Young Stand Growth Modeling for Intensively-Managed Loblolly Pine Plantations in Southeastern U.S.

James A. Westfall, Harold E. Burkhart, H. Lee Allen

ABSTRACT. Intensively managed loblolly pine stands are often subjected to a variety of silvicultural treatments at time of planting or shortly thereafter. However, most loblolly pine growth-and-yield models predict growth after crown closure has occurred. In this article, we describe the development and implementation of a system of equations designed to simulate growth of loblolly pine before the onset of intraspecific competition. Treatment response functions were also developed for various site preparation, herbaceous weed control, and fertilization practices. These functions modify the baseline model predictions to simulate the effects of treatments on tree growth and stand development. This system was incorporated into the PTAEDA2 growth-and-yield simulator to make growth projections from time of planting through rotation age for intensively managed stands of loblolly pine in the southeastern United States. Growth simulations specifying either bedding or disking showed increases in volume growth for both treatments. The shear-and-pile site-preparation method reduced growth rates slightly. Volume growth responses to herbaceous weed control were positive, with magnitude of increase largely depending on duration of treatment. Increases in volume attributable to fertilization at planting were related to types of element applied. The largest predicted response was for phosphorus fertilization, whereas application of potassium was the least effective fertilization treatment. Site preparation, weed control, and fertilization treatment combinations produced additional volume gains when compared to single treatments, while maintaining predicted values that are within biological limits for loblolly pine growth. Levels of response to treatments are consistent with results from published studies on intensive management practices. The addition of the precompetitive growth system did not significantly affect the predictive behavior of the PTAEDA2 model for untreated stands. FOR. SCI. 50(6):823–835.

Key Words: Site preparation, competition control, onset of competition, growth and yield, fertilization.

GROWTH-AND-YIELD MODELS are an important decision-making tool in forest management. Models must have the ability to account for effects of current and, to some extent, future silvicultural practices. Over the past few decades, the competitive nature of the forest industry has resulted in implementation of increasingly intensive management efforts (Albaugh et al. 1998, Martin and Jokela 2004). Many of these practices are used

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before planting or in the first few growing seasons, which reflects the emphasis that is being placed on early stand development (Morris et al. 1993, Nilsson and Allen 2003). Growth and mortality trends in young stands often play a major role in determining rotation-age stand structure and yield (Nilsson and Albrektson 1994).

Silvicultural treatments that have been shown to enhance growth and minimize mortality in young stands include mechanical site preparation (DeWit and Terry 1983, Edwards and Shiver 1991), herbaceous weed control (Creighton et al. 1987, Zutter et al. 1987), and fertilization (Schmidtling 1973, Gent et al. 1986). However, the results of these practices often are highly variable (Bolstad and Allen 1987, Miller et al. 1991). This variability, along with the wide spectrum of possible combinations and intensities of early management regimes, has led to few attempts at modeling early stand growth. Zhang et al. (1996) developed a system of equations to predict individual-tree attributes for juvenile loblolly pine. These equations accounted for effects of site quality and stand density, but did not include treatment effects. Mason et al. (1997) presented a stand-level model for intensively managed radiata pine for ages 0–5 years and discussed the concept of links with rotation-length models. The lack of modeling efforts for young stands is reflected in many tree growth models, where predictions are absent for young stands (Burkhart et al. 1987, Zhang et al. 1995).

The increasing number of studies undertaken to evaluate growth and treatment response in juvenile loblolly pine plantations over the past two decades (e.g., Amateis et al. 1988, Lauer et al. 1993, Allen and Lein 1998) indicates the importance of early-stand dynamics and the implications for rotation-length outcomes. The effects of early treatments on stand structure and development can be significant and may influence the type and timing of silvicultural treatments applied later in the rotation. To evaluate both short- and long-term effects of early treatments, growth models capable of projecting stand development from time of establishment through rotation age over a range of site, stand, and silvicultural treatment scenarios are needed.

The objective of this study was to develop an individual-tree growth-simulation system for young intensively managed loblolly pine plantations and incorporate this system into the PTAEDA2 growth simulator (Burkhart et al. 1987), which was developed for closed-canopy loblolly pine stands. This integrated system would allow simulation of tree growth and stand development from the time of planting through rotation age. Additionally, the simulator should have the capability to include various site preparation, fertilization, and herbaceous weed control management options. A growth model with these features would give forest managers the ability to evaluate a number of potential management scenarios, which may assist in planning and implementing silvicultural practices that will allow rotation-length goals to be achieved.

Data

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. The Auburn University Silvicultural Herbicide Cooperative provided two data sets. The Competition Omission Monitoring Project (COMProject) was established in 1984–85. Four competition control treatments were implemented at 13 locations across the Southeast (Miller et al. 1995). Individual tree measurements were taken immediately after planting and annually thereafter through age 11 years and again at age 15 years.

The AUSHC Growth Impact Study was established over a five-year period to evaluate the effects of herbaceous weed control treatments. The growth response of loblolly pine was studied at 13 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. Measurement schedules varied by location, but data exist for ages 1–9 years, inclusive, and for most ages from 11–20 years.

The North Carolina State University Forest Nutrition Cooperative (NCSFNC) Regionwide 14 study was established during 1989–2000 at 21 locations, most being situated in the Upper Coastal Plain region (NCSFNC 2000). Intensity of fertilization treatments ranged from check (no fertilization) to application of nitrogen (N), phosphorus (P), and potassium (K). Individual trees were measured for both height and diameter dimensions at the time of establishment and at two-year intervals thereafter.

The NCSFNC also provided data from their Regionwide 7 study, which was initiated at 12 locations between 1978 and 1981. A factorial design was used to apply combinations of fertilization, site-preparation, and herbaceous control treatments (Allen and Lein 1998). Treatments varied by location, but were generally matched to soil characteristics (e.g., bedding versus no bedding on poorly drained sites). Measurements of tree diameter at breast height (dbh) and height were taken every second growing season over the entire length of the study.

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. 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 dbh were measured at age three and five years for plots having attained those ages. Height data were obtained annually through age five years.

Additional data for this research were from a set of loblolly pine spacing trials established in 1983 by the Loblolly Pine Growth and Yield Research Cooperative at Virginia Polytechnic Institute and State University (Virginia Tech). Four locations were selected—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-ft (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 three years. Trees were measured annually until age 10 years and bi-annually thereafter.

Data were also available from a long-term thinning study maintained by the Loblolly Pine Growth and Yield Research Cooperative. During 1981–82, 186 locations were chosen in cutover, site-prepared loblolly pine plantations ranging in age from 8 to 25 years (Burkhart et al. 1985). Three plots were established at each location, representing check (no thin), light thinning (approximately ⅓ of the basal area removed), and heavy thinning (approximately ½ of the basal area removed). Since establishment, these plots have been remeasured five times at three-year intervals.

