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Stand Level Growth and Survival Equations for Cutover Sites Loblolly Pine Plantations in the Mid-Gulf Region of Southern United States

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By

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Improved equations for predicting future dominant height, diameters, and number of surviving trees in a forest stand were developed for loblolly pine in the mid-Gulf region of southern United States using tree data from 115 stands across the region. The data were split into two sets and models were fitted on each data set using contemporary statistical modeling approaches in SAS® and R® software. Several models were fitted and compared. Fitted models were evaluated based on two-fold cross validation techniques. The best equations had high fit indices and acceptable prediction standard errors. Model parameter estimates were significant at 5% significance level and exhibited logical model behavior. In the future, the system level performance of these equations will be evaluated after which the equations will be incorporated into the Cutover Sites Loblolly Pine growth and yield simulator developed and maintained by the Mississippi Forest and Wildlife Research Center.

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CHAPTER I

INTRODUCTION

Introduction

Forests of the southern United States are a significant source of world timber with approximately 58% of US timber and 16% of world timber coming from these forests (Wear and Greis 2002). In Mississippi, forest cover constitutes 65% of the land area of the State of Mississippi with 15.5 million acres of forest land belonging to private landowners, 1.8 million acres to the forest industry, and 2.3 million acres to the state, local and federal governments (Oswalt and Bentley 2011; Glass 2013). Pine forests cover 6.62 million acres or 33% of the forested area of the State. Loblolly pine is the largest component of Mississippi's pine forests and it is primarily managed for timber production. In 2010, forestry and related sectors contributed $10.38 billion to the State's economy (Dahal et al. 2013), which was approximately 11% of the State's GDP according to the United States Bureau of Economic Analysis State-level GDP figures for 2010. Additionally, total carbon sequestered by forests of Mississippi is approximately 990 million tons, which is approximately 2% of the United States total forest carbon storage (USDA Forest Service 2013). Therefore, Mississippi forests play significant economic and ecological roles in the State and southern United States region in general and hence up-to-date, reliable and versatile growth and yield prediction systems are needed to enable accurate valuation and policy guidance for the State's forest resource.

Forest growth and yield models are essential because trees take a long time to grow from seedling stage to maturity. For example, plantation loblolly pine takes at least 25 years to reach rotation age. The models provide information on future yields which helps in making management and policy decisions on forests. Several growth and yield models that are specific to loblolly pine in Mississippi and the surrounding States have been developed. For example, the whole stand diameter distribution model of Matney and Farrar (1992), Virginia Tech's diameter distribution model FASTLOB (Amateis et al. 2001), and the individual tree distance-dependent model PTAEDA (Burkhart et al. 2008). FASTLOB and PTAEDA are region-wide models developed using data from a range of sites geographically distributed from southern Maryland to eastern parts of Texas and Oklahoma. The model developed by Matney and Farrar (1992) is more specific to the mid-Gulf region than the others and therefore the best for use in this region. There is need to update the forest growth and survival equations in this model using contemporary statistical modeling approaches and new data in model development. This would provide a better-parameterized model as well as cover part of the region that is not well represented in the previously developed model.

The contemporary modeling approaches considered included the Generalized Algebraic Difference Approach (GADA) of dominant height prediction (Cieszewski and Bailey 2000) and the two-step method of mortality prediction proposed by Woollons (1998). The most important attributes of GADA models includes site index curves that are polymorphic with multiple asymptotes. These methods were not used in the model version developed by Matney and Farrar (1992). The GADA method has been previously used to develop site index curves for plantation loblolly pine in the southern United

States (Diéguez-Aranda et al. 2006; Lauer and Kush 2010). This approach has the advantage of using current dominant height and age only to predict future dominant height. The two-step method of mortality prediction has also been found to work well for loblolly pine in Piedmont and Atlantic coastal plain of southern United States (Zhao et al. 2007). It has also worked well in Scots pine in northwestern Spain (Diéguez-Aranda et al. 2005).

Objectives

The objective of the current study was to develop stand growth and survival prediction equations for loblolly pine planted on cutover sites in the mid-Gulf region of southern United States. The specific equations developed were:

a) Dominant height prediction equations (also known as site index equations).

b) Diameter prediction and projection equations.

c) Equations to predict number of surviving trees (i.e. survival/mortality equations).

These equations will in future be incorporated in to the Cutover Sites Loblolly Pine (CoLob) growth and yield simulator developed and maintained by the Mississippi Forest and Wildlife Research Center.

CHAPTER II

LITERATURE REVIEW

Forest stand development models

There are two broad categories of forest growth and yield models 1) whole stand models and 2) individual tree models. Whole stand models are made up of equations that are based on stand level characteristics such as age, basal area per unit area, and site index. These models work well for natural, even-aged, single species stands. Examples of whole stand models include the model of Sullivan and Clutter (1972) for natural stands of loblolly pine in the southeastern US, and the model for loblolly and slash pine in East Texas, US by Coble (2009).

Whole stand models that include a system to recover the predicted stand's diameter distribution from predicted stand characteristics are referred to as diameter distribution models. The components predicted by diameter distribution models include dominant height, arithmetic mean diameter (AMD), quadratic mean diameter (QMD), minimum dbh (DMIN), and number of surviving trees. Examples of diameter distribution models include the model of Matney and Farrar (1992) for loblolly pine plantations in the mid-Gulf southern US, a model for loblolly pine plantations in Virginia, USA, by Cao et al. (1982), and a model by Zeide and Zhang (2000) for loblolly pine plantations in Virginia, USA.

Individual tree models equations are based on tree level characteristics such as dbh and height. These equations predict survival of individual trees. The equations generally include a competition index computed from neighbor tree dimensions. These models are higher in resolution, which makes them well-suited to mixed species stands and uneven-aged stands. Examples of individual tree models include PTAEDA for plantation loblolly pine in southern United States (Burkhart et al. 2008), the US Forest Service's southern variant of the Forest Vegetation Simulator(FVS) (Keyser 2008), and a model for uneven- aged pine in Louisiana/Arkansas by Murphy and Shelton (1996). The current study focused on whole stand models. Specifically, this study looked at the following components of a whole stand model: 1) dominant height/site index prediction, 2) diameter growth prediction/projection, and 3) number of surviving trees prediction (survival or mortality).

Dominant height/site index prediction

The dominant height/site index prediction model is one of the most important components of whole stand growth and yield model systems. In the model future dominant height prediction is done by the inverted site index equations. Most current dominant height prediction/site index equations are based on the algebraic difference approach (ADA), which was introduced in forestry by Bailey and Clutter (1974). The main limitation of the ADA approach is that it did not allow for polymorphic site index equations with multiple asymptotes. Examples of ADA dominant height prediction/site index models include:

Chapman-Richards

$$Ht = SI\left(\frac{1-exp(b_1 Age)}{1-exp(b_1 IAge)}\right)^{b_2} \quad [2.1]$$

Log Logistic

$$Ht = SI\left(\frac{1+b_1 IAge^{b_2}}{1+b_1 Age^{b_2}}\right) \quad [2.2]$$

Logistic

$$Ht = SI\left(\frac{1+b_1 exp(b_2 IAge)}{1+b_1 exp(b_2 Age)}\right) \quad [2.3]$$

Lundqvist-Korf

$$Ht = SI \times exp\left(-b_1\left(\frac{1}{IAge} - \frac{1}{Age}\right)\right) \quad [2.4]$$

In Equations 2.1 to 2.4, *Ht* is dominant height, *SI* is site index, *IAge* is index age and b_1, b_2 are parameters.

