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RCDlob: A Growth and Yield Model for Loblolly Pine that Incorporates Root-Collar Diameter at Time-of-Planting

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ABSTRACT

An individual tree model for loblolly pine (*Pinus taeda* L.) was developed to predict the response resulting from varying root-collar diameter (RCD) at time of planting. Data for this model were obtained from four plantations in the Lower Atlantic Coastal Plain of the United States. The study involved two levels of silvicultural intensity (1- standard; 2- intensive) and two bareroot seedling ideotypes (1 – standard; 2 – morphologically improved). Measurements were made up to age 12 years. The output from RCDlob was compared to two existing loblolly pine growth and yield model programs. Based on these analyses, a model system was developed that resulted in reasonable estimates of stand development for planting densities ranging from 988 to 1730 trees per hectare and stand ages up to 25 years. This model has been incorporated into a downloadable Windows-based Visual Basic program.

Keywords: loblolly pine, seedling quality, plantation, root-collar diameter

INTRODUCTION

A number of growth and yield models have been developed for loblolly pine (*Pinus taeda* L.) plantations (Smalley and Bailey 1974; Baldwin and Feduccia 1987; Lenhart 1996; Baldwin and Cao 1999; Burkhart *et al*. 2004) but none of these relate root-collar diameter (RCD) at the time-of-planting to future tree growth. Throughout the world, only a few models relate seedling size at establishment to future growth and yield. For example, in New Zealand, groundline diameter (GLD) at time-of-planting was used as a predictor of growth and survival of *Pinus radiata* D. Don (Mason 2001). In South Africa, survival up to two years after planting was modeled using GLD for *P. radiata* (Zwolinski *et al*. 1994).

Bareroot nurseries in the southern U.S. sometimes produce seedlings with an average RCD at planting of less than 4 mm (South *et al*. 2001). Many nursery managers prefer small seedlings over large-diameter seedlings since the costs associated with lifting, shipping and planting are minimized. Since planters are paid based on the number of seedlings planted and not on the number of seedlings surviving after a certain amount of time, planters often prefer to plant seedlings with small root systems (South *et al*. 2001). Growing seedlings at lower seedbed densities will produce stock with larger roots and the cost of production will increase (perhaps by $4 to $7 per thousand seedlings). Large-diameter seedlings will also reduce hand-planter revenue per hour because of greater seedling root mass that requires more time to plant properly (South *et al*. 2001). However, seedling root mass does not affect the speed of machine planting. Morphologically-improved seedlings (MI) generally cost more to produce and purchase than standard seedlings (South *et al*. 2005a) but they have exhibited greater outplanted growth and survival compared to standard seedlings (Shoulders 1961; Shipman 1964; Sluder 1979; South *et al*. 1985; Dierauf *et al*. 1993; South 1993; South *et al*. 1995, 2001; South and Rakestraw 2002). Planting bareroot pine seedlings that were grown at low nursery densities may provide economic advantages (Caulfield *et al*. 1987; South 1993; South and Rakestraw 2002; South *et al*. 2005a), especially when outplanted at wider spacings (South 1993; South and Rakestraw 2002; South *et al*. 2005a).

Resource managers currently utilize tools to determine the economic trade-offs among various regeneration options. Some may want to compare increased seedling and outplanting costs associated with MI seedlings with the gains obtained from greater survival and growth. To make such calculations, a manager must make assumptions about the performance of MI seedlings. Although several papers provide information to support such assumptions, a predictive model would allow resource managers to conduct growth and economic analyses using customized costs and revenues. A modern establishment model would allow users to vary the distribution of seedling sizes at time-of-planting (e.g. Mason 2001). The objective of this research was to develop mortality, diameter at breast height (DBH), and height models to relate RCD of *P. taeda* seedlings at time-of-planting to future growth and economic returns. These models were developed for *P. taeda* stands in the Coastal Plain of Georgia and South Carolina.

MATERIALS AND METHODS

Data

Data for the model were obtained from four sites located on the Atlantic Lower Coastal Plain in Georgia and South Carolina (South *et al*. 2001; VanderSchaaf and South 2003). Two seedling ideotypes (average RCD [MRCD] across all sites; 5.0 mm for the standard seedlings and 8.5 mm for the MI seedlings) were established by using different nursery culture (South *et al*. 2001) and were used as sub-plots. Two regeneration management levels (0 – standard, 1 – intensive) were used as main plots. Both scenarios involved raking, piling, and burning all residual debris followed by a bedding treatment in the summer. In addition to these site preparation treatments, the standard management scenario included a broadcast herbicide treatment of hexazinone and sulfometuron in March plus fertilization with diammonium phosphate (DAP). In addition, the intensively managed plots received a broadcast her-

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Table 1 Plot-level summary of the data used in model fitting. Min = minimum; Max = maximum.