Methods

Several protocols were applied uniformly to each data set. Estimation of site index was performed with the site index equation used in the PTAEDA2 simulator (Burkhart et al. 1987). Excluding the Growth and Yield Research Cooperative thinning study, site index (base age 25 years) was estimated from check plots (no treatments applied) for each replication at the oldest available age. Trees in the dominant canopy were defined as trees having a dbh greater than the quadratic mean diameter. Data from the remeasurement period closest to age 25 years were used to compute site index for plots in the Virginia Tech thinning study. For these data, site trees used in the computations were those identified as dominant or co-dominant at the time of measurement.

To estimate total tree volume for trees having dbh measurements, the combined-variable equation used in the PTAEDA2 model was used (Burkhart et al. 1987). Volume calculations for trees <4.5 ft in height used groundline diameter to predict conic volumes.

Fitting of prediction equations for attributes that are sensitive to density, such as tree diameter and crown ratio, requires removal of data collected where competitive situations exist. Trees were removed when the mean stand dbh times 2.75 (plot radius factor for basal area factor [BAF] 10 ft^2/ac) exceeded the average intertree distance. This definition was based on Daniels' (1976) method of identifying competitors, which is used to compute a competition index in the PTAEDA2 model.

Height and diameter growth responses to fertilization and herbaceous control treatments were calculated as percent increase in accumulated growth as compared to check plots within the same replication. Data used for evaluating growth responses attributable to site-preparation methods had no check plots. As such, growth responses to site-preparation treatments were computed using the chop-and-burn method as the baseline for comparison.

Application of the growth response functions for fertilization, site-preparation, and herbaceous weed control assume independence (i.e., additivity of effects). Some studies have shown that additivity is appropriate for certain treatment combinations (Swindel et al. 1988, Tiarks and Haywood 1986). Most of the data used for this research is from studies designed to evaluate effects of specific types of treatments. Given this limitation, no attempt was made to account for interactions among treatments. Further research on this subject is warranted.

The PTAEDA2 model contains a stochastic element (based on a random number seed) that modifies predicted growth rates. This is accomplished by adding a random component to the predicted height increment. This component has a variance equal to the mean squared error from the fitting of the height increment equation. Thus, the user can create variability between each simulation run for the same set of input parameters. The reported growth simulation results are average values from five runs using simulated plot sizes of 20 rows having 20 trees each. For the validation exercise, the number of simulation runs was increased to 10 to better meet the assumptions underlying the statistical methods.

The predictive ability of equations was assessed with independent data when possible. In other cases, data splitting was used to evaluate model performance. Data splitting was accomplished by random assignment of observations into 50% fitting/50% validation arrangements, with final parameter estimates obtained by fitting to all data. All statistical analyses were performed using SAS statistical software (SAS 1999). Unless otherwise indicated, results were significant at the Type I error rate of 0.05.

Model Development

Growth simulation requires the generation of an initial stand and a system that projects the development of the stand over time. This was accomplished by generating a height distribution at each age from which individual tree heights were assigned. A flexible distribution that is often used to describe tree size frequencies is the Weibull distribution. The general formulation of the Weibull probability density function is

$$f(x) = (\gamma/\beta)[(x-\alpha)/\beta]^{\gamma-1}\exp\{-[(x-\alpha)/\beta]^{\gamma}\}, \quad (1)$$

where x = Weibull random variable, α = left-side location parameter, β = scale parameter, and γ = shape parameter.

To generate height distributions, maximum likelihood estimates for the two-parameter Weibull formulation (α = 0) were calculated for each check plot in the AUSHC Growth Impact Study for ages 1–11 years. These estimates were used to fit parameter prediction equations that are primarily functions of site index and age. A similar approach was taken by Nigh and Love (1999), who used age and site index to predict mean stand heights for young stands of lodgepole pine. The shape and scale parameters for the Weibull distribution of tree heights are estimated by the equations

$$\hat{\beta} = 0.0192 \times \mathrm{SI} \times A^{1.4169} \quad (2)$$

$$R^2 = 0.97 \quad \text{Std. Error} = 1.48,$$

and

$$\hat{\gamma} = 1 + 0.0343 \times \frac{\text{SI}}{\ln(N)} \times A^{1.0693} \tag{3}$$

$R^2 = 0.51$ Std. Error = 1.20,

where $\hat{\beta}$ = Weibull scale parameter estimate, $\hat{\gamma}$ = Weibull shape parameter estimate, ln = natural logarithm, N = number of trees surviving per acre, SI = site index (base age 25 years), and A = plantation age (years).

Parameter estimates obtained from initial fits for both models were used to predict shape and scale values in the validation data. No notable bias was found for either model, and final estimates and fit statistics were obtained from fitting to combined fit/validation data. The R^2 values reported for these and all subsequent equations are based on corrected total sums-of-squares and are computed as $(SS_{total} - SS_{error})/SS_{total}$. Additionally, the coefficients shown for each model are estimates of the population parameters.

Assignment of tree heights was accomplished by generating a random value from a [0, 1] uniform distribution for each tree. This value was substituted into the Weibull cumulative distribution function solved for height (Bailey and Dell 1973),

$$HT = \hat{\beta} \times [-\ln(1 - U)]^{1/\hat{\gamma}}, \tag{4}$$

where HT = individual tree height (ft), U = uniformly distributed random value, and other variables as previously defined.

Scale and shape parameter predictions were used to estimate the height distribution of the age-one stand. Given that the left-tail location parameter is zero, an additional constraint was needed to establish the age-one height distribution. The smallest observed heights at age one year in the data were 0.2 ft, suggesting that 0.2 ft would be the smallest tree height likely to be observed. Thus, the minimum height at age one year was set at 0.2 ft. If the predicted tree height was below 0.2 ft, a different value from the uniform distribution was assigned to calculate a new tree height.

The value assigned from the uniform distribution to each tree at age one year is maintained for estimating individual-tree heights for subsequent iterations of the precompetitive growth simulation. Thus, trees remain in the same relative position in the tree size distribution until competition is assumed to have begun. This approach is supported by observed data in the Virginia Tech spacing trials, where tree diameters maintained their relative positions in the distribution after differentiation had begun to occur. Nilsson et al. (2002) found a similar pattern of development in young stands of lodgepole pine.

After tree heights are assigned, other tree dimensions can be predicted. Individual-tree diameter prediction was based on tree height, under the assumption that taller trees will have larger radial size than shorter trees. Simulation of early growth requires a measure other than dbh for trees that have not obtained breast height. As such, groundline diameter was predicted for trees less than 4.5 ft in height through an equation fitted to AUSHC COMProject check plot data,

$$D_g \exp(-1.8480 + \text{HT}^{0.4317}) \tag{5}$$

$R^2 = 0.89$ Std. Error = 1.37,

where D_g = groundline diameter (in.) and HT = tree height (ft).

For validation of the groundline diameter equation, independent data were available from the Virginia Tech spacing trials. Plots of residuals indicated that a slight, but consistent, under-prediction was present. This discrepancy may likely be the result of the increased growth provided by herbaceous control treatments performed on study plots.

Individual trees having attained 4.5 ft or more in height will have predicted dbh values. The AUSHC Growth Impact check plot data were used to fit the model,

$$D = -1.5439 + 0.4973 \times \text{HT}^{0.7859} \tag{6}$$

$R^2 = 0.83$ Std. Error = 1.36,

where D = dbh (in.) and HT = tree height (ft).