Recently, Cieszewski and Bailey (2000) developed an approach that was referred to as the Generalized Algebraic Difference Approach (GADA), which has been used to develop dominant height prediction/site index equations (e.g Diéguez-Aranda et al. 2006; Lauer and Kush 2010). The advantage of the GADA approach is that equations from this approach are polymorphic with multiple asymptotes. In addition, GADA equations allow for direct prediction of future dominant height from current dominant height and age without intermediate calculation of site index. Examples of GADA models include:

A Chapman-Richards GADA model

$$Ht = Ht_0 \left(\frac{1-exp(-b_1 A)}{1-exp(-b_1 A_0)}\right)^{b_2+\frac{b_3}{X_0}} \qquad [2.5]$$

where $X_0 = 0.5(ln(Ht_0) - b_2 L_0 + \sqrt{(ln(Ht_0) - b_2 L_0)^2 - 4b_3 L_0)}$

with $L_0 = ln(1 - exp(-b_1 A_0))$

and

Hossfeld (1822) Log logistic GADA model

$$Ht = \frac{b_0 + X_0}{1 + \frac{b_1}{X_0} A^{b_2}} \qquad [2.6]$$

where $X_0 = 0.5\left(Ht_0 - b_0 + \sqrt{(Ht_0 - b_0)^2 + 4b_1 Ht_0 {A_0}^{b_2}}\right)$

In Equations 2.5 and 2.6, Ht is dominant height at time A, Ht_0 is the dominant height at time A_0, and b_0, b_1, b_2, b_3 are parameters.

Diameter/Basal area growth prediction/projection

Diameter growth/basal area growth of individual trees is a measure of increase in dbh over a given period of time. It is essential to forecast future stand average diameter or basal area growth in whole-stand models because it determines timber value and stand density. Various equation forms have been used for predicting/projecting stand basal area or arithmetic or quadratic mean diameter. For example, the following model form is used in FASTLOB growth and yield system (Amateis et al. 2001) to predict basal area:

$$BA = exp\left(b_0 + b_1 \ln\left(\frac{H}{Age}\right) + b_2 \ln(N) + b_3 \ln(Age)\right) \qquad [2.7]$$

In the model system by Zarnoch et al. (1991), the basal area prediction for slash pine was modeled as:

$$BA = b_0 \, H^{b_1} N^{b_2} \, exp^{b_3 \frac{1}{Age}} \qquad [2.8]$$

In Equations 2.7 and 2.8, BA is basal area, H is dominant height, N is number of trees per acre, and b_0, b_1, b_2, b_3 are parameters. In some model systems, future basal area is projected from current basal area. For example, in the model system by Coble (2009) future basal area is projected from current basal area as:

$$\ln BA_2 = b_0 + \frac{A_1}{A_2}\left(\ln BA_1 - b_0 - b_1 \ln N_1 - b_2 \ln H_1 - b_3 \frac{\ln N_1}{A_1} - b_4 \frac{\ln H_1}{A_1}\right) + b_1 \ln N_2 + b_2 \ln H_2 + b_3 \frac{\ln N_2}{A_2} + b_4 \frac{\ln H_2}{A_2} \qquad [2.9]$$

Likewise, in the model form developed by Sullivan and Clutter (1972) for natural stands of loblolly pine in southeastern US, the future basal area is projected from current basal area as:

$$\ln BA_2 = \frac{A_1}{A_2} \ln(BA_1) + b_1 \left(1 - \frac{A_1}{A_2}\right) + b_2 SI \left(1 - \frac{A_1}{A_2}\right) \qquad [2.10]$$

In equation 2.9 and 2.10, BA_2 is future basal area per acre, BA_1 is current basal area per acre, N_1 is current number of trees per acre, N_2 is future number of trees per acre, H_1 is current dominant height at time A_1, H_2 is future dominant height at time A_2, SI is site index, and b_0, b_1, b_2, b_3, b_4 are parameters.

In other model systems, average diameter is predicted instead of BA being predicted. For example, in the growth and yield model system by Matney and Farrar (1992), stand AMD and QMD get predicted as:

$$AMD/QMD = b_0 (N)^{b_1} exp\left[\frac{-b_2}{\sqrt{H}} + b_3 A\right] \qquad [2.11]$$

In the model by Baldwin and Feduccia (1987) AMD and QMD get predicted as:

$$AMD/QMD = b_0(H)^{b_1} N^{b_2} e^{\frac{b_3}{A}} \quad [2.12]$$

Another model form that has been used to predict AMD and QMD is the following form from the work of Cao (2004):

$$AMD/QMD = exp[b_1 + b_2 RS + b_3 \, ln(N) + b_4 \, ln(H) + \frac{b_5}{A}] \quad [2.13]$$

In Equations 2.11 to 2.13, RS is relative spacing, N is number of trees per acre, H is dominant height, A is current stand age, and b_0, b_1, b_2, b_3, b_4 are parameters.

Apart from predicting AMD and QMD as shown in Equations 2.11 to 2.13, the average diameters may be projected from current average diameters. For example, in the growth and yield model system by Matney and Farrar (1992), future AMD is projected from current AMD as:

$$AMD_1 = AMD_0 \left[1 + (A_1 - A_0) exp\left[b_0 - b_1 A_0 - b_2 \left(\frac{H_0}{A_0}\right) + \frac{b_3}{A_0} - \frac{b_4}{\sqrt{A_0}}\right]\right] \quad [2.14]$$

where, AMD_0 is initial arithmetic mean diameter, H_0 is initial dominant height, A_0 is initial stand age, A_1 is future stand age, and b_0, b_1, b_2, b_3, b_4 are parameters. The QMD projection Equation is exactly the same form as the AMD projection equation [2.14] with QMD_1 and , QMD_0 in place of AMD_1 and AMD_0, respectively.

A similar equation to Equation 2.11, with QMD in place of AMD, is used to predict future QMD in the Matney and Farrar (1992) growth and yield system. Because stand AMD must always be less than the corresponding QMD, some researchers use an AMD prediction equation that is constrained by the corresponding QMD. For example, Russell et al. (2012) modeled AMD as:

$$AMD = QMD - \exp\left(b_0 + b_1 \frac{1}{A}\right) \qquad [2.15]$$

where, A is current stand age, and b_0, b_1 are parameters.

Prediction of number of trees surviving in a stand

As a stand grows, some of the trees die due to various reasons such as competition for resources (e.g. nutrients, water, and light) and due to natural disturbances such as fire, wind, snow or fungal pathogens. Mortality due to competition is described as regular mortality and that due to natural disturbances is described as irregular mortality (Vanclay 1995). Forest growth and yield modeling systems typically focus on regular mortality (Monserud and Sterba 1999). Various methods of predicting the number of trees that will be surviving in a stand at a given time have been developed. The difference equation approach, which is based on the integral of the proportional instantaneous mortality rate as demonstrated by Clutter et al. (1983), has been widely used in stand level models (Pienaar et al. 1990; Amateis et al. 1997; Coble 2009). To improve the behavior of difference equation mortality models, which predict some mortality even for time intervals when no mortality is expected, Woollons (1998) proposed an approach in which the mortality predicted by the difference equation model is scaled by the probability of mortality occurring during the prediction interval in question. A few mortality models that apply this approach have been developed for forest stands in the southern United States (Zhao et al. 2007; Thapa and Burkhart 2015). Survival analysis approaches that model mortality using Poisson mixture models have also been applied to forest stands in the southern United States. Rose et al. (2004) developed a whole stand mortality model, based on survival analysis hazard functions, for loblolly pine in

Georgia. Affleck (2006), using loblolly pine data from Virginia and North Carolina, demonstrated the use of Poisson, negative binomial, and generalized Poisson models in modeling stand level mortality.

Use of location variables in forest growth and survival models

Growth and survival of trees in stands that are the same in all aspects except location may differ. For example Hasenauer et al. (1994) found that per acre volume of loblolly pine of a given site index, in the Atlantic Coastal plain of southern United States, was different from that of a similar stand in the Gulf Coastal plain. Such differences may be accounted for by including variables for location in growth or mortality models. There are several growth and survival models where location variables are used. For example, Amateis et al. (2006) used dummy variables for physiographic region in equations for predicting site index and basal area of loblolly plantations. Likewise, Bravo-Oviedo et al. (2008) developed a height growth model that included dummy variables for soil type. In a study on loblolly pine diameter distribution, Russell et al. (2012) included latitude and longitude information in equations for predicting quadratic mean dbh and arithmetic mean dbh. Similarly, Thapa and Burkhart (2015) developed a mortality model for loblolly pine that included dummy variables for climate and soil characteristics. Another example can be seen in the publication by Zhao et al. (2007) where separate survival equations for second–rotation loblolly pine plantations were developed for the piedmont/upper Atlantic coastal plain and for the lower Atlantic coastal plain.