Age	Basal area per hectare (sq. m) Min	Mean	Max	Total tree height (m) Min	Mean	Max	QMD (cm) Min	Mean	Max
Morphologically-Improved seedlings, Standard regeneration scenario									
1	.	.	.	0.7	0.8	0.9	.	.	.
2	.	.	.	2.0	2.1	2.2	.	.	.
3	0.2	0.5	0.5	3.1	3.6	3.9	1.5	2.0	2.3
4	0.5	0.7	0.9	4.2	4.8	5.4	2.3	2.5	3.0
7	10.3	14.7	19.1	5.9	7.6	8.9	9.7	11.4	13.0
8	13.1	18.1	23.0	8.6	9.8	10.8	10.7	13.2	15.2
10	17.0	22.5	29.4	9.7	11.5	13.1	12.2	14.5	16.3
12	20.9	27.3	35.4	12.0	13.8	15.1	13.7	16.0	17.8
Morphologically-Improved seedlings, Intensive regeneration scenario									
1	.	.	.	0.7	0.8	1.0	.	.	.
2	.	.	.	2.4	2.5	2.7	.	.	.
3	0.7	0.7	0.9	4.0	4.3	4.5	2.3	2.5	2.8
4	1.1	1.4	1.4	5.5	6.0	6.2	3.3	3.6	3.6
7	16.5	20.4	25.7	7.7	9.2	10.9	12.2	13.7	15.7
8	23.0	24.3	26.9	11.0	11.8	13.4	14.0	15.2	16.5
10	24.6	28.9	36.3	11.7	13.1	14.0	15.0	16.3	18.8
12	28.5	34.0	42.5	14.5	15.5	16.3	16.0	17.8	20.3
Standard seedlings, Standard regeneration scenario									
1	.	.	.	0.5	0.6	0.7	.	.	.
2	.	.	.	1.5	1.8	2.0	.	.	.
3	0.2	0.2	0.5	2.7	3.1	3.6	1.3	1.5	2.3
4	0.5	0.7	0.7	3.5	4.3	5.1	1.8	2.3	2.8
7	8.7	12.4	15.2	5.2	6.9	8.8	8.9	10.7	12.2
8	10.3	16.8	24.1	7.8	9.2	10.3	9.7	12.7	15.7
10	14.7	20.7	28.2	9.2	11.0	11.9	11.7	14.0	17.0
12	18.8	25.0	33.1	10.9	13.1	14.6	13.2	15.5	18.3
Standard seedlings, Intensive regeneration scenario									
1	.	.	.	0.5	0.6	0.7	.	.	.
2	.	.	.	1.8	2.1	2.3	.	.	.
3	0.2	0.5	0.7	3.5	3.8	4.0	2.0	2.3	2.5
4	0.7	1.1	1.1	5.0	5.5	5.6	2.8	3.3	3.3
7	14.0	18.6	22.7	7.4	8.5	10.1	11.7	13.2	14.5
8	17.4	22.3	25.0	9.9	11.2	12.0	13.7	15.0	16.3
10	20.2	26.9	33.8	11.7	12.7	13.3	15.0	16.0	17.8
12	24.6	31.5	38.8	14.0	14.8	15.2	15.7	17.5	19.1

bicide application of imazapyr and metsulfuron in mid-summer of the planting year and again one-year later. A treatment of DAP plus potassium chloride was applied 2 years after planting. Detailed descriptions of treatments and block-plots were provided by South *et al.* (2001). Sampling age was up to 12 years (**Table 1**) and planting density varied by site from 1282 to 1495 seedlings per hectare.

Modeling

A distance-independent individual tree model procedure was used to relate growth and yield to RCD at time-of-planting. A logistic regression model was used to estimate the probability of individual tree survival (Hamilton 1986; Moore *et al.* 2004). Equations presented in this paper are collectively referred to as RCDlob. Due to the time and costs involved in measuring RCD, few if any operational (yet alone research) plantings will include measuring RCD. Thus, this model system only projects growth and yield from the time of planting. Our model system cannot be used to project growth of existing stands.

