTAEDA (Daniels and Burkhart 1975) and PTAEDA2 (Burkhart et al. 1987). The two main subsystems in PTAEDA4.0 deal with the generation and growth of an initial, pre-competitive stand and the post-competitive growth and dynamics of that stand. Management subroutines were added to this framework to adjust model parameters for initial growing conditions and simulation of treated stands. The input, output and economic routines add flexibility and utility to the use of the simulator.

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

	At Plot Establishment			At Remeasurement		
	Min.	Mean	Max.	Min.	Mean	Max.
Stand Variables						
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			
Tree Variables						
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	0.1	0.44	0.94	0.1	0.40	0.93

Initial Stand Generation

For new stands established on bare ground, rectangular planting schemes in PTAEDA4.0 may be specified in two ways. A user may specify the distance between trees and between rows or the number of trees planted per acre. In cases where an existing stand is to be simulated, the number of trees surviving at the beginning is specified and square spacing is assumed. From stand initiation information, a plot of 25 rows with 25 trees per row is generated. A fixed number of trees (625) was chosen rather than a fixed plot size so that, in effect, plot size would increase with decreasing density.

Juvenile stands are grown to the point of crown closure (onset of intraspecific competition) using tree growth equations and methodology from Westfall et al. (in press). Once intraspecific competition begins, growth of trees is accomplished using methodology from PTAEDA2 (Burkhart et al. 1987) and from Westfall and Burkhart (2001).

Competition Index

The competition index used in PTAEDA4.0 is that of Hegyi (1974) and applied by Daniels and Burkhart (1975):

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

where
D_i = DBH of subject tree i
D_j = DBH of competitor tree j
$DIST_{ij}$ = distance between subject tree i and j^{th} competitor
CI_i = Competition Index of the ith tree
n = the number of neighbors 'in' with a BAF 10 'sweep' centered at the subject tree.

Growth Relationships

Prior to crown closure, a pre-competitive stand is grown annually using the young-tree growth equations and methodology presented by Westfall et al. (in press). After crown closure, a second set of growth equations utilizing the competition index is used to grow the trees 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 Sharma et al. (2002) was fitted to the remeasurement data from the permanent plots in cutover, site prepared plantations to produce the following equation:

$$HD = \frac{147.2}{1 - \left(1 - \frac{147.2}{SI}\right)\left(\frac{25}{A}\right)^{1.17407}}$$

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 that 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:

$$HIN = PHIN (b_1 + b_2 CR^{b_3}exp(-b_4CI_p-b_5CR))$$

where HIN = height increment (ft.)
       PHIN = potential height increment (ft.)
         CR = crown ratio
       CI_p = pine competition index
       b_1-b_5 = parameters estimated from the data.

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

$$HIN = PHIN (b_1 + b_2 CR^{b_3}exp(-b_4CI_p-b_5MCI_{HW}-b_6CR))$$

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 2). 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 PTAEDA4.0 was the same as that applied by Daniels and Burkhart (1975) and is shown below:

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

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

where D_0 = 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:

PDIN = 0.286583HIN + 0.209472

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

The diameter increment model (DIN) appropriate for thinned and unthinned stands developed by Westfall and Burkhart (2001) was utilized for PTAEDA4.0:

DIN = TRV1 * PDIN (b_1 CR^{b_2}exp(-$b_3$$CI_p$))

where:

$$TRV1 = \left(\frac{BA_b}{BA_a}\right)^{\frac{A_s-A_t}{HD^2}} \exp\left(\frac{(A_s - A_t)^2}{(A_s / A_t)^{b_1}}\right)$$

BA_b = basal area before thinning
BA_a = basal area after thinning
A_s = stand age
A_t = age at time of thinning
HD = dominant height
CR = crown ratio
CI = competition index
b_1 = parameter to be estimated
and all other variables are as previously defined.