CHAPTER III

METHODS

Study area and data

The models that were developed in this study will be applicable to loblolly pine plantations in the mid-Gulf region of southern United States. The region encompasses the States of Alabama, Mississippi, Louisiana, and Arkansas. The models were developed from data that were collected from 115 non-intensively managed loblolly pine plantation stands in this region (see map in Figure 1) between 1981 and 1989. These stands were considered to be non-intensively managed because site preparation was limited, genetically improved planting stock was not used, hardwood competition was not controlled, and fertilizer was not applied. Data from 59 of the stands were collected from permanent measurement plots that were installed and managed by the Forest Modeling Research Cooperative (FMRC) at Virginia Tech. Data from the rest of the stands were collected from permanent measurement plots that were installed and managed by the Mississippi State University Loblolly Pine Growth and Yield Cooperative (MSU Lob Coop).

The 59 FMRC stands were 8 to 25 years old at the time of installation and were re-measured at 3-years intervals after installation. Each of the 59 locations had three 0.1 to 0.25-acre treatment plots: an un-thinned plot, a lightly thinned (25% of basal area removed) plot, and a heavily thinned (50% of basal area removed) plot. Thinning was done at the time of plot establishment in stands that were 8 years of age or older and had never been thinned before. Data collected included each tree's dbh, total height, and crown class in addition to information on plot location characteristics. The 56 MSU Lob Coop stands were 4 to 31 years old at the time of installation and 7 to 34 years old at the time of second or third measurement. A minimum of two and a maximum of four measurement plots, ranging between 0.1-0.25-acre, were installed per stand. Some of the stands had one of the plots thinned. Measurements were taken at plot establishment and then after 3 years for one to two re-measurements. The same type of tree and plot data were collected on these plots as was collected in the FMRC plots.

The 115 stands contained a total of 377 measurement plots that ranged in age between 4 and 34 years. Summary information on mensurational characteristics of these stands is given in Table 1. Site index, QMD, AMD, DMIN, and number of trees per acre (TPA) were calculated for each plot. Data were then randomly split into two equal datasets – Dataset 1 and Dataset 2 – that were both used for model fitting and model validation. For example, if Dataset 1 was used as the model fitting dataset then Dataset 2 was used as the model validation dataset and vice versa. Model evaluation was done by two-fold cross-validation techniques. The best models were re-fitted to the combined Dataset 1 and Dataset 2 data to estimates a final set of parameters for equation application purposes.

Table 3.1 Summary statistics for some of the mensurational attributes of the stands used in the study

Stand Attribute	Minimum	Median	Maximum
Site index at base age 25 years (ft)	36.5	60.7	84.6
Basal area (ft^2/acre)	18.9	96.9	193.5
Hardwood composition (percent of total basal area)	0.0	0.0	51.0
Arithmetic mean diameter (inches)	3.4	7.1	11.6
Quadratic mean diameter (inches)	3.6	7.3	11.8
Minimum diameter (inches)	0.7	4	7.8
Maximum diameter (inches)	2.3	9.2	22.1
Number of surviving trees/acre	44	303	1187
Age	4	17	34

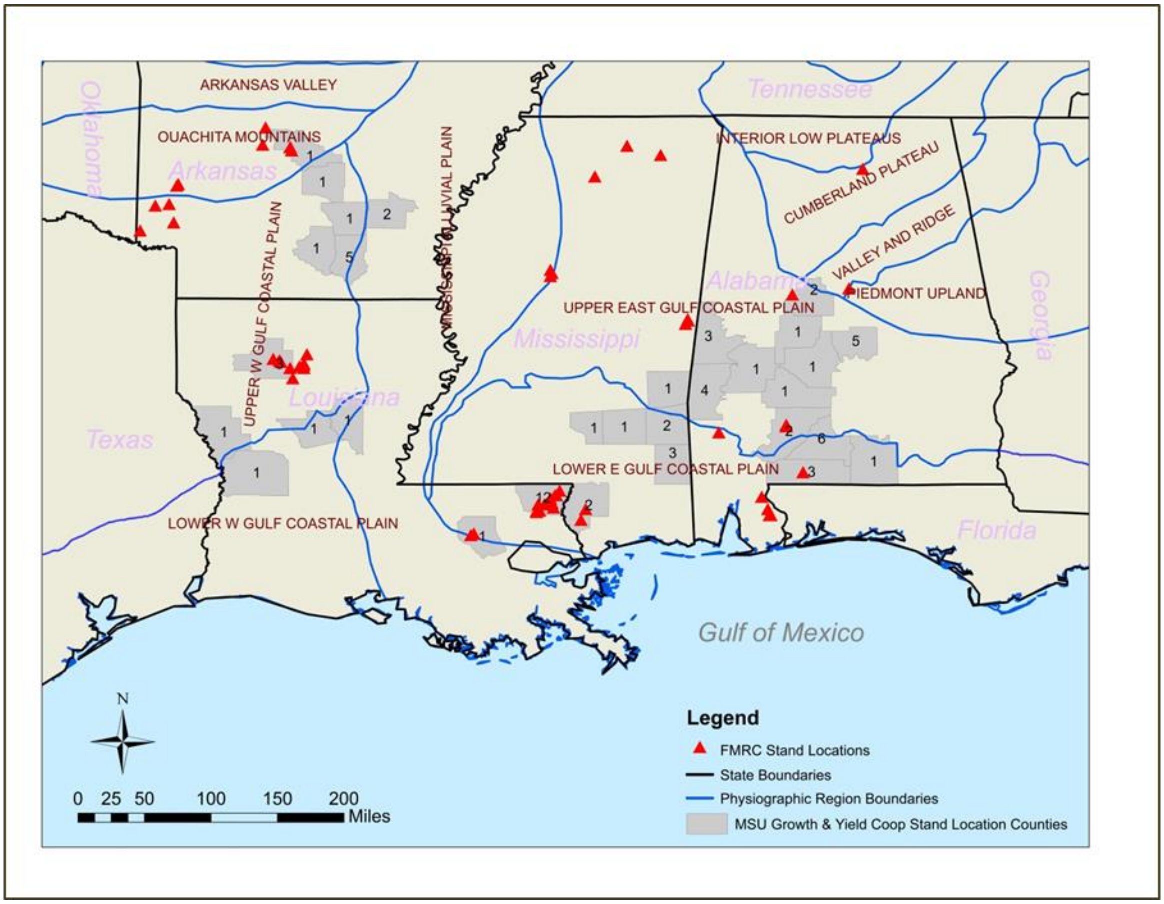

Figure 3.1 Locations of the 115 stands from which data used in the current study were obtained.

The red triangles indicate locations of the 59 stands measured by FMRC. The gray zones are the county locations of the 56 stands measured by MSU Loblolly Pine Growth and Yield Cooperative. The names of the physiographic regions are indicated within each region.

Data Analysis

Models investigated in the current study were fitted by nonlinear regression analysis using R® (R Core Team 2014) and SAS (SAS Institute Inc. 2002 - 2004) software. Model forms adopted were mostly those from the literature. Some of the models were developed in the current study. Effects of physiographic region and hardwood competition on diameter growth and number of surviving trees were also tested. For predicting number of trees surviving in a stand, separate models were investigated for thinned and for unthinned stands.

Dominant height prediction/site index models

Two approaches of fitting dominant height prediction/site index models, the guide curve approach and the difference equation approach, were investigated. The models were fitted by nonlinear regression analysis using R® software and, the MODEL procedure in SAS® ETS.