Mortality equations

Parameter estimates for the mortality equations were obtained using Proc Logistic (SAS 1989). The dependent variable for equations [1] and [2] is the probability that a tree will survive into the next growing season. When estimating whether a tree that has not reached breast height will survive to the next growing season, equation [1] was used:

$$\ln\left[\frac{\hat{P}_i}{1-\hat{P}_i}\right] = b_{11} + b_{12}\left[\frac{\text{RCD}}{\text{MRCD}}\right]e^{\text{Treat}} \quad [1]$$

Where:

$\hat{P}_i$ = probability an individual tree will survive into the next growing season

Treat = 0 – standard regeneration scenario, 1 – intensive regeneration scenario

RCD = root collar diameter of the seedling at time of planting (mm)

MRCD = mean root collar diameter for all seedlings planted (mm)

b_{1i} = parameters to be estimated

After the tree reaches breast height, equation [2] was used to estimate the probability of a tree surviving into the next growing season:

$$\ln\left[\frac{\hat{P}_i}{1-\hat{P}_i}\right] = b_{21} + b_{22}\,\text{DBH} + b_{23}\text{Age}^{0.5} + b_{24}\text{BA} \quad [2]$$

Where:

$\hat{P}_i$ = probability an individual tree will survive into the next growing season

DBH = diameter at breast height (cm)

Age = from time of planting (yr)

BA = basal area per hectare (sq. m)

b_{2i} = parameters to be estimated.

A tree survives to the next growing season if its probability of survival exceeds the value of a uniformly distributed random number that is generated by year and individual tree for all trees surviving from the previous age. Parameter estimates for equations [1] and [2] and their associated standard errors are presented in

Table 2 Parameter estimates and their associated standard errors for equations [1] and [2]. Std. Error = standard error of the estimate.

	Estimate	Std. Error
Equation [1]		
b_{11}	5.5044	0.9605
b_{12}	0.2626	0.5229
n	1938	
Equation [2]		
b_{21}	9.7588	0.9581
b_{22}	0.5406	0.0611
b_{23}	-2.8126	0.5567
b_{24}	-0.0874	0.0365
n	10629	

Table 2.

Height and diameter equations

Both linear and nonlinear regression equations were examined for height and DBH. Equations for a particular dependent variable were selected using both statistical and biological properties, but biological properties were the overriding concern. Parameter estimates were checked to make sure they were consistent with biological theory (e.g. greater numbers of trees per hectare surviving at a particular age should reduce the estimate of DBH). Additionally, predicted values of stand development were examined to determine whether a particular equation or sets of equations produced reasonable estimates across a range of ages and values of the regressors. After accounting for biologically meaningful variables, the function with the lowest untransformed average absolute value residual was selected. Residuals were examined for trends.

To extrapolate predictions of individuals beyond age 12 years, the Chapman-Richards equation was selected to model both individual tree height, equation [3], and DBH, equation [4]:

$$\hat{\text{Ht}} = b_{31}\,(1\text{-}e^{b_{32}\text{Age}})^{b_{33} + b_{34}\text{RCD} + b_{35}\text{Treat}} \qquad [3]$$

Where:

$\hat{\text{Ht}}$ = estimated total individual tree height (m)
b_{3i} = parameters to be estimated, and all else is as previously defined.

$$\hat{\text{DBH}} = [b_{41}+ b_{42}\text{LnHt}+ b_{43}\text{LnTPH}](1\text{-}e^{b_{44}\text{Age}})^{b_{45} + b_{46}\text{Treat}} \qquad [4]$$

Where:

$\hat{\text{DBH}}$ = estimated individual tree DBH (cm)
Ln = natural logarithm
TPH = trees per hectare
b_{4i} = parameters to be estimated, and all else is as previously defined.

Proc Model (SAS 1989) and the Gauss-Newton algorithm were used to estimate parameters of the individual tree height and DBH model functions (**Table 3**). To avoid potential simultaneous equation bias and to account for potential cross-equation correlation of the errors, a simultaneous parameter estimation methodology (Borders 1989) was used to estimate parameters of equations [3] and [4].

All variables were reported to be significant at p-values less than 0.0001. These models were developed using longitudinal data and thus errors are most likely serially correlated which can result in biased confidence intervals and hypothesis tests, even asymptotically. However, at least for equation [3], parameter estimates are still asymptotically unbiased (Schabenberger and Pierce 2002, pg. 51). Even though serial correlation was ignored when estimating parameters of all equations, the parameter estimates would still be highly significantly different from zero if the correlation was modeled since all regressors are known to biologically impact the dependent variables. Since all variables were reported significant at p-values less than 0.0001 and biological meaning is more of a concern than statistical significance of coefficients, the autocorrelation was ignored when estimating parameters.