Crown Ratio

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. The crown ratio model (CR) for thinned and unthinned stands developed by Dyer and Burkhart (1987) and modified by Westfall and Burkhart (2001) was incorporated into PTAEDA4.0:

CR = 1.0 – exp((b_1 – b_2/A_s)(D/H) + (TRV2)

where:

$$TRV2 = T\left(\frac{BA_b}{BA_a}\right)\left(b_3 D^{b_4}\right)\exp\left(\frac{-(A_s - A_t)}{(A_s)^{0.5}}\right)$$

T = indicator variable equal to 0 for unthinned stands and thinned stands at time of thinning, or 1 for thinned stands after first growing season following thinning
D = diameter at breast height
b_1, b_2, b_3, b_4 = parameters to be estimated
and all other variables are as previously defined.

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 O,l data (Table 2). 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 PTAEDA4.0, 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 that are difficult to quantify. Two methods are available in PTAEDA4.0 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 computation 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 hardwoods).

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

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

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

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 that 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 time 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.

The equations for predicting HIN, DIN, PLIVE and CR were fitted to the data using nonlinear least squares (Table 2). 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.

Table 2. Growth and mortality equations used in the tree and stand growth simulation program PTAEDA4.0.

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

$DIN = PDIN(0.8000CR^{0.74295} \exp(-0.69851CI_p)) \left(\dfrac{BA_b}{BA_a}\right)^{\frac{As-At}{HD^2}} \exp\left(\dfrac{(A_s - A_t)^2}{(A_s / A_t)^{30.829}}\right)$ 0.58   0.091

$PLIVE = 1.02797 CR^{0.03790} \exp(-0.00230CI_p{}^{2.65206})$ ---   ---

$CR = 1.0 - \exp((-1.78246 - 34.1967/A_s)(D/H) + T\left(\dfrac{BA_b}{BA_a}\right)\left(0.03206D^{0.43665}\right)\exp\left(\dfrac{-(A_s - A_t)}{(A_s)^{0.5}}\right)$ 0.63   0.071

Equations used when specifying percent hardwoods

	R^2	$S_{y.x}$

$HIN = PHIN(0.27861 + 2.2506CR_{HW}{}^{0.58852} \exp(-0.27575CI_p-0.24289MCI_{HW} -1.12339CR))$ 0.46   0.751

$DIN = PDIN(0.7997 CR_{HW}{}^{0.73339} \exp(-0.70168CI_p-0.16931MCI_{HW}))$ *

$\left(\dfrac{BA_b}{BA_a}\right)^{\frac{As-At}{HD^2}} \exp\left(\dfrac{(A_s - A_t)^2}{(A_s / A_t)^{30.904}}\right)$ 0.58   0.090

$PLIVE = 1.02788 CR_{HW}{}^{0.03778} \exp(-0.00230CI_p{}^{2.65114} + MCI_{HW}{}^{2.65114})$ —   ---

$CR = 1.0 - \exp((-1.78246 - 34.1967/A_s)(D/H)(1.0-PHDWD)$
$+ T\left(\dfrac{BA_b}{BA_a}\right)\left(0.00773D^{1.2825}\right)\exp\left(\dfrac{-(A_s - A_t)}{(A_s)^{0.5}}\right)$ 0.62   0.073

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

Stock-Table Options

There are three stock-table output options in PTAEDA4.0: (1) green-weight (default), (2) cords-board feet and (3) cubic feet. 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, green-weight of the total stem for all trees 1-inch DBH and greater, and green-weight of three mutually exclusive product classes (pulpwood, chip and saw and sawtimber) is generated by 1-inch DBH classes according to merchantability limits specified by the user.

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 7 inches. 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.

If option (3) 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. 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).

Tree Weight and Volume Equations

The green weight equations used in PTAEDA4.0 were developed from data acquired from across the loblolly pine growing region (Bullock and Burkhart 2003). Total stem weight is predicted by:

$$GWT_{Tot} = -4.3238 + 0.1397D^2H$$

where   GWTTot = total stem green weight with bark, lbs
         D = DBH in inches
         H = total height in feet

Merchantable green weight to a specified top diameter limit was predicted by:

$$GWT_d = GWT_{Tot} (\exp(-0.9468(d^{4.3397}/D^{4.1697})))$$

where   GWTd = stem green weight with bark (lbs) to top diameter d (ob)
and all other variables are as previously defined.

