Determination of Fertility Rating (FR) in the 3-PG Model for Loblolly Pine (*Pinus taeda* L.) Plantations in the Southeastern United States

Santosh Subedi

Dissertation submitted to the Faculty of the

Virginia Polytechnic Institute and State University

in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

in

Forestry

Thomas R. Fox, Chair

Randolph H. Wynne

Harold E. Burkhart

Brian D. Strahm

April 9, 2015

Blacksburg, Virginia

Keywords: Process-based models, Soil fertility, Soil physical and chemical properties, Partial least square regression, Juvenile fertilization, Midrotation fertilization

Determination of Fertility Rating (FR) in the 3-PG Model for Loblolly Pine (*Pinus taeda* L.) Plantations in the Southeastern United States

Santosh Subedi

(ABSTRACT)

Soil fertility is an important component of forest ecosystem, yet evaluating soil fertility remains one of the least understood aspects of forest science. Phytocentric and geocenctric approaches were used to assess soil fertility in loblolly pine plantations throughout their geographic range in the United States. The model to assess soil fertility using a phytocentric approach was constructed using the relationship between site index and aboveground productivity. Geocentric models used physical and chemical properties of the A-horizon. Soil geocentric models were constructed using two modeling approaches. In the first approach, ordinary least squares methods of multiple regression were used to derive soil fertility estimated from site index using soil physical and chemical properties from the A-horizon. Ordinary least squares methods were found unsuitable due to multicollinearity among the soil variables. In the second approach, a multivariate modeling approach, partial least squares regression, was used to mitigate multicollinearity effects. The best model to quantify soil fertility using soil physical and chemical properties included N, Ca, Mg, C, and sand percentage as the significant predictors. The 3-PG process-based model was evaluated for simulating the response of loblolly pine to changes in soil fertility. Fertility rating (FR) is a parameter in 3-PG that scales soil fertility in the range of 0 to 1. FR values estimated from phytocentric and geocentric approaches were tested against observed production. The 3-PG model prediction of aboveground productivity described 89% percent of the variation in observed aboveground productivity using FR derived from site index and 84% percent of the variation in observed aboveground productivity using FR derived from physical and chemical properties of the A-horizon. A response function to model dynamics of FR (ΔFR) due to one time midrotatoin fertilization of N and P was developed using the Weibull function. The magnitude of ΔFR varied with intensity of N and time since application of fertilizer. The hypothesis that repeated fertilization with N and P eliminate major nutrient deficiency in the southeastern US was tested and a relationship between baseline fertility rating and fertilizer response was developed. An inverse relationship was observed between fertilizer response and baseline FR.

Dedication

To the memory of my grandmother Tili Aryal,

whose role in my life was, and remains, immense.

Acknowledgments

I would like to thank the following personnel for providing me with the inspiration and opportunity to embark on my PhD candidature. I am deeply indebted to my advisor, Dr. Tom Fox, for the guidance and mentorship he provided me. I must also thank my committee members, Dr. Harold Burkhart, Dr. Randy Wynne, and Dr. Brian Strahm for their insightful comments and friendly advice. Special gratitude goes to Dr. Ram Thapa, Dr. Nabin Gyawali, and Shakuntala Sharma.

Within the department of Forest Resources and Environmental Conservation, I thank: Dr. Janaki Alavalapati, Sue Snow, Kathryn Hollandsworth, and many others. I would like to extend my appreciation to the Forest Productivity Cooperative for financial and technical assistance.

Funding for this work was provided in part by the Virginia Agricultural Experiment Station and the McIntire Stennis Program of the National Institute of Food and Agriculture, U.S. Department of Agriculture. I greatly acknowledge the Pine Integrated Network: Education, Mitigation, and Adaptation Project (PINEMAP) which is a Coordinated Agricultural Project funded by the USDA National Institute of Food and Agriculture, Award #2011-68002-30185.

Table of Contents

List of Tables

List of Figures

Chapter 1

Introduction

1.1 Justification

Soil fertility is one the most important, yet least understood aspects of forest ecosystems. Study of soil fertility in forest ecosystems is complicated by the complex relationship between soil properties and stand productivity and immense variability in properties and characteristics of soils within relatively small geographic areas. Furthermore, the deep rooting systems of trees which are capable of exploring soil throughout the soil profile complicates the relationship between soil properties and stand productivity (Landsberg et al., 2003; Dye et al., 2004). Due to these complexities, soil fertility in forest ecosystems is measured by indirect approaches namely phytocentric and geocentric. The phytocentric approach uses tree based metrics to estimate soil fertility, while the geocentric approach uses the physical site characteristics as a relative indicator of soil fertility.

Site quality determines potential productivity of forest ecosystem and site quality to a large extent is a function of the physical, chemical, and biological properties of soil as modified by anthropogenic factors (Augusto et al., 2002). Many traditional growth and yield models and process based models require some quantitative information about site quality/soil fertility to predict growth, yield, and physiological outputs of crop species. Site index is a realized measure of site quality and is widely used in many traditional growth and yield models as a driver of productivity (Burkhart and Tomé, 2012). Similarly, several geocentric approaches using soil physical properties, topographic features,and climatic characteristics have attempted to quantify site quality/soil fertility (Carmean, 1975; Fontes et al., 2003; Hagglund, 1981; Sampson et al., 2008).

Productivity of loblolly pine in the southeastern US is primarily limited by nutrient availability (Fox et al., 2007). Most southeastern loblolly pine systems are deficient in N and P (Allen, 1987; Allen et al., 1990; Albaugh et al., 1998; Sampson and Allen, 1999; Jokela and Martin, 2000; Will et al., 2002; Carlson et al., 2008). Fertilization with N and P alone have shown significant growth response in several stages of stand development. Previous studies on loblolly pine have suggested that soil moisture is not as limiting as nutrients to productivity in the southeastern US. This is probably because the southeastern US receives fairly well distributed rainfall through out the year and annual precipitation exceeds potential evapotranspiration (Samuelson et al., 2008; Albaugh et al., 1998).

The 3-PG model (Physiological Principles Predicting Growth) has been parameterized and tested on many commercially important species throughout the globe (Almeida et al., 2004; Stape et al., 2004; Landsberg et al., 2001; Bryars et al., 2013; Rodŕiguez et al., 2002; Coops et al., 2005). Past results with the 3-PG model have shown that 3-PG can be used to predict productivity with a limited number of input variables and unique parameter sets for each species.

3-PG is a monthly time-step process-based model. It requires 40 species-specific parameters. Additionally, 3-PG requires three sets of input variables: climatic data, stand initialization data, and site-specific data. Climatic data includes monthly averages of maximum temperature, minimum temperature, vapor pressure deficit, and radiation. Stand initialization data consists of initial stocking and initial biomass of seedlings. Site-specific data includes available soil water, soil textural class, and fertility rating. The 3-PG model has four biological sub-models to model C assimilation, C allocation, stand dynamics, and evapotranspiration. Biomass pools and stand density are the primary outputs from 3-PG (Figure 1.1). Fertility rating (FR) is a site-specific variable in 3-PG that describes soil nutrient status on a scale of 0 to 1. FR is an important variable in 3-PG that affects leaf area index and hence absorbed photosynthetically active radiation (APAR), canopy light use efficiency and canopy conductance.

Many approaches have been taken to model FR in 3-PG. Typically FR is used in 3-PG as an adjustable or tunable factor for describing soil nutrient status to fit model results from 3-PG with observed values (Landsberg et al., 2003). Consequently, detecting the proper value of FR is a subjective decision based on the experience of the user. The validity of 3-PG growth predictions would be improved if a quantitative method could be developed to determine FR based on measured input parameters. In this study, both phytocentric and geocentric approaches were used to determine FR on the 3-PG model for loblolly pine in the southeastern US.

Site index is one of the most common measure of site quality because the height growth of dominant trees is less correlated with stocking and highly correlated with productivity (Burkhart and Tomé, 2012). Forest productivity is maximum at locations where trees achieve maximum height (Ryan and Yoder, 1997). The Soil Survey Geographic Database (SSURGO) includes site index values for loblolly pine on all major soil groups across the southeastern counties. If FR in the 3-PG model can be estimated using site index, SSURGO dataset presents a potential to predict productivity of loblolly pine using the 3-PG model based on the soil series in each county.

Geocentric approaches use soil characteristics, topographic features, and climatic factors as the predictors of site quality. It can be an alternative to the phytocentric approach in areas where vegetation cover is absent or where landscape level estimates of productivity are desired. However, applying the geocentric approach may not always be paractical, affordable or accurate for management applications (Skovsgaard and Vanclay, 2008). In addition, computational problems related to multicollinearity may arise when many variables are used to assess soil quality (Morzuch and Ruark, 1991; Kayahara et al., 1995; Guan et al., 2013; Vega-Nieva et al., 2013).

Soil is multivariate in nature and soil processes can be better understood with multivariate analytical methods. Multivariate analysis allows simultaneous analysis of multiple variables. In the 1980's and before, ordinary least square methods of multiple regression were used to model site quality using soil-site methods (Carmean, 1975). For example Carmean (1967) used multiple linear regression to predict height of black oak from soil and topographic variables and Brown and Loewenstein (1978) applied linear regression that involved nine soil properties as individual variables to predict site index of mixed conifer stands in northern Idaho. After the 1990s several multivariate approaches including principal component regression, path analysis, and partial least square regression were used.

Partial least square regression (PLSR) is a method used to assess the relationship between response variables and multiple predictors (Wold et al., 2001). The method is different from principal component analysis as it not only captures the variation in the predictor matrix but also describes the maximum possible covariance between predictor and response variables (Mevik and Wehrens, 2007) and it is a robust method when multicollinearity exists. PLSR selects scores and loadings to describe maximum possible covariance between predictor and response variables. Scores are the transformed values of original data and loadings are the weights by which each original values should be multiplied to get the scores. Mathematically, if X represents the original predictor matrix, PLSR decomposes X into TP' where T is called the score matrix and P the loading matrix (Hervè, 2010). In this way, much of the relationship between dependent variables and independent variable is explained. PLSR may be used to identify variables that explain soil fertility and to develop a relationship between those variables and soil fertility.

1.2 Objectives

This research attempts to model the soil fertility rating (FR) used in 3-PG in loblolly pine plantations the southeastern US. To meet the research goal, the following specific objectives were outlined:

I. Derive a method to predict fertility ratings (FR) in 3-PG using site index in loblolly pine plantations in the southeastern US.

II. Assess the potential of 3-PG to predict productivity of loblolly pine across a region based on site index for soil series available in the SSURGO database.

III. Use physical and chemical properties from A-horizon soil to predict FR

IV. Model the growth response of loblolly pine to repeated fertilization from a young age using the 3-PG model by changing FR values.

V. Model the growth response of loblolly pine to a single midrotation fertilization using the 3-PG model by changing FR values dynamically through the rotation.

Each part of this dissertation describes integrated parts of the research. Chapter 2 describes the phytocentric method for quantifying soil fertility using site index. In this chapter, the relationship between stand productivity and site index was used to estimate *a priori* FR that was used in the process model 3-PG. In chapter 3, physical and chemical properties of the A horizon were used to estimate FR. In chapters 4 and 5, base-line fertility ratings were adjusted by modifying FR with response functions to account for fertilization. Chapter 6 focuses on general discussion and conclusions.

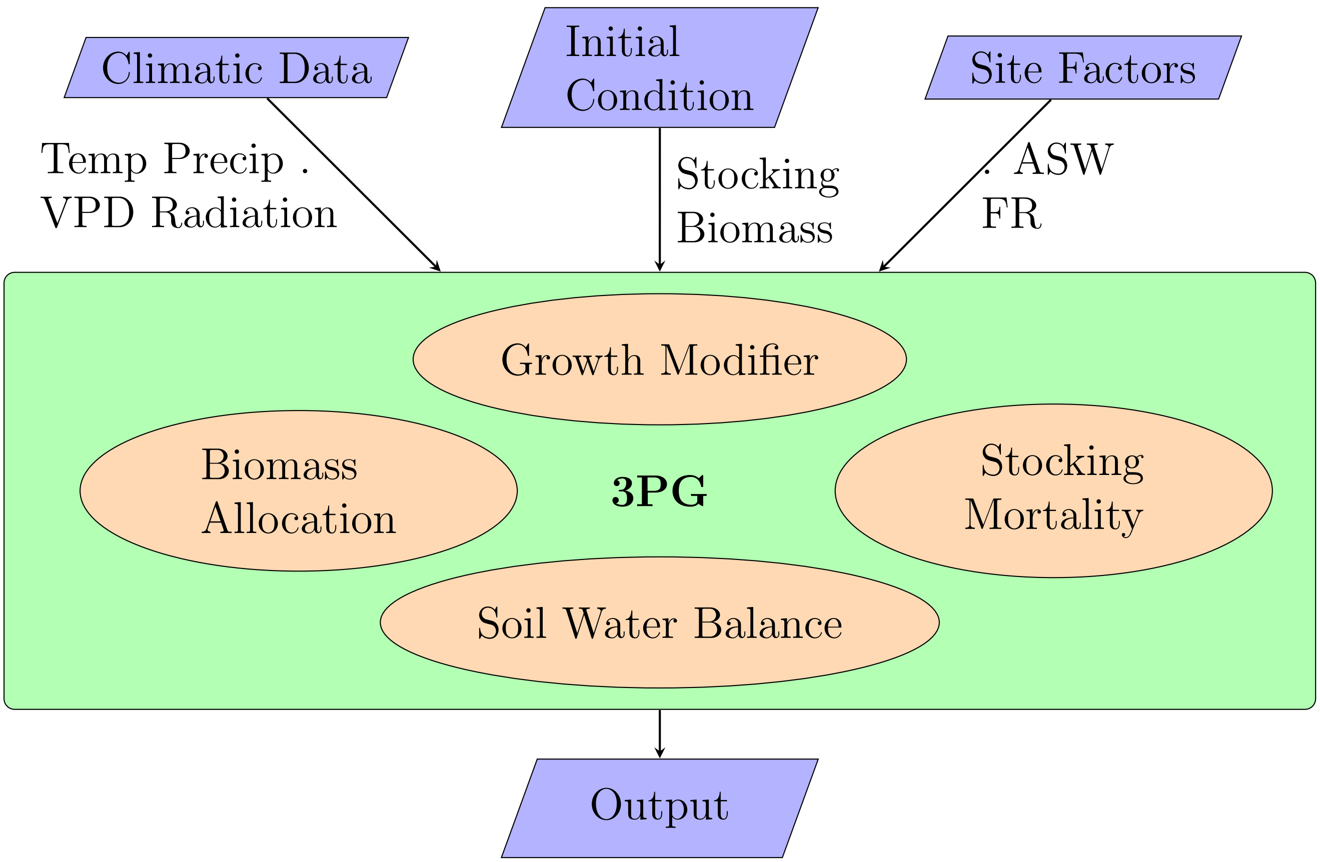

Figure 1.1: Schematics of the 3-PG model. 3-PG requires 40 species specific parameters. Climatic data, stand initialization data, and site-specific factors are the input variables. The four biological submodels: growth modifier, biomass allocation, soil water balance, and stocking/mortality determine C assimilation, C allocation, evapotranspiration, and stand dynamics. The typical outputs from 3-PG include biomass pools and stand density. Figure adapted from Landsberg and Sands (2011).

References

Albaugh, T. J., Allen, H. L., Dougherty, P. M., Kress, L. W., and King, J. S. (1998). Leaf area and above- and belowground growth responses of loblolly pine to nutrient and water additions. *For. Sci.*, 44:317–328.

Allen, H. L. (1987). Forest fertilizers: nutrient amendment, stand productivity, and environmental impact. *J. For.*, 85:37–46.

Allen, H. L., Dougherty, P. M., and Campbell, R. G. (1990). Manipulation of water and nutrients -practice and opportunity in southern U.S. pine forest. *For. Ecol. Mange.*, 30:437–453.

Almeida, A. C., Landsberg, J. J., and Sands, P. J. (2004). Parameterization of 3-PG model for fast-growing *Eucalyptus grandis* plantations. *For. Ecol. Manage.*, 193:179–195.

Augusto, L., Ranger, J., Binkley, D., and Rothe, A. (2002). Impact of several common tree species of European temperate forests on soil fertility. *Ann. For. Sci.*, 59:233–253.

Brown, H. G. and Loewenstein, H. (1978). Predicting site productiivty of mixed conifer stands in northern Idaho from soil and topographic variables. *Soil Sci. Soc. Am. J.*, 42:967–971.

Bryars, C., Maier, C., Zhao, D., Kane, M., Borders, B., Will, R., and Teskey, R. (2013). Fixed physiological parameters in the 3-PG model produced accurate estimates of loblolly pine growth on sites in different geographic regions. *For. Ecol. Manage.*, 289:501–514.

Burkhart, H. E. and Tomé, M. (2012). *Modeling Forest Trees and Stands.* Springer. Netherlands.

Carlson, C. A., Fox, T. R., Allen, H. L., and Albaugh, T. J. (2008). Modeling mid-rotation fertilizer response using the age-shift approach. *For. Ecol. Manage.*, 256:256–262.

Carmean, W. H. (1967). Soil survey refinements for predicting black oak site quality in southeastern Ohio. *Soil Sci. Soc. Amer. Proc.*, 31:805 – 810.

Carmean, W. H. (1975). Forest site quality evaluation in the United States. *Adv. Agron.*, 27:209–269.

Coops, N. C., Waring, R. H., and Law, B. E. (2005). Assessing the past and future distribution and productivity of ponderosa pine in the Pacific Northwest using a process model, 3-PG. *Ecol. Model.*, 183:107–124.

Dye, P. J., Jacobs, S., and Drew, D. (2004). Verification of 3-PG growth and water-use predictions in twelve *Eucalyptus* plantation stands in Zululand, South Africa. *For. Ecol. Manage.*, 193:197–218.

Fontes, L., Tomé, M., Thompson, F., Yeomans, A., Luis, J. S., and Savill, P. (2003). Modeling the Douglas-fir (*Psuedotsuga menziesii* (Mirb.) Franco) site index from site factors in Portugal. *Forestry*, 76:491–507.

Fox, T. R., Allen, H. L., Albaugh, T. J., Rubilar, R., and Carlson, C. A. (2007). Tree nutrition and forest fertilization of pine plantations in the southern United States. *South. J. Appl. For.*, 31:5–11.

Guan, Y., Wei, J., Zhang, D., Zu, M., and Zhang, L. (2013). To indentify the important soil properties affecting dinoseb adsorption with statistical analysis. *Sci. World. J.*, pages 1–7.

Hagglund, B. (1981). Evaluation of forest site productivity. *For. Abst.*, 42:515–527.

Hervè, A. (2010). Partial least squares regression and projection on latent structure regression (pls regression). *Wiley Interdisciplinary Reviews: Computational Statistics*, 2:97–106.

Jokela, E. J. and Martin, T. A. (2000). Effects of ontogeny and soil nutrient supply on production, allocation, and leaf area efficiency in loblolly and slash pine stands. *Can. J. For. Res.*, 30(10):1511–1524.

Kayahara, G. J., Carter, R. E., and Klinka, K. (1995). Site index of western hemlock (*Tsuga heterophylla*) in relation to soil nutrient and foliar chemical measures. *For. Ecol. Manage.*, 74:161–169.

Landsberg, J. and Sands, P. (2011). *Physiological Ecology of Forest Production-Principles, Processes and Models*, volume 4. Elsevier.

Landsberg, J., Waring, R., and Coops, N. (2003). Performance of the forest productivity model 3-PG applied to a wide range of forest types. *For. Ecol. Manage.*, 172:199–214.

Landsberg, J. J., Johnson, K. H., Albaugh, T. J., Allen, H. L., and McKeand, S. E. (2001). Applying 3-PG, a simple process-based model designed to produce practical results, to data from loblolly pine experiments. *For. Sci.*, 47:43–51.

Mevik, B.-H. and Wehrens, R. (2007). The pls package: Principal component and partial least squares regression in R. *J. Stat. Softw.*, 18:1–24.

Morzuch, B. J. and Ruark, G. A. (1991). Principal components regression to mitigate the effects of multicollinearity. *For. Sci.*, 37:191–199.

Rodŕiguez, R., Espinosa, M., Real, P., and Inzunza, J. (2002). Analysis of productivity of radiata pine plantations under different silvicultural regimes using the 3-PG process-based model. *Aust. For. J.*, 65:165–172.

Ryan, M. G. and Yoder, B. J. (1997). Hydraulic limits to tree height and tree growth. *BioScience*, 47:235–242.

Sampson, A. and Allen, H. L. (1999). Regional influences of soil available water and climate, and leaf area index on simulated loblolly pine productivity. *For. Ecol. Manage.*, 124:1–12.

Sampson, D. A., Wynne, R. H., and Seiler, J. R. (2008). Edaphic and climatic effects on forest stand development, net primary production, and net ecosystem productivity simulated for Coastal Plain loblolly pine in Virginia. *J. Geophys. Res.*, 113:1–14.

Samuelson, L. J., Marrianne, F. G., Stokes, T. A., and Coleman, M. D. (2008). Fertilizaton not irrigation influences hydralulic traits in plantation-grown loblolly pine. *For. Ecol. Manage.*, 255:3331 – 3339.

Skovsgaard, J. P. and Vanclay, J. K. (2008). Forest site productivity: a review of the evolution of the dendrometric concepts for even-aged stands. *Forestry*, 81:13–31.

Stape, J. L., Ryan, M., and Binkley, D. (2004). Testing the utility of the 3-PG model for growth of *Eucalyptus grandis x urophylla* with natural and manipulated supplies of water and nutrients. *For. Ecol. Manage.*, 193:219–234.

Vega-Nieva, D. J., Tomé, M., Tomé, J., Fontes, L., Soares, P., Ortiz, L., Basurco, F., and Rodríguez-Soalleiro, R. (2013). Developing a general method for the estimation of fertility rating parameter of the 3-PG model: application in *Eucalyptus globulus* plantations in Northwestern Spain. *Can. J. For. Res.*, 43:627–636.

Will, R. E., Munger, G. T., Zhang, Y., and Borders, B. E. (2002). Effects of annual fertilization and complete competition control on current annual increment, foliar development, and growth efficiency of different aged *Pinus taeda* stands. *Can. J. For. Res*, 32:1728–1740.

Wold, S., Sjöström, M., and Eriksson, L. (2001). PLS-regression: a basic tool of chemometrics. *Chemometri. Intell. Lab. Syst.*, 58:109 – 130.

Chapter 2

Determination of Fertility Rating (FR) in the 3-PG Model for Loblolly Pine Plantations in the Southeastern United States Based on Site Index

Abstract

A method was developed to predict the soil fertility rating (FR) used in the model 3-PG for loblolly pine plantations based on the relationship between stand productivity and site index. Then FR was used in 3-PG to predict loblolly pine yield and mortality on 21 sites across the southeastern United States. When observed yield and stem number were compared against the simulated values, 89% of the variation in yield and 89% of the variation in stand density were explained by simulated values. The model also performed well using FR derived *a priori* from site index when tested against an independent data set containing the control plots from a mid-rotation fertil-

ization study. Although there was a slight positive bias in the predicted volume, 73% of the variations in observed volume was explained by 3-PG. 3-PG performed poorly on sites where stochastic events affected mortality and soil nutrient supply varied substantially through time. The USDA NRCS SSURGO dataset contains site index values for loblolly pine for the major soil series in most of the counties in the southeastern US. The potential of using site index from SSURGO data to predict regional productivity of loblolly pine was assessed by comparing site index values from SSURGO with field inventory data in the study sites. Good correlation was observed between site index reported in SSURGO database and site index observed in field inventory across the major soil series in the southeastern US. Site index values from SSURGO dataset were used to derive FR values to predict loblolly pine productivity at a regional scale. When the 3-PG model was used with FR values derived using site index values from SSURGO database to predict loblolly pine productivity across the broader regions, the model provided realistic outputs of loblolly pine productivity.

2.1 Introduction

The 3-PG model (Landsberg and Waring, 1997), Physiological Principles Predicting Growth, is a process model that predicts forest productivity based on radiation use efficiency, carbon balance, and partitioning. 3-PG and its variants have been calibrated and tested on many commerically important tree species around the globe. Work with *Eucalyptus grandis* (Almeida et al., 2004; Stape et al., 2004), *Pinus patula* (Dye, 2001), *Pinus taeda* (Landsberg et al., 2001; Bryars et al., 2013), *Pinus radiata* (Rodŕiguez et al., 2002), and *Pinus ponderosa* (Coops et al., 2005) have found that 3-PG can accurately predict growth under a variety of management regimes and climatic and edaphic conditions.

3-PG calculates the amount of photosynthetically active radiation (PAR, ϕ_p) intercepted by a stand (APAR, ϕ_{pa}) which is then converted into gross primary productivity (GPP,P_G) using canopy quantum efficiency (α_c), constrained by enviromental factors such as vapor pressure deficit (D), mean temperature (T), soil moisture (θ_s), frost days, and site nutrient status (Almeida et al., 2004). Canopy quantum efficiency, α_c, is calculated as: $\alpha_{\mathrm{c}} = \mathrm{f_T f_N f_f}\varphi\alpha_{\mathrm{Cx}}$, where α_{Cx} is the theoretical maximum canopy quantum efficiency, $\mathrm{f_T}$, $\mathrm{f_N}$, $\mathrm{f_f}$, and φ are temperature, nutrition, frost, and physiology related modifiers, respectively. The physiology related modifier (φ) is defined by the multiplication of an age-dependent modifier ($\mathrm{f_{Age}}$) and the most restrictive of the vapor pressure deficit ($\mathrm{f_D}$) and soil water modifiers (f_θ); such that $\varphi = \mathrm{f_{Age}}\ \min\{\mathrm{f_D f}_\theta\}$. Under non-limiting conditions, all these modifiers have values of 1 (Landsberg and Waring, 1997; Almeida et al., 2004; Landsberg et al., 2003). Net primary productivity (NPP, P_n) is calculated as a fixed proportion of $\mathrm{P_G}$ that accounts for autotrophic respiration. P_n is then allocated to aboveground and belowground biomass production.