Table 3 Model fitting results and parameter estimates and their associated standard errors for equations [3] and [4]. Std. Error = standard error of the estimate; RMSE = root mean square error; DW = Durbin-Watson test statistic.

	Estimate	Std. Error
Equation [3]		
b_{31}	35.44596	1.5552
b_{32}	-0.052883	0.00346
b_{33}	1.3735	0.0274
b_{34}	-0.01592	0.00102
b_{35}	-0.14722	0.00805
n	14424	
Adj. R^2	0.8921	
RMSE	1.7845	
DW	0.9026	
Equation [4]		
b_{41}	47.22408	1.4760
b_{42}	7.826371	0.0909
b_{43}	-7.12185	0.1994
b_{44}	-0.820726	0.0196
b_{45}	25.42849	1.9081
b_{46}	-4.79999	0.7024
n	14424	
Adj. R^2	0.8952	
RMSE	1.9773	
DW	1.0595	

A sigmoid growth curve ensures reasonable estimates of the response variables at ages of 15, 20, and 25 years. Estimates of yield rather than increment were used since remeasurement intervals varied and modeling growth directly produced poor predictions at ages greater than 15. The Chapman-Richards equation form provides an estimated biological constraint on yield, which resulted in a better estimate of growth at ages greater than 15 for these data. Zeide (1989) reported the Chapman-Richards equation was superior to many other sigmoid growth equations for predicting DBH but found the Power Decline I, or the Korf (Zeide 1993), sigmoid growth equation was superior to the Chapman-Richards equation for predicting DBH. For this study, the Korf equation resulted in reasonable estimates of DBH at older ages, but the combination of this equation with the mortality model, equation [2], resulted in an over-prediction of mortality at older ages. Other growth equations tested were the Gompertz, Logistic, Monomolecular, and the Weibull, but they were found to overestimate DBH. Thus, the Chapman-Richards equation was selected to predict DBH.

The allometric relationship between individual tree height and DBH is widely known – often referred to as the constant-stress theory (Zeide and VanderSchaaf 2002). Although most use DBH to predict height, for this study DBH is modeled as a function of height. The first reason for this is that it is desired to predict growth at young ages (i.e. 1 and 2 years) as well as for older ages. Resource managers want to know when basal area growth at 1.37 m above the ground begins on trees in relation to RCD. One approach is to first predict height and, once predicted height values have reached DBH (1.37 m), predict DBH. Thus, natural resource managers can use this model for not only long-term growth and yield and economic analyses in relation to RCD, but also to get a reasonable idea of when basal area production begins on individual trees relative to RCD. Secondly, it is a reasonable assumption for the range of planting densities used in model fitting, and for the range of planting densities that we recommend our model system is applicable for (988 to 1730 trees per hectare [TPH]), that height is largely independent of stand density. However, DBH is highly correlated with stand density. Since we want to use RCDlob for planting densities beyond those used in model fitting, based on the constant-stress theory, predicting DBH as a function of height provides a constraint on individual tree DBH.

Due to the fact that we recommend this model system not be used for planting densities greater than 1730 seedlings per hectare, it is a reasonable assumption that DBH is independent of planting density until age 4. The prediction of DBH from equation [4] in-

Table 4 Model fitting results and parameter estimates and their associated standard errors for equation [5]. Std. Error = standard error of the estimate; RMSE = root mean square error; DW = Durbin-Watson test statistic.

	Estimate	Std. Error
Equation [5]		
b_{51}	0.48684	0.00691
b_{52}	1.065264	0.00946
b_{53}	0.102054	0.0144
b_{54}	0.079745	0.00438
n	3663	
Adj. R^2	0.8542	
RMSE	0.2978	
DW	1.5282	

cludes TPH. Thus, a separate equation was fit to predict DBH up to and including age 4:

$$\hat{DBH} = b_{51}\text{Ht}^{b52}\left[\frac{\text{RCD}}{\text{MRCD}}\right]^{b53}\left[e^{\text{Treat}}\right]^{b_{54}} \quad [5]$$

Where:

b_{5i} = parameters to be estimated, and all else is as previously defined.

All parameter estimates were reported to be significant at p-values smaller than 0.0001 (**Table 4**). All trees at ages 3 and 4 were greater in height than 1.37 m and thus DBH was measured on all trees. When using this equation for prediction, for those trees that have not yet reached breast height, DBH should be set equal to 0.