Validation of the dbh equation used check plot data from AUSHC COMProject. Analyses of predicted and observed dbh values showed good predictive ability for trees having dbh <4 in. However, a trend toward over-prediction was found for trees having diameters of ≥ 4 in. Trees of this size represented a small portion of the data ($\sim 3\%$).

In addition to predicted height and diameter dimensions, height-to-crown was estimated for each tree after 4.5 ft of height is attained. A height-to-crown equation was fitted to check plot data from the AUSHC COMProject:

$$\text{HTCR} = 0.9198 + 0.9773 \times D^{0.00723A} \times A^{0.00854 \times \text{HT}} \times 1.1614^{A} \tag{7}$$

$R^2 = 0.50$ Std. Error = 1.57,

where HTCR = height to live crown (ft), and other variables as previously defined.

No notable bias in prediction was found when comparing observed and predicted values in the validation data. All data were combined to obtain final parameter estimates.

Prediction of mortality in juvenile stands, especially in the first year after planting, may be one of the most difficult aspects of simulating early stand dynamics. A host of variables, many of which are unmeasured or difficult to quantify, can affect survival of seedlings. Poor microsite conditions, weather, disease, interspecies competition, and wildlife are some factors that influence seedling survival (Amateis et al. 1997). Lacking quantification of many of the variables that affect seedling survival, accurate mortality prediction for individual seedlings is virtually impossible at present. However, prediction of mortality at the stand level can be accomplished and individual-tree mortality may be assigned at random or in a spatially explicit arrangement.

Regardless of spatial distribution, there are two stages of mortality that need to be addressed. In the first year after planting, seedlings acclimate to microsite conditions and become established. From the second growth season onward, seedling survival is less dependent on microsite conditions, and mortality is predicated on disease, hardwood competition, etc. The MeadWestvaco Corporation growth study provided first-year mortality data from stands planted over a five-year period. These plots exist over a range of physiographic regions, drainage classes, and silvicultural treatments. A number of plots had very poor survival in the first year, which was largely attributable to chemical site-preparation treatments. Chemically site-prepared plots having excessive (>30%) first-year mortality were dropped from the fitting data to obtain predicted mortality levels that were consistent with first-year mortality rates found in other studies. The number of trees surviving the first year after planting was determined by

$$\mathrm{TS1} = \mathrm{TP} \times 0.8883 \times \exp(0.0225 \times \mathrm{PHY}0.0375 \times \mathrm{BED} - 0.0262 \times \mathrm{DRN}0.0295 \times \mathrm{DISK}) \quad (8)$$

$$R^2 = 0.62 \quad \text{Std. Error} = 48.0,$$

where TS1 = number of trees per acre surviving at age one, TP = number of trees planted per acre, PHY = physiographic region (1 = coastal plain, 0 = piedmont), BED = bedding site preparation (1 = bedding, 0 = no bedding), DRN = drainage class (1 = poorly drained, 0 = well drained), and DISK = disking site preparation (1 = disking, 0 = no disking).

The data-splitting validation process showed good predictive ability, except for over-estimation of survival for plots having mortality rates greater than 20% in the first year. This trend was expected because loblolly pine plantations generally suffer 5–15% mortality in the first year after planting (R.L. Amateis, Virginia Tech., 2001).

After first-year survival is established, mortality from age two years through the onset of competition was predicted using an equation fitted to NCSFNC Regionwide 7 check plot data,

$$\mathrm{TS} = 0.9857 \times \mathrm{TS1} \times A^{-0.0407} \quad (9)$$

$$R^2 = 0.94 \quad \text{Std. Error} = 29.2,$$

where TS = number trees surviving per acre at age A, and all other variables as previously defined.

Assessment of predictive ability using the validation data for this mortality function showed very similar trends to that of the first-year mortality model. Plots that suffered notably disproportionate levels of mortality, especially at early ages, were associated with estimates of survival that were too high.

Treatment Response Functions

The model system outlined in the preceding section was developed to simulate tree growth for stands that have not been subjected to early silvicultural treatments. The commercial importance of loblolly pine has led to the application of a number of early silvicultural treatments aimed at improving tree growth rates. Site preparation, control of competing vegetation, and fertilization are common intensive-management practices.

The NCSFNC Regionwide 7 study includes a number of site-preparation alternatives. Percent height growth changes up to age 14 were calculated for shear and pile, disking, and bedding treatments to generate data for model fitting. There was no opportunity to develop a diameter response model for site preparation treatments, because dbh measurements were not available until age four in this study. Lacking any alternative, percent diameter growth response was assumed the same as that of height response. The equation developed to modify growth response is

$$\mathrm{SP} = (0.1078 \times \mathrm{BED} + 0.1045 \times \mathrm{DISK} - 0.0666 \times \mathrm{SHP}) - A^{1.7872} \times \exp(-0.4057 \times A) \quad (10)$$

$$R^2 = 0.56 \quad \text{Std. Error} = 0.07,$$

where SP = percent height and dbh growth response, SHP = shear and pile (1 = shear/pile, 0 = no shear/pile), and all other variables as previously defined.

Predicted responses show that the bedding treatment provided the greatest gains in growth (Figure 1). Disking also had a positive effect on growth, although slightly less in magnitude than bedding. The shear/pile treatment resulted in less growth than the chop/burn baseline treatment. The shear/pile operation also reduces the effectiveness of any subsequent bedding or disking. The negative effects of the shear/pile treatment likely result from removal of nutrients during the piling operation.

The AUSHC Growth Impact Study was designed to evaluate growth responses to reduced interspecies competition. Percent increases in height and diameter growth attributable to one- and two-year herbaceous control treatments were calculated from these data. These values were used to fit the height and diameter response models,

$$\mathrm{HHERB} = (0.8004 + 0.1539 \times \mathrm{YR2} - 0.2324 \times \mathrm{PHY}) \times A^{1.2903} \times \exp(-0.00988 \times \mathrm{SI} - 0.4191 \times A) \quad (11)$$

$$R^2 = 0.47 \quad \text{Std. Error} = 0.16,$$

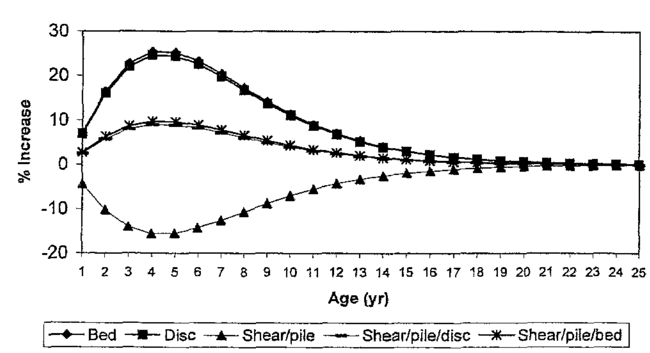

Figure 1. Predicted percent increase in height and diameter growth for various site-preparation treatments for site index 60 ft.

and

$$\text{DHERB} = (1.2244 + 0.2801 \times \text{YR2} - 0.3866 \times \text{PHY}) \times A^{5.3475} \times \exp(-0.0185 \times \text{SI} - 1.5779 \times A) \quad (12)$$

$$R^2 = 0.65 \quad \text{Std. Error} = 0.27,$$

where HHERB = percent increase in height, DHERB = percent increase in diameter, YR2 = two-year treatment indicator (1 = two-year treatment, 0 = one-year treatment), and all other variables as previously defined.