The cubic-foot volume equations used in PTAEDA4.0 were derived using stem analysis data from 767 dominant, codominant or intermediate crown class trees grown in thinned and unthinned cutover, site-prepared loblolly pine plantations (Tassissa, et al. 1997). Total stem volume is predicted by:

$$V_{tob} = 0.25663 + 0.00239D^2H \text{ (thinned)} \qquad V_{tob} = 0.21949 + 0.00238D^2H \text{ (unthinned)}$$

$$V_{tib} = -0.13431 + 0.00203D^2H \text{ (thinned)} \qquad V_{tib} = -0.01039 + 0.00196D^2H \text{ (unthinned)}$$

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:

$$V_{ob} = V_{tob}\exp(-1.04007(d^{5.25569}/D^{4.99639})) \text{ (thinned)} \qquad V_{ob} = V_{tob}\exp(-0.78579(d^{4.92060}/D^{4.55878})) \text{ (unthinned)}$$

$$V_{ib} = V_{tib}\exp(-1.24933(d^{5.22906}/D^{5.02295})) \text{ (thinned)} \qquad V_{ib} = V_{tib}\exp(-0.91505(d^{4.93352}/D^{4.60614})) \text{ (unthinned)}$$

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

Site Preparation and Fertilization

From the work of Westfall et al. (in press), equations that quantify young tree growth based on site conditions have been incorporated into PTAEDA4.0. Users can select from site preparation treatments that include bedding, discing, chop and burn, shear and pile and herbaceous weed control of one- or two-year duration. Selections of physiographic region (coastal plain or piedmont) and drainage class (well or poor) will result in young stand projections that are representative of actual growing conditions. If nitrogen, phosphorus and/or potassium fertilization has occurred at planting, then the appropriate boxes should be checked.

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

When fertilization occurs as a midrotation treatment, the fertilizer response functions of Hynynen et al. (1998) are used in PTAEDA4.0. These equations were developed using data from midrotation loblolly pine plantations across the southeastern United States. Information about dose and nutrient elements (nitrogen and/or phosphorus) 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 green weight or cubic foot output options are used, volume estimates in PTAEDA4.0 for fertilized stands do not include form change, but are computed using the same volume equations used for unfertilized 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 PTAEDA4.0, 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 PTAEDA4.0 by crown ratio.

A user may thin by rows, by stem quality, from below, by a combination of these methods, or directly on the computer screen using the graphical thinning option. 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 ith row to be removed is specified. Due to the algorithm used for row thinning, a row thinning may be prescribed in PTAEDA4.0 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.

Research has shown that approximately 20 percent of trees in loblolly pine plantations of the type included here will never produce sawtimber, no matter how large they become because they possess some defect or have poor form. A quality thinning automatically removes all trees in the stand that have poor stem form, are diseased, or have some other defect that would forever preclude them from becoming sawtimber quality. A quality thinning prescribed in PTAEDA4.0 will remove all poor quality trees and thus can be specified only once in any simulation run. Where an existing stand has been specified, the user can input manually the percent defective by diameter class.

Stand and stock tables of trees removed during thinning operations can be obtained as optional output from PTAEDA4.0. 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, PTAEDA4.0 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.

Pruning

Pruning may be accomplished in PTAEDA4.0 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, no attempt was made to account for changes in tree form due to pruning.

Treescape

Treescape ("T" on the toolbar) 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 Treescape display when the mouse pointer is moved inside the tree's crown. When thinning on the Treescape screen, clicking the right mouse button positioned over a tree removes that tree. Replacing a thinned tree occurs by holding down the <shift> key while clicking the right mouse button over the tree.

VERIFICATION PROCEDURES

PTAEDA4.0 was evaluated with regard to certain growth and yield relationships that have been well established. Simulation runs over a range of site indexes and number of planted loblolly pine at ages through 50 years were made in order to evaluate untreated, baseline projections. Figures 1a-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 2a-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 area 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 3a-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 4a-b).