Biological interpretation of parameter estimates

Due to the asymptotic nature of equation [3], regardless of treatment, eventually the expected total tree height will be estimated to be the same for all trees. It is our opinion that the asymptotic nature of equation [3] is biologically reasonable. South and Rakestraw (2002) stated that planting larger diameter seedlings typically produces an advance in stand development or Type 1 growth response (Nilsson and Allen 2003; VanderSchaaf and South 2004). This is also known as an "age-shift" response, which does not increase the carrying capacity of the site. Since both regeneration treatments consist of relatively intense site preparation and there were few hardwoods present, we do not believe that hardwood competition in these stands will affect long-term productivity. In these trials, an "age-shift" is likely due primarily to (1) additional herbaceous weed control (South *et al*. 2006); and to (2) use of seedlings with larger roots (South *et al*. 1985; South 1993; Zeide 1993; South and Rakestraw 2002). Age shifts are produced in equation [3] by using a common asymptote but a rate parameter that varies relative to seedling size and regeneration scenario.

The final concern related to the asymptotic nature of equation [3] is whether the additional DAP treatment for the intensive regeneration scenario will produce an increase in carrying capacity (termed a Type 2 response). Phosphorus (P) is often limiting on flatwoods sites and substantial gains in yield of loblolly pine have been observed following P fertilization. We recommend our model system only be used to estimate stand development to age 25 years. Until age 25 years, selecting an intensive rather than a standard regeneration scenario will produce increases in height growth and thus the additional DAP treatment will produce gains in height. However, the magnitude of the gains will likely confirm to the law of diminishing returns (South *et al*. 2005b).

Since LnTPA is included as a regressor in the asymptote of equation [4], differences in the asymptotic DBH will be observed for ages 25 years and younger when varying planting density. We believe this is biologically correct.

Diameter-distributions

Equations [1] through [5] allow us to obtain reasonable estimates of stand density development. However, those equations do not provide very realistic diameter-distributions. In fact, if one selects a stand to be planted with only one RCD then a diameter distribution will not occur at any age. Thus, equations were developed and tested to estimate the variance of total tree height across time, which can then be used to generate a height distribution for any age and regeneration combination. Since DBH is predicted as a function of total tree height, a diameter-distribution will also be generated. The first approach used was to obtain the residuals from the fitting of equation [3], square them, and then use gamma regression to estimate parameters of a model containing regressors thought to influence height variability. However, this method did not produce good results, particularly when extrapolating to older ages.

Therefore, a second approach was employed where the variance of total tree height was calculated for each experimental unit by age (producing a total of 240 observations). Thus, for each measurement age, regeneration scenario, and MRCD combination by site, a variance was calculated. These variances were then used as the dependent variable to fit equation [6]:

$$\hat{Var} = b_{61}\text{Age}^{b_{62}}\left[e^{\text{Treat}}\right]^{b_{63}}\text{MRCD}^{b_{64}} \quad [6]$$

Where:

$\hat{Var}$= predicted variance in total tree height
b_{6i} = parameters to be estimated, and all else is as previously defined.

Proc Model of SAS and the Gauss-Newton algorithm were used in model fitting. The model form and parameter estimates of equation [6] are biologically sound, as age increases variability increases while it is thought that more intensive regeneration scenarios and greater MRCDs produce more uniform stands (**Table 5**). All parameter estimates were reported to be significant at p-values smaller than 0.0283. For each surviving tree, equation [6] allows for a random component with mean equal to 0 and standard deviation equal to the square root of the expected value of equation [6] to be added to any expected total tree height predicted using equation [3]. Total tree heights are assumed to be normally distributed (Burkhart *et al*. 2004) about the expected value of equation [3]; to avoid unrealistic height distributions at older ages, a z-score of 2 is used to produce a distribution containing 95% of the likely height observations.

Based on the expected height for any age and treatment combination and the predicted random component for an individual tree, a DBH is predicted for each individual tree. Due to the variability in height, a diameter distribution will be generated. Although total tree height and DBH can be estimated for any age in a single step, in order to produce reasonable mortality patterns across a rotation, RCDlob is run recursively (i.e. annually).

It is difficult to validate our model with independent data because RCD is rarely, if ever, measured in research or operational plantings. In addition, for those studies where RCD was measured, the regeneration scenarios were vastly different. Thus, we present verification analyses.

Table 5 Model fitting results and parameter estimates and their associated standard errors for equation [6]. Std. Error = standard error of the estimate; RMSE = root mean square error; DW = Durbin-Watson test statistic.