Fertility rating (FR), is a site-specific variable in 3-PG that relates soil fertility to stand productivity. FR is used in 3-PG as an index of nutrient availability and the effects of FR on P_G are determined by the impact of FR on leaf area index (LAI) which affects APAR, canopy light use efficiency, and canopy conductance. The nutrient modifier (f_N) in 3-PG is calculated as: $f_N = 1 - (1 - f_{N0})(1 - FR)^{n_{fN}}$, where f_{N0} is the value of f_N when FR = 0 and n_{fN} is an exponent which determines the shape of the response. In 3-PG, f_{N0} is set at 0.5 (Bryars et al., 2013) and n_{fN} is set to 1 so that the fertility modifier is a linear function of FR (Landsberg and Sands, 2011). FR also has a direct effect on the partitioning coefficient, m, which is used to calculate partitioning to roots (Landsberg and Waring, 1997). It is calculated as: $m = m_0 + (1 - m_0)FR$, where m_0 is set to 0.1 (Bryars et al., 2013). Therefore when FR = 0, m = 0.1 and when FR = 1, m = 1.

Several studies have attempted to use the relationship between soil properties and tree growth to estimate FR. Sampson et al. (2008) used clay and sand percentage obtained from State Soil Geograhic Survey (STATSGO) database to predict FR. Vega-Nieva et al. (2013) used clay content and Ca, K, and Na in the soil profile to predict FR. In both cases 3-PG predictions of stand growth using the estimated FR values closely matched the observed data. However, they were not validated on independent sites. Stape et al. (2004) used a different approach based on the observed growth response following fertilization to predict FR in clonal eucalyptus stands. They first calculated fertilizer response (FER) by subtracting the ratio of biomass growth to initial biomass in fertilized plots from control plots. Sites with the lowest observed FER were given an arbitrary FR value of 0.6 and the sites with FER =0 were given FR values of 1. This method of FR estimation requires fertilization trials on all the soils in a region which is both costly and time consuming (Landsberg et al., 2003).

Site index is one of the most common measures of site quality because the height growth of dominant trees is less correlated with stocking than diameter growth and highly correlated with productivity (Burkhart and Tomé, 2012). Dye et al. (2004) used site index to estimate FR. However, they used it as a tunable parameter to match the outcome of 3-PG with observed data. The objective of this study was to use site index for the *a priori* prediction of

FR that could be used as a fixed rather than a tunable parameter. We calculated FR based on site index and then used 3-PG_{lob} (Bryars et al., 2013), a variant of 3-PG to simulate growth of loblolly pine across the southeastern US. This study also assessed the potential to use site index from the Soil Survey and Geographic Database (SSURGO) database to predict FR for individual soil series in a county. Site index in SSURGO dataset is defined as the average height that dominant and codiminant trees of a given species attain in a specified number of years and it is applied to well stocked and even-aged stands. The relationship between site index values in SSURGO dataset and site index values obtained from field inventory was assessed; then site index values from SSURGO dataset were used to derive FR values spatially based on mapped soil series for regional application of 3-PG.

2.2 Materials and Methods

2.2.1 Model Calibration

2.2.1.1 Study Site Description

This study was conducted using data from the control plots of a loblolly pine fertilization trial installed at 21 sites (FNC, 2008) located in the Southern United States (figure 2.1). The fertilization trial was established in the early to mid 1990s as an incomplete factorial design of nutrient dose (0 to 269 Kg ha^{-1}) and application frequency (0, 1, 2, 4, and 6 years) to evaluate the rates and frequencies of fertilization to optimize growth and fertilizer use efficiency. First generation open pollinated seedlings were planted at all sites at densities ranging from 1215 trees ha^{-1} to 2141 trees ha^{-1}. Study sites represented six physiographic provinces. Four of the sites were located in the Lower Coastal Plain, one in the Upper

Coastal Plain, six in the Piedmont, five in the Western Gulf Coastal Plain, four in the Eastern Gulf Coastal Plain, and one in the Valley and Ridge (Table 2.1). The majority of soils on the study sites have a udic moisture regime. Soil series present at each site were typical forest soils in each physiographic provinces.

Average monthly maximum temperature in the month of July ranged from 31.7^{0}C in Brunswick, Virginia to 34^{0}C in Angelina, Texas. Lowest average monthly minimum temperature in January ranged from -3^{0}C in Brunswick, Virginia to 4.3^{0}C in Brantley, Georgia. Average annual precipitation ranged from 1165.6 mm in Brunswick, VA to 1491.2 mm in Montgomery, Mississippi. Highest and lowest monthly average rainfall were 167.7 mm in Marengo, Alabama and 62.3 mm in Marion, Georgia, respectively. Average annual precipitation on all the study sites exceeds potential evaportranspiration rate reported in the southeastern US (Lu et al., 2003). Solar radiation ranged from 7.1 MJ m^{-2} day^{-1} in December to 21.2 m^{-2} day^{-1} in June. Average annual solar radiation ranged from 14.62 MJ m^{-2} day^{-1} in Craven, North Carolina to 15.6 MJ m^{-2} day^{-1} in Talbot, Georgia.

This study used data from the control plots on each study site to determine the baseline FR and predict growth. The study sites in Brunswick, Virginia; Craven, North Carolina; and Berkley, South Carolina had four control plots and rest of the study sites has two control plots each. Plot size ranged from 0.028 to 0.059 ha. On these control plots, all the living trees were measured annually for diameter at breast height and total tree height. Mortality and damages to trees were also recorded in each plot.

2.2.1.2 3-PG Parameterization

This study used the parameter set developed for 3-PG by Bryars et al. (2013) with several modifications (Table 2.2). The projected specific leaf area for mature stands (SLA1) was set to be 4 (Akers et al., 2013; Sampson et al., 2011) and we set tSLA = 6 (Dalla-Tea and

Jokela, 1991; Will et al., 2001; Colbert et al., 1990; McCrady and Jokela, 1995). The light extinction coefficient for APAR was set to be 0.69 (Sampson and Allen, 1998). This study set the value of α_{Cx} at 0.053 which is the point between the values of 0.055 and 0.0485 used by Landsberg et al. (2001) and Bryars et al. (2013), respectively for loblolly pine.

2.2.2 FR Calculation from Site Index

The goal of this study was to use site index to calculate a FR value that could be used as a fixed parameter in 3-PG to accurately predict stand growth. This was done in a 3-step process, because stand biomass production is not linearly related to site index (Burkhart and Tomé, 2012) and thus site index and FR are not linearly related. First site index was calculated in each plot using the observed data on the tree height. Then the relationship between site index and volume in each plot was determined. Finally, the relationship between site index and stand volume was used to determine the relationship between site index and FR where FR varies from 0 to 1.

2.2.2.1 Calculation of Site Index

Site index in each plot was calculated using a dynamic site index model for loblolly pine (Diéguez-Aranda et al., 2005). The dynamic site index model was derived with the generalized algebraic difference approach using a large data set from permanent plots. This model is base-age invariant and it estimates site index from any height age combination (Diéguez-Aranda et al., 2005). Average height of the tallest 80% of trees on a plot was used to derive dominant height (Gyawali and Burkhart, 2015). Dominant height in each plot at age 11 or 12 were used to calculate site index.

2.2.2.2 Determine Relationship Between Stand Volume and Site Index

Most of the plots in the study areas were thinned at age 12, so volume at age 11 was used to derive the relationship between site index and yield to avoid confounding effect of thinning. Volume for each tree was calculated using the equation from Van Deusen et al. (1981): Volume=0.1365 + 0.0024437 * DBH^2 H, where volume is in cubic feet outside bark, DBH is in inches, and H, total tree height, is in feet. Values were calculated in English units and converted to metric units. Stand volume was determined by summing the volume of individual trees in the plot and using the plot area to adjust to a per hectare value. The relationship between site index (m) and stand volume(m^3 ha^{-1}) in the plots was fit using three different equations: linear, exponential, and sigmoidal with the following forms.

1. Linear (Volume $= \beta_0 + \beta_1$SI)
2. Exponential (Volume $= e^{\alpha_0+\alpha_1 SI}$)
3. Sigmoid (Volume $= \dfrac{\gamma_1}{1 + e^{\gamma_2+\gamma_3 SI}}$)

Where β_0 and β_1 represent intercept and slope parameter for the linear model; α_0 and α_1 represent parameters for the exponential function; and γ_1, γ_2, and γ_3 represent parameters for the sigmoid function. R^2 and the leave-one-out cross validation method were used to determine the equation with the best fit using the following selection criteria: Root Means Square Error (RMSE), Mean Absolute Error (MAE), and Predicted Residual Sums of Square (PRESS) statistics.

RMSE was calculated as the standard deviation of the difference between y_i-$\hat{y}_{i,-i}$, where y_i is observed volume per hectare and $\hat{y}_{i,-i}$ is the predicted value for the volume using the model with all observation in the fitting data except the observed volume on that plot. MAE was calculated as:

$\mathrm{MAE} = \sum_{\mathrm{i}=1}^{\mathrm{n}} \frac{|\ \mathrm{y_i} - \hat{\mathrm{y}}_{\mathrm{i},-\mathrm{i}}\ |}{\mathrm{n}}$, where n is the number of observations and y_i and $\hat{y}_{i,-i}$ are as described above

Similarly, PRESS statistic was calculated as:

$\mathrm{PRESS} = \sum_{\mathrm{i}=1}^{\mathrm{n}} (\mathrm{y_i} - \hat{\mathrm{y}}_{\mathrm{i},-\mathrm{i}})^2$

2.2.2.3 Calculate Relationship between FR and Site Index

After selecting the equation with the best fit between stand volume and site index, an expression for FR based on site index was derived. Based on the range of site index observed on the control plots, an assumption was made that site index of 10.7 m (35 ft) corresponded to FR=0 with a yield of 20.7 m^3 ha^{-1} and site index of 30.5 m (100 ft) with a yield of 281.8 m^3 ha^{-1} corresponded to FR=1. Then the volume at site index values between the maximum and minimum site indices was used to derive the relationship between site index and FR. We fit a sigmoidal equation: $\mathrm{FR} = \frac{\beta_0}{1+e^{\beta_1+\beta_2\ \mathrm{SI}}}$, where β_0,β_1, and β_2 are coefficients derived from data.

2.2.3 Validation of the Relationship between FR and Site Index

The FR values derived using the above procedure were used as input in 3-$\mathrm{PG_{lob}}$ (Bryars et al., 2013) to predict growth in the control plots at the 21 study sites. Weather data including mean monthly temperature, rainfall, frost days, and vapor pressure deficit were obtained from Daymet Surface Weather and Climatic Summaries (`http://daymet.ornl.gov`). Stand initialization data were obtained from data collected in each plot. Soil texture and moisture information were obtained from Soil Survey Geographic Database (SSURGO). Species specific parameters in Table 2.2 were used. These data and the FR value calculated from measured site index were input into 3-$\mathrm{PG_{lob}}$ and the output was generated for total aboveground biomass, stem number, and LAI annually for each plot. The predicted values from 3-PG_{lob} were compared with measured values in each plot. A linear model was fitted between observed aboveground biomass and model simulated aboveground biomass and the null hypothesis of slope is equal to 1 was tested. Aboveground biomass for each tree was calculated using the equation: Aboveground biomass = 0.026256 $DBH^{2.015144}$ $HT^{0.864052}$, where aboveground biomass is in kg, DBH is in cm, and HT, total tree height, is in m (Gonzalez-Benecke et al., 2014). Stand aboveground biomass was determined by summing the aboveground biomass of individual trees in the plot and using the plot area to adjust to a per hectare value. Similarly, a linear model was fitted between observed stem density and fitted stem density and the null hypothesis of slope is equal to 1 was tested using the predicted value as a regressor(Piñeiro et al., 2008).

After the model performance was tested using data from the control plot at the 21 sites, the performance of 3-PG_{lob} was evaluated against independent data not used in the model development. We used control plots at six sites of a loblolly pine mid-rotation fertilization trial located in the southern United States. This fertilization trial was established in the mid 1980s as a factorial design of N (0,112, 224, and 336 kg ha^{-1}) and P (0, 28, and 56 kg ha^{-1}) fertilization (see Gyawali and Burkhart (2015) and Amateis et al. (2000)). These independent study sites also represent a wide range of stand age, soil type, and climate across the southeastern US. We used control plots on each study site to independently validate FR derived *a priori* from site index in the 3-PG model. Table 2.3 shows location, age, planting density, FR, average annual precipitation, and soil series of the sites used for independent validation of FR derived *a priori* from site index.

2.2.4 Application of FR Model in SSURGO Database

The wider application of our approach to estimate loblolly pine productivity requires readily available site index values. The SSURGO dataset has detailed data on all soils mapped in the United States. SSURGO database includes site index values of loblolly pine on the majority of soil types on a county by counties basis for the entire southeastern US. We tested the potential to predict loblolly pine productivity across broader regions in the southeastern US using site index derived for individual soil series for three counties in the southeastern US using SSURGO data. SSURGO dataset has site index values of loblolly pine at base age 50 years. We converted it to site index base age 25 using base age invariant site index model developed by Diéguez-Aranda et al. (2005). To illustrate the utility of this approach, Kemper County, Mississippi was selected and loblolly pine productivity was estimated spatially in that county with the 3-PG model using the FR values derived from the SSURGO dataset.

2.3 Results

2.3.1 Relationship between Site Index and Volume

Measured site index ranged from 16 to 30 m (base age 25) in the control plots. The exponential, sigmoidal, and linear relationship between volume and site index had R^2 values of 0.93, 0.92, and 0.93, respectively (Figure 2.2). When leave-one-out cross validation was carried out among the three model forms, MAE, RMSE, and PRESS statistics were lowest for the linear model, followed by the sigmoid model (Table 2.4). But the sigmoidal model performed better when extrapolated outside the regressor variable hull. Both the exponential and linear models performed poorly when each model was extrapolated outside the regressor variable hull. For example, the linear model predicted negative yield when site index was below 12.9 m. Therefore, the sigmoidal model was selected as the best model to predict volume (m^3 ha^{-1}) from site index at base age 25 (m).

$$\text{Volume} = \frac{379.57}{1 + \mathrm{e}^{4.556-0.185\ \mathrm{SI}}}$$

2.3.2 Relationship between Site Index and FR

Using the sigmoidal relationship to predict volume from site index, values for volume at site index values of 10.67 m and 30.48 m were calculated as 26.70 and 281.78 m^3 ha^{-1} at age 11. Based on the assumption that these represent the minimum and the maximum site index for loblolly pine in the southeastern United States, the value of FR was set to 0 at 26.70 m^3 ha^{-1} and the FR value was set to 1 at 281.78 m^3 ha^{-1}. The difference between 281.78 and 26.70 was then distributed evenly between the FR values of 0 and 1 (Table 2.5) and the relationship between FR and site index was determined using a sigmoid model (Figure 2.3).

$$\mathrm{FR} = \frac{1.190}{1 + e^{(-(-5.899+0.245\ \mathrm{SI}))}} \tag{2.1}$$

This equation was used to predict FR in 3-PG based on site index.

2.3.3 Model Evaluation

Using the FR values predicted from site index, 3-PG accurately predicted yield and mortality of loblolly pine in the control plots from the 21 sites in this study. Overall, using FR determined *a priori* from site index using equation 2.1, the measured aboveground biomass and predicted aboveground biomass from 3-PG had an R^2 of 0.89 and the measured stand tree density and predicted stand tree density also had an R^2 value of 0.89 (Figure 2.4). The slope of the relationship between measured aboveground biomass and predicted aboveground biomass was not significantly different from 1 ($p<0.001$). Similarly, the slope between measured values of stand density and modeled values of stand density was not different from one ($p<0.001$). 3-PG predicted yield well at 17 sites. As found in most modeling work, there was more variation when observed vs predicted growth were examined on individual sites. Figure 2.5 illustrates results from several study sites where prediction matched well with the observed values and the sites where prediction didn't match well with the observed values. Among the sites where prediction didn't match well with the observed values are the sites dominated by Spodosols in the Lower Coastal Plain and the sites where some stochastic events caused high level of mortality.

3-PG also performed well when evaluated against the independent data from the mid-rotation stands not used to develop the relationship between site index and FR. The predicted values from 3-PG explained 73% of the variation in measured aboveground biomass and 86% of the variation in measured stand density in the independent data (Figure 2.6). However, there was a positive bias in the predicted aboveground biomass in the data set with a significant difference from the 1:1 line. The slope of the relationship between observed stand density and predicted stand density was not significantly different from 1 ($p<0.001$). 3-PG predicted mortality accurately on the majority of the sites. The largest discrepancies in mortality predictions were observed in Kershaw, South Carolina; Brantley, Georgia; Vernon, Louisiana; and Sabine, Louisiana. The site in Kershaw, South Carolina suffered higher rates of mortality due to lightning, the site in Brantley Georgia suffered higher mortality due to unknown reasons, and the site in Vernon, Louisiana had no mortality.

The predicted LAI value from 3-PG increased as FR increased reaching peak LAI of 5.5, 4, and 2 for FR values of 0.96, 0.64, and 0.21, respectively. LAI measurements were available on 4 of the 21 study sites, 3-PG predicted LAI reasonably well on these sites. About 53% of the variation in observed LAI was described by the predicted LAI (Figure 2.7). LAI estimations across the fertility gradients were within the range of observed LAI. For the young stands, estimated LAI increased until reaching the maximum value. Time to reach the maximum LAI was a function of FR. Higher FR values tend to shorten the time to reach maximum LAI (Figure 2.7).

2.3.4 County Level Productivity Estimation

Site index values in SSURGO and observed site index at the study sites were highly correlated. Seventy-five percent of the variance in the observed site index was described by SSURGO site index (Figure 2.8). We used Kemper County, Mississippi as a case study to evaluate the potential to use SSURGO based data on site index to predict FR for individual soil series and then use 3-PG to spatially predict productivity of loblolly pine across a county. Figure 2.9 shows spatial pattern of aboveground biomass for 12-year-old loblolly pine in Kemper County, Mississippi predicted by 3-PG using the SSURGO series and site index information. Table 2.6 shows the major soil series mapped in Kemper County, Mississippi; Brunswick County, Virginia; and Brantley County, Georgia, the SSURGO estimate of site index, SSURGO site index adjusted for base age 25 using base age invariant site index model developed by Diéguez-Aranda et al. (2005), and the predicted FR values from adjusted site index using equation 2.1.

2.4 Discussion

Our hypothesis that FR can be estimated from site index and used as a fixed parameter in 3-PG was supported by the results of these simulations. When the independent estimate of FR from site index was input into 3-PG$_{lob}$, the simulated value of yield matched the measured yield well, with an R^2 value of 0.89 and the slope of the relationship between observed aboveground biomass and predicted aboveground biomass was not significantly different from 1. Previous work on 3-PG to predict loblolly pine growth and yield by Landsberg et al. (2001) at a single location in North Carolina and by Bryars et al. (2013) on multiple locations across Georgia also showed that 3-PG could predict loblolly pine growth and yield accurately. The present study was carried out on a wider range of sites across the South. This study used 48 control plots located at 21 study sites across 9 states in the southeastern United States and found that aboveground biomass and mortality were predicted reasonably well in the majority of sites in all the physiographic regions. The model also performed well when used against the independent data from mid-rotation stands not used in the model development. The predicted values from the model explained 73% of the variance in the observed aboveground biomass and 86% of the variance in measured stem density which indicates that the model can be applied across a wide range of ages and stand conditions. The model to predict FR from site index provided robust *a priori* estimates of FR in 3-PG. This is an improvement over previous work with 3-PG that has used FR as a tunable parameter to match 3-PG simulations to observed data (Landsberg et al., 2003).

Mortality has been ignored or considered zero in many previous studies with 3-PG, such as those in clonal eucalyptus stands (Almeida et al., 2004; Stape et al., 2004; Sands and Landsberg, 2002). 3-PG predicted mortality poorly in a study with *Pinus radiata* in southeastern New Zealand (Pinjuv et al., 2006). Bryars et al. (2013) also found poor predictions of mortality for loblolly pine in Georgia. In contrast, when used to simulate stocking in native eucalyptus forest in southeastern Australia, 3-PG performed well and explained about 89% of the variability in observed data (Tickle et al., 2001). Similar results were observed in our study where the relationship between observed and predicted mortality had an R^2 of 0.88. In the 21 study sites in this study, there were only 4 sites where large discrepancies were observed. Two of these sites suffered higher mortality due to causes not related to stand density. At 10 of 21 study sites 3-PG predicted stocking within ± 30 trees ha^{-1}.

Results from this study also demonstrate that 3-PG can be calibrated to accurately reproduce observed LAI in loblolly pine stands. Our model predictions of LAI as a function of FR were reasonable based on observed values (Vose et al., 1994; Akers et al., 2013). Good correspondence was obtained between simulated LAI across fertility gradients and reported LAIs. For example, LAI values of 5.5 on sites with higher FR values matched well with LAI values observed by Akers et al. (2013) and Zhao et al. (2012) and LAI simulated on medium and low fertility ratings corresponded well with LAI reported by Peduzzi et al. (2012) for loblolly pine. Both magnitude of the maximum LAI and the time to reach it were observed as the functions of FR. Our results support the assertion from Vose et al. (1994) that slow growing stands reach maximum LAI later than fast growing stands. An average value for growth efficiency on control plots for loblolly pine in the southeastern United States is approximately 7.2 m^3 ha^{-1} yr^{-1} LAI^{-1} (Albaugh et al., 1998; Vose and Allen, 1988). In this study, the sites with low fertility such as the control plots in Oglethorpe, Georgia had CAI near 17 m^3 ha^{-1} yr^{-1} at age 11. The predicted LAI for this site was 2.40, which translates into growth efficiency rate of 7.1 m^3 ha^{-1} yr^{-1} LAI^{-1}. The sites with high fertility such as the control plots in Marengo, Alabama had CAI near 34 m^3 ha^{-1} yr^{-1} at age 9. The predicted LAI for this site was 5.4 which translates into growth efficiency rate of 6.3 m^3 ha^{-1} yr^{-1} LAI^{-1}.

Results from this study show that while prediction of loblolly pine aboveground biomass by 3-PG across the broader region is reasonably accurate, predictions at individual specific sites may be poorer. This result has been observed in other models of pine growth such as empirical growth and yield models (Burkhart and Tomé, 2012). In this study 3-PG performed well at most of the sites with finer textured Alfisols and Ultisols. 3-PG predictions of aboveground biomass were less accurate in sandy Spodosols and Entisols. On these soils

3-PG predictions were generally more accurate at younger ages and then declined with time. Temporal variation in nutrient availability may cause the poorer prediction on the sandy soils.

Nutrient availability in pine plantations varies through time, especially for N which is often the nutrient most limiting productivity (Fox et al., 2007) and therefore should be highly related to FR. Nitrogen availability is generally high early in the rotation due to the rapid decomposition of organic matter and mineralization of N contained in slash and logging debris (Fox et al., 2007). The assart effect (Romell, 1957; Tamm, 1964) causes a relatively short-lived pulse of N during the early phase of stand development as the forest floor and logging debris decompose. The assart effect is more pronounced in sandy Spodosols (Fox et al., 2007). After the assart effect disappears, N availability continues to decline as the forest floor accumulates and acts as a sink for N (Miller, 1981; Piatek and Allen, 2001; Kiser and Fox, 2012). The impact of the assart effect and the accumulation of N in the forest floor on N availability is greater on sandy soils with low organic matter that are inherently less fertile than fine-textured soils. Tree growth is initially rapid but then slows as nutrient availability declines and nutrient deficiency develops (Miller, 1981; Fox et al., 2007). Albaugh et al. (2006) showed that height growth decreased through time in a sandy site in North Carolina that is similar to the soil at the site in Kershaw, South Carolina. The observed height growth decreased significantly in the later stage of stand development in the control plots. This suggests that FR should vary through time to more accurately predict soil nutrient availability on the sandy soils. Management practices such as N fertilization temporarily increase nutrient availability in soils which increased growth on nutrient deficient soils (Fox et al., 2007). Therefore including a temporal component to FR may also enable 3-PG to predict the response to silvicultural practices such as N fertilization.

This study suggests that FR can also be estimated from the site index values in the SSURGO dataset and used in 3-PG model. The 3-PG model produced realistic values of aboveground productivity when FR values were derived using site index values from SSURGO database. Our results show that 3-PG predicted aboveground productivity ranging from 40-85 Mg ha^{-1} at 12 years across Kemper County, Mississippi. These values correspond well with the previously reported productivity range in the southeastern United States (Zhao et al., 2012; Borders and Bailey, 2001; Haywood and Burton, 1990).

2.5 Conclusion

In most previous work with 3-PG FR has been used as a tunable parameter that is adjusted so that predicted values match observed data. An unbiased *a priori* estimate of FR would greatly enhance the utility of the 3-PG model (Bryars et al., 2013). The results presented in this study indicated that FR can be accurately estimated *a priori* from site index and used to accurately predict the growth and stocking of loblolly pine across the southeastern US with single parameter set. SSURGO data on soils contains loblolly pine site index information for many major soil types in each of the southeastern counties. Our work on Kemper County, Mississippi showed that 3-PG has the potential to estimate loblolly pine productivity using the FR values estimated using soil based site index values from SSURGO database. Future refinements that enable FR to vary through time would likely improve 3-PG predictions in loblolly systems on sandy soils of the southeastern United States.

Table 2.1: Location (State, County), physiographic regions, latitude / longitude, soil series, average annual precipitation, and average maximum and minimum temperature (^{0}C) for study sites used to determine relationship between site index and FR in 3-PG.