Guide curve approach with ADA

The guide curve approach, with algebraic difference approach (ADA), is the traditional method of constructing dominant height prediction/site index equations. In this method, dominant height is predicted as a function of age which results in anamorphic dominant height prediction equations. The following guide curve equations were investigated:

Lundqvist-Korf 1st form

$$Ht = b_0 \times exp\left(b_1 \times \frac{1}{Age}\right) \quad [3.1]$$

Lundqvist-Korf 2nd form

$$Ht = b_0 \times exp\left(b_1 \times \frac{1}{Age^{0.5}}\right) \quad [3.2]$$

Lundqvist-Korf 3rd form

$$Ht = b_0 \times exp\left(b_1 \times \frac{1}{Age^{b_2}}\right) \quad [3.3]$$

Log Logistic

$$Ht = \frac{b_0}{(1 + b_1 \times Age^{b_2})} \qquad [3.4]$$

Chapman-Richards

$$Ht = b_0 \times \left(1 - exp(b_1 \times Age)\right)^{b_2} \qquad [3.5]$$

In Equations 3.1 to 3.5, Ht is dominant height, at a given age Age, and b_1, b_2 are model parameters.

Difference equation method with ADA

In the difference equation approach with ADA, future dominant height is projected as a function of current dominant height, current age, and future age. This approach also results in anamorphic dominant height prediction equations. The following difference equation approaches with ADA, equations were investigated:

Chapman-Richards

$$Ht_1 = Ht_0 \times \left(\frac{(1 - exp(b_1 \times Age_1))}{(1 - exp(b_1 \times Age_0))}\right)^{b_2} \qquad [3.6]$$

Log-Logistic

$$Ht_1 = Ht_0 \times \frac{(1 + b_1 \times Age_0{}^{b_2})}{(1 + b_1 \times Age_1{}^{b_2})} \qquad [3.7]$$

Lundqvist-Korf 2nd form

$$Ht_1 = Ht_0 \times exp\left(b_1 \times \left(\frac{1}{Age_0{}^{0.5}} - \frac{1}{Age_1{}^{0.5}}\right)\right) \qquad [3.8]$$

Lundqvist-Korf 3rd form

$$Ht_1 = Ht_0 \times exp\left(b_1 \times \left(\frac{1}{Age_1{}^{b_2}} - \frac{1}{Age_0{}^{b_2}}\right)\right) \qquad [3.9]$$

In Equations 3.6 to 3.9, Ht_1 is future dominant height, $Ht_0$is current dominant height, Age_0 is current stand age, Age_1 is future stand age and b_1, b_2 are model parameters.

Difference equation approach with GADA

The difference form of GADA (Equations 3.10 and 3.11) were used as the polymorphic multiple asymptote dominant height prediction models in the current study. The difference equation models investigated were:

Chapman-Richards polymorphic multiple asymptotes GADA model

$$Ht_1 = Ht_0 \left(\frac{1-exp(-b_1 A_1)}{1-exp(-b_1 A_0)}\right)^{\frac{b_2}{X_0}} \qquad [3.10]$$

where $X_0 = 0.5(ln(Ht_0) + \sqrt{(ln(Ht_0)^2 - 4b_2 L_0)}$

with $L_0 = ln(1 - exp(-b_1 A_0))$

and

Log logistic polymorphic multiple asymptotes GADA model

$$Ht_1 = Ht_0 \frac{\left(1+\left(\frac{b_1}{X_0}\right)\times {A_0}^{b_2}\right)}{\left(1+\left(\frac{b_1}{X_0}\right)\times {A_1}^{b_2}\right)} \qquad [3.11]$$

where $X_0 = 0.5\left(Ht_0 + \sqrt{(Ht_0)^2 + 4b_1 Ht_0 {A_0}^{b_2}}\right)$

In Equations 3.10 and 3.11, Ht_1 is future dominant height at time A_1, Ht_0 is the dominant height at time A_0, and b_1, b_2 are parameters. The difference equation model forms in Equations 3.10 and 3.11 were previously used by Wang et al. (2007).

Diameter prediction/projection models

The following AMD and QMD prediction equations were adopted from the literature and modified to include the effects of physiographic region and hardwood competition:

$$AMD = b_0(TPA)^{b_1} \times exp(b_2 \times (Ht^{-0.5}) + b_3Age + b_4\%HW) \quad [3.12]$$

$$AMD = (b_{00} + b_{01} \times X_1 + b_{02} \times X_2)(TPA)^{b_1} \times exp(b_2 \times (Ht^{-0.5}) + b_3Age) \quad [3.13]$$

$$AMD = (b_{00} + b_{01} \times X_1 + b_{02} \times X_2)(TPA)^{b_1} \times exp(b_2 \times (Ht^{-0.5}) + b_3Age + b_4\%HW) \quad [3.14]$$

$$AMD = b_0(Ht)^{b_1}\ TPA^{b_2}\ exp\left(\frac{b_3}{Age}\right) + b_3\%HW \quad [3.15]$$

$$AMD = (b_{00} + b_{01} \times X_1 + b_{02} \times X_2)(Ht)^{b_1}\ (TPA)^{b_2} \times exp\left(\frac{b_3}{Age}\right) \quad [3.16]$$

$$AMD = (b_{00} + b_{01} \times X_1 + b_{02} \times X_2)(Ht)^{b_1}\ (TPA)^{b_2} \times exp\left(\frac{b_3}{Age}\right) + b_4\%HW \quad [3.17]$$

$$AMD = exp[b_0 + b_1RS + b_2\,ln(TPA) + b_3\,ln(Ht) + \frac{b_4}{Age} + b_5\%HW] \quad [3.18]$$

$$AMD = exp[(b_{00} + b_{01} \times X_1 + b_{02} \times X_2) + b_1RS + b_2\,ln(TPA) + b_3\,ln(Ht) + \frac{b_4}{Age} \quad [3.19]$$

$$AMD = exp[(b_{00} + b_{01} \times X_1 + b_{02} \times X_2) + b_1RS + b_2\,ln(TPA) + b_3\,ln(Ht) + \frac{b_4}{Age} + b_5\%HW] \quad [3.20]$$

In Equations 3.12 to 3.20, AMD is stand arithmetic mean diameter, *RS* is relative spacing, *TPA* is number of trees per acre, *Ht* is dominant height, X_1 is a dummy variable whose value is 1 for the lower coastal plain and zero otherwise, X_2 is a dummy variable whose value is 1 for the upper coastal plain and zero otherwise, $\%HW$ is the % hardwood proportion of the stand, Age is the current stand age, and the $b_{00}, b_{01}, b_{02}, b_1, b_2, b_3, b_4, b_5$ are the model parameters. Equations 3.12 to 3.14 were adopted from on Matney and Farrar (1992), Equations 3.15 to 3.17 were adopted from Baldwin and Feduccia (1987), and Equations 3.18 to 3.20 were adopted from Cao (2004). The QMD prediction equations were exactly the same form as the AMD prediction equations 3.12 to 3.20 with QMD in place of AMD, respectively. The predicted diameter growth Equations 2.11, 2.12, and 2.13 were also investigated.

Likewise, the projected diameter growth Equations 2.14 and 2.15 were investigated.