	Estimate	Std. Error
Equation [6]		
b_{61}	0.175488	0.0795
b_{62}	1.720258	0.1626
b_{63}	-0.25472	0.0611
b_{64}	-1.06244	0.1387
n	240	
Adj. R^2	0.6619	
RMSE	0.5099	
DW	1.2069	

RESULTS AND DISCUSSION

The equations in RCDlob have biologically meaningful parameter estimates. Biologically based estimates aid in predicting response variables beyond the domain of the regressor values used to estimate parameters. Therefore, RCDlob allows the user to model stands established at 988 trees per hectare even though the data were from stands established at more than 1200 trees per hectare. In order to determine if output from RCDlob was reasonable, we compared the output of two other models with that from RCDlob.

Comparison with other models

Explicitly quantifying differences between RCDlob and other models would be difficult due to the stochastic nature of our model. Even so, we wanted to see whether predictions from RCDlob are reasonable for ages and initial stocking beyond those used in model fitting (e.g. 25 years and 988 planted trees per hectare). The growth and yield models selected for comparison [Ptaeda 3.1 (Burkhart *et al.* 2004) and Baldwin and Feduccia (1987), a model for Western Gulf loblolly pine] were developed using data from cutover sites. Predictions from RCDlob might not parallel those from the Western Gulf model since RCDlob was fitted using data from genetically improved seedlings in the Lower Atlantic Coastal Plain. Ptaeda 3.1 is a distance-dependent individual tree model while the Western Gulf model is a stand-level diameter distribution model. Model structure differences between our model and the two existing models should have minimal impact on growth and yield predictions.

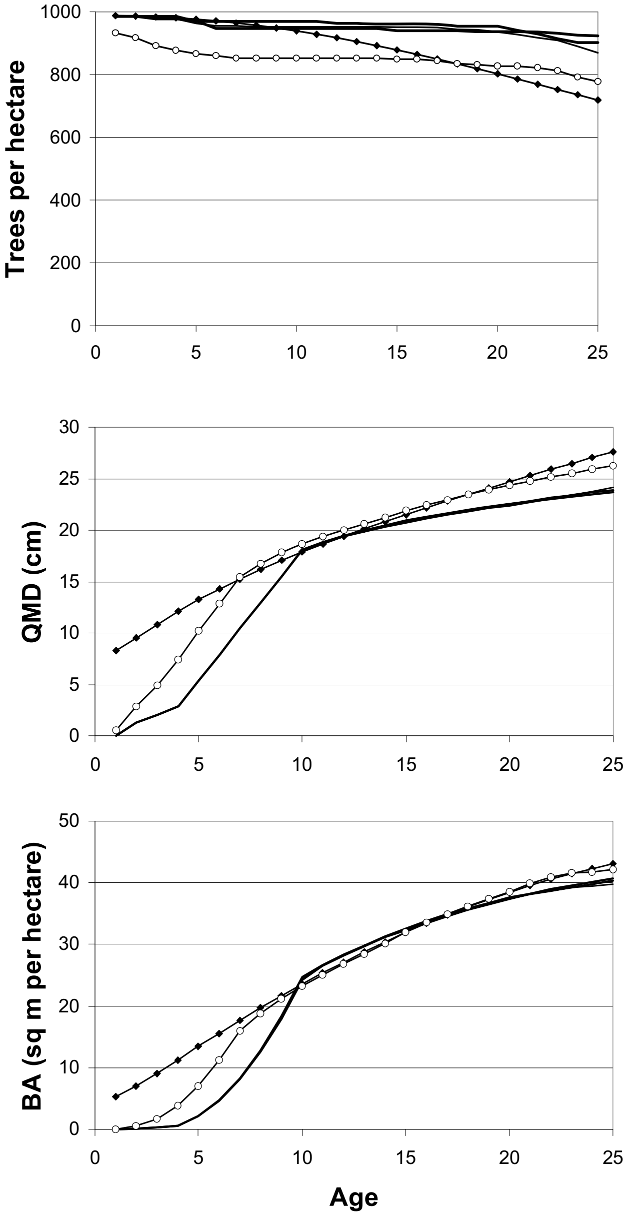

Fig. 1 Comparison of projections from three RCDlob simulations (lines with no points) to two other cutover loblolly pine plantation growth and yield models (Baldwin and Feduccia 1987 = filled black diamonds, Burkhart *et al*. 2004 = nonfilled circles) for a planting density of 988 seedlings per hectare. In RCDlob, a Standard regeneration scenario was selected using 4.5 mm seedlings (half of the seedlings were 4 mm and half were 5 mm).