These models provide maximum response at early ages, and response decreases thereafter (Figure 2). The predicted diameter growth response attains a maximum earlier and declines more quickly when compared to the height response. This phenomenon may be related to the enhanced growth rate, which provides an earlier onset of intraspecies competition and resulting effects on diameter increment.

Data from the NCSFNC Regionwide 14 study were used to evaluate effects of nutrient enhancements. Height and diameter growth responses to fertilization treatments were assessed by computing a percentage increase in growth for each fertilization treatment at each age. Equations that predict growth responses of height and diameter to 45 lbs/ac nitrogen (N), 50 lbs/ac phosphorus (P), and/or 100 lbs/ac potassium (K) applications at time of planting were developed and fitted,

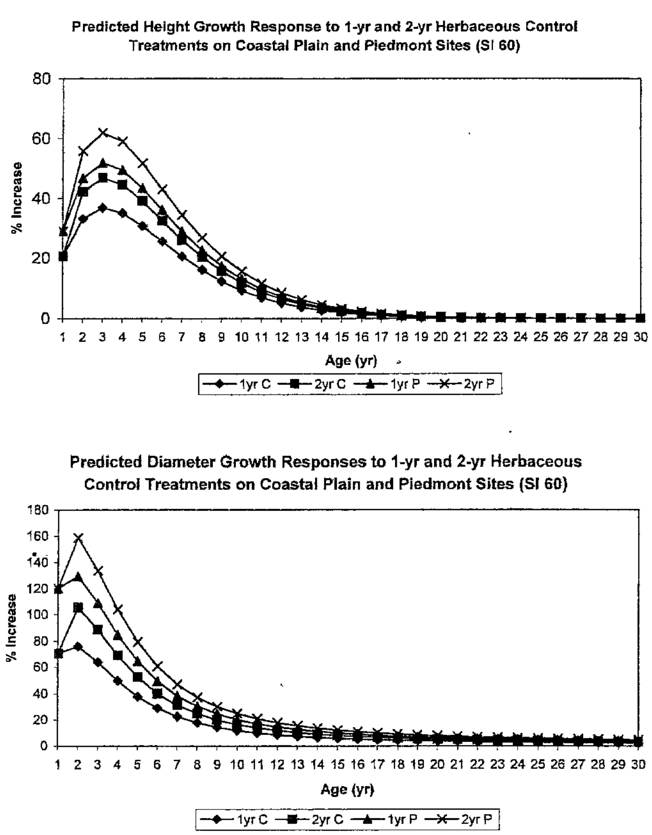

Figure 2. Predicted percent increase in height and diameter growth for one-year and two-year herbaceous control treatments on Coastal Plain and Piedmont sites for site index 60 ft.

HFERT

$$= (17.5395 \times N + 30.4219 \times \text{P} + (1 - \text{P})\text{K} \times 12.3892) \times \exp(-0.0679 \times \text{SI} \times A^{0.1271}) \quad (13)$$

$$R^2 = 0.63 \quad \text{Std. Error} = 0.15,$$

and

$$\text{DFERT} = [(58.516 \times 7N + 94.2161 \times \text{P} + 24.7521 \times \text{K}) \times \exp(-0.0923 \times \text{SI}) \times A^{1.2107}] \times \exp(-0.4476 \times A) \quad (14)$$

$$R^2 = 0.62 \quad \text{Std. Error} = 0.18,$$

where HFERT = percent increase in height, DFERT = percent increase in diameter, N = indicator variable (1 = nitrogen, 0 = no nitrogen), P = indicator variable (1 = phosphorus, 0 = no phosphorus), K = indicator variable (1 = potassium, 0 = no potassium).

These equations allow the user to specify certain combinations of N, P, and K elements. For height response, the addition of K had little or no effect in the presence of P. Thus, the height model is designed to provide a response to K only when P is absent. The diameter response model does not have this condition and growth resulting from K and P applications is additive. The response curves generated by these models for fertilization applications of various combinations of N, P, and K at a site index of 60 ft (18.3 m) are shown in Figure 3. Growth responses from fertilization at planting reach a maximum at an early age. However, the gains in growth did not diminish quickly, and increased tree sizes were evident for most operational rotation lengths.

Incorporation into the PTAEDA2 Model

To construct a growth model capable of making projections from stand establishment through rotation age, the young-stand growth model system described above was incorporated into the PTAEDA2 growth-and-yield model. The existing PTAEDA2 model generates a stand at an age of eight years, which is the time intraspecies competition is assumed to begin. Incorporation of the baseline precompetitive growth system was accomplished by replacing the age-eight stand generation subroutine. To account for the effects of silvicultural practices, the aforementioned treatment response equations were incorporated into the growth subroutines. In the juvenile growth phase, predicted responses were directly applied to predicted tree dimensions for check plots.

A different approach was needed for extending treatment effects into the competitive growth subroutine. After competition is assumed to have begun, incremental diameter and height growth is predicted on an annual basis and added to the cumulative amount from the previous year. As such, there is no baseline associated with check plots, and the treatment response functions cannot be applied directly to predicted tree dimensions. The estimated increases in height growth from the response functions for specified treatments

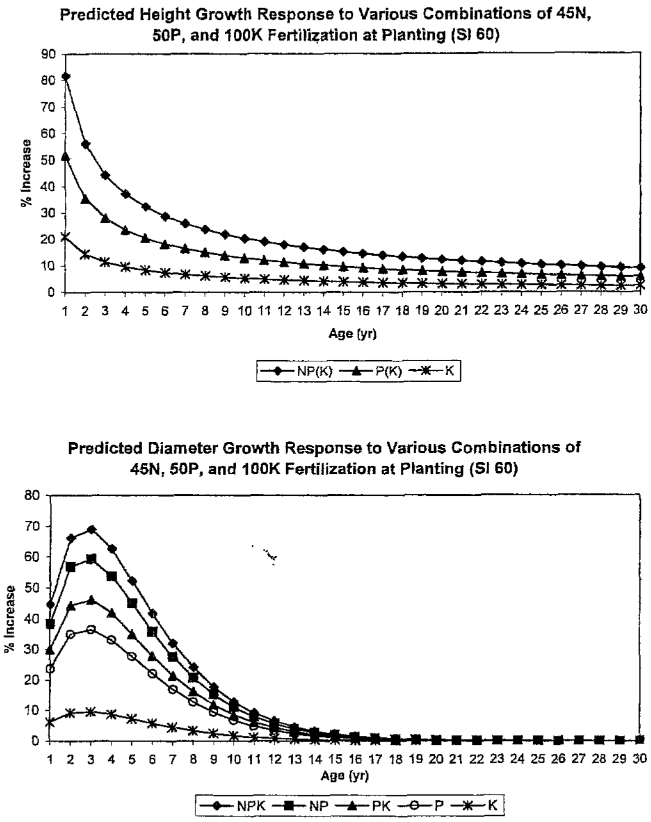

Figure 3. Predicted percent increase in height and diameter growth for various combinations of 45N/50P/100K fertilization at planting for site index 60 ft.

were applied directly to the predicted height of dominants at each age. The difference between predicted height of dominants for two successive growing seasons is the potential height increment (PHIN). PHIN plays a large role in both height and diameter increment prediction. Thus, changes to PHIN resulting from treatment effects result in adjustments to annual height and diameter growth.