The following AMD and QMD projection models, adopted with modifications from Matney and Farrar (1992), were investigated:

$$AMD_1 = AMD_0\left[1 + (Age_1 - Age_0)exp\left[(b_{00} + b_{01} \times X_1 + b_{02} \times X_2) - b_1 Age_0 - b_2\left(\frac{Ht_0}{Age_0}\right) + \frac{b_3}{Age_0} - \frac{b_4}{\sqrt{Age_0}}\right]\right] \quad [3.21]$$

$$AMD_1 = AMD_0\left[1 + (Age_1 - Age_0)exp\left[b_0 - b_1 Age_0 - b_2\left(\frac{Ht_0}{Age_0}\right) + \frac{b_3}{Age_0} + b_4\%HW\right]\right] \quad [3.22]$$

$$AMD_1 = AMD_0\left[1 + (Age_1 - Age_0)exp\left[(b_{00} + b_{01} \times X_1 + b_{02} \times X_2) - b_1 Age_0 - b_2\left(\frac{Ht_0}{Age_0}\right) + \frac{b_3}{Age_0} - \frac{b_4}{\sqrt{Age_0}} + b_4\%HW\right]\right] \quad [3.23]$$

Equations 3.21 to 3.23, AMD_1 is the future stand arithmetic mean diameter, AMD_0 is the current stand arithmetic mean diameter, Ht_0 is the initial dominant height, Age_0 is the initial stand age, Age_1 is the future stand age is dominant height, X_1 is a dummy variable whose value was 1 for lower coastal plain and zero otherwise, X_2 is a dummy variable whose value was 1 for upper coastal plain and zero otherwise, $\%HW$ is the % hardwood proportion of the stand, and the b_{00}, b_{01}, b_{02}, b_1, b_2, b_3, b_4, b_5 are model parameters. The same AMD projection Equations [3.21-3.23] were also used to project QMD by substituting AMD_1, AMD_0 with $QMD_1$and QMD_0, respectively.

The following equations for predicting DMIN progression in a stand, were investigated:

$$DMIN = b_0(AMD)^{b_1} \quad [3.24]$$

$$DMIN = b_0(QMD)^{b_1} \quad [3.25]$$

$$DMIN = \exp(b_0 + b_1 AMD) \quad [3.26]$$

$$DMIN_1 = DMIN_0 \times (1 + (Age_1 - Age_0) \times AMD^{b_1}) \quad [3.27]$$

In Equations 3.24 to 3.26, $DMIN$ is stand minimum dbh, AMD is the stand's arithmetic mean diameter, QMD is the stand's quadratic mean diameter, and b_0, b_1 are model parameters. In Equation 3.27, $DMIN_1$ is the future minimum tree dbh, $DMIN_0$ is the current minimum tree dbh, Age_1 is the future stand age, Age_0 is the current stand age, and b_1 is a parameter. Equations 3.24 and 3.25 were adopted from Matney and Farrar (1992), Equation 3.26 from Russell et al. (2012), and Equation 3.27 was developed in the current study.

The best AMD, QMD, and DMIN models were fitted simultaneously, as an equation system, by 3-stage least squares procedures, according to the procedure of Borders (1989), using the MODEL SAS® ETS, to provide the final model for predicting stand minimum and average diameters.

Models for predicting number of trees surviving in a stand

Two approaches of modeling tree survival in a stand were investigated. The traditional one-step approach and the two-step approach of Woollons (1998). In the

Woollons (1998) approach, the first part of the survival prediction is an equation for predicting the probability that all trees in the stand will survive. Data from stands that experienced some mortality during the three year re-measurement interval, and those from stands that did not experience mortality, were used in this part of model development. The model was fitted by logistic regression using the LOGISTIC procedure in SAS® STAT software. Selection of significant variables was done in the logistic regression procedure by the STEPWISE SELECTION method in SAS® software.

$$p(x) = \frac{exp(b_0+b_1Age+b_2SI+b_3N_0+b_4\%HW+b_5X_1+b_6X_2)}{1+exp(b_0+b_1Age+b_2SI+b_3N_0+b_4\%HW+b_5X_1+b_6X_2)} \quad [3.28]$$

where, $p(x)$ is the probability of survival in a given stand over a 3-year period, Age is stand age, $N_0$is number of trees per unit area, SI is site index, $\%HW$ is the % hardwood of the stands, X_1 is a dummy variable whose value was 1 for lower coastal plain and zero otherwise, X_2 is a dummy variable whose value was 1 for upper coastal plain and zero otherwise, and b_0, b_1, b_2, b_3, b_4, b_5, b_6 are model parameters.

The second part of the Woollons (1998) approach is the equation for predicting the future number of trees from the current number of trees. This part of the model was investigated using only the stands that experienced mortality. The following equations, adopted from Thapa and Burkhart (2015), and from Zhao et al. (2007) were evaluated to determine the best equation:

$$N_2 = N_1 exp\left(b_1(A_2 - A_1)\right) \quad [3.29]$$

$$N_2 = N_1 exp\left(b_1\left({A_2}^{b_2} - {A_1}^{b_2}\right)\right) \quad [3.30]$$

$$N_2 = N_1 exp\left(b_1(A_2 - A_1)\right)\left(\frac{A_2}{A_1}\right)^{b_2} \quad [3.31]$$

$$N_2 = N_1 exp\left(b_1\left({b_2}^{A_2} - {b_2}^{A_1}\right)\right) \quad [3.32]$$

$$N_2 = \left[{N_1}^{b_0} + b_1(A_2 - A_1)\right]^{\frac{1}{b_0}} \quad [3.33]$$

$$N_2 = \left[{N_1}^{b_0} + b_1\left({A_2}^{b_2} - {A_1}^{b_2}\right)\right]^{\frac{1}{b_0}} \quad [3.34]$$

$$N_2 = \left[{N_1}^{b_0} + b_1(A_2 - A_1) + b_2 \mathrm{In}\left(\frac{A_2}{A_1}\right)\right]^{\frac{1}{b_0}} \quad [3.35]$$

$$N_2 = \left[{N_1}^{b_0} + b_1\left({b_2}^{A_2} - {b_2}^{A_1}\right)\right]^{\frac{1}{b_0}} \quad [3.36]$$

$$N_2 = N_1 exp(b_0 + b_1 SI)(A_2 - A_1) \quad [3.37]$$

$$N_2 = N_1 exp\left(b_1 SI^{b_2}(A_2 - A_1)\right) \quad [3.38]$$

$$N_2 = N_1 exp\left(b_1\left(\frac{SI}{10000}\right)^{b_2}\right)\left({A_2}^{b_3} - {A_1}^{b_3}\right) \quad [3.39]$$

$$N_2 = N_1 exp\left(b_1 SI^{b_2}\left({b_3}^{A_2} - {b_3}^{A_1}\right)\right) \quad [3.40]$$

$$N_2 = \left[{N_1}^{b_0} + b_1 SI^{b_2}(A_2 - A_1)\right]^{\frac{1}{b_0}} \quad [3.41]$$

$$N_2 = \left[{N_1}^{b_0} + b_1\left(\frac{SI}{10000}\right)^{b_2}(A_2 - A_1) + b_3 \mathrm{In}\left(\frac{A_2}{A_1}\right)\right]^{\frac{1}{b_0}} \quad [3.42]$$

$$N_2 = \left[{N_1}^{b_0} + b_1\left(\frac{SI}{10000}\right)^{b_2}\left({A_2}^{b_3} - {A_1}^{b_3}\right)\right]^{\frac{1}{b_0}} \quad [3.43]$$

$$N_2 = \left[{N_1}^{b_0} + b_1\left(\frac{SI}{10000}\right)^{b_2}\left({b_3}^{A_2} - {b_3}^{A_1}\right)\right]^{\frac{1}{b_0}} \quad [3.44]$$

In Equations 3.29 to 3.44, A_1 is the current stand age, A_2 is the future stand age, N_1 is the current number of trees per unit area, N_2 is the future number of trees per unit are, *SI* is the site index, and b_0, b_1, b_2, b_3 are model parameters.

The traditional one-step approach was investigated using the annual mortality rate equation of Matney and Farrar (1992). The model form for this equation is

$$M = b_0 N_1 \left[\frac{(Ht_1)}{A_1}\right]^{\frac{2}{3}} \qquad [3.45]$$

where, M is annual mortality of a stand, Ht_1 is the current stand dominant height, N_1 is the current number of trees per unit area, A_1 is the current stand age, and b_0 is a model parameter. The same Equation [3.45] form was used for thinned and unthinned stands. This equation was fitted to all plot data irrespective of whether the plot experienced mortality during the period between measurements.