Study site	**State, County**	**Physiographic Province**	**LAT / LONG**	**Soil Series**	**Precipitation (mm yr $^{-1}$)**	**Temperature max / min**
180101	South Carolina, Kershaw	Piedmont	34.45 / -80.50	Lakeland	1208.5	32.6 / -0.5
180301	Georgia, Oglethorpe	Piedmont	33.89 / -82.91	Mecklenburg	1237.3	32.9 / -0.6
180601	Virginia, Brunswick	Piedmont	36.68 / -77.99	Cecil	1165.6	31.7 / -3.0
180801	North Carolina, Craven	LCP	35.23 / -76.97	Leaf	1235.9	32 / 0.9
181101	South Carolina, Berkeley	LCP	33.19 / -80.19	Lynchburg	1289.5	33.4 / 1.3
181201	Alabama, Coosa	Piedmont	32.91 / -86.38	Louisa	1412.6	32.6 / 0.3
181502	Georgia, Floyd	Valley & Ridge	34.15 / -85.38	Townley	1371.8	32.1 / -1.0
181503	Texas, Angelina	WGCP	31.13 / -94.46	Kurth	1331.3	34.1 / 2.5
182201	Georgia, Wilkes	Piedmont	33.81 / -82.96	Appling	1240.6	32.9 / -0.3
183101	Louisiana, Sabine	WGCP	31.72 / -93.56	Sacul	1370.6	33.8 / 1.2
183102	Louisiana, Vernon	WGCP	31.34 / -93.18	Sacul	1489.8	33.8 / 2.1
183601	Mississippi, Kemper	EGCP	32.70 / -88.58	Smithdale	1451.4	33.3 / 0.6
183901	Alabama, Marengo	EGCP	32.37 / -87.84	Savannah	1431.5	33.3 / 1.2
184201	Georgia, Brantley	LCP	31.34 / -81.82	Leon	1310.3	33.2 / 4.3
184202	Georgia, Brantley	LCP	31.34 / -81.83	Leon	1308.2	33.2 / 4.3
184301	Georgia, Marion	UCP	32.17 / -84.63	Troup	1275.9	33.1 / 2.0
184401	Arkansas, Bradley	WGCP	33.49 / -92.13	Savannah	1402.1	33.5 / 0.8
184501	Alabama, Marengo	EGCP	32.25 / -87.55	Brantley	1418.5	33.3 / 1.4
184801	Texas, Newton	WGCP	30.48 / -93.78	Evadale	1496.8	33.7 / 3.7
185201	North Carolina, Montgomery	Piedmont	35.28/ -79.94	Herndon	1212.7	32.5 / -1.0
185301	Mississippi, Montgomery	EGCP	32.55/ -89.64	Shubuta	1491.2	33.2 / 0.7

Table 2.2: 3-PG parameters and their values for loblolly pine used in this study

	Parameters	Meaning	Unit	Value
1	pFS2	Ratio of foliage:stem partitioning at stem diameter = 2 cm		0.40
2	pFS20	Ratio of foliage:stem partitioning at stem diameter = 20 cm		0.25
3	StemConst	Constant in stem mass diameter relationship		0.10
4	StemPower	Power in stem massvdiameter relationship		2.50
5	pRx	Maximum fraction of NPP to roots		0.40
6	pRn	Minimum fraction of NPP to roots		0.20
7	SLA0	Projected specific leaf area at the beginning of plantation	m^2 Kg^{-1}	6.40
8	SLA1	Projected specific leaf area for mature stand	m^2 Kg^{-1}	4.00
9	tSLA	Age at which SLA is mean of SLA0 and SLA1	year	6.00
10	k	Extinction coefficient for APAR by canopy		0.69
11	fullCanAge	Age at full canopy cover	year	4.00
12	MaxIntcptn	Maximum proportion of rainfall intercepted by canopy		0.20
13	LAImaxIntcptn	LAI for maximum rainfall interception		5.00
14	α_{Cx}	maximum canopy quantum efficiency	molC $molPAR^{-1}$	0.053
15	MaxCond	Maximum canopy conductance	m s^{-1}	0.006
16	LAIgcx	Canopy LAI for maximum canopy conductance		3.00
17	CoeffCond	Defines stomatal response to VPD	$mbar^{-1}$	0.02
18	BLcond	Canopy boundary layer conductance	m s^{-1}	0.10
19	wSx1000	Maximum stem mass per tree at 1000 trees ha^{-1}	kg $tree^{-1}$	235.00
20	thinPower	Power in self thinning law		1.60
21	mF	Fraction of mean foliage biomass per tree on dying trees		0.00

22	mR	Fraction of mean root biomass per tree on dying trees		0.20
23	mS	Fraction of mean stem biomass per tree on dying trees		0.40
24	fracBB0	Branch and bark fraction at stand age 0		0.40
25	fracBB1	Branch and bark fraction for mature stand		0.10
26	tBB	Age at which brak fraction is mean of fracBB0 and fracBB1		15.00
27	gammaFx	Maximum litterfall rate	$month^{-1}$	0.042
28	gammaF0	Litterfall rate at age 0	$month^{-1}$	0.001
29	tgammaF	Age at which litterfall rate is mean of gammaFx and gammaF0		18.00
30	Rttover	Average monthly root turnover rate		0.0168
31	m0	Value of m when FR is zero		0.10
32	fN0	Value of fN when FR is zero		0.50
33	Tmin	Minimum temperature for growth	^0C	4
34	Topt	Optimum temperature for growth	^0C	25
35	Tmax	Maximum temperature for growth	^0C	38
36	kF	Number of days production lost for each frost day		1
37	MaxAge	Maximum stand age used to compute relative age		40
38	nAge	Power of relative age in age modifier		3
39	rAge	relative age to make age modifier 0.5		0.20
40	y	NPP to GPP ratio		0.47

Table 2.3: Location (County, State), latitude / longitude, planting density, range of age, FR, average maximum temperature, average annual precipitation, and soil series of the sites used for independent validation of FR derived from site index

Location (County, State)	**LAT / LONG**	**Planting density (Trees ha^{-1})**	**Age (years)**	**FR**	**Avg max T (^{0}C)**	**Avg annual ppt (mm yr^{-1})**	**Soil series**
Lancaster, South Carolina	34.55 / -80.63	1097	12-16	0.34	36.13	1157.60	Appling
Covington, Alabama	31.20 / -86.25	1147	11-19	0.38	35.51	1547.86	Florala
Kemper, Mississippi	32.40 / -81.44	865	11-19	0.51	36.76	1429.97	Wilcox
Effingham, Georgia	36.21 / -76.94	1509	10-20	0.35	36.28	1208.37	Leefield
Bertie, North Carolina	32.75 / -88.45	1442	10-20	0.34	33.88	1280.63	Norfolk
Howard, Arkansas	34.03 / -94.02	1000	10-16	0.33	38.20	1375.83	Sacul

Table 2.4: Comparison of model fit statistics for exponential, sigmoid, and linear relatoinship between stand volume outside bark ($m^3 ha^{-1}$) and site index (m) at base age 25 based on leave-one-out cross validation, Root Mean Square Error (RMSE), Mean Absolute Error (MAE), and Predicted Residual Sums of Squares (PRESS).

Model name	**Model form**	**RMSE**	**MAE**	**PRESS**
Exponential	$\text{Volume} = e^{(2.855+0.094\ \text{SI})}$	20.590	15.51	13157.47
Sigmoid	$\text{Volume} = \dfrac{379.57}{1+e^{4.556-0.185\ \text{SI}}}$	19.70	16.36	12029.60
Linear	Volume = -207.693 + 16.115 SI	18.51	15.33	10622.70

Table 2.5: Value of volume (m^3 ha^{-1}) that corresponded to the value of FR based on the assumed linear incremental relationship and the respective value of site index (m) based on the sigmoidal relationship between stand volume and site index

Volume (m^3 ha^{-1})	**Site index (m)**	**FR**
26.70	10.70	0
52.03	14.73	0.1
77.55	17.34	0.2
103.00	19.36	0.3
128.53	21.09	0.4
154.10	22.66	0.5
179.70	24.15	0.6
205.61	25.61	0.7
230.72	27.11	0.8
256.20	28.70	0.9
281.78	30.50	1

Table 2.6: Soil series, site index at base age 50, site index adjusted for base age 25 using Diéguez-Aranda et al. (2005), and FR values derived from site index using equation 2.1 in Kemper County, Mississippi; Brunswick County, Virginia; and Brantley County, Georgia based on SSURGO database.

Kemper				Brunswick				Brantley			
Series	SI	Adjusted SI	FR	Series	SI	Adjusted SI	FR	Series	SI	Adjusted SI	FR
Bibb	30.48	20.67	0.36	Appling	25.91	16.98	0.18	Albany	28.96	19.42	0.29
Daleville	28.96	19.42	0.29	Ashlar	22.86	14.60	0.11	Bladen	28.65	19.18	0.28
Freest	27.43	18.19	0.23	Badin	24.38	15.78	0.14	Bonifay	25.91	16.98	0.18
Jena	30.48	20.67	0.36	Cecil	25.30	16.50	0.16	Centenary	25.91	16.98	0.18
Kinston	30.48	20.67	0.36	Chewacla	25.60	16.74	0.17	Eulonia	27.43	18.19	0.23
Kipling	27.43	18.19	0.23	Emporia	25.91	16.98	0.18	Florala	27.43	18.19	0.23
Kirkville	28.96	19.42	0.29	Enon	20.42	12.75	0.07	Foxworth	24.38	15.78	0.14
Mantachie	29.87	20.17	0.33	Fluvanna	23.17	14.84	0.11	Fuquay	25.91	16.98	0.18
Mayhew	27.43	18.19	0.23	Georgeville	24.69	16.02	0.15	Hurricane	27.43	18.19	0.23
Mooreville	28.96	19.42	0.29	Goldston	22.56	14.37	0.10	Kinston	30.48	20.67	0.36
Oktibbeha	23.17	14.84	0.11	Helena	25.60	16.74	0.17	Lakeland	22.86	14.60	0.11
Ora	25.30	16.50	0.16	Herndon	24.38	15.78	0.14	Leefield	25.60	16.74	0.17
Prentiss	26.82	17.71	0.21	Iredell	20.42	12.75	0.07	Leon	22.86	14.60	0.11
Quitman	28.04	18.68	0.25	Lignum	23.17	14.84	0.11	Lynn Haven	24.38	15.78	0.14
Ruston	25.60	16.74	0.17	Madison	21.95	13.90	0.09	Mascotte	21.34	13.44	0.08
Savannah	24.69	16.02	0.15	Mattaponi	24.38	15.78	0.14	Meggett	30.48	20.67	0.36
Smithdale	26.21	17.22	0.19	Pacolet	23.77	15.31	0.12	Meldrim	25.91	16.98	0.18
Sweatman	25.30	16.50	0.16	Rion	24.38	15.78	0.14	Ogeechee	27.43	18.19	0.23
Wilcox	24.69	16.02	0.15	Riverview	30.48	20.67	0.36	Olustee	24.38	15.78	0.14

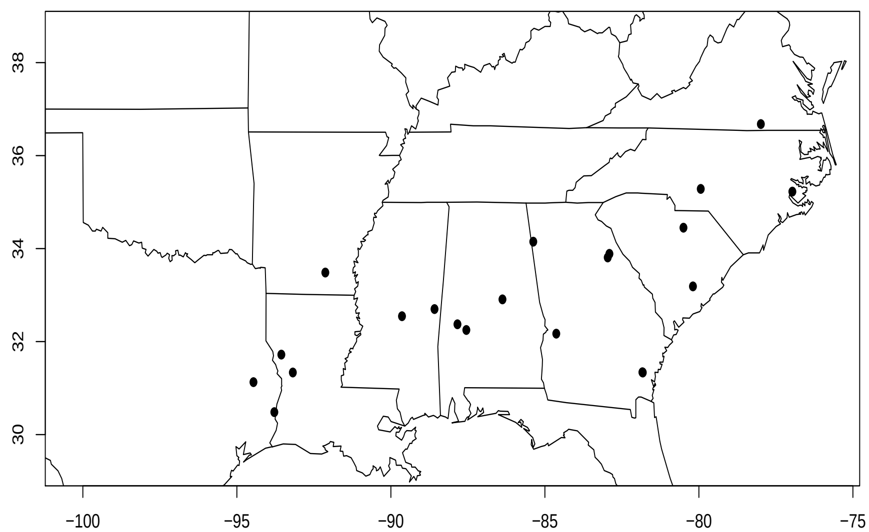

Figure 2.1: Location of study sites used to develop and test fertility rating for loblolly pine in 3-PG model

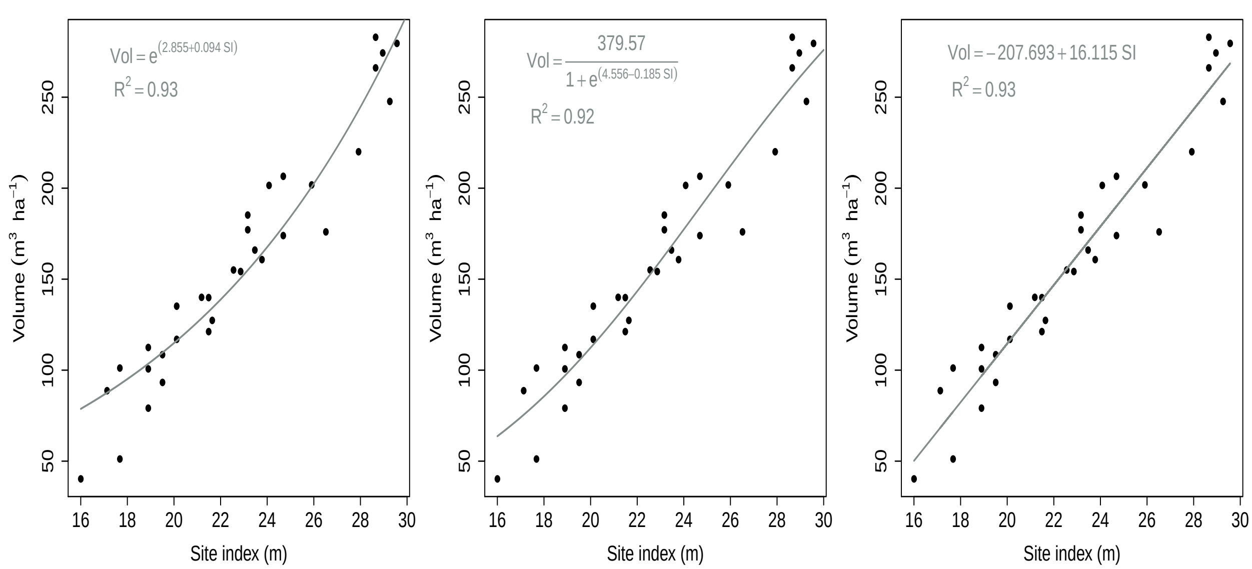

Figure 2.2: Scatter plot between volume (m^3 ha^{-1}) and site index (m). Left, middle, and right diagram showed exponential, sigmoidal, and linear relationships, respectively.

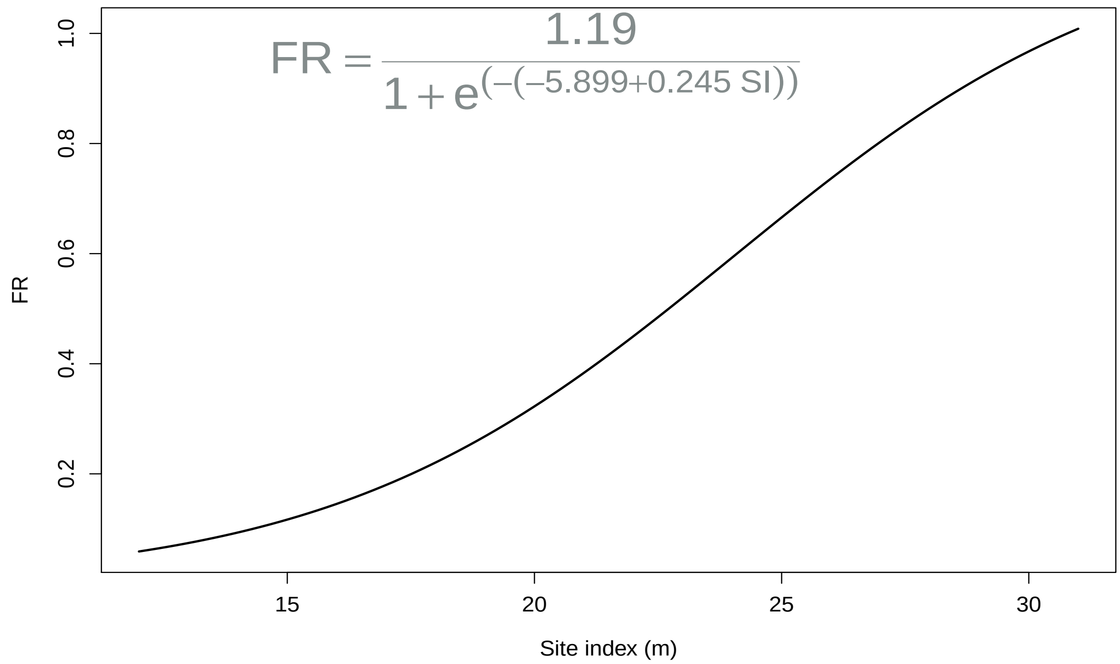

Figure 2.3: Sigmoidal relationship between FR and site index based on the relationship between stand volume and site index illustrated in Table 3.

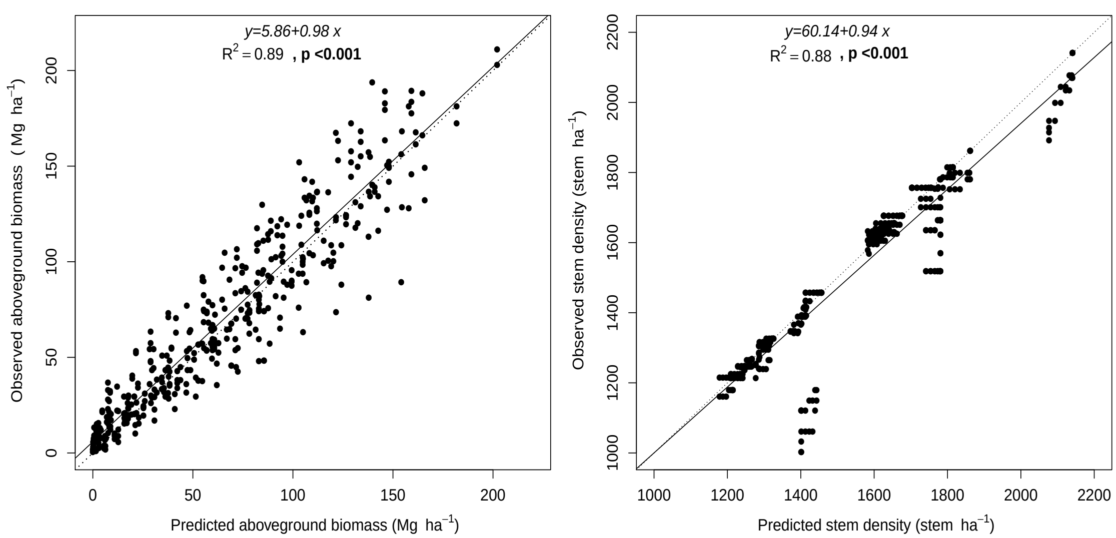

Figure 2.4: Relationship between observed aboveground biomass (Mg ha^{-1}) and modeled aboveground biomass (left) and measured stem density (stem ha^{-1}) and modeled stem density across the 48 control plots at the 21 study sites located across the southeastern United States. Solid lines represent linear fit between observed and predicted values and dotted lines represent the 1:1 line between observed and predicted values.

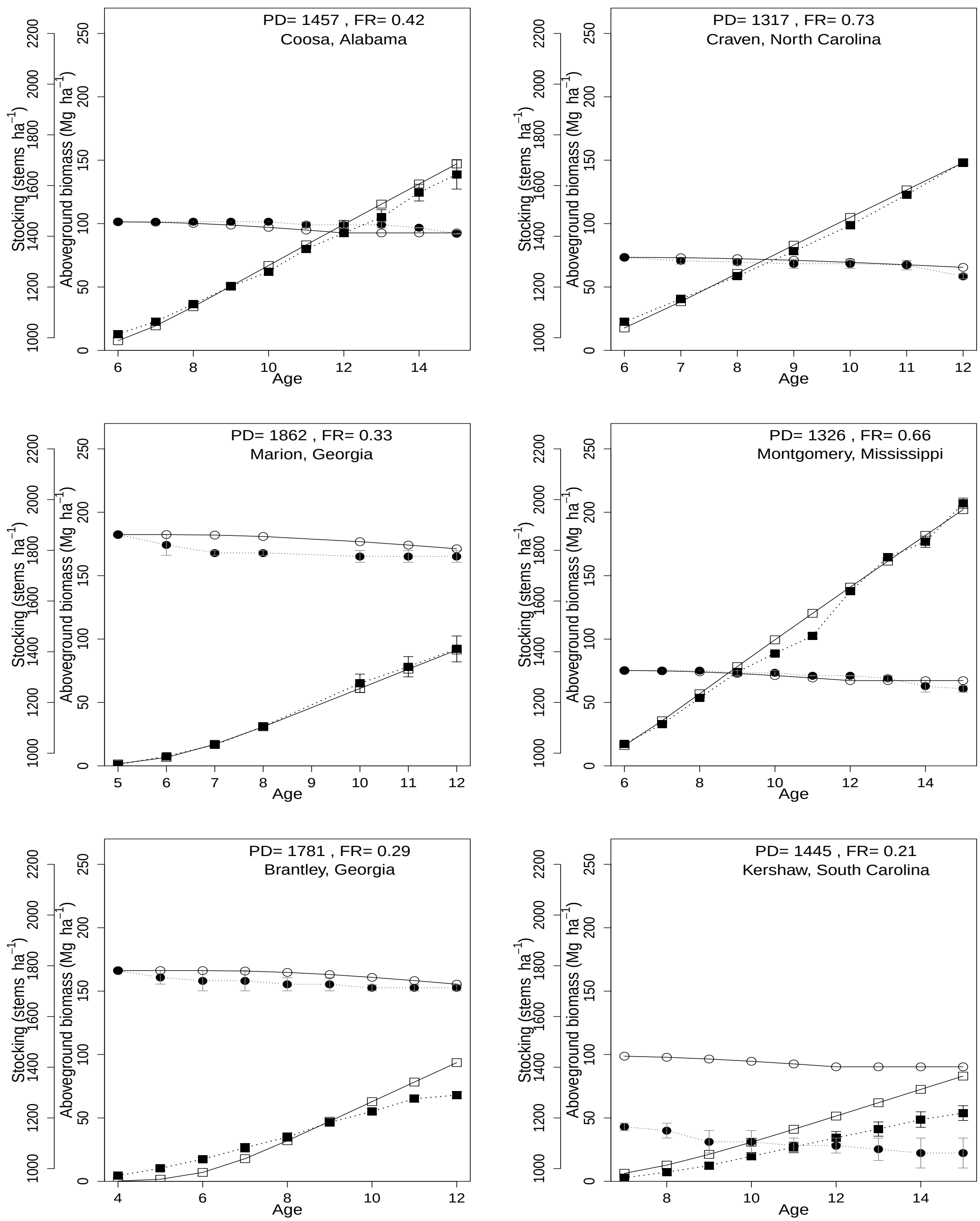

Figure 2.5: The relationship between observed (dotted line, filled rectangles and circles) and 3-PG predicted (solid line, unfilled rectangles and circles) values for aboveground biomass (rectangle) and stand density (circle) in some the study sites. The species specific parameters in the 3-PG to predict biomass and stocking were used from Bryars et al. (2013). Planting density (PD, stems ha^{-1}), FR, and location (county, state) for each installation were given inside the plot.

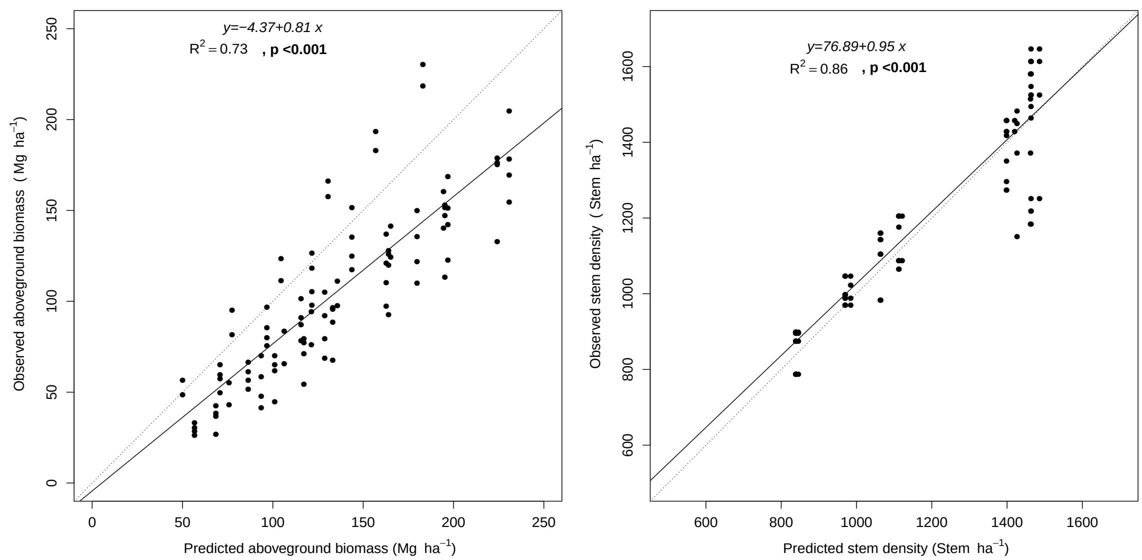

Figure 2.6: Relationship between observed aboveground biomass (Mg ha^{-1}) and modeled aboveground biomass (left) and measured stem density (stem ha^{-1}) and modeled stem density in the control plots of mid-rotation sites which are independent from the study sites listed in Table 4.1. Solid lines represent linear fit between observed and predicted values and dotted lines represent the 1:1 line between observed and predicted values.