Defining the Onset of Competition

In the PTAEDA2 model, the competitive stress experienced by an individual tree is estimated by Daniels' (1976) modification of Hegyi's (1974) distance-dependent diameter-ratio formulation,

$$\mathrm{CI}_i = \sum_{j=1}^{N} \left[\left(\frac{\mathrm{D}_j}{\mathrm{D}_i} \right) \times \frac{1}{\mathrm{Dist}_{ij}} \right], \qquad (15)$$

where CI_i = competition index of the ith subject tree, D_j = dbh of jth competitor, D_i = dbh of ith subject tree, Dist_{ij} = distance between subject tree i and jth competitor, and N = number of competitors captured by BAF 10 prism sweep centered at the subject tree.

The addition of a precompetitive growth phase to PTAEDA2 required definition of the onset of competition. Given that Daniels' measure identifies competitors based on a BAF 10 prism sweep centered on the subject tree, an expedient point-density (PD) definition of onset of competition would be when average stand diameter times the plot radius factor exceeds the average intertree distance.

Although the competition index defined by Daniels is well-correlated with individual tree growth, the identification of competitors is based on the arbitrary value of BAF 10. Radtke and Burkhart (1999) characterized the age of onset of competition in the Virginia Tech spacing trials as the inflection point of the stand-level basal area growth curve. These values were compared to results obtained from the PD formulation for the same sample plots. Plotting mean stand diameter at age of inflection (A^*) and at the PD threshold (the point where average dbh times 2.75 equals intertree distance) versus individual-tree growing space shows that the trend line for the PD method is lower than the trend line based on observed data at A^* (Figure 4). Assuming that the inflection-point approach provides an accurate assessment of the point at which intraspecies competition begins to affect growth, the PD method defines the age of onset of competition too early in the development of the stand.

Minimizing the sum of squared deviations between the two measures showed that multiplying the PD-defined mean stand diameter by 1.29 provided values that were nearly identical to those obtained at A^* (Figure 4). Dividing these adjusted mean stand diameters by average intertree distance provided the plot radius factor for identification of competitors. The PD method is practically equivalent to the inflection-point analysis when a plot radius factor of 2.13 is used.

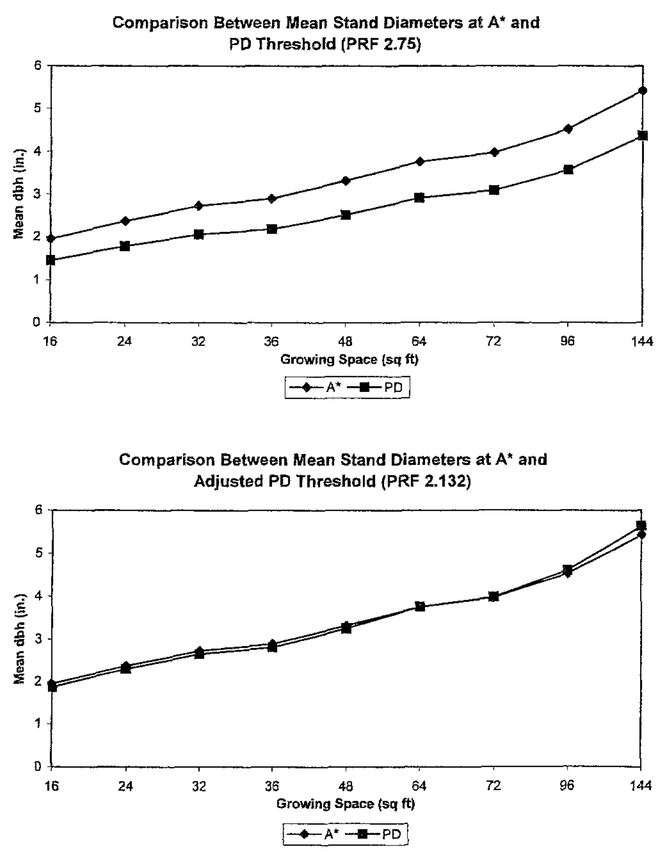

Figure 4. Mean stand diameter versus growing space at A^* and PD threshold, and at A^* and adjusted PD threshold.

This value corresponds to a BAF of ~16.7 ft^2/ac (3.8 m^2/ha).

In the growth simulation process, if mean stand diameter multiplied by 2.13 exceeds the average intertree distance, then intraspecies competition is assumed to have begun and subsequent growth is predicted using the competitive growth system. Because the competitive growth subroutine uses dbh only, it is also required that all trees attain 4.5 ft in height.

Growth Simulation

Having incorporated the young-stand growth equations, treatment response functions, and definition of onset of competition into the PTAEDA2 model, an assessment of the model output was undertaken. An initial review of simulation output revealed that excessively large tree dimensions were predicted for trees in the upper portion of the size distribution when certain treatments or treatment combinations were applied. To prevent this occurrence, an upper limit on predicted tree diameters was estimated by a linear model developed from the NCSFNC Regionwide 7 data,

$$\text{MAXD} = -0.46491 + 1.12421 \times A \qquad (16)$$

$$R^2 = 0.98 \quad \text{Std. Error} = 0.59,$$

where MAXD = maximum allowable predicted dbh (in.) value at age A.

The least-squares regression provided a prediction line that passed through the mean of the fitting data. As such, some observed tree dbh values were greater than those predicted from the MAXD model. To avoid excessive truncation of the upper tail of the tree-size distribution, an additional amount equal to 1 standard error (0.59) was added to the predicted MAXD value for each age. These limits may affect predicted values for periods of one to three years, depending on the intensity of the specified treatment(s). This limitation usually occurred where predicted treatment responses were at or near maximum values. The need to impose this limitation suggests that the use of multipliers may not be appropriate over the entire range of tree sizes.