Model Fitting and Model Evaluation

Fitted models were evaluated using prediction root mean square error ($RMSE_p$) which was computed as

$$RMSE_p = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)}{n-p}} \qquad [3.46]$$

where $RMSE_p$ is prediction root mean square error, y_i is the observed value of the response variable for the i^{th} plot, $\hat{y}_i$ is the model predicted value for this response variable in the i^{th} plot, n is the number of study plots in the data set, and p is the number of model parameters. Prediction root mean square error was calculated for each cross-validation data. The $RMSE_p$ for the model was obtained by averaging the cross-validation $RMSE_p$ values for Dataset 1 and Dataset 2.

CHAPTER IV

RESULTS AND DISCUSSION

Dominant height prediction/site index models

The $RMSE_p$ values for the dominant height prediction/site index models evaluated are shown in Table.

Table 4.1 Prediction root mean square values for dominant height prediction/site index models.

Model #	Model Name &Type	Cross-validation $RMSE_p$		Average $RMSE_p$(ft)
		Dataset 1	Dataset 2	
3.1	Lundqvist-Korf 1st form GC ADA	3.631	3.394	3.512
3.2	Lundqvist-Korf 2nd form GC ADA	2.314	2.540	2.427*
3.3	Lundqvist-Korf 3rd form GC ADA	2.306	2.551	2.429
3.4	Log-logistic GC ADA	2.322	2.557	2.440
3.5	Chapman-Richards GC ADA	2.328	2.562	2.445
3.8	Lundqvist-Korf 2nd form DE ADA	2.356	2.517	2.436
3.9	Lundqvist-Korf 3rd form DE ADA	2.372	2.517	2.445
3.6	Chapman-Richards DE ADA	2.345	2.526	2.436
3.7	Log-logistic DE ADA	2.349	2.514	2.431
3.10	Chapman-Richards DE GADA	2.214	2.417	2.316*
3.11	Log-logistic DE GADA	2.280	2.392	2.336

Note: GC stands for guide curve and DE stands for difference equation. The ADA models are anamorphic whereas, the GADA models are polymorphic with multiple asymptotes. The * in average $RMSE_p$ column indicates the equation with lowest average $RMSE_p$ and considered the best model

From Table 4.1 it can be can see that the best anamorphic model was the Lundqvist-Korf 2nd form and the best polymorphic multiple asymptotes model was Chapman-Richards difference equation GADA.

Equations 4.1 and 4.2, below resulted from fitting, respectively, the lowest $RMSE_p$ ADA (anamorphic) model (Equation 3.2 in Table 4.1) and the lowest $RMSE_p$ GADA (polymorphic multiple asymptotes) model (Equation 3.10 in Table 4.1) to the combined Dataset 1 and Dataset 2 data:

$$Ht_1 = SI \times exp\left(b_1 \times \left(\frac{1}{{A_0}^{0.5}} - \frac{1}{IAge^{0.5}}\right)\right) \qquad [4.1]$$

$$Ht_1 = Ht_0\left(\frac{1-exp(-b_1A_1)}{1-exp(-b_1A_0)}\right)^{\frac{b_2}{X_0}} \qquad [4.2]$$

where $X_0 = 0.5(ln(Ht_0) + \sqrt{(ln(Ht_0)^2 - 4b_2L_0)}$

with $L_0 = ln(1 - exp(-b_1A_0))$

In Equation 4.1 and 4.2, Ht_1 is the dominant height at age A_1 and Ht_0 is the dominant height at the prediction age A_0, SI is site index, *IAge* is index age, and b_1, b_2 are models parameter. Equation 4.1 resulted from applying out ADA to the guide curve equation that resulted from Equation 3.2.

The parameter estimates for Equations 4.1 and 4.2, and the corresponding fit statistics, are given in Table 4.2.

Table 4.2 Final Parameter estimates and fit statistics for the best dominant height prediction/site index models for plantation loblolly pine in the mid-Gulf southern US.

Model #	Parameter	Estimates	SEE	p-value	Measure of fit	
					FI	RMSE (ft)
4.2	b_1	0.070	0.003	<2e-16	0.973	2.294
	b_2	6.664	0.183	<2e-16		
4.1	b_1	6.875	0.098	<2e-16	0.854	N/A

Note: SEE is standard error of estimate and FI is fit index

Table 4.2 shows that all the parameter estimates in the model were significantly different at a 5% significance level. Comparing the two models in Table 4.2, it can be seen that the polymorphic multiple asymptotes model was the better one (according to the results in Table 4.1). This means that height growth curves in loblolly pine stands in the mid-Gulf region have different shapes with multiple asymptotes.

Diameter prediction/projection models

The $RMSE_p$ values for the diameter prediction models evaluated are shown in Tables 4.3, 4.4 and 4.5

Table 4.3 Prediction root mean square error for the AMD prediction equations evaluated.

	Cross-validation $RMSE_p$		
Model #	Data set 1	Dataset 2	Average $RMSE_p$ (inches)
2.11	0.589	0.476	0.532
2.12	0.635	0.55	0.592
2.13	0.603	0.519	0.561
3.12	0.59	0.459	0.524
3.13	0.564	0.465	0.515
3.14	0.553	0.433	0.493*
3.15	0.635	0.532	0.583
3.16	0.854	0.554	0.704
3.17	0.704	0.527	0.615
3.18	0.602	0.504	0.553
3.19	0.590	0.514	0.552
3.20	0.577	0.486	0.531

Note: The * values in the average $RMSE_p$ column indicate the models with the lowest average $RMSE_p$ which is considered the best model

Table 4.4 Prediction root mean square error for the QMD prediction equations evaluated.

Model #	Cross-validation $RMSE_p$ Data set 1	Dataset 2	Average $RMSE_p$ (inches)
2.11	0.580	0.457	0.518
2.12	0.621	0.521	0.570
2.13	0.591	0.494	0.542
3.12	0.582	0.450	0.516
3.13	0.547	0.440	0.493
3.14	0.541	0.413	0.477*
3.15	0.623	0.513	0.568
3.16	0.774	0.520	0.647
3.17	0.597	0.502	0.550
3.18	0.591	0.489	0.540
3.19	0.569	0.484	0.527
3.20	0.561	0.466	0.513

Note: The * values in the average $RMSE_p$ column indicate the models with the lowest average $RMSE_p$ which is considered the best model.

Table 4.5 Prediction root mean square error for the DMIN prediction equations evaluated.

Model	Cross-validation $RMSE_p$ Dataset1	Dataset 2	Average $RMSE_p$ (inches)
3.24	0.827	0.862	0.844*
3.25	0.857	0.914	0.886
3.26	0.870	0.917	0.894

Note: The * values in the average $RMSE_p$ column indicate the models with the lowest average $RMSE_p$ which is considered the best model.

Equation 3.14 was found to be the best equation for AMD and QMD prediction. This equation included physiographic region and percent hardwood composition of a stand which indicates that these factors affected diameter growth in the stands. Similarly, Equation 3.24 was identified as the best equation for DMIN prediction.

The AMD, QMD and DMIN prediction equations that resulted from fitting the best models from Tables 4 to 6 to the combined Dataset 1 and Dataset 2 data, using 3-stage least squares regression, were:

$$QMD = (103.869 - 11.401X_1 - 6.978X_2)N^{-0.194}exp\left[\frac{-9.329}{\sqrt{Hd}} - 0.00478\,Age - 0.00222\%HW\right] \quad [4.3]$$

Fit Index = 0.94, **standard error of estimate** = 0.45 inches

$$AMD = QMD - exp\left(-1.452 - 0.906 \times \frac{\log(N)}{Age}\right) \quad [4.4]$$

Fit Index = 0.99, **standard error of estimate** = 0.07 inches

$$DMIN = 0.1662\ (AMD)^{0.0297} \qquad [4.5]$$

Fit Index = 0.75, **standard error of estimate** = 0.75 inches

In Equations 4.3 to 4.5, QMD is the stand QMD, AMD is the stand AMD, $DMIN$ is the stand DMIN, *N* is a number of trees per acre, X_1 is a dummy variable whose value is 1 for lower coastal plain and zero otherwise, X_2 is a dummy variable whose value is 1 for upper coastal plain and zero otherwise, *Hd* is the stand dominant height, $\%HW$ is the percentage of basal area that is hardwood, and Age is the current stand age. According to the dummy variable parameter estimates in Equation 4.3, the diameter growth in lower coastal plain is lower than that in the upper coastal plain. The equation also shows that increased percent hardwood has the negative effect on the diameter growth, as has been observed in loblolly pine stands (Burkhart and Sprinz 1984; Knowe 1992).