The growth and yield relationships shown in Figures 1-4 indicate that simulation results from PTAEDA4.0 predict reasonable trends over typical age, site index and initial density combinations.
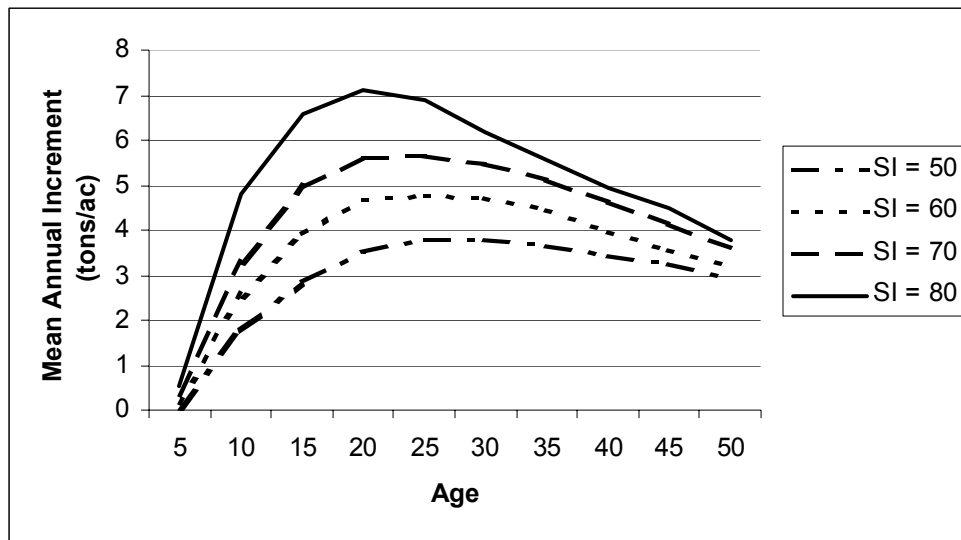

Figure 1a. Projected mean annual increment for 600 trees planted on site index land 50, 60, 70 and 80.
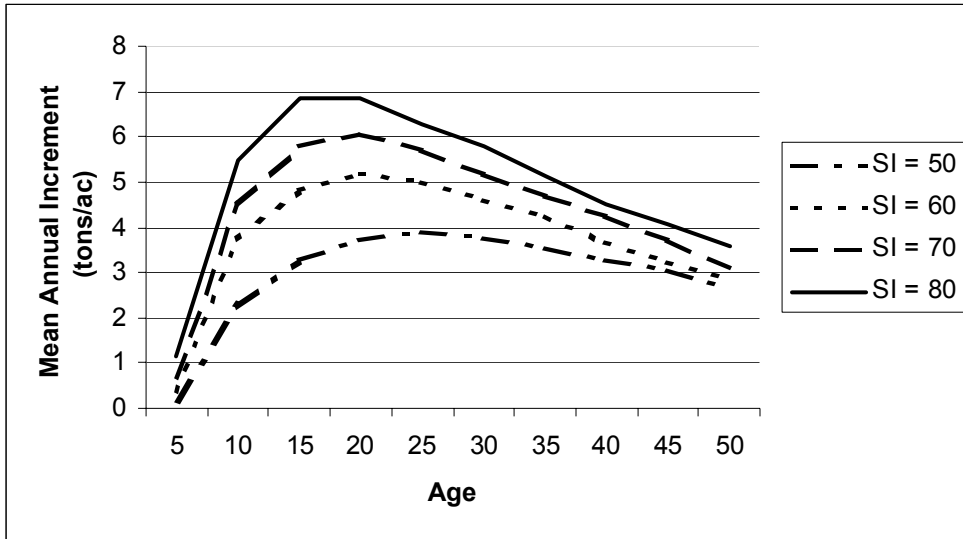
Figure 1b. Projected mean annual increment for 1200 trees planted on site index land 50, 60, 70 and 80.
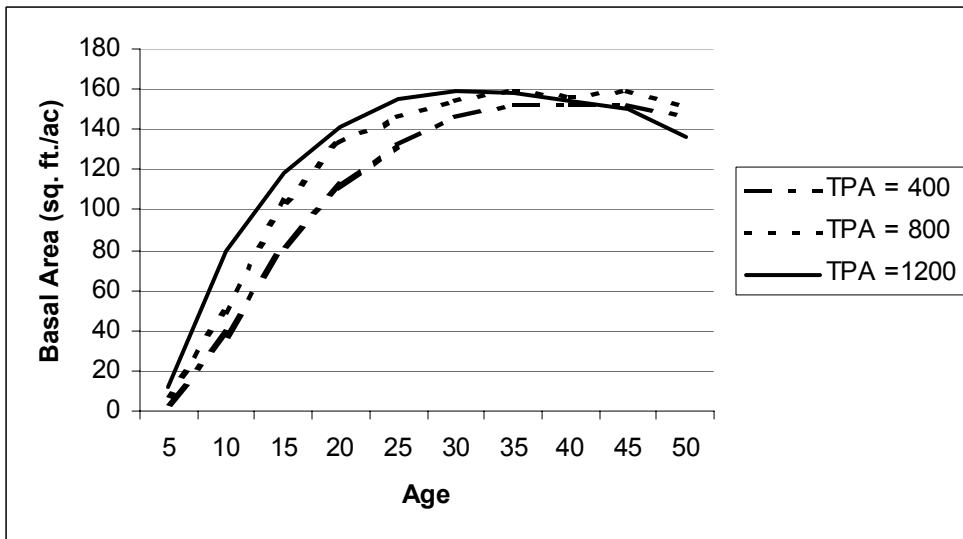