An area of interest was comparing the predictive output of the new system with that of the existing PTAEDA2 model. The first point at which this evaluation can be made is at age eight years, where PTAEDA2 generates the initial stand. Figure 5 illustrates the volume growth relationships between the original model and the juvenile growth version for site index values of 40, 60, and 80 ft (12.2, 18.3, and 24.2 m). At site index 40 and 60 ft (12.2 and 18.3 m), the predicted volume obtained from the juvenile-growth enhanced model was slightly higher than PTAEDA2 output. These higher values likely provide a better representation of stand growth. Baldwin et al. (2001) analyzed data from 100 check plots in the Virginia Tech thinning study and found that the PTAEDA2 model under-predicted stand volumes. At roughly 30 years, the mean predicted stand volumes from PTAEDA2 were ~600 ft^3/ac (42 m^3/ha) lower than observed plot volumes. The mean predicted stand volume using the juvenile growth model was nearly 400 ft^3/ac (28 m^3/ha) higher than PTAEDA2 output, which more closely approximates the observed data. At site index 80 ft (24.2 m), volume growth trajectories were nearly identical for both models.

Modeled Outcomes of Treatment Effects

Site preparation had both positive and negative effects on growth and yield, depending on the type of site preparation performed. The effect of bedding on stand growth and development was characterized by early gains in volume growth, which diminished at later ages. Disking the site before planting produced increases of similar magnitude. The shear-and-pile site-preparation treatment resulted in reduced growth when compared to the baseline model. However, these initial losses diminish somewhat, and volume growth progresses at a rate similar to that of the baseline after age 15 years. The predicted percent increases in volume at ages 8 and 25 years for selected treatments and treatment combinations are provided in Table 1.

First-year mortality prediction was based, in part, on the implementation of bedding or disking site preparation. Both treatments produced increased survival rates. Initial numbers of surviving trees between treated and check plots were notably different. However, there was little difference by roughly age 24 years. Rates of mortality were unaffected by the shear-and-pile treatment.

Growth simulations specifying one- and two-year herbaceous weed control treatments resulted in predicted values

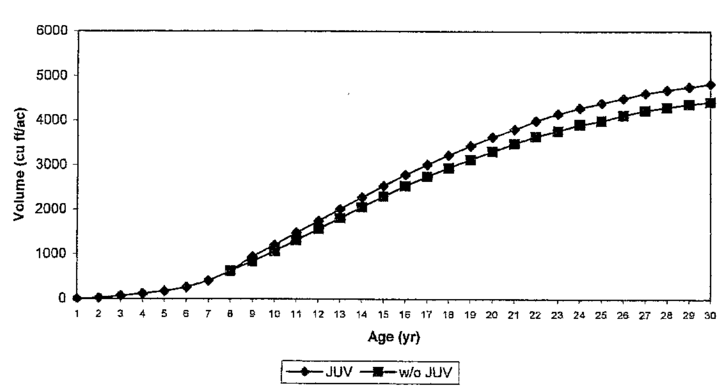

Figure 5. Predicted mean volume growth for PTAEDA2 with and without juvenile growth phase for site index 60 ft.

Table 1. **Predicted percent increase in total volume at stand ages 8 and 25 for various treatments at site index 60 ft and 680 trees/ac planted.**

Treatment	Percent Increase	
	Age 8	Age 25
Bed	59.7	4.2
Disc	53.9	2.8
Shear/Pile	−23.3	−3.4
2-yr Herbaceous (Piedmont)	94.1	8.3
1-yr Herbaceous (Coastal)	51.0	1.8
100K Fertilization	11.1	3.2
45N/50P/100K Fertilization	74.0	19.9
2-yr Herb (Coastal) and 45N/50P/100K	146.0	25.8
Bed and 2-yr Herb (Coastal)	161.8	10.8
Bed, 2-yr Herb (Coastal), and 45N/50P/100K	238.3	25.9

that were consistent with expected responses. Volume gains attributable to herbaceous weed control treatments were most pronounced early in the development of the stand. The greatest improvements in volume were associated with the two-year treatment in Piedmont locations. The smallest gains were associated with Coastal sites receiving a herbaceous weed control treatment in the first year only.

Simulated volume growth under fertilization treatments varied considerably, depending on the elements chosen for application. The predicted increases in stand volume were the highest for the N/P/K treatment. Conversely, applications of K alone resulted in the smallest enhancements to estimated volumes as compared to untreated stands.

Multiple Treatments

In addition to selecting individual treatments for growth simulations, the user can also specify combinations of treatments. To present the results in a concise manner, only certain treatment levels and combinations are considered. Generally, responses to treatment combinations not specifically reported can be inferred. For instance, one can assume that herbaceous weed control and K fertilization will result in less response than weed control combined with a treatment of N/P/K.

Combining two years of herbaceous weed control with N/P/K fertilization produced a significant increase in growth, especially for early stand ages. Notable improvements in stand volume resulting from treatment were still evident at age 25. The predicted increases in mean stand volume for ages 1–30 years are shown in Figure 6.

Bedding site preparation combined with two-year herbaceous weed control was also evaluated. This treatment combination also showed notable early growth improvements when contrasted with growth projections for untreated stands. As treatment effects diminish over time, projected stand volumes are not as great as those found when combining fertilization with two-year herbaceous control.

Growth projections that combined the effects of site preparation, herbaceous weed control, and fertilization treatments were performed. The combination of bedding, two-year herbaceous weed control, and N/P/K fertilization was used to evaluate growth responses when three treatment

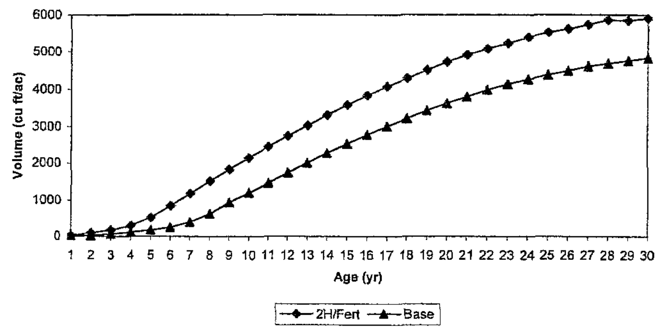

Figure 6. Predicted mean volume growth for combined two-year herbaceous control and 45N/50P/100K fertilization at site index 60 ft with 680 trees/ac planted.

options were specified. As anticipated, projected rates of growth greatly exceeded the estimates given for check plots (Figure 7). Improvements in stand volume of over 200% were predicted for early ages. Significant gains in stand volume were still present at age 25, largely because of the fertilization treatment.

The remarkable projected growth increases for the combined site preparation, herbaceous weed control, and fertilization treatments leads to the question of biological maximums. The simulations performed to evaluate effects of all three treatments used a site index of 60 ft (18.3 m) with 680 trees/ac (1,680 trees/ha) planted. Under this scenario, simulation output showed that growth increases attributable to treatment effects did not push predicted values beyond a point that would be considered unattainable for loblolly pine stands (Figure 7). Under an extremely intensive site preparation, vegetation control, and fertilization management regime, Borders and Bailey (2001) reported stand volumes near 6,000 ft^3/ac (420 m^3/ha) at age 12 for loblolly pine planted at 680 trees/ac (1,680 trees/ha).