Diameter projection model

The $RMSE_p$ values for the diameter projection models evaluated are shown in Table 4.6.

Table 4.6 Prediction root mean square error for the AMD and QMD projection equations evaluated.

Model#	Cross-validation $RMSE_p$ Dataset 1	Dataset 2	Average $RMSE_p$ (inches)
2.14 for AMD	0.348	0.379	0.364*
2.14 for QMD	0.329	0.357	0.343*
3.22 for AMD	0.349	0.386	0.368
3.22 for QMD	0.33	0.364	0.347
3.21 for AMD	0.322	1.0451	0.683
3.21 for QMD	0.741	0.352	0.546
3.23 for AMD	0.621	0.387	0.504
3.23 for QMD	0.738	0.447	0.592

Note: The * value in average $RMSE_p$ column indicate the models with the lowest average $RMSE_p$, and considered the best QMD/AMD models.

From Table 4.6 it can be seen that model 2.14 was the best model for AMD and QMD projection. The AMD, QMD and DMIN projection equations that resulted from fitting the best models from Tables 4.6, and the DMIN projection model Equation 3.27, to the combined Dataset 1 and Dataset 2 data, using 3-stage least squares regression, were:

$$QMD_1 = QMD_0 \left[1 + (Age_1 - Age_0)exp\left[-2.071 - 0.0473Age_0 - 0.450\left(\frac{Hd_0}{Age_0}\right) + \frac{11.667}{Age_0}\right]\right] \quad [4.6]$$

Fit Index = 0.96, **standard error of estimate** = 0.32 inches

$$AMD_1 = AMD_0 \left[1 + (Age_1 - Age_0)exp\left[-2.113 - 0.0446Age_0 - 0.4618\left(\frac{Hd_0}{Age_0}\right) + \frac{12.131}{Age_0}\right]\right] \quad [4.7]$$

Fit Index = 0.96, **standard error of estimate =** 0.34 inches

$$DMIN_1 = DMIN_0 \times (1 + (Age_1 - Age_0) \times AMD_0)^{-1.5981} \quad [4.8]$$

Fit Index = 0.68, **standard error of estimate** = 0.83 inches

In Equations 4.6 to 4.8, AMD_0 is the initial AMD, QMD_0 is the initial QMD, QMD_1 is the future stand QMD, AMD_1 is the future stand AMD, Hd_0 is the initial dominant height, Age_0 is the initial stand age, Age_1 is the future stand age, $DMIN_1$ is the future DMIN, and $DMIN_0$ is the current DMIN.

Predicting number of trees surviving in a stand

The models adopted for the 2-step approach of predicting the number of trees surviving in a stand were the probability of the survival model:

$$\hat{p}(Mort) = \left(\frac{\exp(b_0+b_1Age_0+b_2SI+b_3N_0)}{1+\exp(b_0+b_1Age_0+b_2SI+b_3N_0)}\right)^{\frac{1}{3}} \qquad [4.9]$$

and the unadjusted number of trees surviving model Equation 3.31:

$$N_1 = N_0exp\big(b_1(A_2 - A_1)\big)\left(\frac{A_2}{A_1}\right)^{b_2}$$

In these equations $\hat{p}(\text{Mortality})$ is the probability of mortality over a one-year period for a stand that is Age_0 years old, whose base-age-25 site index is SI, and containing N_0 number of trees per acre; N_1 is the number of trees per acre that are expected to be surviving in the stand at age A_1, before accounting for the probability of mortality in the stand and b_0, b_1, b_2, b_3 are model parameters. With the two equations, the number of surviving trees at age A_1, in a stand containing N_0 trees per acre at age A_0, is computed as:

$$N_{adj} = N_0 - p(Mort)^{(A_1-A_0)}(N_0 - N_1) \qquad [4.10]$$

A comparison of the 2-step survival prediction approach using Equations 4.9, 3.31, and 4.10 to the 1-step survival prediction approach using Equation 3.45, is given in Table 4.7.

Table 4.7 Prediction root mean square error for the stand survival equations investigated

Prediction Approach	Stand type	Cross-validation $RMSE_p$ Dataset1	Dataset 2	Average $RMSE_p$ (TPA /3-year period)
2-step with				
Equations	unthinned	29.32	62.20	45.76*
4.9, 3.31, and 4.10	thinned	61.25	53.81	57.53
1 step with	unthinned	31.69	63.97	47.83
Equation 3.45	thinned	42.97	46.33	44.65*

Note: The * in average $RMSE_p$ column indicates the model with the lowest average $RMSE_p$ and considered the best survival prediction approach.

According to the results in Table 4.7, the two-step survival prediction approach proposed by Woollons (1998) worked better for unthinned stands than the traditional one-step approach. For thinned stands the traditional one-step approach performed better one. The parameter estimates resulting from fitting the 2-step approach Equations 4.9 and 3.31 to the combined Dataset 1 and Dataset 2 from unthinned stands are given in Table 4.8.

Table 4.8 Final parameter estimates for the best 2-step survival model for plantation loblolly pine in the mid-Gulf southern US.

Model#	Parameter	Estimate	Standard error	P-value
4.9	b_0	-11.269	1.223	<.0001
	b_1	0.214	0.026	<.0001
	b_2	0.075	0.014	<.0001
	b_3	0.009	.0009	<.0001
3.31	b_1	-0.068	0.008	<.0001
	b_2	0.641	0.106	<.0001

The parameter estimates in the model were significantly different from zero at 95% confidence level (α= 0.05).

The parameter estimates resulting from fitting the 1-step approach Equation 3.45 to the combined Dataset 1 and Dataset 2 from thinned stands are given in Table 4.9.

Table 4.9 Final parameter estimates for the best 1-step survival model for plantation loblolly pine in the mid-Gulf southern US.

Model#	Parameter	Estimate	Standard error	t- value	Pr(>|t|)
3.45	b_0	0.007	0.001	7.072	<.0001

The parameter estimates in the model were significantly different at 5% significance level (α= 0.05).

Generally, the mortality rate was higher in unthinned stands than in thinned stands. Thus, the results in Table 4.7 imply that if a stand has a higher mortality rate, the 2-step approach would perform better. But if a stand has a low mortality rate, the 2-step approach may not be necessary.

CHAPTER V

CONCLUSIONS AND FUTURE WORK

Equations for predicting stand level height, diameter, and survival were developed for cutover site stands of loblolly pine in the mid-Gulf region. Additional data were used to estimate the parameters and so the models should work better over a larger area than the previously developed model. The parameter estimates in the equations exhibited logical model behavior and were all significant at α= 0.05 significance level. The developed equations should be reliable for predicting dominant height, diameter and survival for non-intensively managed loblolly pine stands in the mid-Gulf region of southern United States. In future, the system level performance of these equations will be tested after which the equations will be incorporated into the Cutover Sites Loblolly Pine (CoLob) growth and yield simulator developed and maintained by the Mississippi Forest and Wildlife Research Center.

The dominant height prediction equations developed using contemporary modeling approaches produced slightly more accurate predictions than those developed using older methods. The practical significance of this improvement will be investigated when the models get incorporated into a growth and yield system.

The findings regarding the 2-step survival prediction approach proposed by Woollons (1998) was mixed. The approach predicted survival in unthinned stands better than the traditional one-step approach but was less accurate for thinned stands. Future research is needed to determine whether the 2-step approach only performs better under certain stand conditions.