Figure 2a. Basal area projections for site index 50 land and 400, 800 and 1200 trees per acre planted.
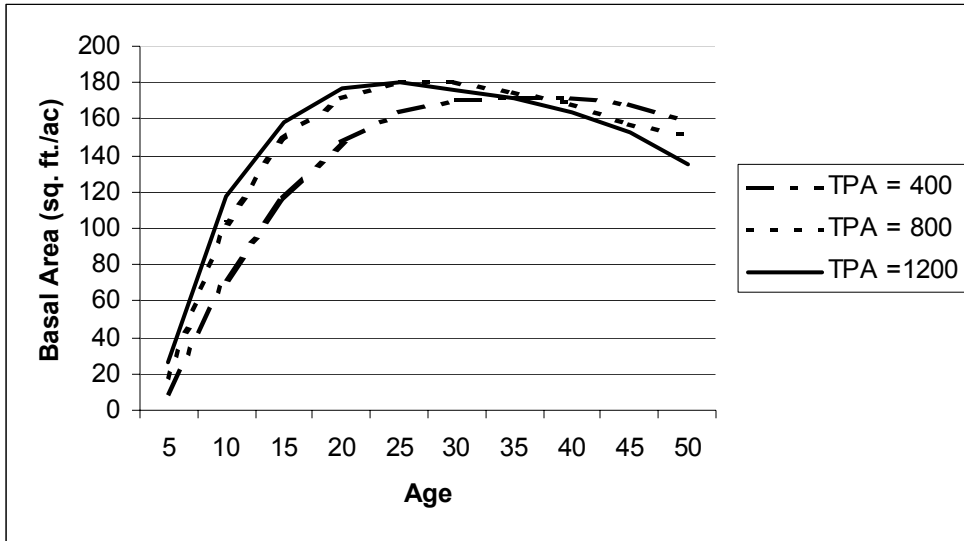
Figure 2b. Basal area projection for site index 70 land and 400, 800 and 1200 trees per acre planted.
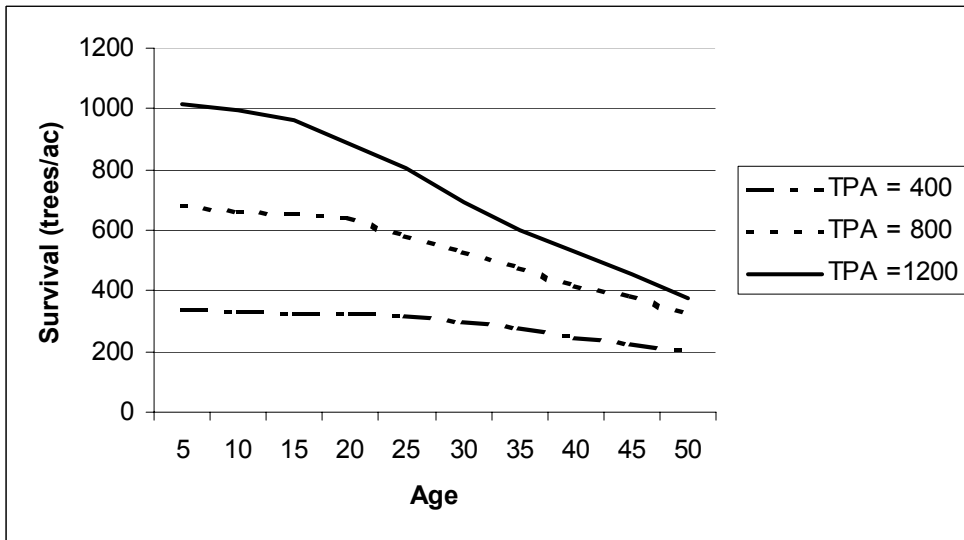