It was expected that increasing planting density and site index under the three-treatment scenario would result in higher estimated stand volumes at each age. The PTAEDA2 model provides limits for various input parameters. The upper limit for site index is set at 90 ft (27.4 m) and no more than 2,500 trees/ac (6,178 trees/ha) can be planted. The point of interest here is what predicted outputs would be given if the model were set to the highest levels for site

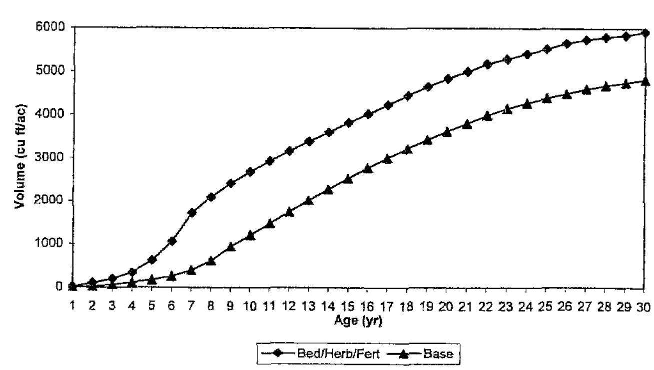

Figure 7. Predicted mean volume growth for combined bedding, two-year herbaceous control, and 45N/50P/100K fertilization treatments at site index 60 ft with 680 trees/ac planted.

index, number of trees planted, site preparation, herbaceous weed control, and fertilization. These settings should result in the highest attainable rates of growth. If the predictive output of the model is reasonable at these extreme values, then it seems a safe assumption that the user would be unable to create a scenario where estimated growth rates are implausible.

When the input parameters were maximized, predicted stand volume increased rapidly early in the life of the stand. Volume continued to increase until the stand age reached 25 years, where the maximum value of approximately 7,809 ft^3/ac (546 m^3/ha) was attained. Projected stand volumes past this point declined slightly, but were maintained just under the 7,800 ft^3/ac (545 m^3/ha) level.

These predicted values are within the range of observed data for loblolly pine. The greatest observed cumulative volume growth across 186 unthinned plots in the Virginia Tech thinning study was nearly 8,600 ft^3/ac (602 m^3/ha). This value occurred at age 23, where estimated site index was roughly 84 ft (25.6 m). Observed data from the previous measurement three years earlier showed that volume was continuing to increase. This is essentially what occurred in the simulation at these ages. The estimated maximum volume from simulation of 7,809 ft^3/ac (546 m^3/ha) is biologically feasible for loblolly pine plantations.

Validation

Validation refers to comparing simulator output with observed data to evaluate predictive ability. Reynolds et al. (1981) used the PTAEDA simulator (Daniels and Burkhart 1975) to demonstrate the application of statistical tests for validation of simulation output. Differences between observed and mean simulated stand volumes were used to test hypotheses of equality between observed and simulated volume distributions. To evaluate the predicted values generated as part of this research, 39 unthinned plots from the Virginia Tech thinning study served as observed data. The specific plots were chosen because planting density estimates were available. Fortunately, most of these plots have survived throughout the study, which provides a range of ages from 8 to 37 years for validation purposes.

Although Reynolds et al. (1981) computed several statistics for comparative purposes, the nonparametric tests were recommended because of the minimal assumptions required for validity. The test statistic distribution was approximated by the standard normal distribution. The test based on the statistic V_3^* (Reynolds' notation) was chosen to compare simulated versus observed volume distributions:

$$V_3^* = \frac{\sum_{i=1}^{n}\left(R_i - \frac{m+2}{2}\right)^2 - n \times \frac{m \times (m+2)}{12}}{\sqrt{n \times \frac{(m-1) \times m \times (m+2) \times (m+3)}{180}}}, \tag{17}$$

where m = number of simulation runs for each plot, R_i = rank of observed plot volume among observed value and m simulated values for each plot, and n = total number of observed and estimated volumes (= $m + 1$).

Table 2 shows the calculated test statistics for selected age ranges and for a single test over a wide range of ages. The age categories were selected so that, within any age group, measurements from each plot would only appear once over the interval. Thus, data used to calculate V_3^* were independent within each age group. However, the test statistics were not independent across age categories because of the use of remeasurement data from the same plots. The test that covers the age range of 9–37 years was computed using a randomly chosen remeasurement period for each of the 39 plots. This procedure produced a set of independent data for a single overall test of simulator output.

The values of V_3^* were significant at the 0.05 level for all age classes and for the overall test. This suggested that the mean or variance of the predicted stand volume distribution was different from that of observed data. An examination of differences between observed and predicted values (D) showed that volume was overpredicted for relatively young stands (Table 2). This condition dissipated as stand age increased, where mean observed and simulated stand volumes are in close agreement in the 23–25 year range. However, underprediction of stand volume increased thereafter. This trend was also noted in the analyses of Reynolds et al. (1981), suggesting that the addition of the precompetitive growth system did not have a large impact on overall model behavior.

It is notable that, even when D is relatively small (e.g., the 23–25 year range), the value of V_3^* is still large. As noted by Reynolds et al., small variance estimates for simulated volumes can result in elevated test statistic values. Analyses conducted by Baldwin et al. (2001) using data from the same thinning study showed that the variance of simulated per-acre volumes for 100 study plots was smaller than was observed on measured plots. In the context of this evaluation, variance discrepancies may play a larger role than

Table 2. Summary of statistics and error intervals associated with model validation tests for ages 8–37 years in three-year age classes.

Age	N	V^*_3	D	$\%D$	S_{CI}	S_{PI}
8–10	7	3.47	−195.8	−35.4	90.7	256.7
11–13	20	6.73	−308.0	−22.1	72.9	334.2
14–16	30	7.86	−321.0	−14.8	73.5	409.1
17–19	36	9.62	−332.1	−11.7	77.3	470.9
20–22	38	9.28	−190.5	−5.4	86.9	545.1
23–25	38	7.51	18.8	0.5	111.3	697.9
2628	31	6.83	216.4	4.6	132.6	751.0
29–31	19	5.20	481.1	9.3	170.6	763.2
32–34	8	3.80	769.3	13.7	163.7	492.0
35–37	3	2.94	1425.7	22.4	359.2	718.4
9–37	39	9.28	−24.1	0.7	120.5	762.4

Age = age range of observed data (years).
N = number of plots in age range.
V^*_3 = test statistic based on ranks.
D = mean difference between observed and simulated volumes (ft^3/ac).
$\%D$ = percent difference (D/Obs. volume) * 100.
S_{CI}, S_{PI} = respective standard errors of mean differences for computation of confidence and prediction intervals.

shifts in means in determining the values of V_3^* for many of the age classes listed.

In addition to evaluating agreement between observed and simulated volume distributions, a measure of the range of expected error in volume prediction may also be useful to users of the model. Table 2 provides standard errors to compute volume and prediction intervals for volume-per-acre estimates. Precision in the lowest and highest age groups suffered from a small number of observations, resulting in relatively wide error intervals. The overall value of D (mean difference between observed and simulated volumes) was −24.1 ft^3/ac (−1.7 m^3/ha) with a 95% confidence interval of −267.6 ft^3/ac to 219.4 ft^3/ac (−18.73 m^3/ha to 15.35 m^3/ha). The offsetting effect of overprediction for young stands and underprediction for older stands results in statistics that are consistent with results in the 23–28 year range.