LITERATURE CITED

Affleck, D.L. 2006. Poisson mixture models for regression analysisof stand-level mortality. Canadian journal of forest research 36(11):2994-3006.

Amateis, R.L., H.E. Burkhart, H.L. Allen, and C. Montes. 2001. FASTLOB (A stand-level growth and yield model for fertilized and thinned loblolly pine plantations). Department of Forestry, Virginia Tech, Blacksburg, VA. 27 p.

Amateis, R.L., H.E. Burkhart, and J. Liu. 1997. Modeling survival in juvenile and mature loblolly pine plantations. Forest ecology and management 90(1):51-58.

Amateis, R.L., S.P. Prisley, H.E. Burkhart, and J. Liu. 2006. The effect of physiographic region and geographic locale on predicting the dominant height and basal area of loblolly pine plantations. Southern Journal of Applied Forestry 30(3):147-153.

Bailey, R.L., and J.L. Clutter. 1974. Base-age invariant polymorphic site curves. Forest Science 20(2):155-159.

Baldwin, V.C., and D.P. Feduccia. 1987. Loblolly pine growth and yield prediction for managed west gulf plantations. USDA Forest Service. Research Paper. SO-236. 27 p.

Borders, B.E. 1989. Systems of equations in forest stand modeling. Forest Science 35(2):548-556.

Bravo-Oviedo, A., M. Tome, F. Bravo, G. Montero, and M. Del Rio. 2008. Dominant height growth equations including site attributes in the generalized algebraic difference approach. Canadian journal of forest research 38(9):2348-2358.

Burkhart, H.E., R.L. Amateis, J.A. Westfall, and R.F. Daniels. 2008. PTAEDA4.0: Simulation of Individual Tree Growth, Stand Development, and Economic Evaluation in Loblolly Pine Plantations. Department of Forestry, Virginia Tech, Blacksburg, VA. 23 p.

Burkhart, H.E., and P.T. Sprinz. 1984. A model for assessing hardwood competition effects on yields of loblolly pine plantations. School of Forestry and Wildlife Resources, Virginia Tech, Blacksburg, Virginia. Publication No. FWS-3-84. 55 p.

Cao, Q.V. 2004. Predicting parameters of a Weibull function for modeling diameter distribution. Forest science 50(5):682-685.

Cao, Q.V., H.E. Burkhart, and R. Lemin Jr. 1982. Diameter distributions and yields of thinned loblolly pine plantations. FWS-Virginia Polytechnic Institute and State University, School of Forestry and Wildlife Resources (USA).

Cieszewski, J., and L. Bailey. 2000. Generalized algebraic difference approach: theory based derivation of dynamic site equations with polymorphism and variable asymptotes. Forest Science 46(1):116-126.

Clutter, J.L., J.C. Fortson, L.V. Pienaar, G.H. Brister, and R.L. Bailey. 1983. Timber management: a quantitative approach. John Wiley & Sons, Inc., New York, NY. 3333 p.

Coble, D.W. 2009. A new whole-stand model for unmanaged loblolly and slash pine plantations in east Texas. Southern Journal of Applied Forestry 33(2):69-76.

Dahal, R.P., I.A. Munn, and J.E. Henderson. 2013. Forestry in Mississippi: the impact of the industry on the Mississippi economy—an input-output analysis. Mississippi State University, Forest and Wildlife Research Center. Res. Bull. FO 438. 22 p.

Diéguez-Aranda, U., H.E. Burkhart, and R.L. Amateis. 2006. Dynamic site model for loblolly pine (Pinus taeda L.) plantations in the United States. Forest Science 52(3):262-272.

Diéguez-Aranda, U., F. Castedo-Dorado, J.G. Álvarez-González, and R. Rodríguez-Soalleiro. 2005. Modelling mortality of Scots pine (Pinus sylvestris L.) plantations in the northwest of Spain. European Journal of Forest Research 124(2):143-153.

Glass, P. 2013. State of Mississippi southwest district forest inventory. Mississippi Institute for Forest Inventory, Jackson MS. 20 p.

Hasenauer, H., H.E. Burkhart, and H. Sterba. 1994. Variation in potential volume yield of loblolly pine plantations. For. Sci. 40(1):162-176.

Keyser, C. 2008. Southern (SN) variant overview—Forest Vegetation Simulator. USDA For. Serv., Internal Rep., Forest Management Service Center, Fort Collins, CO.

Knowe, S.A. 1992. Basal area and diameter distribution models for loblolly pine plantations with hardwood competition in the Piedmont and Upper Coastal Plain. South. J. Appl. For. 16(2):93-98.

Lauer, D.K., and J.S. Kush. 2010. Dynamic site index equation for thinned stands of even-aged natural longleaf pine. Southern Journal of Applied Forestry 34(1):28-37.

Matney, T.G., and R.M. Farrar. 1992. A thinned/unthinned loblolly pine growth and yield simulator for planted cutover site-prepared land in the Mid-Gulf South. Southern Journal of Applied Forestry 16(2):70-75.

Monserud, R.A., and H. Sterba. 1999. Modeling individual tree mortality for Austrian forest species. Forest Ecology and Management 113(2):109-123.

Murphy, P.A., and M.G. Shelton. 1996. An individual-tree basal area growth model for loblolly pine stands. Canadian journal of forest research 26(2):327-331.

Oswalt, S.N., and J. Bentley. 2011. Mississippi, 2010 Forest Inventory and Analysis Factsheet. USDA Forest Service Southern Research Station. e-Science Update. SRS-037. 4 p.

Pienaar, L.V., H.H. Page, and J.W. Rheney. 1990. Yield prediction for mechanically site-prepared slash pine plantations. Southern Journal of Applied Forestry 14(3):104-109.

R Core Team. 2014. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Rose, J., E. Charles, M.L. Clutter, B.D. Shiver, D.B. Hall, and B. Borders. 2004. A generalized methodology for developing whole-stand survival models. Forest Science 50(5):686-695.

Russell, M.B., H.E. Burkhart, R.L. Amateis, and S.P. Prisley. 2012. Regional locale and its influence on the prediction of loblolly pine diameter distributions. Southern Journal of Applied Forestry 36(4):198-203.

SAS Institute Inc. 2002 - 2004. SAS 9.4 Help and Documentation. SAS Institute Inc., Cary, NC.

Sullivan, A.D., and J.L. Clutter. 1972. A simultaneous growth and yield model for loblolly pine. Forest Science 18(1):76-86.

Thapa, R., and H.E. Burkhart. 2015. Modeling stand-level mortality of loblolly pine (Pinus taeda L.) using stand, climate, and soil variables. Forest Science 61(5):834-846.

USDA Forest Service. 2013. Forest Inventory Data Online: Forest Carbon Estimation.

Vanclay, J.K. 1995. Synthesis: Growth models for tropical forests: A synthesis of models and methods. Forest Science 41(1):7-42.

Wang, M.L., B. Borders, and D.H. Zhao. 2007. Parameter estimation of base-age invariant site index models: which data structure to use? For. Sci. 53(5):541-551.

Wear, D.N., and J.G. Greis. 2002. Southern Forest Resource Assessment. USDA, Forest Service, Southern Research Station. Gen. Tech. Rep. . SRS-53. 635 p.

Woollons, R. 1998. Even-aged stand mortality estimation through a two-step regression process. Forest Ecology and Management 105(1):189-195.

Zarnoch, S.J., D.P. Feduccia, V.C.J. Baldwin, and T.R. Dell. 1991. Growth and Yield Predictions for Thinned and Unthinned Slash Pine Plantations on Cutover Sites in the West Gulf Region.

Zeide, B., and Y. Zhang. 2000. Diameter variability in loblolly pine plantations. Forest ecology and management 128(3):139-143.

Zhao, D., B. Borders, M. Wang, and M. Kane. 2007. Modeling mortality of second-rotation loblolly pine plantations in the Piedmont/Upper Coastal Plain and Lower Coastal Plain of the southern United States. Forest Ecology and Management 252(1-3):132-143.