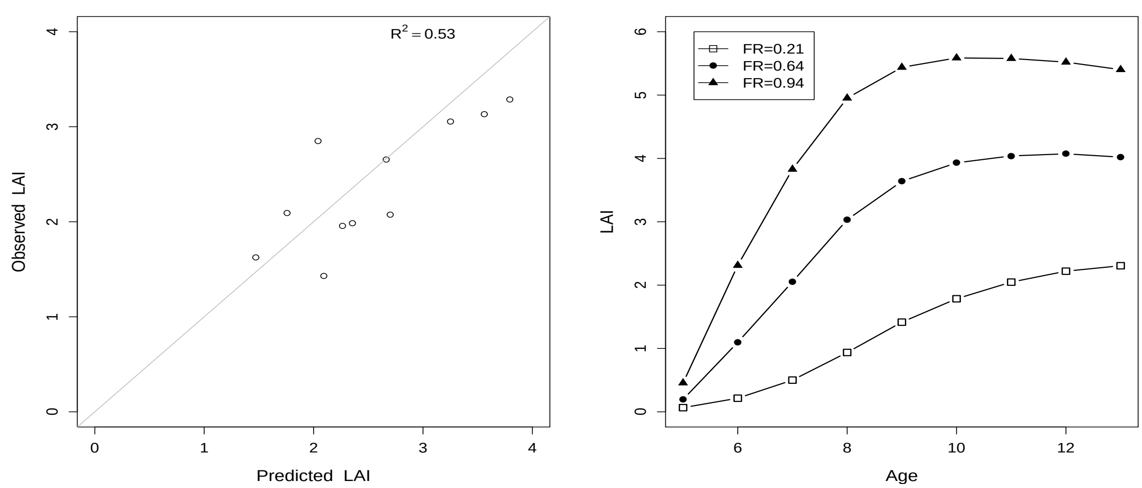

Figure 2.7: Relationship between measured LAI and 3-PG_{lob} predicted LAI (left)and LAI simulations from 3-PG across fertility gradients (right).

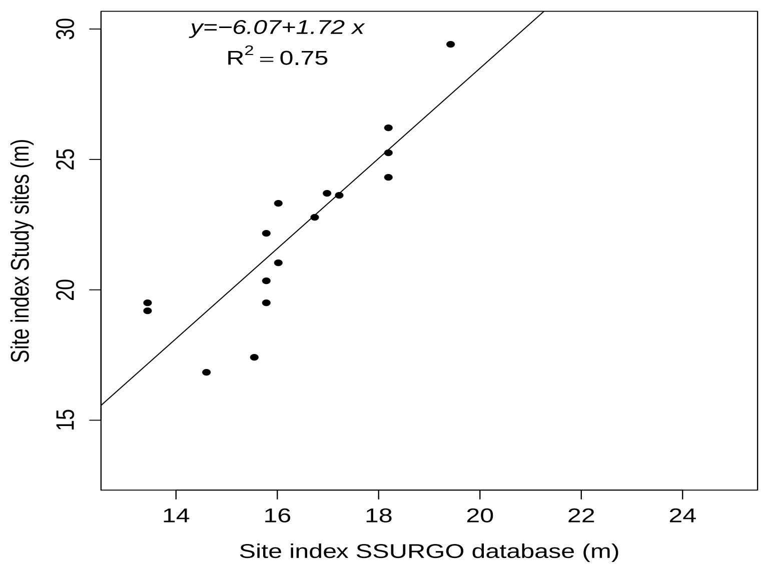

Figure 2.8: The relationship between SSURGO site index at base age 25 derived from base age 50 using Diéguez-Aranda et al. (2005) and the site index in the study sites at base age 25.

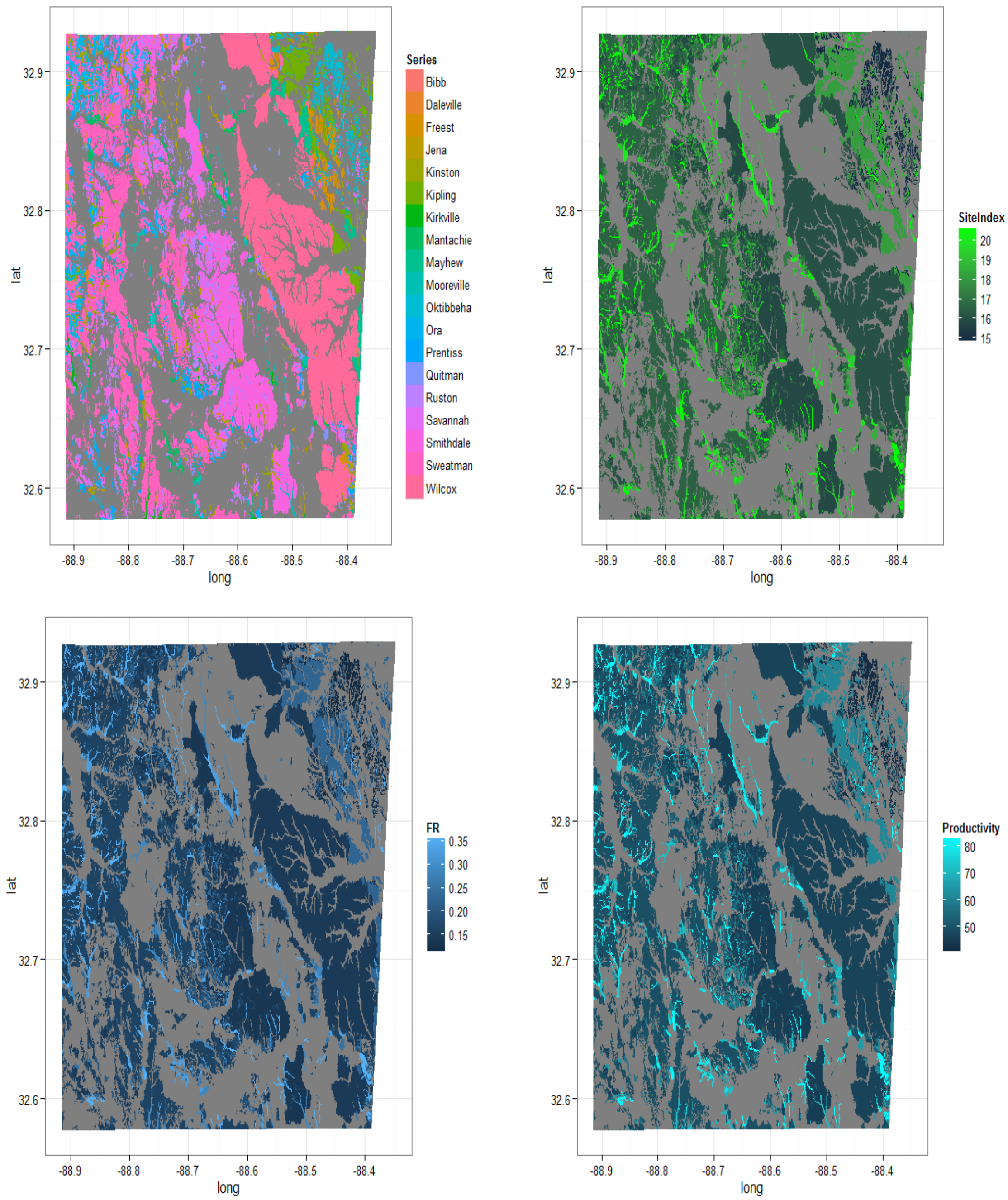

Figure 2.9: Map of 3-PG predicted aboveground biomass (Mg ha^{-1}) for 12-year-old loblolly pine in Kemper County, Mississippi. Top left diagram shows soil series mapped in Kemper County Mississippi based on SSURGO database. Top right diagram shows site index at base 25 calculated from SSURGO site index at base age 50 using base age invariant method developed by Diéguez-Aranda et al. (2005). Bottom left diagram shows FR values based on site index and bottom right diagram shows 3-PG predicted aboveground biomass based on FR values calculated from SSURGO site index.

References

Akers, M. K., Kane, M., Zhao, D., Teskey, R. O., and Daniels, R. F. (2013). Effects of planting density and cultural intensity on stand and crown attributes of mid-rotation loblolly pine plantations. *For. Ecol. Manage.*, 310:468 – 475.

Albaugh, T. J., Allen, H. L., Dougherty, P. M., Kress, L. W., and King, J. S. (1998). Leaf area and above- and belowground growth responses of loblolly pine to nutrient and water additions. *For. Sci.*, 44:317–328.

Albaugh, T. J., Allen, H. L., and Fox, T. R. (2006). Individual tree crown and stand development in *Pinus taeda* under different fertilization and irrigation regimes. *For. Ecol. Manage.*, 234:10–23.

Almeida, A. C., Landsberg, J. J., and Sands, P. J. (2004). Parameterization of 3-PG model for fast-growing *Eucalyptus grandis* plantations. *For. Ecol. Manage.*, 193:179–195.

Amateis, R. L., Liu, J., Ducey, M. J., and Allen, H. L. (2000). Modeling response to midrotation nitrogen and phosphorus fertilization in loblolly pine plantations. *South. J. Appl. For.*, 24:207–221.

Borders, B. and Bailey, R. L. (2001). Loblolly pine-pushing the limits of growth. *South. J. Appl. For.*, 25:69–74.

Bryars, C., Maier, C., Zhao, D., Kane, M., Borders, B., Will, R., and Teskey, R. (2013). Fixed physiological parameters in the 3-PG model produced accurate estimates of loblolly pine growth on sites in different geographic regions. *For. Ecol. Manage.*, 289:501–514.

Burkhart, H. E. and Tomé, M. (2012). *Modeling Forest Trees and Stands.* Springer. Netherlands.

Colbert, S. R., Jokela, E. J., and Neary, D. G. (1990). Effects of annual fertilization and sustained weed control on dry matter partitioning, leaf area, and growth efficiency of juvenile loblolly and slash pine. *For. Sci.*, 36:995–1014.

Coops, N. C., Waring, R. H., and Law, B. E. (2005). Assessing the past and future distribution and productivity of ponderosa pine in the Pacific Northwest using a process model, 3-PG. *Ecol. Model.*, 183:107–124.

Dalla-Tea, F. and Jokela, E. J. (1991). Needlefall, canopy light interception, and productivity of youg intensively managed slash and loblolly pine stands. *For. Sci.*, 37:1298–1313.

Diéguez-Aranda, U., Burkhart, H. E., and Amateis, R. L. (2005). Dynamic site model for loblolly pine (*Pinus taeda* L.) plantations in the United States. *For. Sci.*, 52:262–272.

Dye, P. J. (2001). Modelling growth and water use in four *Pinus patula* stands with the 3-PG model. *South. Afr. For. J.*, 191:53–63.

Dye, P. J., Jacobs, S., and Drew, D. (2004). Verification of 3-PG growth and water-use predictions in twelve *Eucalyptus* plantation stands in Zululand, South Africa. *For. Ecol. Manage.*, 193:197–218.

FNC (2008). Eight year growth and foliar response of young loblolly pine planations to repeated nutrient additions. Bulletin 62, Forest Productivity Cooperative, North Carolina State Univeristy, Virginia Tech and Universidad de Concepciòn, Raleigh, NC.

Fox, T. R., Allen, H. L., Albaugh, T. J., Rubilar, R., and Carlson, C. A. (2007). Tree nutrition and forest fertilization of pine plantations in the southern United States. *South. J. Appl. For.*, 31:5–11.

Gonzalez-Benecke, C., Gezan, S., Albaugh, T., Allen, H., Burkhart, H., Fox, T., Jokela, E., Maier, C., Martin, T., Rubilar, R., and Samuelson, L. (2014). Local and general above-stump biomass functions for loblolly pine and slash pine trees. *For. Ecol. Manage.*, 334:254 – 276.

Gyawali, N. and Burkhart, H. E. (2015). General response functions to silvicultural treatments in loblolly pine plantations. *Can. J. For. Res.*, 45:252–265.

Haywood, J. D. and Burton, J. D. (1990). Phosphorous fertilizer, soils, and site preparation influence loblolly pine productivity. *New For.*, 3:275–287.

Kiser, L. C. and Fox, T. R. (2012). Soil accumulation of nitrogen and phosphorus following annual fertilization of loblolly pine and sweetgum on sandy sites. *Soil Sci. Soc. Am. J.*, 76:2278–2288.

Landsberg, J. and Sands, P. (2011). Chapter 9 - the 3-PG process-based model. In *Physiological Ecology of Forest Production*, volume 4 of *Terrestrial Ecology*, pages 241 – 282. Elsevier.

Landsberg, J., Waring, R., and Coops, N. (2003). Performance of the forest productivity model 3-PG applied to a wide range of forest types. *For. Ecol. Manage.*, 172:199–214.

Landsberg, J. J., Johnson, K. H., Albaugh, T. J., Allen, H. L., and McKeand, S. E. (2001). Applying 3-PG, a simple process-based model designed to produce practical results, to data from loblolly pine experiments. *For. Sci.*, 47:43–51.

Landsberg, J. J. and Waring, R. H. (1997). A generalized model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. *For. Ecol. Manage.*, 95:209–228.

Lu, J., Sun, G., McNulty, S. G., and Amatya, D. M. (2003). Modeling actual evapotranspiration from forested waterwater across the southeastern united states. *J. Am. Wat. Res. Assoc.*, 39:887–896.

McCrady, R. L. and Jokela, E. J. (1995). Growth phenology and crown structure of selected loblolly pine families planted at two spacings. *For. Sci.*, 42:46–57.

Miller, H. G. (1981). Forest fertilization: some guiding concepts. *Forestry*, 54:157–167.

Peduzzi, A., Wynne, R. H., Fox, T. R., Nelson, R. F., and Thomas, V. A. (2012). Estimating leaf area index in intensively managed pine plantations using airborne laser scanner data. *For. Ecol. Manage.*, 270:54 – 65.

Piñeiro, G., Perlman, S., Guerschman, J. P., and Parule, J. M. (2008). How to evaluate models: Observed vs. predicted or predicted vs. observed. *Ecol. Model.*, 216:316–322.

Piatek, K. B. and Allen, H. L. (2001). Are forest floors in mid-rotation stands of loblolly pine (*Pinus taeda*) a sink for nitrogen and phosphorus? *Can. J. For. Res*, 31:1164–1174.

Pinjuv, G., Mason, E. G., and Watt, M. (2006). Quantitative validation and comparison of a range of forest growth model types. *For. Ecol. Manage.*, 236:37–46.

Rodŕiguez, R., Espinosa, M., Real, P., and Inzunza, J. (2002). Analysis of productivity of radiata pine plantations under different silvicultural regimes using the 3-PG process-based model. *Aust. For. J.*, 65:165–172.

Romell, L. (1957). Man-made nature of northern lands. In *Proceedings and papers of the sixth technical meeting of the International Union for Conservation of Nature and Natural Resources*, pages 51–53, Edinburgh. Society for the Promotion of Nature Reserves, London.

Sampson, D. A. and Allen, H. L. (1998). Light attenuation in a 14-year-old loblolly pine stand as influenced by fertilization and irrigation. *Trees*, 13:80–87.

Sampson, D. A., Amatya, D. M., Lawson, C. D. B., and Skagg, R. W. (2011). Leaf area index (LAI) of loblolly pine and emergent vegetaion following a harvest. *Trans. Am. Soc. Agr. Biol. Eng.*, 54:2057–2066.

Sampson, D. A., Wynne, R. H., and Seiler, J. R. (2008). Edaphic and climatic effects on forest stand development, net primary production, and net ecosystem productivity simulated for Coastal Plain loblolly pine in Virginia. *J. Geophys. Res.*, 113:1–14.

Sands, P. J. and Landsberg, J. J. (2002). Parameterization of 3-PG for planation grown *Eucalyptus globulus*. *For. Ecol. Manage.*, 163:273–292.

Stape, J. L., Ryan, M., and Binkley, D. (2004). Testing the utility of the 3-PG model for growth of *Eucalyptus grandis x urophylla* with natural and manipulated supplies of water and nutrients. *For. Ecol. Manage.*, 193:219–234.

Tamm, C. O. (1964). Determination of nutrient requirements of forest stands. *Int. Rev. For. Res.*, 1:115–170.

Tickle, P. K., Coops, N. C., Hafner, S. D., and Team, T. B. S. (2001). Assessing forest productivity at local scales across a native eucalypt forest using a process model, 3PG-SPATIAL. *For. Ecol. Manage.*, 152:275–291.

Van Deusen, P. C., Sullivan, A. D., and Matvey, T. G. (1981). A prediction system for cubic foot volume of loblolly pine applicable through much of its range. *South. J. Appl. For.*, 5:186–189.

Vega-Nieva, D. J., Tomé, M., Tomé, J., Fontes, L., Soares, P., Ortiz, L., Basurco, F., and Rodríguez-Soalleiro, R. (2013). Developing a general method for the estimation of fertility rating parameter of the 3-PG model: application in *Eucalyptus globulus* plantations in Northwestern Spain. *Can. J. For. Res.*, 43:627–636.

Vose, J. M., Dougherty, P. M., Long, J. N., Smith, F. W., Gholz, H. L., and Curran, P. J. (1994). Factors infuencing the amount and distribution of leaf area of pine stands. *Ecol. Bull.*, 43:102–114.

Vose, M. and Allen, H. L. (1988). Leaf area, stemwood growth, and nutrition relationships in loblolly pine. *For. Sci.*, 34:547–563.

Will, R. E., Barron, G. A., Burkes, E. C., Shiver, B., and Teskey, R. O. (2001). Relationship between intercept radiation, net photosynthesis, respiration, and rate of stem volume growth of *Pinus taeda* and *Pinus elliottii* stands of different densities. *For. Ecol. Manage.*, 154:155–163.

Zhao, D., Kane, M., Borders, B., Subedi, S., and Akers, M. (2012). Effects of cultural intensity and planting density on stand-level aboveground biomass production and allocation for 12-year-old loblolly pine plantations in the Upper Coastal Plain and Piedmont of the southeastern United States. *Can. J. For. Res*, 42:111–122.

Chapter 3

Predicting Fertility Rating (FR) in the Process Model 3-PG for Loblolly Pine Plantation Using Soil Physical and Chemical Properties

Abstract

The soil fertility rating (FR) in the 3-PG model was determined using a geocentric approach in a two step procedure. Soil physical and chemical properties from A-horizon soil were used to predict site index which was then used to predict the fertility rating (FR). Two modeling approaches were used to predict FR from soil properties. First, ordinary least squares method of multiple linear regression was used which selected Ca, K, and sand percentage as the significant predictor variables. However, ordinary least squares method of multiple regression was found unsuitable to model site index from soil properties due to severe multicollinearity. Second, partial least squares re-

gression was used which selected N, Ca, Mg, C, and sand percentage as the significant predictors. The partial least squares regression approach adequately addressed the multicollinearity in the data and produced a suitable model to predict site index and subsequently FR. Selected soil variables described 78% of the variance in the FR. When the FR values obtained using the partial least squares regression were input into the 3-PG model 83% of the variance in the observed aboveground biomass was explained by the 3-PG simulated aboveground biomass.

3.1 Introduction

Site quality determines potential productivity of forest ecosystem. Site quality is to a large extent determined by the physical, chemical, and biological properties of soil as modified by anthropogenic factors such as fertilization (Augusto et al., 2002). However, site quality is also influenced by climatic factors such as rainfall, temperature, and frost-free growing season. It is difficult to quantify site quality from soil properties in forested ecosystem because of the complex relationship between soil properties and stand productivity (Landsberg et al., 2003; Dye et al., 2004).

Site quality is a driving variable in both deterministic process based models and empirical growth and yield models of forest ecosystems. Site index is the most widely used measure of site quality in these models because of the high correlation between site index and productivity (Burkhart and Tomé, 2012). Numerous soil-site studies have attempted to relate site index to measured soil properties (Carmean, 1975; Hagglund, 1981; Bravo and Montero, 2001; Fontes et al., 2003). These soil-site studies often used regression techniques to predict site index from the edaphic and topographic properties of a site (Carmean, 1975; Baker and Broadfoot, 1979; Wang, 1995; Beaulieu et al., 2011). Many soil-site methods were implemented using ordinary least squares method of multiple linear regression where some measure of fertility is used as a response variable and soil variables are used as the regressors (Carmean, 1975; Hagglund, 1981; Fontes et al., 2003). Multiple linear regression has several weakness such as low precision in diverse topography and geologic formations (Verbyla and Fisher, 1989), multicollinearity (Fontes et al., 2003; Kayahara et al., 1995), and lack of linearity in many ecological relationships. Partial least squares (PLS) regression is a multivariate regression method used to assess the relationship between one or multiple response variables and multiple predictors (Wold et al., 2001). PLS regression decomposes the predictor matrix into orthogonal scores and loadings and the response variable is regressed on the columns of score matrix (Mevik and Wehrens, 2007; Hervè, 2010).

The 3-PG model has been calibrated and tested on several commercially important tree species (Dye, 2001; Landsberg et al., 2003; Stape et al., 2004; Almeida et al., 2010; Bryars et al., 2013). FR is a parameter in 3-PG that links soil fertility to plant productivity. In the past FR has been assigned using subjective procedures (Landsberg and Sands, 2011). It has often been used as a tunable parameter that is adjusted in the simulations to match the simulated values with the observed data (Landsberg et al., 2003). In other instances expert opinion has been used to estimate FR (Fontes et al., 2006).

Soil-site methods have been used to estimate soil fertility and determine FR as an input parameter in 3-PG including soil physical properties and chemical properties (Almeida et al., 2010; Sampson et al., 2008; Stape et al., 2004; Vega-Nieva et al., 2013). Theoretically, soil fertility is best estimated when the physical, chemical, and biological properties are used. For example when Vega-Nieva et al. (2013) used chemical and physical properties to estimate soil fertility they had better fit statistics than researchers who used only chemical properties (Stape et al., 2004) or physical properties (Sampson et al., 2008). The present study was carried out to understand the potential of using soil physical and chemical properties of the A-horizon to estimate FR values. Our research objective was to develop a predictive equation for FR based on measured soil properties.

3.2 Materials and Methods

This study used measured soil properties in the control plots at fifteen installations of a fertilizer study established in juvenile loblolly pine plantations in the southeastern United States (Figure 3.1) to determine the fertility rating (FR) used in 3-PG. The fertilization trial was established in the 1990s as an incomplete factorial design of nutrient dose and application frequency to optimize growth and fertilizer use efficiency. However, the control plots were left unfertilized. Plot size ranged from 0.028 ha to 0.059 ha. Stand age at fertilization averaged 4 years. First generation open pollinated seedlings were planted at all sites. The installations covered a wide range of soil types, stand ages, and climatic conditions across the southeastern US (Table 3.1).

Surface soil (0-15 cm) samples from the control plots were collected with a bucket auger prior to study establishments as a composite of at least 10 randomly located cores. The composite samples were thoroughly mixed and stones were removed. Samples were air-dried and passed through a 2 mm sieve and then analyzed for chemical and physical properties using standard methods. Soil C and N were determined by dry combustion on a CNS analyzer. P, K, Ca, and Mg were extracted using Mehlich 3 extraction procedure (Mehlich, 1984) and analyzed on an Inductively Coupled Plasma (ICP) spectrophotometer. Soil texture was determined using the hydrometer method. Soil pH was measured by a combination electrode in the supernatant of 2:1 water to soil slurry.

Site index in each control plot was determined from tree total height measured at age 11 using a dynamic site index model for loblolly pine (Diéguez-Aranda et al., 2005). This dynamic site index model is base-age invariant and estimates site index from any height-age pair. Average height of the tallest 80% of trees on each plot was used to determine dominant height (Gyawali and Burkhart, 2015). The FR values in each plot were then calculated from measured site index using the equation developed in chapter 2 page 24.

$$\mathrm{FR} = \frac{1.19}{1 + \mathrm{e}^{-(-5.899+0.245\ \mathrm{SI})}}$$

Soil chemical and physical properties were then used as independent parameters to predict FR using two methods of regression analysis: 1) Multiple linear regression using ordinary least squares; and 2) partial least squares regression. Soil data were averaged by site for the regression analysis.

First multiple linear regression was used to examine the relationship between FR and the soil physical and chemical properties measured. Mean Square Error (MSE), Adjusted R^2, Predicted Residual Sum of Squares (PRESS), C_p, and Akaike Information Criterion (AIC) were used to evaluate candidate models and identify the best regressor variables in the candidate models. We performed exhaustive variable search in which all possible combinations of soil variables were used to search the best subsets of the soil variables for predicting FR based on MSE, Adjusted R^2, PRESS, C_p, and AIC. In addition to exhaustive variable search, we used N, Ca, and sand percentage as the explanatory variables to model FR. Several previous works on loblolly pine have described N, Ca, and sand percentage as the important determinants of soil fertility and stand productivity in the southeastern United States (Fox et al., 2007; Allen et al., 1990; Richter et al., 1994; Albaugh et al., 1998). To assess multicollinearity, Variance Inflation Factor (VIF) for each variable was calculated as:

$$\mathrm{VIF_i} = \frac{1}{1 - \mathrm{R_i^2}}$$

where R_i^2 is the R^2 value when i^{th} predictor is regressed with the rest of the predictors. Studentized residuals (Lund, 1975) were computed and used to identify outliers. It was expected that 5% of the studentized residuals could be outside of ±2 margin by chance alone, so a Bonferroni adjustment to the p-value was used (Fox, 2008). The Bonferroni adjusted outlier test reports the Bonferroni adjusted p-value for the largest absolute studentized residual, using the t-distribution with n-k-2 degrees of freedom where n is the number of observations k is the number of parameters in the model. These analyses indicated that the site in Maregno County, Alabama (denoted as 183901) was a potential outlier (Figure 3.2). Therefore, the results were compared with and without this potential outlier to determine its impact.