Although the adequacy of simulation output from age eight onward remained largely unchanged, it was still necessary to evaluate the predictive ability of the precompetitive growth system. This was accomplished by using data from a site-preparation study located in the Piedmont region of Georgia and South Carolina. Lantagne (1984) gives a detailed description of this study. These data were chosen because of the existence of tree measurements on areas having received chop-and-burn site preparation, which is the baseline preplanting treatment in the model presented here.

These data are complicated by the fact that a drought occurred in the first growing season after planting, which resulted in very poor survival. To perform a validation analysis similar to that for closed-canopy stands, observed volumes at age six years were scaled to estimate volume per acre if observed and predicted survival rates were similar.

These data were used to calculate the V_3^* statistic and confidence intervals based on differences in observed versus predicted volumes. The value of V_3^* was 4.77, indicating that the mean and variance of the predicted volume significantly deviated from the observed values. The value of D for these plots was −61.6 ft^3/ac (4.31 m^3/ha), suggesting that slight overprediction existed at age six years. The 95% confidence interval for D produced lower and upper confidence limits of −17.3 ft^3/ac (1.21 m^3/ha) and −105.9 ft^3/ac (7.41 m^3/ha), respectively. These results are consistent with those reported above for the 8–10-year age class.

Verification

Because all available data on early treatments were used to develop the response functions, we look at response levels reported in other research to corroborate the adequacy of model outputs. Stafford et al. (1985) reported growth responses to shear-and-pile for loblolly pine at age three. These data were consistent with the model in that the shear/pile treatment resulted in less growth than the chop/burn method. The study reported that height growth was reduced by nearly 0.25 ft (0.08 m), whereas losses in radial growth were 0.07 in. (0.18 cm). The model predicted (based on site index 60) reductions of roughly 0.9 ft (0.27 m) for height growth and slightly over 0.1 in. (0.25 cm) for diameter growth. The same study also contained information on growth trends where site preparation consisted of shear/pile/disc. The reported increases in age-three height and diameter were approximately 0.6 ft (0.18 m) and 0.2 in. (0.50 cm), respectively. Model output shows increases of 0.4 ft (0.12 m) for height and 0.2 in. (0.50 cm) for diameter are predicted when shear/pile/disc is specified.

Growth responses to bedding and disking treatments were evaluated by Pehl and Bailey (1983) for 10-year-old loblolly pine. Growth simulation with bedding site preparation slightly overpredicted the mean stand height (20.5 ft [6.2 m] versus 23.0 ft [7.0 m]), whereas predictions of basal area (83 ft^2/ac [19.1 m^2/ha] versus 78 ft^2/ac [17.9 m^2/ha]) and volume (1,225 ft^3/ac [85.7 m^3/ha] versus 1,108 ft^3/ac [77.5 m^3/ha]) were slightly less than the observed data. The disked areas in this study showed comparable performance to the bedding treatment. Respective mean stand height, basal area, and volume at age ten were 21.3 ft (6.5 m), 81.3 ft^2/ac (18.7 m^2/ha), and 1,403 ft^3/ac (98.1 m^3/ha). The estimated stand attributes from simulation output were 21.5 ft (6.6 m) mean stand height, 67.7 ft^2/ac (15.6 m^2/ha) of basal area, and 903 ft^3/ac (63.1 m^3/ha) in stand volume. The model predicted stand height well, but basal area and volume were underpredicted. A confounding factor was that study plots were heavily invaded by volunteer pines, which may have contributed to the predictive bias.

Comparisons between model output and observed data for herbaceous control treatments were also performed. Pienaar and Shiver (1993) published age five- and age eight-year results from a study of application of herbaceous weed control treatments. The results of growth simulations with herbaceous control indicated that the research plots had more basal area and volume than was predicted by the model for each density level. For 800 trees/ac planted, the study showed basal area to be 133 ft^2/ac (30.6 m^2/ha), whereas the model predicted 117 ft^2/ac (26.9 m^2/ha). Similarly, study volume was estimated as 2,060 ft^3/ac (144.1 m^3/ha), whereas 1,866 ft^3/ac (130.5 m^3/ha) was predicted by simulation. An area of discrepancy was in predicted levels of survival, because the research plots had notably low rates of mortality. This situation likely contributed to the underestimation of growth by the model.

Model predictions of response to fertilization were the most difficult to verify because of the range of rates of application found in published reports. Gent et al. (1986) evaluated growth response to rates of P and N+P fertilization in age three to five year loblolly pine stands. Rates of element application averaged over the study sites were similar to the rates used to develop the fertilization response equation for the simulation model. That study reported average gains in height growth of 53% and 61%, respectively, for P and N+P fertilization. Model output for P and N+P fertilization estimated gains in mean height of 24% and 43%, respectively. Study results also showed improved diameter growth attributed to P (68% increase) and N+P (79% increase) fertilization. The model predicted gains in diameter growth of 47% and 77%. Percent increases in simulated growth were less than observed on plot data from that study. It would be desirable to develop response models where application rates are continuous variables. This would allow for better direct comparisons between model output and study results.

The verification efforts have shown that predicted growth and yield may be either under- or overestimated for any given study. This is expected because of the nature of the simulation process, which is designed to represent average growth rates and treatment responses. In some situations, comparisons were confounded with differences in mortality rates.

Conclusion

Impacts of intensive management practices on growth of loblolly pine have been extensively reported over the last two decades. The general growth response trends for site preparation, herbaceous weed control, and fertilization treatments reported in many of these studies were evident in the data used for this research. The intensity and duration-of-treatment effects were dependent on the practice used and attribute of interest.

Because of the overall lack of information needed to develop precise site-specific responses, environmental stand conditions were evaluated using site index estimates. Undoubtedly, site index does not always capture the array of conditions that affect treatment response. This was confirmed by the relatively high variation in growth response for each of the treatments studied, and resulted in observed responses for any particular stand to be more or less than that predicted by the model. Further research is needed to incorporate comprehensive site information into growth and treatment response models.

Successful incorporation of the young-stand growth system into the existing PTAEDA2 model was accomplished using site index as a driver for annual growth rates. Site index was used as a point of reference across the growth systems, and served as a vehicle for carrying treatment responses into the competitive growth phase. This approach worked well for most of the site, stand, and treatment combinations available within the model. However, in situations where predicted response to treatments was high, the tree sizes in the upper tail of the size distribution became excessively large. This implies that equal application of treatment response to each tree may not be appropriate.

The tendency of the model to overpredict per-acre volume for younger stands and to underestimate volume at later ages was consistent with the behavior of the existing PTAEDA2 model. These discrepancies were, at least in part, attributable to differences in observed versus predicted mortality rates. Foresters who use the growth model developed in this research can expect similar performance to that of the PTAEDA2 model, while having the added flexibility to examine precompetitive growth trends and evaluate effects of early silvicultural treatments over the length of a rotation.

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