Figure 3a. Projected survival for site index 50 land and 400, 800 and 1200 trees per acre planted..
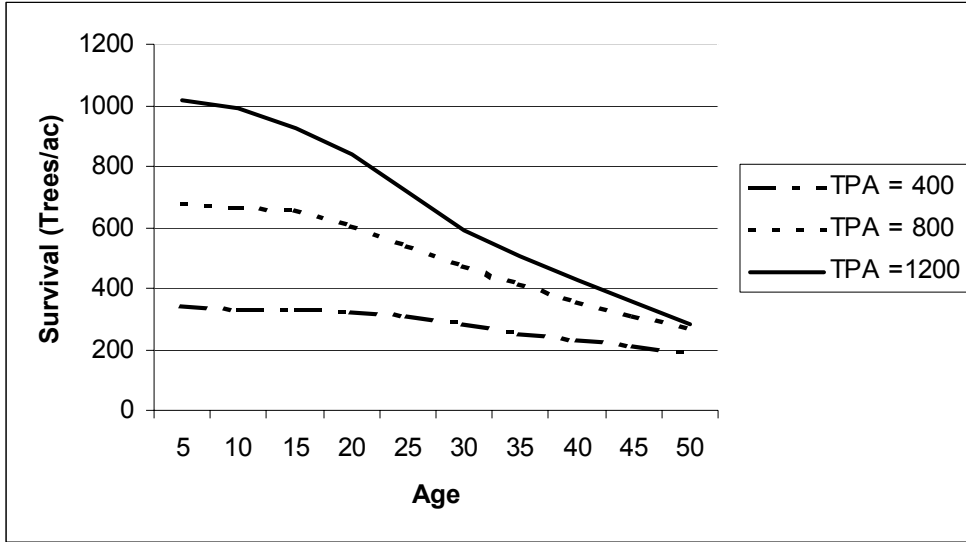
Figure 3b. Projected survival for site index 70 land and 400, 800 and 1200 trees per acre planted.
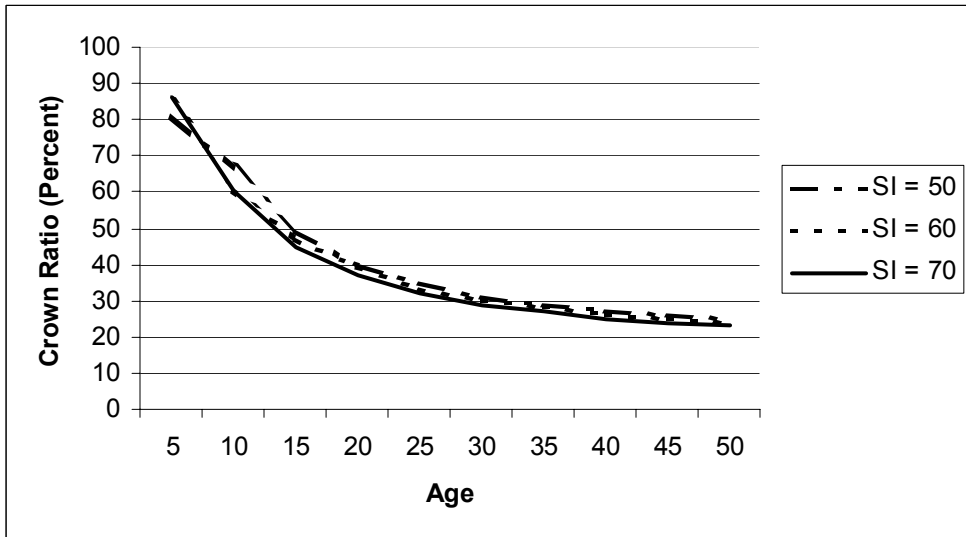