We used PLS regression (Wold et al., 2001) to address multicollinearity inherent in the soil data that are problems in ordinary least square method of multiple linear regression. PLS regression is a multivariate approach that combines features from principal component analysis and multiple linear regression (Mevik and Wehrens, 2007). Principal component analysis is suboptimal for prediction purposes because it only captures the maximum variation in the predictor matrix. PLS regression chooses scores and loadings to describe the maximum possible covariance between predictor and response variables (Mevik and Wehrens, 2007). The columns of score matrix are called latent variables or latent vectors. To choose the optimum number of latent vectors, the Predicted Residual Sums of Squares (PRESS) statistics approach suggested by (Hervè, 2010) was used. In addition, Root Mean Square Error Prediction (RMSEP), the percentage of explained variance for predictors, and the percentage of explained variance for the response variable were calculated. In order to select the best predictors of FR, the Variable Importance for Projection (VIP) statistics was used (Wold, 1995). VIP summarizes the contribution of each predictor in the model. Predictors with VIP values less than 0.8 were culled from the model. We subtracted the mean from each predictor and then divide by standard deviation prior to PLS regression. In order to examine outliers, we calculated distance from each point in the PLS regression model with respect to the predictors (Distances from x-model) and the responses (Distances from y-model). Any point dramatically farther from the model than the rest was considered as the potential outlier (SAS Institute Inc, 2008). Distances from x-model identify how well the predictor scores describe observations and distances from y-model identify how well observations are described by the y-scores (Wold et al., 2001).

The best model for each regression method - partial least squares and ordinary least squares was selected and leave-one-out cross validation was carried out to generate FR values. FR values derived from leave-one-out cross validation procedure were input int the 3-PG model to generate total aboveground biomass and stand density values for each control plot. Weather data including mean monthly temperature, rainfall, and vapor pressure deficit were obtained from Daymet Surface and Climatic Summaries (`www.daymet.org`). We used the parameter set developed for 3-PG by Bryars et al. (2013) with several modification (Table 3.2). The projected specific leaf area for mature stands (SLA1) was set to be 4 (Akers et al., 2013; Sampson et al., 2011) and tSLA was set as 6 (Dalla-Tea and Jokela, 1991; Will et al., 2001; Colbert et al., 1990; McCrady and Jokela, 1995). The light extinction coefficient for APAR was set to be 0.69 (Sampson and Allen, 1998). The value of α_{C_x} was set at 0.053 which is the point between the vlaues of 0.055 and 0.0485 used by Landsberg et al. (2001) and Bryars et al. (2013), respectively for loblolly pine.

The predicted values from 3-PG using the value of FR determined from measured soil properties were compared with measured values. A linear model was fitted between observed total aboveground biomass and predicted aboveground biomass and the null hypothesis of slope is equal to 1 was tested. Similarly, a linear model was fit between observed stem density and model simulated stem density and the null hypothesis of slope is equal to 1 was tested using the predicted value as a regressor Piñeiro et al. (2008).

3.3 Results

As expected, high correlations among the soil properties were observed (Table 3.3). For example, very high correlations were observed between N and C (0.92), Ca and N (0.79), and K and Mg (0.83), and silt and sand percentages (0.95). Strong positive correlations were also observed between FR and N and FR and Ca and lower negative correlations were observed between FR and sand percentage.

3.3.1 Ordinary Least Squares Method of Regression

When ordinary least squares (OLS) method of multiple linear regression was carried out using FR as a response variable and N, P, K, Ca, Mg, C, pH, sand, and silt as predictors, none of the predictors were significant at a type I error rate of 0.05. We observed very high values of VIF and severe multicollinearity issues such as negative coefficients for P and C and small coefficients for Ca and Mg (Table 3.4). VIF values were greater than 10 for N, P, K, Mg, C, sand proportion, and silt proportion. Sign of coefficients for P, Mg, and C were negative and coefficients for K, Ca, and Mg were very small.

Table 3.5 shows four best fit models from OLS based on MSE. The model with K, Ca, and C had the lowest MSE and the highest adjusted R^2. This model had the second lowest PRESS, AIC, and Cp statistics. The model with just K and Ca had the lowest PRESS, AIC, and Cp statistics and the third lowest MSE and the third highest adjusted R^2. The model with the K, Ca, and C to predict FR explained about 48% of the variance in FR. When studentized residuals were calculated, the same observation which was flagged as an outlier in Figure 3.2 had a studentized residual of 3.68 (Figure 3.3). When this studentized residual was tested using the Bonferroni outlier test, the Bonferroni adjusted p-value was found to be greater than 0.05 suggesting this site (183901) should be classified as an outlier.

Table 3.5 shows the top four models based on MSE using the dataset without the potential outlier. The best fit model had K, Ca, and sand as the predictors. This model had the lowest MSE, the highest adjusted R^2, and the lowest PRESS, AIC, and Cp. The model explained about 75% of the variability in the FR. Without the outlier, there was a large increase in adjusted R^2 and decrease in MSE, AIC, and PRESS. For example adjusted R^2 increased from 48% to 75% and AIC decreased from -9.6 to -24.8. Figure 3.4 shows that predicted values of FR from linear regression using Ca, K, and sand percentage corresponded well with the FR values derived from site index. When N, Ca, and sand percentage were used as the predictors to model FR using the dataset without the potential outlier, an adjusted R^2 value of 61% was observed. The values for MSE, PRESS, C_p, and AIC were 0.0131, 0.2658, 1.6606, and -18.4072, respectively. Table 3.6 shows coefficients and VIF values for N, Ca, and sand percentage.

3.3.2 Partial Least Squares Method of Regression

The soil variables N, C, Ca, Mg, sand, and silt percentages all had VIP>0.8 in the PLS regression (Table 3.7). When PLS regression was carried out using these variables, cumulative percentage of variance explained by first three latent factors on FR and predictors were 56% and 89%, respectively. The PLSR coefficients and the goodness of fit statistics for three latent vectors are shown in Table 3.8. The PRESS statistics continued to drop with the addition of latent vector indicating the model is not over fitted. When the distance from each point to the PLS model with respect to predictors and the responses were plotted, we found the site flagged as an outlier in Figure 3.2 was dramatically farther from the model than the rest of the points in the predictor space (Figure 3.3).

The PLS regression without the outlier confirmed N, C, Ca, Mg, and sand percentage as the significant variables at a VIP > 0.8 (Table 3.8). The fact that the same variables are in both models suggests issues with multicollinearity are corrected. When the PLS regression was carried out using the significant variables, cumulative percentages of variance explained by first three latent factors on FR and predictors were 78% and 88%, respectively. Both PRESS and RMSEP statistics continue to drop when latent vectors were added . Similary, PRESS and RMSEP decreased when the observation identified as an outlier was removed. Scatterplot between FR values derived from site index and predicted FR values from PLS regression showed strong linear relationship (Figure 3.4).

3.3.3 3-PG Predictions

The PLS regression model had better-fit statistics to predict FR than did the OLS model. PLS regression with N, Ca, Mg, C, and sand percentage explained about 78% of the variance in FR. Using the PLS regression, leave-one-out cross validated FR values were generated and input into the 3-PG model to predict aboveground biomass and stand density in the control plots at the 21 locations. When compared with the observed values, the 3-PG predicted aboveground biomass explained about 83% of the variance in observed aboveground woody biomass and 3-PG predicted stand density explained about 87% of the variance in observed stand density (Figure 3.5). The slope of the relationship between observed aboveground biomass and predicted aboveground biomass had 95% of the confidence interval between 0.894 and 0.995. Similarly, the slope of the relationship between observed stem density and predicted stem density was not found to be significantly different from 1.

3.4 Discussion

High correlations among the soil variables were observed in this study. Similar correlations among edaphic variables were reported by Bravo and Montero (2001); Wang et al. (2012); Kayahara et al. (1995). High correlations among predictor variables caused multicollinearity which resulted in ordinary least square coefficients to have the wrong sign, wrong size, and high standard error. Similar results regarding multicollineartity associated with soil-site methods were reported by Kayahara et al. (1995) when they examined the relationship between site index of western hemlock (*Tsuga heterophylla*) and forest floor, mineral soil, and foliar nutrient status. Our final model to predict FR from the soil variables using OLS multiple linear regression included K, Ca, and sand percentage. Using multiple linear regression about 75% of the variation in FR was explained by the Ca, K, and sand percentage. Multicollinearity caused exclusion of N, which was highly correlated with FR. Multicollinearity can cause errorneous exclusion of the predictors with high true significance (Graham, 2003).

Several approaches have been used to address problems with multicollinearity in soil-site studies. These include classification approaches by Verbyla and Fisher (1989) to predict sites suitable for ponderosa pine based on edaphic variables and vegetation. Discriminant analysis was used by Harding et al. (1985) to categorize site quality based on growth using physiographic, edaphic, and vegetation properties. Other approaches include multivariate regression approach such as principal component regression proposed by Morzuch and Ruark (1991) and used by Kayahara et al. (1995) to predict site index using forest floor and mineral soil chemical measures and path analysis used by Guan et al. (2013) to predict adsorption of a pesticide dinoseb from soil based properties. In this study, we used PLS regression. PLS regression chooses scores and loadings to describe maximum possible covariance between predictor and response variable(Mevik and Wehrens, 2007). PLS may be superior to principal component regression which only captures the predictor matrix characteristics and may thus be suboptimal for prediction purposes.

PLS regression selected N, C, Ca, Mg, and Sand as the significant predictors of FR based on a criteria of VIP > 0.8. N has been identified as one of the nutrient most limiting loblolly pine productivity in the southeastern US (Allen et al., 1990; Haywood et al., 1997; Fox et al., 2007). Selection of N based on its high VIP value to predict FR in this study was consistent with those studies. In addition to N, the model indicated significant effect of C on FR. Soil C has been highlighted as the limiting factor in sandy soils of the southeastern United States (Hunt et al., 1996; Novak et al., 2007, 2009). Higher soil C improves soil productivity by increasing cation exchange capacity and water holding capacity (Hunt et al., 1996; Liang et al., 2006). Among the cations included in the model to predict FR, PLS analysis selected Ca and Mg at a VIP level of 0.8. The limitation of soil Ca and Mg in acidic southeastern soil has been highlighted in a few studies (Huntington, 2000; Richter et al., 1994). Richter et al. (1994) stated that depletion of Ca and Mg after 28 years of forest development from the upper layer of soil is almost 37 times and 6 times higher than that of K. They further stated that K could be buffered in the soil by leaching K from the canopy and the forest floor in addition to mineral weathering, so it remained relatively constant through time. Ca is also important in enhancing uptake of nitrate N (Hodges, 2010) and regulating the assimilation of other nutrients in acidic soils by modifying microbial activities and pH. Soil pH was not selected as a significant predictor at a VIP level of 0.8. Soil pH is not closely linked to soil fertility in loblolly pine forests as loblolly pine naturally occurs on acidic soils and is thus well adapted to acidic soils (Binkley and Fisher, 2013).

Among sand, silt, and clay percentage; sand content was identified as significant at a VIP level of 0.8. In the southeast sandy soils tend to be more nutrient deficient then finer textured soils (Albaugh et al., 1998; Carlson et al., 2008). Sandy soils have lower P availability and lower N mineralization, both of which decreases forest productivity (Reich et al., 1997; Almeida et al., 2010). Reich et al. (1997) reported soil texture as an important predictor for N mineralization and above ground net primary productivity. Similarly, Almeida et al. (2010) made an assertion that the effect of soil fertility on growth is affected by both chemical and physical factors. They reported lowest soil fertility in sandy soils and highest in clay-loam soils supporting the negative correlations between FR and sand percentages observed in our data.

Partial least square regression of FR with N, Ca, Mg, C, and sand proportion had a slightly higher R^2 than the best model from OLS multiple linear regression (0.80 vs 0.78). However because of the higher multicollinearity among variables, ordinary least squares method of multiple linear regression likely have poorer prediction than the PLS model. When leave-one-out cross validated FR values from best fit PLSR model were used as the inputs in 3-PG about 83% of the variation in observed aboveground woody biomass and 87% of the variation in observed stem density is explained by predicted aboveground woody biomass and predicted stand density.

3.5 Conclusion

The PLS regression approach accurately predicted FR based on physical and chemical properties of A-horizon soil. Using these predicted value of FR, the 3-PG model accurately predicted loblolly pine productivity in the southeastern US. Multicollinearity was a problem in the OLS multiple regression and will likely limit the usefulness of OLS multiple linear regression. Multicollinearity makes the regression coefficients highly unstable. PLS regression effectively addressed the effect of multicollinearity and thus allowed inclusion of important soil variables that determine soil fertility in the southeastern United States. PLS regression selected N, Ca, Mg, C, and sand percentage as the significant predictors of FR. These results showed that PLS regression is a better approach than the OLS multiple linear regression approach in modeling FR based on soil properties. This suggests that PLS may also have utility in other situations where soil properties are used to predict tree growth or other ecosystem properties.

Table 3.1: Location (State, County), physiographic regions, latitude / longitude, soil series, average annual precipitation, and average maximum and minimum temperature (^{0}C) for study sites used to determine relationship between FR and soil variables.

Study site	**State, County**	**Physiographic Province**	**LAT / LONG**	**Soil Series**	**Precipitation (mm yr $^{-1}$)**	**Temperature max / min**
180101	South Carolina, Kershaw	Piedmont	34.45 / -80.50	Lakeland	1208.5	32.6 / -0.5
180301	Georgia, Oglethorpe	Piedmont	33.89 / -82.91	Iredell	1237.3	32.9 / -0.6
180601	Virginia, Brunswick	Piedmont	36.68 / -77.99	Cecil	1165.6	31.7 / -3.0
180801	North Carolina, Craven	LCP	35.23 / -76.97	Leaf	1235.9	32 / 0.9
181201	Alabama, Coosa	Piedmont	32.91 / -86.38	Louisa	1412.6	32.6 / 0.3
182201	Georgia, Wilkes	Piedmont	33.81 / -82.96	Appling	1240.6	32.9 / -0.3
183101	Louisiana, Sabine	WGCP	31.72 / -93.56	Sacul	1370.6	33.8 / 1.2
183102	Louisiana, Vernon	WGCP	31.34 / -93.18	Sacul	1489.8	33.8 / 2.1
183901	Alabama, Marengo	EGCP	32.37 / -87.84	Lenoir	1431.5	33.3 / 1.2
184201	Georgia, Brantley	LCP	31.34 / -81.82	Leon	1310.3	33.2 / 4.3
184202	Georgia, Brantley	LCP	31.34 / -81.83	Leon	1308.2	33.2 / 4.3
184301	Georgia, Marion	UCP	32.17 / -84.63	Troup	1275.9	33.1 / 2.0
184401	Arkansas, Bradley	WGCP	33.49 / -92.13	Stough	1402.1	33.5 / 0.8
184501	Alabama, Marengo	EGCP	32.25 / -87.55	Brantley	1418.5	33.3 / 1.4
184801	Texas, Newton	WGCP	30.48 / -93.78	Evadale	1496.8	33.7 / 3.7

Table 3.2: 3-PG parameters and their values for loblolly pine used in this study

	Parameters	Meaning	Unit	Value
1	pFS2	Ratio of foliage:stem partitioning at stem diameter = 2 cm		0.40
2	pFS20	Ratio of foliage:stem partitioning at stem diameter = 20 cm		0.25
3	StemConst	Constant in stem mass diameter relationship		0.10
4	StemPower	Power in stem massvdiameter relationship		2.50
5	pRx	Maximum fraction of NPP to roots		0.40
6	pRn	Minimum fraction of NPP to roots		0.20
7	SLA0	Projected specific leaf area at the beginning of plantation	m^2 Kg^{-1}	6.40
8	SLA1	Projected specific leaf area for mature stand	m^2 Kg^{-1}	4.00
9	tSLA	Age at which SLA is mean of SLA0 and SLA1	year	6.00
10	k	Extinction coefficient for APAR by canopy		0.69
11	fullCanAge	Age at full canopy cover	year	4.00
12	MaxIntcptn	Maximum proportion of rainfall intercepted by canopy		0.20
13	LAImaxIntcptn	LAI for maximum rainfall interception		5.00
14	α_{Cx}	maximum canopy quantum efficiency	molC $molPAR^{-1}$	0.053
15	MaxCond	Maximum canopy conductance	m s^{-1}	0.006
16	LAIgcx	Canopy LAI for maximum canopy conductance		3.00
17	CoeffCond	Defines stomatal response to VPD	$mbar^{-1}$	0.02
18	BLcond	Canopy boundary layer conductance	m s^{-1}	0.10
19	wSx1000	Maximum stem mass per tree at 1000 trees ha^{-1}	kg $tree^{-1}$	235.00
20	thinPower	Power in self thinning law		1.60
21	mF	Fraction of mean foliage biomass per tree on dying trees		0.00

22	mR	Fraction of mean root biomass per tree on dying trees		0.20
23	mS	Fraction of mean stem biomass per tree on dying trees		0.40
24	fracBB0	Branch and bark fraction at stand age 0		0.40
25	fracBB1	Branch and bark fraction for mature stand		0.10
26	tBB	Age at which brak fraction is mean of fracBB0 and fracBB1		15.00
27	gammaFx	Maximum litterfall rate	$month^{-1}$	0.042
28	gammaF0	Litterfall rate at age 0	$month^{-1}$	0.001
29	tgammaF	Age at which litterfall rate is mean of gammaFx and gammaF0		18.00
30	Rttover	Average monthly root turnover rate		0.0168
31	m0	Value of m when FR is zero		0.10
32	fN0	Value of fN when FR is zero		0.50
33	Tmin	Minimum temperature for growth	^0C	4
34	Topt	Optimum temperature for growth	^0C	25
35	Tmax	Maximum temperature for growth	^0C	38
36	kF	Number of days production lost for each frost day		1
37	MaxAge	Maximum stand age used to compute relative age		40
38	nAge	Power of relative age in age modifier		3
39	rAge	relative age to make age modifier 0.5		0.20
40	y	NPP to GPP ratio		0.47

Table 3.3: Pearson's correlation matrix of fertility rating derived from site index and soil based variables

	FR	N	P	K	Ca	Mg	C	pH	SANDP	SILTP	CLAYP
FR	1.00	0.50	0.05	0.05	0.56	0.19	0.32	0.21	-0.32	0.26	0.15
N	0.50	1.00	0.34	0.36	0.79	0.59	0.92	0.07	-0.12	0.05	0.24
P	0.05	0.34	1.00	0.77	0.64	0.52	0.48	-0.73	0.20	-0.41	0.69
K	0.05	0.36	0.77	1.00	0.69	0.83	0.43	-0.47	0.10	-0.20	0.32
Ca	0.56	0.79	0.64	0.69	1.00	0.70	0.74	-0.16	-0.10	-0.01	0.36
Mg	0.19	0.59	0.52	0.83	0.70	1.00	0.51	-0.07	-0.04	-0.04	0.26
C	0.32	0.92	0.48	0.43	0.74	0.51	1.00	-0.12	-0.03	-0.06	0.29
pH	0.21	0.07	-0.73	-0.47	-0.16	-0.07	-0.12	1.00	-0.25	0.43	-0.60
SANDP	-0.32	-0.12	0.20	0.10	-0.10	-0.04	-0.03	-0.25	1.00	-0.95	-0.08
SILTP	0.26	0.05	-0.41	-0.20	-0.01	-0.04	-0.06	0.43	-0.95	1.00	-0.23
CLAYP	0.15	0.24	0.69	0.32	0.36	0.26	0.29	-0.60	-0.08	-0.23	1.00

Table 3.4: Parameter estimates, their respective p-values, and variance inflation factor for each predictors when ordinary least squares method of regression was used to model FR from N (g kg^{-1}), P (mg kg^{-1}), K(mg kg^{-1}), Ca (mg kg^{-1}), Mg (mg kg^{-1}), C (g kg^{-1}), pH, sand percentage, and silt percentage from the A-horizon.

Coefficient	Estimate	p-value	VIF
Intercept	1.832	0.531	0
N	0.3123	0.533	28.5
P	-0.004	0.665	10.02
K	0.001	0.855	25.11
Ca	0.0005	0.308	9.92
Mg	-0.002	0.586	16.70
C	-0.0116	0.406	14.65
pH	0.048	0.858	6.12
SAND	-0.019	0.601	36.36
SILT	-0.017	0.642	42.86

Table 3.5: Top four ordinary least squares models based on mean squared error, adjusted R^2 values, PRESS, Cp, and AIC statistics using exhaustive variable selection in which all possible groupings of explanatory variables was assessed. The upper table represents model parameters and fit statistics using all the dataset and the lower table represents model parameters and fit statistics using the dataset without the potential outlier

	Model with potential outlier included	MSE	Adj R^2	PRESS	Cp	AIC
1	$FR = 0.432 - 2.77\times10^{-3}$ K + 7.0×10^{-4} Ca - 4.5×10^{-3} C	0.02456	0.48	0.43074	-0.92603	-9.63210
2	$FR = 0.360 + 0.41$ N + 4.4×10^{-4} Ca - 0.015 C - 1.36×10^{-3} Mg	0.02519	0.46	0.59492	0.66314	-8.68261
3	$FR = 0.378 - 2.57\times10^{-3}$ K + 5.43×10^{-4} Ca	0.02545	0.46	0.41208	-2.13300	-9.79136
4	$FR = 0.392 + 0.165$ N - 2.28×10^{-3} K + 5.89×10^{-4} Ca - 8.98×10^{-3} C	0.02547	0.46	0.51836	0.72678	-8.51497

	Model with potential outlier excluded	MSE	Adj R^2	PRESS	Cp	AIC
1	$FR= 0.726 - 1.72\times10^{-3}$ K + 4.65×10^{-4} Ca - 5.46×10^{-3} Sand	0.00831	0.75	0.12718	-1.15984	-24.83532
2	$FR= 0.248 - 1.70\times10^{-3}$ K + 4.79×10^{-4} Ca - 5.06×10^{-3} Silt	0.00868	0.74	0.13989	-0.94363	-24.22349
3	$FR= 0.701 - 1.17\times10^{-3}$ P - 1.49×10^{-3}K + 4.80×10^{-4} Ca - 5.06×10^{-3} Sand	0.00895	0.74	0.13580	0.69666	-23.25664
4	$FR= 0.726 - 1.80\times10^{-3}$ K + 5.12×10^{-4} Ca - 1.2×10^{-3} C - 5.2×10^{-3} Sand	0.00896	0.74	0.12732	0.69736	-23.25457

Table 3.6: Parameter estimates, their respective p-values, and variance inflation factor when N (g kg^{-1}), Ca (mg kg^{-1}), and sand percentage from the A-horizon were used to model FR using ordinary least squares method of regression.

Coefficient	Estimate	p-value	VIF
Intercept	0.7877	0.01	
N	0.0650	0.42	2.65
Ca	0.0002	0.10	2.64
Sand	-0.0070	0.04	1.01

Table 3.7: Variable importance in projection (VIP) values for the candidate soil variables in different stages of partial least square regression analysis for estimation of fertility rating (FR). Variables with VIP values less than 0.8 were culled as insignificant during successive stages unless every variable had VIP value greater than or equal to 0.8.