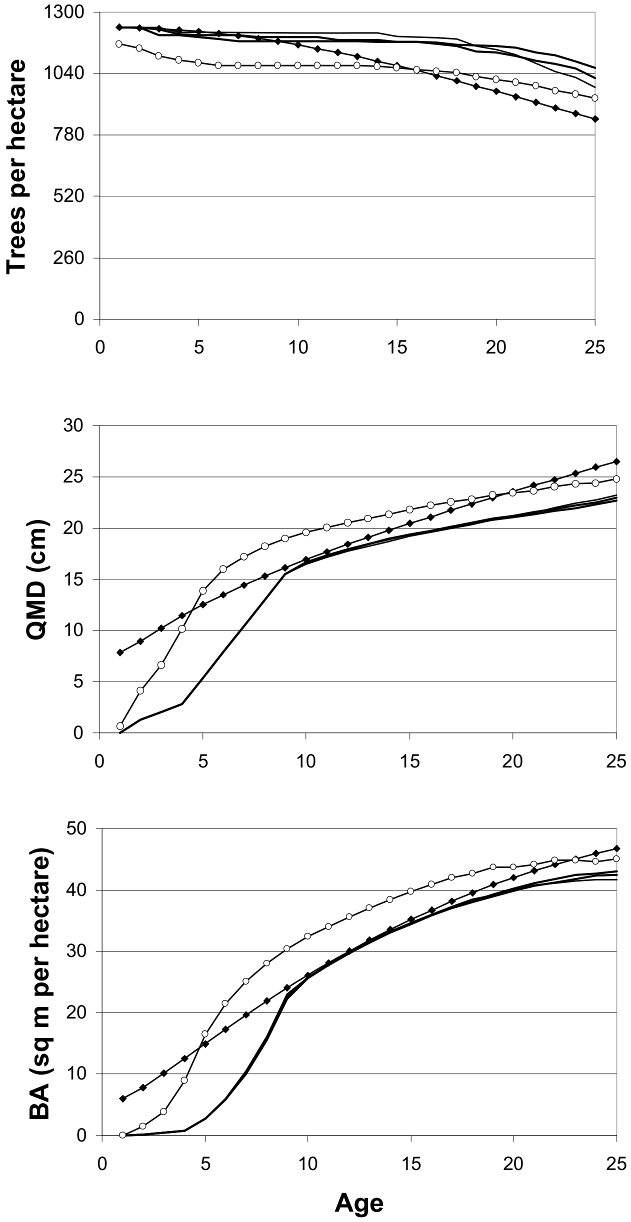

Fig. 2 Comparison of projections from three RCDlob simulations (lines with no points) to two other cutover loblolly pine plantation growth and yield models (Baldwin and Feduccia 1987 = filled black diamonds, Burkhart *et al*. 2004 = nonfilled circles) for a planting density of 1236 seedlings per hectare. In RCDlob, a Standard regeneration scenario was selected using 4.5 mm seedlings (half of the seedlings were 4 mm and half were 5 mm).

Predicted values from RCDlob were compared for planting densities of 988, 1236, and 1730 per hectare using an average RCD of 4.5 mm for all seedlings and a standard regeneration scenario up to age 25 years (**Figs. 1, 2,** and **3**). Due to the stochastic nature of the mortality models in RCDlob, predictions of 3 different runs from RCDlob were com-pared to the other growth and yield model programs.