Figure 4a. Projected mean crown ratio for 600 trees per acre planted and site index 50, 60 and 70.
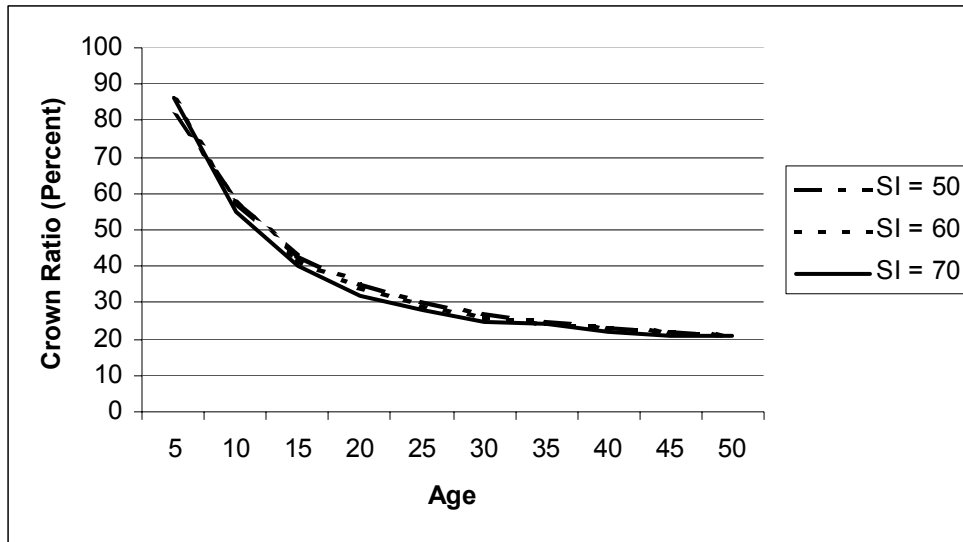
Figure 4b. Projected mean crown ratio for 1200 trees per acre planted and site indexes 50, 60 and 70.

ECONOMIC EVALUATION

PTAEDA4.0 has the capability to evaluate the economic effects of management decisions involving loblolly pine plantations. In order to use the economic evaluation capability of PTAEDA4.0, the following procedures must be followed:

1. The green weight merchandizing option must be specified. This merchandizing option is the default in PTAEDA4.0.
2. When initializing a stand, all relevant cost and price parameters must be specified prior to simulation execution.
3. Establishment cost includes all per acre costs incurred at time of planting. This would include costs for site preparation, planting, seedlings and fertilization at time of planting. Annual costs include the total of all per acre costs, such as maintenance, incurred on an annual basis. Thinning and harvest costs are specified as a percent of the revenue obtained at the time of thinning and harvest. Pruning costs are specified on a per tree basis.
4. Prices for four product classes on a per ton basis can be specified. If the entire stand is to be merchandized as pulpwood, then a constant price for pulpwood must be entered into the four price dialog boxes. Annual revenues include the total of all per acre revenues, such as hunting leases, realized on a yearly basis. The discount rate is a real interest rate, net of inflation, and entered as a percent.