	N	P	K	C	Ca	Mg	pH	SAND	SILT	CLAY
Stage 1	1.25	0.61	0.67	1.0	1.68	0.81	0.77	0.98	1.01	0.71
Stage 2	1.04			0.84	1.29	0.80		0.98	0.96	
WITHOUT 183901										
Stage 1	1.34	0.58	0.73	1.08	1.60	0.90	0.58	1.04	0.95	0.64
Stage 2	1.18			0.97	1.31	0.80		0.87		

Table 3.8: Partial least square regression coefficients and fit statistics of FR vs. soil based properties. The data were centered and scaled prior to analysis. In each stage predictor variables were trimmed based on VIP and size of coefficient. Latent vector 1 represents when one latent vector is used, latent vector 2 represents when two latent vectors are used, and latent vector 3 represents when three latent vectors are used. Cumulative percentage of Explained variance for predictors is denoted as, R^2_X and cumulative percentage of explained variance for the response variable is denoted as R^2_Y

Variable	Latent vector 1	Latent Vector 2	Latent vector 3
Intercept	0.490		
N	0.039	0.050	0.101
C	0.024	-0.009	-0.084
Ca	0.043	0.077	0.191
Mg	0.014	-0.032	-0.125
Sand	-0.024	-0.049	-0.026
Silt	0.020	0.044	0.016
RMSEP	0.173	0.162	0.139
PRESS	0.554	0.527	0.494
R^2_X	0.50	0.79	0.89
R^2_Y	0.31	0.40	0.56
Without potential outlier			
Intercept	0.459		
N	0.0435	0.0497	0.0756
C	0.0338	-0.0152	-0.0338
Ca	0.0466	0.0671	0.1495
Mg	0.0214	-0.0146	-0.0823
Sand	-0.0304	-0.0897	-0.0635
RMSEP	0.118	0.098	0.083
PRESS	0.279	0.267	0.200
R^2_X	0.61	0.82	0.88
R^2_Y	0.55	0.69	0.78

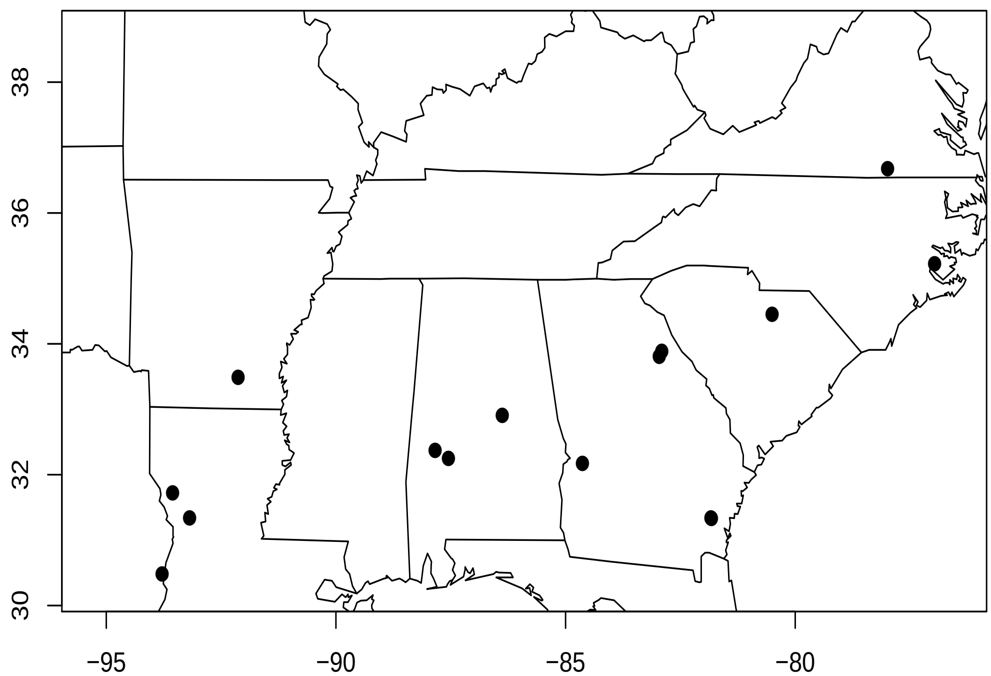

Figure 3.1: Location of study sites used to develop and test the model to estimate fertility rating from soil variables

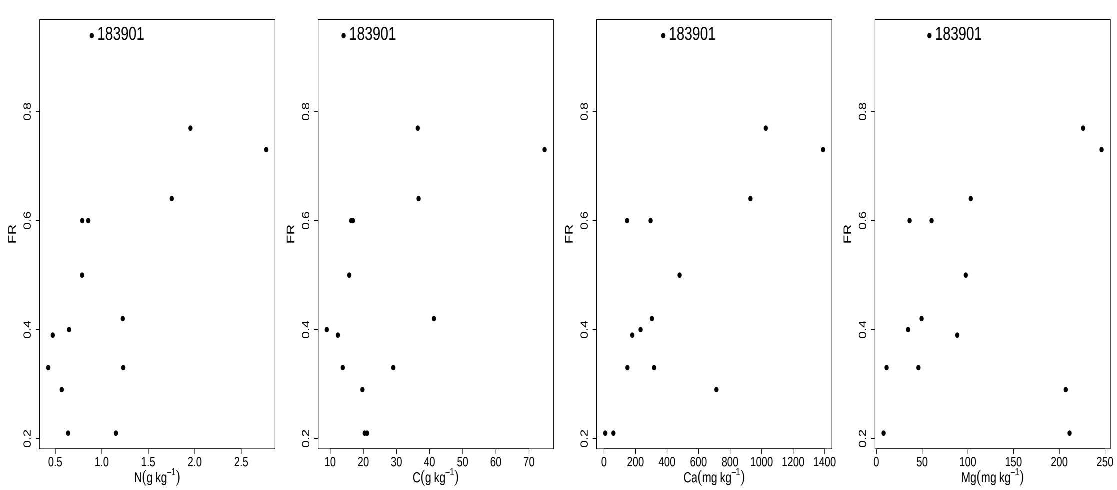

Figure 3.2: Scatter plot showing the relationship between FR derived from site index versus N, C, Ca, and Mg measured from A-horizon.

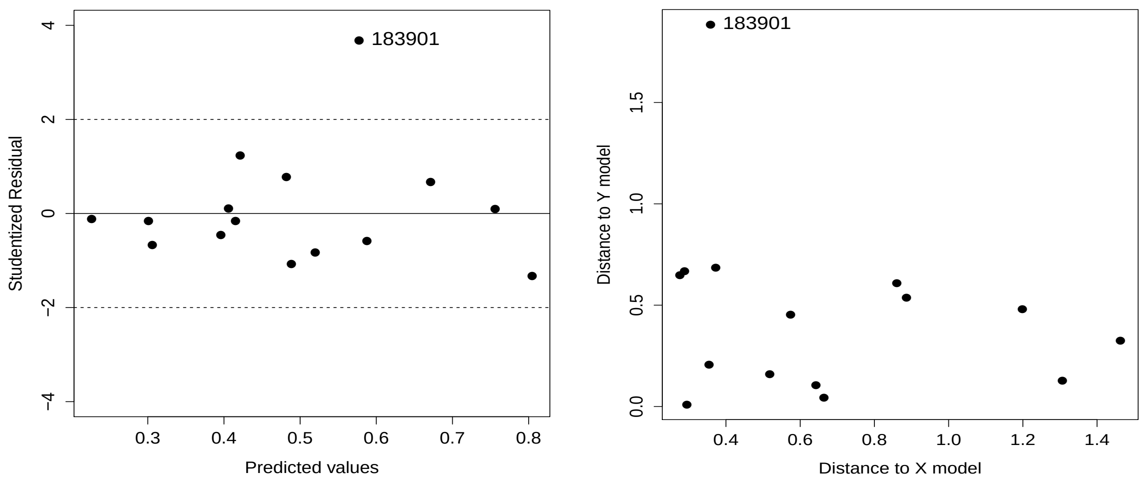

Figure 3.3: Studentized residuals from ordinary least square method of multiple regression (left) and the scatter plot between distances from y-model and distances from x-model using the partial least square regression

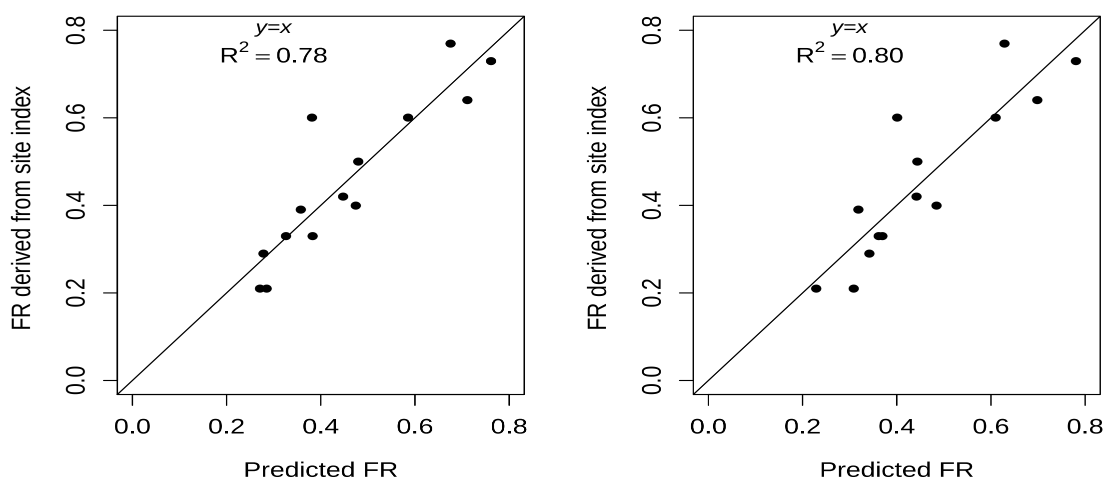

Figure 3.4: Scatter plot showing the relationship between FR derived from site index and estimated FR from soil variables using multiple linear regression with K, Ca, and sand (left) and partial least square regression (right).

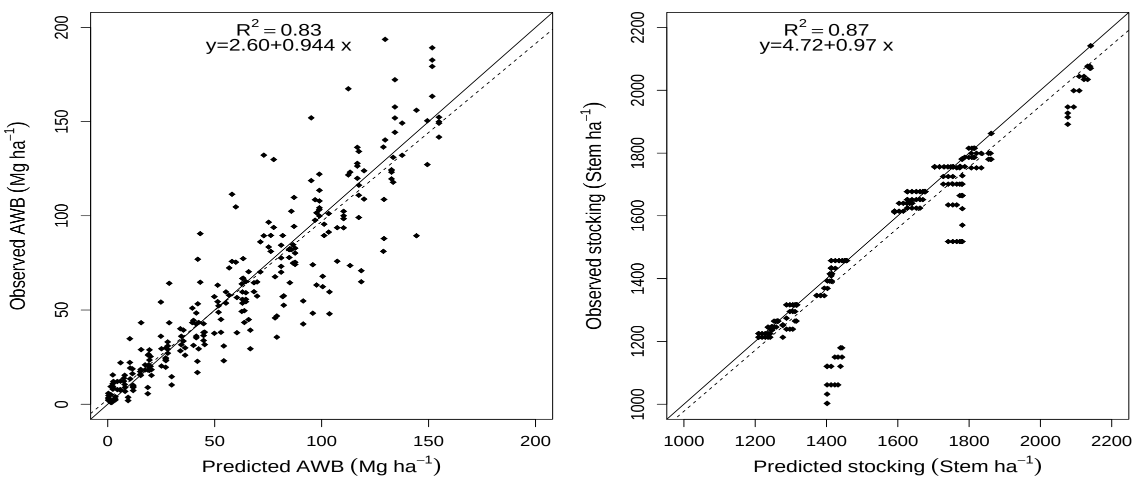

Figure 3.5: Scatter plot showing the relationship between observed aboveground woody biomass and predicted aboveground woody biomass; and observed stem density and predicted stem density from 3-PG using FR values derived from SI.

References

Akers, M. K., Kane, M., Zhao, D., Teskey, R. O., and Daniels, R. F. (2013). Effects of planting density and cultural intensity on stand and crown attributes of mid-rotation loblolly pine plantations. *For. Ecol. Manage.*, 310:468 – 475.

Albaugh, T. J., Allen, H. L., Dougherty, P. M., Kress, L. W., and King, J. S. (1998). Leaf area and above- and belowground growth responses of loblolly pine to nutrient and water additions. *For. Sci.*, 44:317–328.

Allen, H. L., Dougherty, P. M., and Campbell, R. G. (1990). Manipulation of water and nutrients -practice and opportunity in southern U.S. pine forest. *For. Ecol. Mange.*, 30:437–453.

Almeida, A. C., Siggins, A., Batista, T. R., Beadle, C., Fonseca, S., and Loos, R. (2010). Mapping the effect of spatial and temporal variation in climate and soils on eucalyptus plantation production with 3-pg, a process-based growth model. *For. Ecol. Manage.*, 259:1730 – 1740.

Augusto, L., Ranger, J., Binkley, D., and Rothe, A. (2002). Impact of several common tree species of European temperate forests on soil fertility. *Ann. For. Sci.*, 59:233–253.

Baker, J. B. and Broadfoot, W. M. (1979). A particular field method of site evalutation for commercially important southern hardwoods. *USDA For. Serv. Gen. Tech. Rep.*, SO-26:51p.

Beaulieu, J., Raulier, E., Prègent, G., and Bousquet, J. (2011). Predicting site index from climatic, edaphic, and stand structural properties for seven plantation-grown conifer species in Quebec. *Can. J. For. Res.*, 41:682–693.

Binkley, D. and Fisher, R. F. (2013). *Ecology and Management of Forest Soils.* Wiley-Blackwell, UK.

Bravo, F. and Montero, G. (2001). Site index estimation in Scots pine *Pinus sylvestris L.* stands in the High Ebro Basin (northern Spain) using soil attributes. *Forestry*, 74:395–406.

Bryars, C., Maier, C., Zhao, D., Kane, M., Borders, B., Will, R., and Teskey, R. (2013). Fixed physiological parameters in the 3-PG model produced accurate estimates of loblolly pine growth on sites in different geographic regions. *For. Ecol. Manage.*, 289:501–514.

Burkhart, H. E. and Tomé, M. (2012). *Modeling Forest Trees and Stands.* Springer. Netherlands.

Carlson, C. A., Fox, T. R., Allen, H. L., and Albaugh, T. J. (2008). Modeling mid-rotation fertilizer response using the age-shift approach. *For. Ecol. Manage.*, 256:256–262.

Carmean, W. H. (1975). Forest site quality evaluation in the United States. *Adv. Agron.*, 27:209–269.

Colbert, S. R., Jokela, E. J., and Neary, D. G. (1990). Effects of annual fertilization and sustained weed control on dry matter partitioning, leaf area, and growth efficiency of juvenile loblolly and slash pine. *For. Sci.*, 36:995–1014.

Dalla-Tea, F. and Jokela, E. J. (1991). Needlefall, canopy light interception, and productivity of youg intensively managed slash and loblolly pine stands. *For. Sci.*, 37:1298–1313.

Diéguez-Aranda, U., Burkhart, H. E., and Amateis, R. L. (2005). Dynamic site model for loblolly pine (*Pinus taeda* L.) plantations in the United States. *For. Sci.*, 52:262–272.

Dye, P. J. (2001). Modelling growth and water use in four *Pinus patula* stands with the 3-PG model. *South. Afr. For. J.*, 191:53–63.

Dye, P. J., Jacobs, S., and Drew, D. (2004). Verification of 3-PG growth and water-use predictions in twelve *Eucalyptus* plantation stands in Zululand, South Africa. *For. Ecol. Manage.*, 193:197–218.

Fontes, L., Landsberg, J., Tomé, J., Tomé, M., Pacheco, C. A., Soares, P., and Araujo, C. (2006). Calbiration and testing of generalized process-based model for use in Portugese eucalyptus plantations. *Can. J. For. Res.*, 36:3209–3221.

Fontes, L., Tomé, M., Thompson, F., Yeomans, A., Luis, J. S., and Savill, P. (2003). Modeling the Douglas-fir (*Psuedotsuga menziesii* (Mirb.) Franco) site index from site factors in Portugal. *Forestry*, 76:491–507.

Fox, J. (2008). *Applied Regression Analysis and Generalized Linear Models.* SAGE Publications, second edition.

Fox, T. R., Allen, H. L., Albaugh, T. J., Rubilar, R., and Carlson, C. A. (2007). Tree nutrition and forest fertilization of pine plantations in the southern United States. *South. J. Appl. For.*, 31:5–11.

Graham, M. H. (2003). Confronting multicollinearity in ecological multiple regression. *Ecology*, 84:2809–2815.

Guan, Y., Wei, J., Zhang, D., Zu, M., and Zhang, L. (2013). To indentify the important soil properties affecting dinoseb adsorption with statistical analysis. *Sci. World. J.*, pages 1–7.

Gyawali, N. and Burkhart, H. E. (2015). General response functions to silvicultural treatments in loblolly pine plantations. *Can. J. For. Res.*, 45:252–265.

Hagglund, B. (1981). Evaluation of forest site productivity. *For. Abst.*, 42:515–527.

Harding, R. B., Grigal, D. F., and White, E. H. (1985). Site quality evaluation for white spruce plantations using discriminant analysis. *Soil Sci. Soc. Am. J.*, 49:229–232.

Haywood, J. D., Tiarks, A. E., and Sword, M. A. (1997). Fertilization, weed control, and pine litter influence loblolly pine stem productivity and root development. *New For.*, 14:233–249.

Hervè, A. (2010). Partial least squares regression and projection on latent structure regression (pls regression). *Wiley Interdisciplinary Reviews: Computational Statistics*, 2:97–106.

Hodges, S. C. (2010). Soil fertility basics, soil science extension. Technical report, North Carolina State University.

Hunt, P. G., Karlen, D. L., Matheny, T. A., and Quisenberry, V. L. (1996). Changes in carbon content of a norfolk loamy sand after 14 yyear of conservation or conventional tillage. *J. Soil Water Conserv.*, 51:255 – 258.

Huntington, T. G. (2000). The potential for calcium depletion in forest ecosystems of southeastern united states: Review and analysis. *Glob. Biogeochem. Cycles*, 14:623–638.

Kayahara, G. J., Carter, R. E., and Klinka, K. (1995). Site index of western hemlock (*Tsuga heterophylla*) in relation to soil nutrient and foliar chemical measures. *For. Ecol. Manage.*, 74:161–169.

Landsberg, J. and Sands, P. (2011). *Physiological Ecology of Forest Production-Principles, Processes and Models*, volume 4. Elsevier.

Landsberg, J., Waring, R., and Coops, N. (2003). Performance of the forest productivity model 3-PG applied to a wide range of forest types. *For. Ecol. Manage.*, 172:199–214.

Landsberg, J. J., Johnson, K. H., Albaugh, T. J., Allen, H. L., and McKeand, S. E. (2001). Applying 3-PG, a simple process-based model designed to produce practical results, to data from loblolly pine experiments. *For. Sci.*, 47:43–51.

Liang, B., Lehmann, J., Solomon, D., Kinyangi, J., Grossman, J., ONeill, B., Skjemstad, J. O., Thies, J., Luizao, F. J., Petersen, J., and Neves, E. G. (2006). Black carbon increases cation exchange capacity in soils. *Soil Sci. Soc. Am. J.*, 70:1719 – 1730.

Lund, R. E. (1975). Tables for an approximate test for outliers in linear models. *Technometrics*, 17:473–476.

McCrady, R. L. and Jokela, E. J. (1995). Growth phenology and crown structure of selected loblolly pine families planted at two spacings. *For. Sci.*, 42:46–57.

Mehlich, A. (1984). Mehlich 3 soil test extractant: A modification of mehlich 2 extractant. *Commun. Soil Sci. Plant Anal.*, 15(12):1409–1416.

Mevik, B.-H. and Wehrens, R. (2007). The pls package: Principal component and partial least squares regression in R. *J. Stat. Softw.*, 18:1–24.

Morzuch, B. J. and Ruark, G. A. (1991). Principal components regression to mitigate the effects of multicollinearity. *For. Sci.*, 37:191–199.

Novak, J. M., Bauer, P. J., and Hunt, P. G. (2007). Carbon dynamics under long-term conservation and disk tillage management in a Norfolk loamy sand. *Soil Sci. Soc. Am. J.*, 71:453–456.

Novak, J. M., Busscher, W. J., Laird, D. L., Ahmedna, M., Watts, D. W., and Niandou, M. A. S. (2009). Impact of biochar amendment of fertility of a southeastern coastal plain soil. *Soil Sci.*, 174:105–112.

Piñeiro, G., Perlman, S., Guerschman, J. P., and Parule, J. M. (2008). How to evaluate models: Observed vs. predicted or predicted vs. observed. *Ecol. Model.*, 216:316–322.

Reich, P. B., Grigal, D. F., Aber, J. D., and Gower, S. T. (1997). Nitrogen mineralization and productivity in 50 hardwood and conifer stands on diverse soils. *Ecology*, 78:335–347.

Richter, D. D., Markewitz, D., Wells, C. G., Allen, H. L., April, R., Heine, P. R., and Urrego, B. (1994). Soil chemical change during three decades in an old-field loblolly pine (*Pinus taeda* L.) ecosystem. *Ecology*, 75:1463–1473.

Sampson, D. A. and Allen, H. L. (1998). Light attenuation in a 14-year-old loblolly pine stand as influenced by fertilization and irrigation. *Trees*, 13:80–87.

Sampson, D. A., Amatya, D. M., Lawson, C. D. B., and Skagg, R. W. (2011). Leaf area index (LAI) of loblolly pine and emergent vegetaion following a harvest. *Trans. Am. Soc. Agr. Biol. Eng.*, 54:2057–2066.

Sampson, D. A., Wynne, R. H., and Seiler, J. R. (2008). Edaphic and climatic effects on forest stand development, net primary production, and net ecosystem productivity simulated for Coastal Plain loblolly pine in Virginia. *J. Geophys. Res.*, 113:1–14.

SAS Institute Inc (2008). *SAS/STAT 9.2 User's Guide*. SAS Institute Inc, Cary, NC.

Stape, J. L., Ryan, M., and Binkley, D. (2004). Testing the utility of the 3-PG model for growth of *Eucalyptus grandis x urophylla* with natural and manipulated supplies of water and nutrients. *For. Ecol. Manage.*, 193:219–234.

Vega-Nieva, D. J., Tomé, M., Tomé, J., Fontes, L., Soares, P., Ortiz, L., Basurco, F., and Rodríguez-Soalleiro, R. (2013). Developing a general method for the estimation of fertility rating parameter of the 3-PG model: application in *Eucalyptus globulus* plantations in Northwestern Spain. *Can. J. For. Res.*, 43:627–636.

Verbyla, D. L. and Fisher, R. F. (1989). An alternative approach to coventional soil-site regression modeling. *Can. J. For. Res*, 19:179–184.

Wang, G. G. (1995). White spruce site index in relation to soil, understory vegetation, and foliar nutrients. *Can. J. For. Res.*, 25:29–38.

Wang, S., Wang, X., and Ouyang, Z. (2012). Effects of land use, climate, topography, and soil properties on regional soil organic carbon and total nitrogen in the Upstream Watershed of Miyun Reservoir, North China. *J. Env. Sci.*, 24:387–395.

Will, R. E., Barron, G. A., Burkes, E. C., Shiver, B., and Teskey, R. O. (2001). Relationship between intercept radiation, net photosynthesis, respiration, and rate of stem volume growth of *Pinus taeda* and *Pinus elliottii* stands of different densities. *For. Ecol. Manage.*, 154:155–163.

Wold, S. (1995). PLS for multivariate linear modeling. *Chemometr. Methods Mol. Design*, 2:195–218.

Wold, S., Sjöström, M., and Eriksson, L. (2001). PLS-regression: a basic tool of chemometrics. *Chemometri. Intell. Lab. Syst.*, 58:109 – 130.

Chapter 4

Modeling Repeated Fertilizer Response in Loblolly Pine Plantations by Adjusting FR in the 3-PG Process Model

Abstract

Productivity of loblolly pine in the southeastern US is frequently limited by soil nutrient availability. Therefore, fertilization is commonly used to increase nutrient availability and subsequent growth. This study used the soil fertility rating (FR) in the 3-PG model to predict fertilizer growth response of loblolly pine stands. We used the growth response following fertilization in a regional study installed at 11 locations to determine how FR is affected by repeated fertilization with N and P starting at a young age. FR values in the stands that received no fertilization treatment, baseline FR, were determined using the previously developed relationship between site index

and FR. Two locations that did not respond to biannual fertilization of N and P were considered non-nutrient deficient. The baseline FR values on the control plots at these sites averaged 0.9. We assumed that this was the maximum FR value for loblolly pine in the southern US in an environment where N and P are non-deficient. FR was then adjusted to this value in the fertilized plots at the other sites and used in 3-PG to predict growth. Using this adjusted FR value 92% of the the variation in observed aboveground biomass in the fertilized plots was described by 3-PG simulated aboveground biomass. We then derived the relationship between response to repeated fertilization and baseline FR in the control plots. An inverse relationship was observed between baseline FR and fertilizer response. Baseline FR described 56% of the variation in the fertilizer response.

4.1 Introduction

Forest productivity in the southeastern United States is primarily limited by soil fertility (Fox et al., 2007; Colbert et al., 1990; Albaugh et al., 1998; Jokela and Martin, 2000). Fertilization is an important silvicultural practice used to improve soil fertility in nutrient limited sites. Fertilization, mainly with N and P, produced significant growth responses in loblolly pine plantations at various stages of stand development (Allen, 1987; Allen et al., 1990; Albaugh et al., 1998; Sampson and Allen, 1999; Jokela and Martin, 2000; Will et al., 2002; Subedi et al., 2012).

The growth response of loblolly pine following N fertilization is relatively short-lived, generally lasting only 8 to 10 years depending on the amount of N applied (Hynynen et al., 1998), Therefore, repeated applications of N are needed to maintain elevated soil N availability that can lead to a sustained, long-term growth response (Albaugh et al., 1998; Kiser and Fox, 2012).

Previous studies on loblolly pine systems of the southeastern United States suggest that soil nutrient supply is dynamic and varies through time (Fox et al., 2007; Allen et al., 1990). Fox et al. (2007) proposed a general nutrient demand and supply curve for loblolly pine in the southeastern United States. In general, nutrient deficiency develops in loblolly pine systems in the southeastern United States around crown closure and the disparity between demand and supply of nutrients increases thereafter.

In traditional growth and yield models, the effect of fertilization on tree growth has been incorporated in four ways: modifying site index (Daniels and Burkhart, 1975); an age-shift method (Carlson et al., 2008); developing new models to include fertilizer response directly (Amateis et al., 2000; Bailey et al., 1989); and using multiplicative or additive response terms to scale growth models from control plots (Hynynen et al., 1998; Gyawali and Burkhart, 2015). Incorporating fertilizer response in the process based model 3-PG (Landsberg and

Waring, 1997) is generally accomplished by adjusting FR, the soil fertility parameter (Landsberg et al., 2003; Bryars et al., 2013; Stape et al., 2004). In the 3-PG model fertility rating (FR) is a parameter that ranges from 0 to 1, with a value of 1 assigned to sites where nutrients are non-limiting. FR has a multiplicative effect on canopy quantum efficiency and a linear effect on biomass allocation (Landsberg and Waring, 1997; Vega-Nieva et al., 2013) and is considered one of the most important parameters in 3-PG. Yet, FR has no simple and objective means of measurement (Bryars et al., 2013; Stape et al., 2004; Vega-Nieva et al., 2013). Fertilization studies have been used to calibrate FR (Landsberg et al., 2001, 2003; Stape et al., 2004; Bryars et al., 2013). For example, Landsberg et al. (2003) used a fertilization trial to calibrate fertility rating (FR), where they gave an FR value of 0.1 to the plots that received no fertilization and FR value of 1 to the plots that received fertilization.

This study used data from a study of repeated fertilization with N and P in loblolly pine plantations to calibrate FR in the 3-PG model. It was hypothesized that repeated fertilization with N and P beginning at young ages and continuing biannually throughout the rotation would eliminate nutrient deficiency leading to a long-term growth response that could be modeled by increasing FR for the entire rotation. This study used a twin-plot approach to assess the soil fertility rating in the repeated fertilized plots. Fertilized plots where there was little or no increased growth were assumed to have sufficient nutrient availability. The degree of fertilizer response was used to quantify the soil fertility rating in the repeated fertilized plots. We hypothesized that an inverse relationship exists between baseline fertility ratings and fertilizer response.