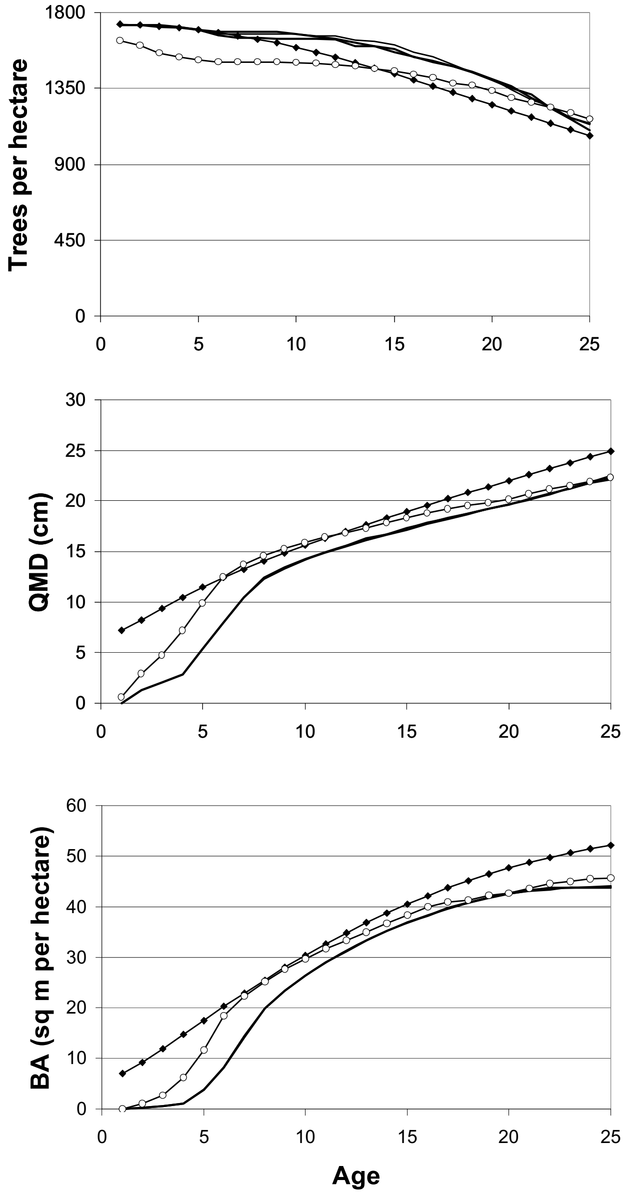

Fig. 3 Comparison of projections from three RCDlob simulations (lines with no points) to two other cutover loblolly pine plantation growth and yield models (Baldwin and Feduccia 1987 = filled black diamonds, Burkhart *et al*. 2004 = nonfilled circles) for a planting density of 1730 seedlings per hectare. In RCDlob, a Standard regeneration scenario was selected using 4.5 mm seedlings (half of the seedlings were 4 mm and half were 5 mm).

Generally, data used to fit both Ptaeda 3.1 and the Western Gulf models were from stands operationally planted prior to 1985. Thus, it is a reasonable assumption that the research plots were planted using seedlings that had an average RCD near 4.5 mm and, at the maximum, a standard regeneration scenario. For Ptaeda 3.1, site preparation consisted of bedding and shear and pile, an herbaceous weed control treatment was conducted during the first year, and a first-year N and P fertilization treatment was conducted. Of the regeneration options available within Ptaeda 3.1, we believe these are most consistent with the standard regeneration scenario used in this study. Additionally, for Ptaeda 3.1, all predictions were based on square planting configurations.

To avoid unreasonable predictions of early DBH development, estimates from RCDlob are based on a maximum annual diameter growth of 2.54 cm up to age 10 years. Since equations [3] and [4] do not predict future height and DBH as a function of previous height and DBH; respectively, random components based on equation [6] are not carried over to the next growing season. For each year, random components are added to a predicted individual tree height independent of previous random components for that particular tree. Therefore, in order to include a maximum annual diameter growth up to age 10 years, random height components are not utilized until age 11 years, thus diameter distributions are not generated until age 11 years.

RCDlob gives similar estimates of stand development when compared to the two other models across the range of planting densities from 988 to 1730 planted trees per hectare (**Figs. 1, 2,** and **3**). In general, RCDlob has greater predicted survival than the two other models, particularly for young ages. This may be reflective of the greater regeneration intensities in our dataset, even for the standard regeneration scenario, and the fact that our models were developed using observations from plantations established experimentally and not operationally. In addition, RCDlob generally has lower basal area and DBH development which is consistent with our data based on the regeneration scenario and MRCD selected. In contrast, the model by Baldwin and Feduccia (1987) does not have an inflection point for the basal area curve. Although the model was fit using data from plantations younger than age 10 years, the majority of their data are from plantations older than age 10 years and thus their model may not be very applicable for ages younger than 5 to 10 years. Based on this analysis, RCDlob produces reasonable estimates of stand development when extrapolating beyond the ages and planting densities of the data used in model fitting.

CONCLUSIONS

RCDlob is the first growth and yield model that allows the user to vary initial RCD for loblolly pine. It has been implemented into a Visual Basic program that allows the user to input cost data and price data for pulpwood, chip-n-saw and sawtimber sized products. Since the program outputs weight in short tons as well as net-present values, plantation managers can easily calculate the cost/benefit ratio for planting MI seedlings. In the past, many land managers have deferred to the economic goals of hand-planters when defining the desired seedling size for outplanting. Now managers in the Lower-Coastal Plain can determine for themselves how much revenue might be obtained by planting large-diameter loblolly pine seedlings.

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