At the end of the simulation, an economic summary table is presented with a returns section followed by a cost section and a net present value calculation. The returns section lists the activities performed during the rotation and the present value of annual revenues, thinnings and final harvest. The costs section lists the present value of costs incurred during the rotation. Net present value of one rotation is shown at the bottom of the economic summary along with the equal annual equivalent. Equal annual equivalent can be viewed as the amount of an annual payment

that would just pay off the net present value for the rotation. It can be useful for comparing investments that yield a periodic return (such as pine plantations) with those that yield an annual return (such as agricultural crops). It can also be used to compare alternative investments having unequal lives (Haney and Gunter 2002).

LINKAGE WITH THE STAND VISUALIZATION SYSTEM

The Stand Visualization System (SVS) developed by the Forest Service has been linked to the trees in the simulator so they can be displayed with SVS. For each year of a simulated rotation, a file is created containing output for 100 trees that includes its coordinate location, height, height to live crown, dbh, and status (alive or dead). By clicking on the SVS toolbar button, users can view the stand at any age during the rotation. By progressing through the years, users can see trees grow, die, fall and decay. Details of the SVS system and information about how it can be fully utilized can be found at: http://forsys.cfr.washington.edu/svs.html.

Users can access tree files displayed by SVS for each year of the simulation by clicking on the SVS yellow folder button (next to the SVS button) on the toolbar. The tree data in these files can be exported to other programs for further analyses.

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COMPUTING CONSIDERATIONS

Preface

The equations that comprise PTAEDA4.0 have been programmed into a Windows application for implementation with Windows 95 or newer operating systems. The PTAEDA4.0 software is available for $175 by contacting:

> Ralph L. Amateis
> Department of Forestry
> Virginia Tech
> Blacksburg, VA 24061
> *ralph@vt.edu*

Most of the functionality of the PTAEDA4.0 software follows that of other Windows applications and experienced users of Windows software should have no trouble implementing PTAEDA4.0. There are, however, nuances peculiar to this application for which additional explanation may be helpful.

Saving PTAEDA4.0 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

Cell values in the stand and stock table output can be highlighted with the arrow keys or by dragging the mouse and then copied to the Windows clipboard. This type of non "Select all" copying is tab delimited for spreadsheet column alignment. This facilitates pasting from the Windows clipboard into other Windows applications such as spreadsheets or graphics packages. Using the "Select all" option under the Edit menu item highlights the entire output for copying as a block of text to the clipboard. "Select all" copying has columns aligned with spaces for pasting into text documents.

Terminating a simulation

A PTAEDA4.0 simulation run can be terminated and a new run begun 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. Alternatively, the "Reset" button on the toolbar can be used to terminate a simulation run and remove all stand and stock table output from the output window.

Macro facility

The macro facility in PTAEDA4.0 allows recording and playback of a sequence of user inputs to the initialize and midrotation projection/treatment toolbar buttons. There are two macro "modes" that can be selected by the user under the "Macro" menu item. The Manual Dialog Mode (default) lets the user see and alter input to the dialog boxes as the macro is executing. The Automatic Dialog Mode does not display the dialog boxes; the user has less control over macro execution but execution proceeds more quickly.

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. If the Automatic Dialog

Mode has been selected, the macro will play without pause to the end. If the Manual Dialog Mode has been selected, the macro will pause at each dialog box to allow the user to alter input. Using the step button on the macro portion of the toolbar allows playing the macro one step at a time.

Macros may be saved to disk for playing at a later time by using the "Save macro" command 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 PTAEDA4.0 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 and pruning treatment 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 PTAEDA4.0 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. The macro limit is about 1000 steps.