4.2 Methods

4.2.1 Study Site Description and Data Collection

Data from eleven installations of a fertilizer study established in juvenile loblolly pine stands in the southeastern United States were used in this study (Figure 1). The fertilization trial was established in the 1990s as an incomplete factorial design of nutrient dose and application frequency to evaluate the rates and frequencies of fertilization to optimize growth and fertilizer use efficiency. Plot size ranged from 0.028 ha to 0.059 ha. Average stand age during fertilization was 4 years. First generation open pollinated seedlings were planted at all sites. The installations covered a wide range of soil types, stand ages, and climatic conditions across the southeastern US (Table 4.1).

Data from the unfertilized control plots and the fertilization treatment plots receiving 134.4 Kg ha^{-1} N + 13.44 kg ha^{-1} P applied biannually were used. It was assumed that repeated fertilization with N and P biannually eliminated N and P deficiency and would lead to long-term increase in productivity. Among the eleven installations, the sites in Brunswick, Virginia and Berkley, South Carolina had four replicates of each treatment and the rest of study sites had two replicates of each treatment. All living trees were measured annually for diameter at breast height and total tree height. Mortality and damages to trees were also recorded. Aboveground biomass for each tree was calculated using the equation: Aboveground biomass = 0.026256 $DBH^{2.015144}$ $HT^{0.864052}$, where aboveground biomass is in kg, DBH is in cm, and HT, total tree height, is in m (Gonzalez-Benecke et al., 2014). Stand aboveground biomass was determined by summing the aboveground biomass of individual trees in the plot and using the plot area to adjust to a per hectare value.

4.2.2 3-PG Parameterization

This study used the parameter set developed for 3-PG by Bryars et al. (2013) with several modification (Table 4.2). The projected specific leaf area for mature stands (SLA1) and tSLA were set at 4 and 6, respectively (Akers et al., 2013; Sampson et al., 2011; Dalla-Tea and Jokela, 1991; Will et al., 2001; Colbert et al., 1990; McCrady and Jokela, 1995). The light extinction coefficient for APAR was set to be 0.69 (Sampson and Allen, 1998). The value of α_{C_x} was set at 0.053 which is the point between the values of 0.055 and 0.0485 used by Landsberg et al. (2001) and Bryars et al. (2013), respectively for loblolly pine. Baseline fertility ratings in the unfertilized plots were derived from site index using the following equation derived in chapter 2.

$$\mathrm{FR} = \frac{1.19}{1 + \mathrm{e}^{(-(-5.899+0.245\ \mathrm{SI}))}} \tag{4.1}$$

4.2.3 Fertilizer Response and Baseline FR

Fertilizer response (Aboveground biomass, Mg ha^{-1}) was calculated for each installation at age 11 as the difference between aboveground biomass in the fertilized plots and control plots. Then a relationship was developed between baseline FR in the control plots derived from site index using equation 4.1 and fertilizer response at age 11. The R^2 and RMSE values were calculated for a fitted relationship between fertilizer response and aboveground productivity.

4.2.4 FR Estimation and Validation

This study modified the approach developed by Stape et al. (2004) and determined the change in FR due to repeated fertilization as follows: First, sites that showed no response to repeated N and P fertilization were identified. Among eleven installations in this study, two installations showed no response to biannual N and P fertilization (Figure 4.2). The FR values in the control plots at these two sites averaged 0.9. Based on this, we assumed 0.9 was the maximum FR value that could be achieved with repeated fertilization of N and P under the assumption that repeated application of fertilizer starting at a young age would alleviate nutrient deficiencies. The FR values in each of the biannually fertilized plots of the remaining nine installations were adjusted to 0.9.

The FR values generated from the above procedure were used as inputs in 3-PG along with parameters from Table 4.2 and the site-specific weather data obtained from `www.daymet.org` to predict growth in the repeatedly fertilized plots. The aboveground biomass predicted from 3-PG was then compared against the aboveground productivity on each site. A linear model was fitted between observed aboveground biomass and predicted aboveground biomass and the null hypothesis of slope is equal to one was tested.

4.3 Results

The fertilizer response varied greatly among the sites depending on the baseline FR values in the control plots. Sites with low baseline FR values had the greatest fertilizer response and the sites with the higher FR values had the lowest fertilizer response (Figure 4.3). At age 11, the relationship between fertilizer response and baseline FR had a negative slope, indicating the inverse relationship between baseline fertility ratings and fertilizer response.

The baseline FR described about 56% of the variance in the fertilizer response and RMSE was 15.6 Mg ha^{-1}.

3-PG predictions of aboveground biomass in the two sites that did not respond to fertilization (Marengo, Alabama and Berkeley, South Carolina) matched well with the observed aboveground biomass-estimated using tree level allometric equations (Figure 4.4). The R^2 and RMSE values between predicted aboveground biomass and observed aboveground biomass were 0.95 and 12.9, respectively.

The 3-PG model predicted aboveground biomass reasonably well at the nine sites where there was response to fertilization (Figure 4.5). The R^2 value between predicted aboveground biomass and observed aboveground biomass was 0.94. However, there was a positive bias when observed values of aboveground biomass were compared against the predicted values. The model overpredicted on several sites. The slope of the relationship between observed aboveground biomass and predicted aboveground biomass was 0.76 and it was found to be significantly different from 1:1 line at type I error rate of 0.05. When we compared observed and 3-PG predicted fertilizer response, the difference between aboveground biomass in fertilized plots and control plots, 70% of the variance in the observed fertilizer response was described by 3-PG predicted fertilizer response (Figure 4.6).

4.4 Discussion

Fertilization had a significant positive influence on aboveground productivity (Figure 4.3). The results showed that fertilizer response is inversely related to baseline FR. At age 11, significant negative slope between baseline FR and fertilizer response was observed. Fertilizer response was greatest on the sites with low baseline FR and lowest on the high baseline FR suggesting that sites with higher baseline FR respond little to fertilizer additions. The negative relationship observed between baseline fertility ratings and fertilizer response was consistent with Littke et al. (2014). They reported negative correlations between fertilizer response and site index on Douglas-fir stand in the coastal Pacific Northwest.

Several other studies have reported comparable results on the aboveground productivity response due to fertilization on inherently nutrient deficient sites. Borders and Bailey (2001) reported significant increases in stand volume due to fertilization in the Lower Coastal Plain on sites that have inherently low fertility. The high fertilizer response on the low fertility rating was also consistent with findings by Albaugh et al. (1998). The present study was carried out on a much wider range of sites with diverse baseline FR values. The range of baseline FR provided a unique opportunity to study fertilizer response in loblolly pine plantation growing under a wider range of site conditions. The baseline FR explained 56% of the variance in the fertilizer response.

3-PG predictions of aboveground biomass and fertilizer response were reasonable in fertilized plots indicating that FR calibrated on fertilized plots was adequate. 3-PG simulated aboveground biomass are in line with the reported potential aboveground productivity of loblolly pine in the southeastern US. For example, Zhao et al. (2012) reported mean annual aboveground biomass increment for 12-year-old intensively managed loblolly pine plantations in the Upper Coastal Plain and Piedmont as 13.6 Mg ha^{-1} yr^{-1} and Borders and Bailey (2001) reported stand volume in the intensively managed loblolly pine plantations in the Lower Coastal Plain as 31.8 m^3ha^{-1} yr^{-1}. Our hypothesis that repeated fertilization with N and P in the southeastern United States eliminates major nutrient deficiency was confirmed in many sites. When fertilizer response (difference in aboveground biomass in the fertilized plots and control plots) in the study sites was compared with the 3-PG predicted fertilizer response, 70% of the variation in the observed fertilizer response was explained by 3-PG predicted fertilizer response.

Landsberg et al. (2001) showed that 3-PG could produce accurate estimates of loblolly pine stand productivity on sites fertilized with N, P, K, Ca, Mg, and B in the sandhills of North Carolina by adjusting FR to 0.4 and α_{C_x} to 0.55. Their study was conducted at a single location. Bryars et al. (2013) expanded the results to four locations in Georgia. They assigned an FR value of one on intensively managed sites and obtained predictions that matched well with the observed values. In the present study, 94% of the variation in the observed aboveground biomass in the fertilized plots was explained by 3-PG predicted aboveground biomass and 70% of the variation in the observed fertilizer response was explained by 3-PG predicted fertilizer response when FR is adjusted to 0.9.

When FR was adjusted to 0.9 on biannually fertilized plots, 3-PG over predicted productivity on several sites including those located in Brantley, Georgia; Nassau, Florida; and Newton, Texas. In those locations, larger discrepancies were also found between observed and modeled values of stand density. This may explain some of the overprediction by the 3-PG model. Discrepancies in stand density prediction may affect prediction of stand biomass (Bryars et al., 2013; Pinjuv et al., 2006). Another potential source of error in the predicted growth in the fertilized plots at some sites was heavy competition that developed from woody and herbaceous plants following fertilization. The calibration sites used in this study had very little weed and hardwood competition. However, several validation sites developed very high level of competition following fertilization. Significant amounts of added nutrients could be used by competing vegetation (Tiarks and Haywood, 1986; Martin and Jokela, 2004; Jokela et al., 2000; Subedi et al., 2014). Amishev and Fox (2006) showed increased competition following fertilization that decreases the growth of loblolly pine in the Virginia Piedmont. The increased competition might decrease the growth response in the fertilized plots and contribute to the over-prediction in the 3-PG model. There is generally more competing vegetation on higher productive sites, which would suggest that the model prediction would be less accurate as productivity increased, a trend observed in this study. Borders and Bailey (2001) reported that in the Lower Coastal Plain sites, competition control combined with fertilization could increase aboveground productivity 12% more than fertilization alone in the midrotation loblolly pine stands. Similarly, in the Piedmont and the Upper Coastal Plain sites, competition control could increase productivity up to 100% and 34% in the midrotation loblolly pine stand, respectively. Finally, N and P fertilization alone might not be adequate to eliminate soil fertility limitations. K, Ca, Mn, and other micronutrients limit productivity in some locations in the southeastern United States (Carlson et al., 2013; Jokela et al., 1991; Vogel and Jokela, 2011). If nutrients other than N and P limited productivity, increasing FR to 0.9 following fertilization might lead to over prediction of the growth response by 3-PG because only N and P were added in the fertilizer.

The methodology proposed in this research for the estimation of FR on plots fertilized repeatedly with N and P, by adjusting FR to 0.9, offers a simple yet theoretically sound modeling framework for evaluation of nutrient limitation on tree growth. This study also provides an opportunity to test assumptions made on previous studies regarding fertility rating in fertilized stands. Previous studies where fertilized plots were given an arbitrary value of 1 (Bryars et al., 2013; Landsberg et al., 2003) lacked independent sites for validation. This study had nine sites across the southeastern US for validation of this approach.

4.5 Conclusion

Fertilization with N and P significantly increases growth in loblolly pine stands in the southeastern United States. Fertilizer response depends upon the inherent soil fertility. Soils that have high inherent fertility showed very little response to fertilization whereas the sites with low inherent fertility had larger fertilizer response. The adaptation of the 3-PG model for repeated fertilized stands was carried out by adjusting baseline FR to 0.9 in fertilized plots. The simulated aboveground biomass from the 3-PG model described 94% of the variance in the observed aboveground biomass following fertilization. However, the 3-PG model tends to over predict fertilizer response. Some of the this overprediction may have been due to poorer prediction of stand density. Increased growth of competing vegetation on fertilized plots may have decreased the growth response in the fertilized plots and contributed to the over prediction of the fertilizer response.

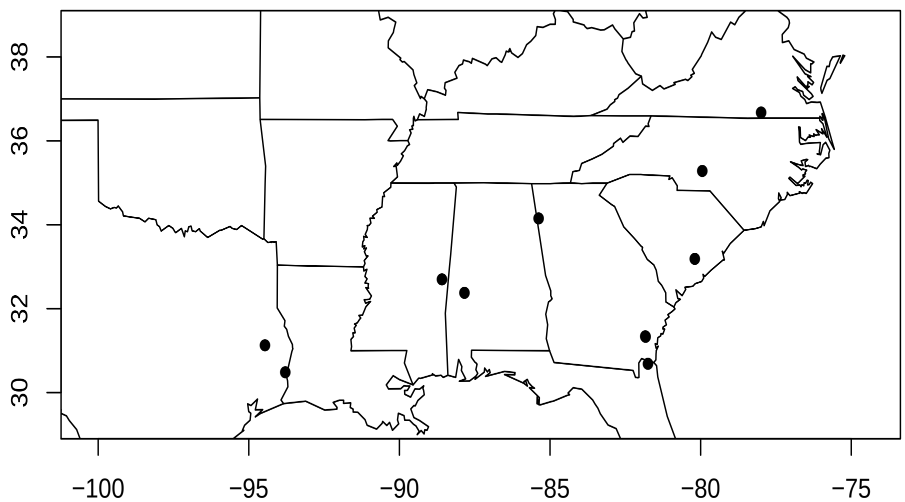

Figure 4.1: Location of study sites used to develop and test fertility rating in repeated fertilization treatment for loblolly pine plantation in the southeastern United States in 3-PG model.

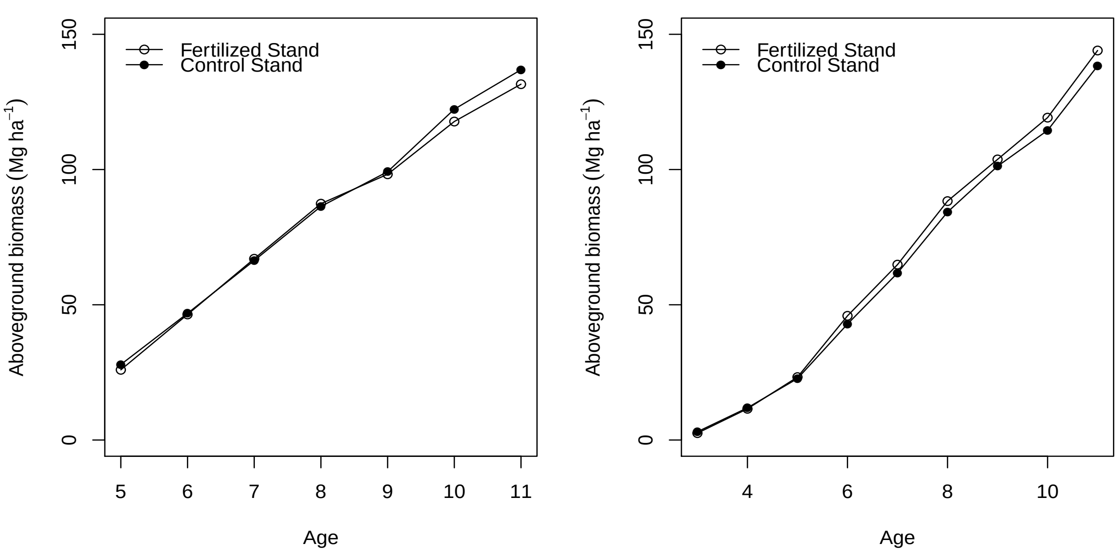

Figure 4.2: Aboveground biomass (Mg ha^{-1}) in biannually fertilized and control plots at Berkeley, South Carolina (left) and Marengo, Alabama (right).

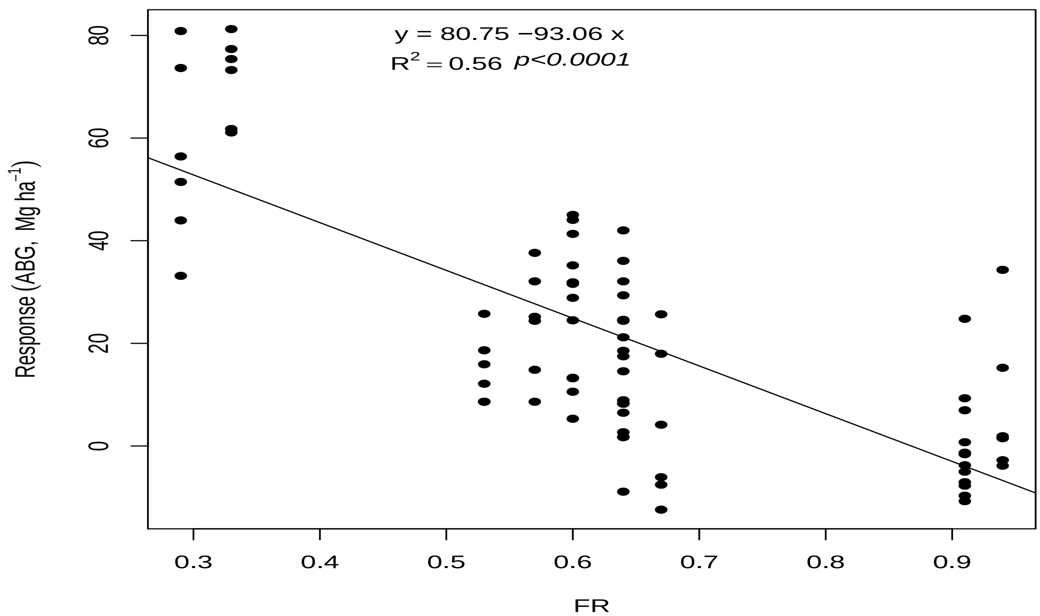

Figure 4.3: Scatterplot between fertilizer response (Aboveground biomass, Mg ha^{-1}) and baseline fertility rating in the biannually fertilized plots at age 11

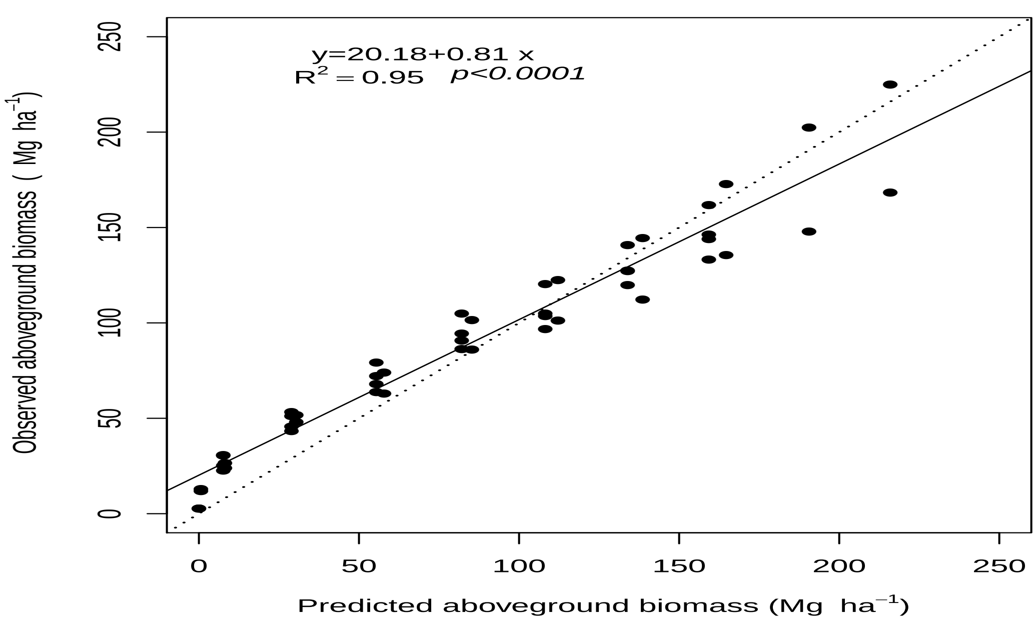

Figure 4.4: The relationship between observed aboveground biomass (Mg ha^{-1}) and 3-PG predicted aboveground biomass (Mg ha^{-1}) on two sites where repeated fetilization with N and P did not increase growth.

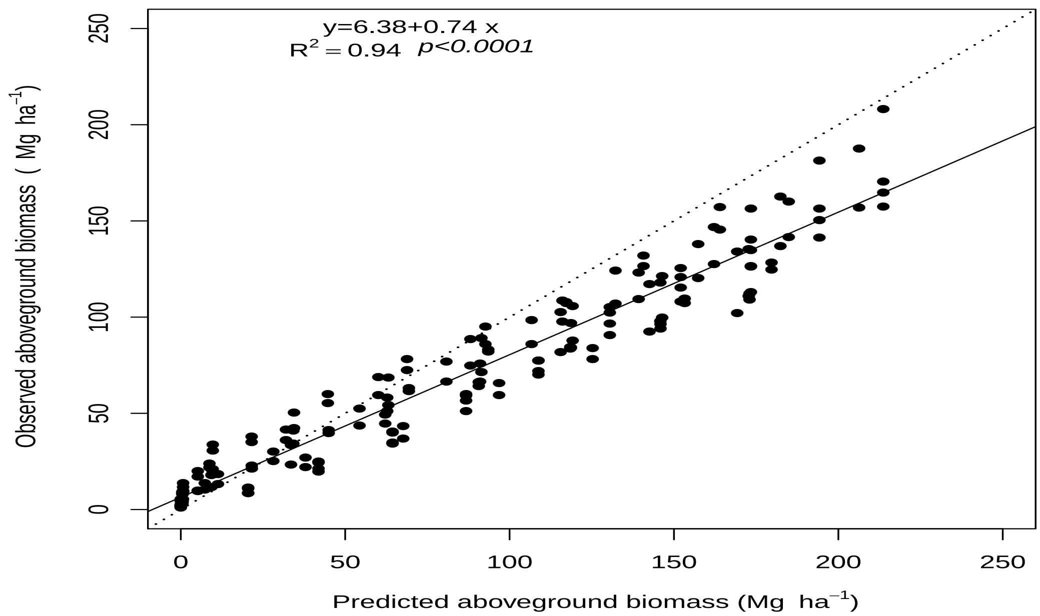

Figure 4.5: The relationship between observed aboveground biomass and 3-PG predicted aboveground biomass on the biannually fertilized plots of the nine sites when FR is adjusted to 0.9

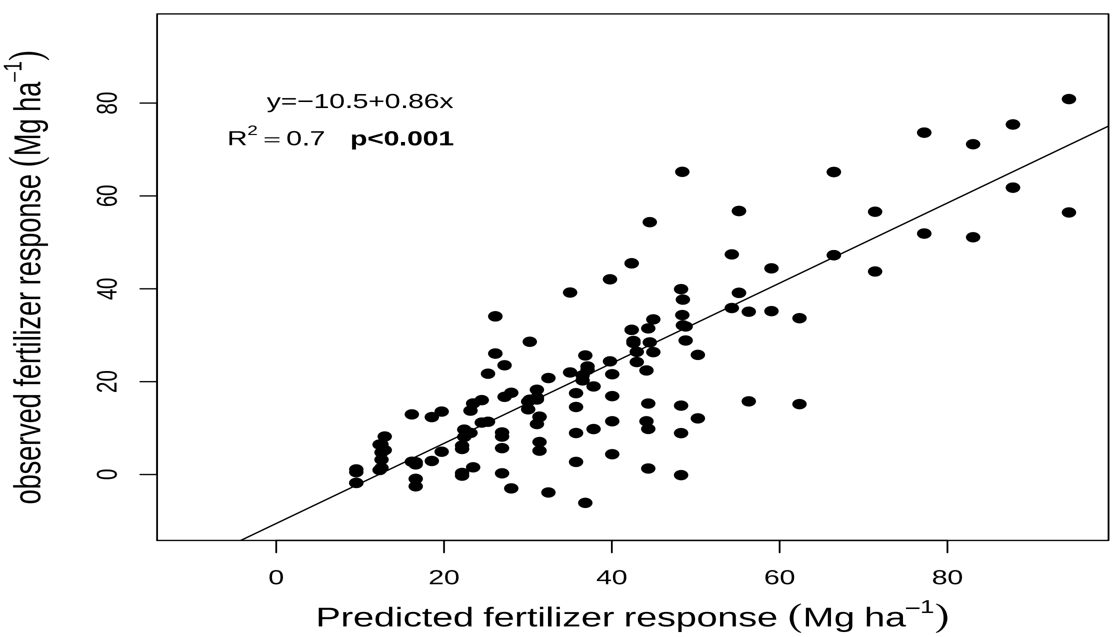

Figure 4.6: The relationship between observed fertilizer response (Mg ha^{-1}) and 3-PG predicted fertilizer response (Mg ha^{-1})

Table 4.1: Location (State, County), physiographic regions, latitude / longitude, soil series, average annual precipitation, and average maximum and minimum temperature (^{0}C) for study sites used to calibrate fertility rating in the biannually fertilized plots

Site	State, County	LAT / LONG	Soil Series	Precipitation (mm yr $^{-1}$)	Temperature max / min
180601	Virginia, Brunswick	36.68 / -77.99	Cecil	1165.6	31.7 / -3.0
181101	South Carolina, Berkeley	33.19 / -80.19	Lynchburg	1289.5	33.4 / 1.3
181502	Georgia, Floyd	34.15 / -85.38	Townley	1371.8	32.1 / -1.0
181503	Texas, Angelina	31.13 / -94.46	Kurth	1331.3	34.1 / 2.5
182401	Florida, Nassau	31.72 / -93.56	Sacul	1370.6	33.8 / 1.2
183601	Mississippi, Kemper	32.70 / -88.58	Smithdale	1451.4	33.3 / 0.6
183901	Alabama, Marengo	32.37 / -87.84	Savannah	1431.5	33.3 / 1.2
184201	Georgia, Brantley	31.34 / -81.82	Leon	1310.3	33.2 / 4.3
184202	Georgia, Brantley	31.34 / -81.83	Leon	1308.2	33.2 / 4.3
184801	Texas, Newton	30.48 / -93.78	Evadale	1496.8	33.7 / 3.7
185201	North Carolina, Montgomery	35.28/ -79.94	Herndon	1212.7	32.5 / -1.0

Table 4.2: 3-PG parameters and their values for loblolly pine used in this study

	Parameters	Meaning	Unit	Value
1	pFS2	Ratio of foliage:stem partitioning at stem diameter = 2 cm		0.40
2	pFS20	Ratio of foliage:stem partitioning at stem diameter = 20 cm		0.25
3	StemConst	Constant in stem mass diameter relationship		0.10
4	StemPower	Power in stem massvdiameter relationship		2.50
5	pRx	Maximum fraction of NPP to roots		0.40
6	pRn	Minimum fraction of NPP to roots		0.20
7	SLA0	Projected specific leaf area at the beginning of plantation	m^2 Kg^{-1}	6.40
8	SLA1	Projected specific leaf area for mature stand	m^2 Kg^{-1}	4.00
9	tSLA	Age at which SLA is mean of SLA0 and SLA1	year	6.00
10	k	Extinction coefficient for APAR by canopy		0.69
11	fullCanAge	Age at full canopy cover	year	4.00
12	MaxIntcptn	Maximum proportion of rainfall intercepted by canopy		0.20
13	LAImaxIntcptn	LAI for maximum rainfall interception		5.00
14	α_{Cx}	maximum canopy quantum efficiency	molC $molPAR^{-1}$	0.053
15	MaxCond	Maximum canopy conductance	m s^{-1}	0.006
16	LAIgcx	Canopy LAI for maximum canopy conductance		3.00
17	CoeffCond	Defines stomatal response to VPD	$mbar^{-1}$	0.02
18	BLcond	Canopy boundary layer conductance	m s^{-1}	0.10
19	wSx1000	Maximum stem mass per tree at 1000 trees ha^{-1}	kg $tree^{-1}$	235.00
20	thinPower	Power in self thinning law		1.60
21	mF	Fraction of mean foliage biomass per tree on dying trees		0.00

22	mR	Fraction of mean root biomass per tree on dying trees		0.20
23	mS	Fraction of mean stem biomass per tree on dying trees		0.40
24	fracBB0	Branch and bark fraction at stand age 0		0.40
25	fracBB1	Branch and bark fraction for mature stand		0.10
26	tBB	Age at which brak fraction is mean of fracBB0 and fracBB1		15.00
27	gammaFx	Maximum litterfall rate	$month^{-1}$	0.042
28	gammaF0	Litterfall rate at age 0	$month^{-1}$	0.001
29	tgammaF	Age at which litterfall rate is mean of gammaFx and gammaF0		18.00
30	Rttover	Average monthly root turnover rate		0.0168
31	m0	Value of m when FR is zero		0.10
32	fN0	Value of fN when FR is zero		0.50
33	Tmin	Minimum temperature for growth	^0C	4
34	Topt	Optimum temperature for growth	^0C	25
35	Tmax	Maximum temperature for growth	^0C	38
36	kF	Number of days production lost for each frost day		1
37	MaxAge	Maximum stand age used to compute relative age		40
38	nAge	Power of relative age in age modifier		3
39	rAge	relative age to make age modifier 0.5		0.20
40	y	NPP to GPP ratio		0.47

References

Akers, M. K., Kane, M., Zhao, D., Teskey, R. O., and Daniels, R. F. (2013). Effects of planting density and cultural intensity on stand and crown attributes of mid-rotation loblolly pine plantations. *For. Ecol. Manage.*, 310:468 – 475.

Albaugh, T. J., Allen, H. L., Dougherty, P. M., Kress, L. W., and King, J. S. (1998). Leaf area and above- and belowground growth responses of loblolly pine to nutrient and water additions. *For. Sci.*, 44:317–328.

Allen, H. L. (1987). Forest fertilizers: nutrient amendment, stand productivity, and environmental impact. *J. For.*, 85:37–46.

Allen, H. L., Dougherty, P. M., and Campbell, R. G. (1990). Manipulation of water and nutrients -practice and opportunity in southern U.S. pine forest. *For. Ecol. Mange.*, 30:437–453.

Amateis, R. L., Liu, J., Ducey, M. J., and Allen, H. L. (2000). Modeling response to midrotation nitrogen and phosphorus fertilization in loblolly pine plantations. *South. J. Appl. For.*, 24:207–221.

Amishev, D. Y. and Fox, T. R. (2006). The effect of weed control and fertilization on survival and growth of four pine species in the Virginia Piedmont. *For. Ecol. Manage.*, 236:93–101.

Bailey, R. L., Burgan, T. M., and Jokela, E. J. (1989). Fertilized midrotaion-aged slash pine planations- stand structures and yield prediction models. *South. J. Appl. For.*, 13:76–80.

Borders, B. and Bailey, R. L. (2001). Loblolly pine-pushing the limits of growth. *South. J. Appl. For.*, 25:69–74.

Bryars, C., Maier, C., Zhao, D., Kane, M., Borders, B., Will, R., and Teskey, R. (2013). Fixed physiological parameters in the 3-PG model produced accurate estimates of loblolly pine growth on sites in different geographic regions. *For. Ecol. Manage.*, 289:501–514.

Carlson, C. A., Fox, T. R., Allen, H. L., and Albaugh, T. J. (2008). Modeling mid-rotation fertilizer response using the age-shift approach. *For. Ecol. Manage.*, 256:256–262.

Carlson, C. A., Fox, T. R., Allen, H. L., Albaugh, T. J., Rubilar, R. A., and Stape, J. L. (2013). Growth responses of loblolly pine in the southeast United States to midrotation applications of Nitrogen, Phosphorous, Potassium, and Micronutrients. *For. Sci.*, 60:157–169.

Colbert, S. R., Jokela, E. J., and Neary, D. G. (1990). Effects of annual fertilization and sustained weed control on dry matter partitioning, leaf area, and growth efficiency of juvenile loblolly and slash pine. *For. Sci.*, 36:995–1014.

Dalla-Tea, F. and Jokela, E. J. (1991). Needlefall, canopy light interception, and productivity of youg intensively managed slash and loblolly pine stands. *For. Sci.*, 37:1298–1313.

Daniels, R. F. and Burkhart, H. E. (1975). Simulation of individual tree growth and stand development in managed loblolly pine plantations. Technical report, Div. For. and Wildl. Res. VA. Polytech. Inst. and State Univ., VA. Publication FWS 5-75 69 p.

Fox, T. R., Allen, H. L., Albaugh, T. J., Rubilar, R., and Carlson, C. A. (2007). Tree nutrition and forest fertilization of pine plantations in the southern United States. *South. J. Appl. For.*, 31:5–11.

Gonzalez-Benecke, C., Gezan, S., Albaugh, T., Allen, H., Burkhart, H., Fox, T., Jokela, E., Maier, C., Martin, T., Rubilar, R., and Samuelson, L. (2014). Local and general above-stump biomass functions for loblolly pine and slash pine trees. *For. Ecol. Manage.*, 334:254 – 276.

Gyawali, N. and Burkhart, H. E. (2015). General response functions to silvicultural treatments in loblolly pine plantations. *Can. J. For. Res.*, 45:252–265.

Hynynen, J., Burkhart, H. E., and Allen, H. (1998). Modeling tree growth in fertilized midrotation loblolly pine plantations. *For. Ecol. Manage.*, 107(13):213 – 229.

Jokela, E. J. and Martin, T. A. (2000). Effects of ontogeny and soil nutrient supply on production, allocation, and leaf area efficiency in loblolly and slash pine stands. *Can. J. For. Res.*, 30(10):1511–1524.

Jokela, E. J., McFee, W. W., and Stone, E. L. (1991). Micronutrient deficiency in slash pine: Response and persistence of added Manganese. *Soil Sci. Soc. Am. J.*, 55:492–496.

Jokela, E. J., Wilson, D. S., and Allen, J. E. (2000). Early growth responses of slash and loblolly pine following fertilization and herbaceous weed control treatments at establishment. *South. J. Appl. For.*, 24:23–30.

Kiser, L. C. and Fox, T. R. (2012). Soil accumulation of nitrogen and phosphorus following annual fertilization of loblolly pine and sweetgum on sandy sites. *Soil Sci. Soc. Am. J.*, 76:2278–2288.

Landsberg, J., Waring, R., and Coops, N. (2003). Performance of the forest productivity model 3-PG applied to a wide range of forest types. *For. Ecol. Manage.*, 172:199–214.

Landsberg, J. J., Johnson, K. H., Albaugh, T. J., Allen, H. L., and McKeand, S. E. (2001). Applying 3-PG, a simple process-based model designed to produce practical results, to data from loblolly pine experiments. *For. Sci.*, 47:43–51.

Landsberg, J. J. and Waring, R. H. (1997). A generalized model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. *For. Ecol. Manage.*, 95:209–228.

Littke, K. M., Harrison, R. B., Zabowski, D., Ciol, M. A., and Briggs, D. G. (2014). Prediction of Douglas-fir fertilizer response using biogeoclimatic properties in the coastal Pacific Northwest. *Can. J. For. Res.*, 44:1253–1264.

Martin, T. A. and Jokela, E. J. (2004). Stand development and production dynamics of loblolly pine under a range of cultural treatments in north-central Florida USA. *For. Ecol. Manage.*, 192:39–58.

McCrady, R. L. and Jokela, E. J. (1995). Growth phenology and crown structure of selected loblolly pine families planted at two spacings. *For. Sci.*, 42:46–57.

Pinjuv, G., Mason, E. G., and Watt, M. (2006). Quantitative validation and comparison of a range of forest growth model types. *For. Ecol. Manage.*, 236:37–46.

Sampson, A. and Allen, H. L. (1999). Regional influences of soil available water and climate, and leaf area index on simulated loblolly pine productivity. *For. Ecol. Manage.*, 124:1–12.

Sampson, D. A. and Allen, H. L. (1998). Light attenuation in a 14-year-old loblolly pine stand as influenced by fertilization and irrigation. *Trees*, 13:80–87.

Sampson, D. A., Amatya, D. M., Lawson, C. D. B., and Skagg, R. W. (2011). Leaf area index (LAI) of loblolly pine and emergent vegetaion following a harvest. *Trans. Am. Soc. Agr. Biol. Eng.*, 54:2057–2066.

Stape, J. L., Ryan, M., and Binkley, D. (2004). Testing the utility of the 3-PG model for growth of *Eucalyptus grandis x urophylla* with natural and manipulated supplies of water and nutrients. *For. Ecol. Manage.*, 193:219–234.

Subedi, P., Jokela, E. J., Vogel, J. G., and Martin, T. A. (2014). Inter-rotational effects of fertilization and weed control on juvenile loblolly pine productivity and nutrient dynamics. *Soil Sci. Soc. Am. J.*, 78:152–167.

Subedi, S., Kane, M., Zhao, D., Borders, B., and Greene, D. (2012). Cultural intensity and planting density effects on aboveground biomass of 12-year-old loblolly pine trees in the upper coastal plain and piedmont of the southeastern united states. *For. Ecol. Manage.*, 267:157 – 162.

Tiarks, A. E. and Haywood, J. D. (1986). Pinus taeda response to fertilization, herbaceous plant control, and woody plant control. *For. Ecol. Manage.*, 14:103–112.

Vega-Nieva, D. J., Tomé, M., Tomé, J., Fontes, L., Soares, P., Ortiz, L., Basurco, F., and Rodríguez-Soalleiro, R. (2013). Developing a general method for the estimation of fertility rating parameter of the 3-PG model: application in *Eucalyptus globulus* plantations in Northwestern Spain. *Can. J. For. Res.*, 43:627–636.

Vogel, J. G. and Jokela, E. J. (2011). Micronutrient limitations in two managed southern pine stands planted on Florida Spodosols. *Soil Sci. Soc. Am. J.*, 75:1117 – 1124.

Will, R. E., Barron, G. A., Burkes, E. C., Shiver, B., and Teskey, R. O. (2001). Relationship between intercept radiation, net photosynthesis, respiration, and rate of stem volume growth of *Pinus taeda* and *Pinus elliottii* stands of different densities. *For. Ecol. Manage.*, 154:155–163.

Will, R. E., Munger, G. T., Zhang, Y., and Borders, B. E. (2002). Effects of annual fertilization and complete competition control on current annual increment, foliar development, and growth efficiency of different aged *Pinus taeda* stands. *Can. J. For. Res*, 32:1728–1740.

Zhao, D., Kane, M., Borders, B., Subedi, S., and Akers, M. (2012). Effects of cultural intensity and planting density on stand-level aboveground biomass production and allocation for 12-year-old loblolly pine plantations in the Upper Coastal Plain and Piedmont of the southeastern United States. *Can. J. For. Res*, 42:111–122.

Chapter 5

Modeling Growth Response Following One-time Midrotation Fertilization in Lobolly Pine Plantations Using FR in the 3-PG Process Model

Abstract

We developed a dynamic function to model the soil fertility rating (FR) used in the 3-PG model to accurately predict growth in loblolly pine stands fertilized one time with N and P during the middle of the rotation. We used data from a series of midrotation loblolly pine plantations across the southeastern United States to model change in FR (ΔFR). This was done using an optimization process where the temporal distribution of the ΔFR was modeled using the Weibull function. Baseline FR, intensity of N fertilization, and year since treatment were used as input regressors to model dynamics of FR following midrotation fertilization. The model accurately described temporal

changes in FR that enabled 3-PG to accurately predict response to midrotation fertilization with N and P. When FR values generated using this function were input into the 3-PG model, 80% of the variation in the observed aboveground biomass in fertilized lobloly pine plantations was described by the 3-PG simulated aboveground biomass.

5.1 Introduction

Soil fertility is a dynamic property of forest soils that varies both spatially across the landscape and temporally during the rotation (Fox et al., 2007; Allen et al., 1990). Loblolly pine plantations in the southeastern US often develop nutrient deficiency near the onset of the stem exclusion phase of stand development and the disparity between stand demand and soil supply of nutrients increases thereafter (Fox et al., 2007). Forest fertilization is an important silvicultural practice to minimize nutrient deficiency and improve stand productivity across the various stages of stand development.

Soil nutrient availability increases following disturbances such as tree harvest, a phenomenon described as the assart effect (Fox et al., 2007; Burger and Pritchett, 1984; Brais et al., 2002) because of higher soil moisture and temperature, that increases organic matter decomposition and nutrient mineralization. However the assart effect is short lived and nutrient availability quickly decreases. Nutrients are tied up in the accumulating forest floor that acts as a sink for nutrients in undisturbed loblolly pine stands (Piatek and Allen, 2001; Kiser and Fox, 2012). Stand demand for nutrients is low during early portions of the rotation and increases through time as tree size increases. Consequently, during midrotation, when nutrient demands are high, nutrient availability is low because the assart effect has declined and the forest floor has accumulated large quantities of N and P (Miller, 1981; Piatek and Allen, 2001; Kiser and Fox, 2012). Midrotation fertilization is aimed at ameliorating nutrient deficiency at this stage of stand development.

As a consequence of the temporal pattern of nutrient supply and demand, the productivity of loblolly pine in the southeastern US is more frequently limited by nutrient availability than by water. Because annual precipitation in the southeastern US exceeds potential evapotranspiration rate (Lu et al., 2005; Allen et al., 1990) and the soils are dominated by udic moisture regimes, adequate water is available in most years. This is supported by previous research that has shown that irrigation has little impact on growth of loblolly pine in the southeastern US. Studies with loblolly pine in the Sandhills of North Carolina (Albaugh et al., 1998) and Lower Coastal Plain and Piedmont of Georgia (Will et al., 2002; Samuelson et al., 2008) have shown that fertilization has a larger impact on growth than irrigation in loblolly pine stands.

Most southeastern loblolly pine stands develop deficiencies of N and P at some point in the rotation (Allen, 1987; Allen et al., 1990; Albaugh et al., 1998; Sampson and Allen, 1999; Jokela and Martin, 2000; Will et al., 2002). Midrotation fertilization with N in loblolly pine plantation commonly produces type 1 response (Snowdon, 2002), characterized by a short term increase in growth that typically last 8 to 10 years (Carlson et al., 2008; Hynynen et al., 1998; Jokela and Stearns-Smith, 1993; Fox et al., 2007).

The 3-PG model has been successfully parameterized to predict growth of many commercially important forest species. 3-PG relies on a fertility rating (FR) parameter to describe soil nutrient availability with values ranging from 0 to 1. Work presented in this dissertation has shown that FR can be accurately predicted based on site index and soil physical and chemical properties. However, in order to accurately model fertilizer response using 3-PG, FR will need to vary during the rotation to account for change in soil nutrient availability caused by fertilization. This study was conducted to develop a model to predict FR that varies through time following midrotation fertilization with various rates of N in an environment where P is non-limiting. We used a regional fertilization trial to model the dynamics of FR following midrotation fertilization of loblolly pine with N and P.

5.2 Methods

5.2.1 Study Sites and Data Collection

Eleven installations of a fertilizer study established in midrotation loblolly pine stands in the southeastern United States between 1989 and 1997 were used in this study. This fertilizer study was established as a factorial design of N (0, 112, 224, and 336 kg ha^{-1}) and P (0, 28, and 56 kg ha^{-1}) fertilization. The study sites represent a wide range of stand age, soil type, physiographic region, and climate across the southeastern US (Table 5.1 and Figure 5.1). Summary statistics of stand variables in the study sites are given in Table 5.3.

Our objective was to develop a function to model changes in FR that match the dynamics of soil fertility following midrotation fertilization with various intensities of N in an environment where P is non-limiting. We used the growth response following a one time fertilization with 112 kg N ha^{-1} + 56 kg P ha^{-1}; 224 Kg N ha^{-1} + 56 kg P ha^{-1}; and 336 kg N ha^{-1} + 56 Kg P ha^{-1} in this analysis. On each study site, the living trees were measured biannually for DBH and total tree height. Mortality and damages to trees were also recorded. Aboveground biomass for each tree was calculated using the equation: Aboveground biomass = 0.026256 $DBH^{2.015144}$ $HT^{0.864052}$, where aboveground biomass is in kg, DBH is in cm, and HT, total tree height, is in m (Gonzalez-Benecke et al., 2014). Stand aboveground biomass was determined by summing the aboveground biomass of individual trees in the plot and using the plot area to adjust to a per hectare value.

5.2.2 3-PG Parameterization

This study used the parameter set developed for 3-PG by Bryars et al. (2013) with several modification (Table 5.2). The projected specific leaf area for mature stands (SLA1) and tSLA were set at 4 and 6, respectively (Akers et al., 2013; Sampson et al., 2011; Dalla-Tea and Jokela, 1991; Will et al., 2001; Colbert et al., 1990; McCrady and Jokela, 1995). The light extinction coefficient for APAR was set to be 0.69 (Sampson and Allen, 1998). The value of α_{C_x} was set at 0.053 which is the point between the values of 0.055 and 0.0485 used by Landsberg et al. (2001) and Bryars et al. (2013), respectively for loblolly pine. Baseline FR values in the unfertilized plots were derived from site index (m) at base age 25 using the following equation derived in chapter 2.

$$\mathrm{FR} = \frac{1.19}{1 + \mathrm{e}^{(-(-5.899+0.245\ \mathrm{SI}))}} \tag{5.1}$$

5.2.3 FR Estimation and Validation

Three installations were selected for calibration and eight installations were selected for validation. The three installations selected for calibration were sites in Greenwood County, South Carolina; Rhea County, Tennessee; and Polk County, Arkansas. The calibration sites had six pairs of biannual measurements of DBH and height at and after the application of fertilizer. In the control plots of the calibration sites the observed values of aboveground woody biomass growth were successfully predicted utilizing parameter values from Table 5.2, weather data from `www.daymet.org`, and FR estimated using equation 5.1 (Figure 5.2).

It has been demonstrated that the growth response of loblolly pine following midrotation fertilization with N and P is short lived (Hynynen et al., 1998). The growth response increases for the first few years after fertilization, reaches a peak around 4 years and then declines until approximately 8 years when the growth of fertilized and unfertilized plots are the same. We assumed this pattern of response corresponds to the change in nutrient availability and developed a function to modify FR to match this pattern. Change in growth due to one time application of fertilizer during midrotation can be modeled using the Weibull function

(Hynynen et al., 1998; Gyawali and Burkhart, 2015). Changes in aboveground biomass through time in the fertilized plots of the calibration sites was used to model changes in FR using a Weibull function. The response function for FR following midrotation fertilization treatment were developed for all three levels of fertilization treatment.

The total amount of N applied, year since treatment (YST), and the baseline FR were used to model adjusted FR values obtained from each site. The following 2-parameter Weibull density function was applied to model the temporal distribution of ΔFR due to fertilization.

$$\mathrm{FR}_{\mathrm{fertilized}} = \text{baseline FR} \; + \; \alpha \mathrm{N}\frac{\gamma}{\beta}\left(\frac{\mathrm{YST}}{\beta}\right)^{\gamma-1} \; \mathrm{e}^{\left(\frac{-\mathrm{YST}}{\beta}\right)^{\gamma}} \tag{5.2}$$

The added term to baseline FR represents the dynamics of ΔFR following fertilization as described by intensity of fertilization (N), years since treatment (YST), and the parameters α, β, and γ. Where γ is the shape parameter and β is the scale parameter. Nonlinear least squares method was used to fit equation 5.2. Root Mean Square Error (RMSE), coefficient of determination (R^2), and graphical analysis were used to evaluate and validate the models.

The adjusted FR value based on the equation developed was used in 3-PG to predict growth in the fertilized plots at the eight sites not used in the model development. The predicted growth response following fertilization was compared to the observed growth response at these sites.

5.3 Results

Figure 5.3 shows mean change in FR (ΔFR) due to fertilization. The magnitude of ΔFR varied with the rate of N and YST. ΔFR increases with increasing rate of N. The pattern of change is mound shaped and is positively skewed.

Results from fitting dynamics of ΔFR following fertilization including parameter estimates, standard error, p-values, RMSE, and R^2 are shown in Table 5.4. All parameters were highly significant ($p<0.0001$). Small RMSE value and high R^2 value indicated that the model fitted well to the data. The 2-parameter Weibull function was found to be adequate in describing dynamics of FR following midrotation fertilization. The response function followed a mound shape (Figure 5.3). The positive value on the estimated parameters of N, α, indicated that FR increased with an increase in amount of N applied. A plot of the observed vs. predicted values of adjusted FR showed good correspondence between observed and predicted values of FR (Figure 5.3).

3-PG predicted aboveground biomass in the fertilized plots well (Figure 5.4). Overall, using FR determined from model 5.2, the observed aboveground biomass and predicted aboveground biomass from 3-PG had an R^2 value of 0.80. The slope of the relationship between observed values of aboveground biomass and modeled values of aboveground biomass had 95% of confidence interval between 0.86 and 0.97. 3-PG predicted average aboveground biomass response curves plotted against years since treatment for various levels of fertilization treatments are shown in Figure 5.5. On average, 3-PG predicted 23.8 Mg ha^{-1}, 16.3 Mg ha^{-1}, and 7.7 Mg ha^{-1} of aboveground fertilizer response after 8 years since treatment for 336 Kg ha^{-1} N + 56 Kg ha^{-1} P, 224 Kg ha^{-1} N + 56 Kg ha^{-1} P, and 112 Kg ha^{-1} N + 56 Kg ha^{-1} P, respectively.

5.4 Discussion

The good results obtained in the control plots of the calibration sites using the 3-PG model parameterized with the unique parameter set, site specific weather data, and baseline FR values derived from site index suggest that the 3-PG model is adequate in predicting loblolly pine productivity for midrotation loblolly pine stands in the southeastern United States.

The 3-PG model using adjusted FR values as a function of amount of N applied, year since treatment, and baseline FR before fertilization accurately predicted growth following midrotation fertilization in loblolly pine. Previous works on 3-PG to model the productivity of loblolly pine in the southeastern US have shown that 3-PG has the potential to model the productivity of loblolly pine productivity (Landsberg et al., 2001; Bryars et al., 2013). This study has expanded on those results and demonstrated that 3-PG can produce accurate estimates of loblolly pine stand growth in midrotation fertilized stands across a range of sites that varied in climate, physiographic provinces, management regimes, stand age, and soil types.

Midrotation fertilizer applications with N and P have been found to increase loblolly pine productivity in the southeastern United States (Jokela and Stearns-Smith, 1993; Hynynen et al., 1998; Gyawali and Burkhart, 2015). N fertilization increases the soil mineral N pool and the duration and magnitude of increase depends on the intensity of N fertilization (Gurlevik et al., 2004; Carlyle, 1995; Mudano, 1986). N fertilization increases mineral N initially but the effect diminishes over time (Carlyle, 1995; Johnson et al., 1980). Johnson et al. (1980) reported decline in soil mineral-N levels from 200 ppm at 20 days to less than 10 ppm within 161 days following a 200-kg Urea-N ha^{-1} fertilization. The decrease in N availability continues through time as N accumulated in the forest floor instead of the mineral soil N pool (Richter et al., 2000; Kiser and Fox, 2012). The modeled change in FR following fertilization enabled 3-PG to accurately predict fertilizer response.

We predicted very small increase in FR due to midrotation fertilization. For example, we predicted an increase of 0.07 in magnitude in FR with 336 Kg N ha $^{-1}$ of fertilization. However, this relatively small change in FR following midrotation fertilization of loblolly pine produced growth increase in 3-PG that were similar to growth increase previously reported (Fox et al., 2007). Fox et al. (2007) showed that annual volume response to midrotation fertilization of 224 kg ha^{-1} N plus P averaged 3.8 m^{3}ha^{-1}yr^{-1} during the first 8 years. The reported growth efficiency for loblolly pine in the southeastern United states is approximately 7.2 $m^3ha^{-1}yr^{-1}$ LAI^{-1} (Albaugh et al., 1998; Vose and Allen, 1988). These values suggest that LAI is increased by approximately 0.52 due to midrotation fertilization with N and P.

FR is a key parameter of the 3-PG model and 3-PG is very sensitive to changes in FR values. Using N rate, year since treatment, and baseline FR as the predictors, dynamics of ΔFR was successfully modeled using the Weibull function with all parameters significant. The coefficient for N intensity was positive which suggests that soil fertility increases with increasing intensity of N fertilization. N is considered as the nutrient most limiting growth in temperate and boreal forest regions (Reich et al., 1997). Similar results regarding increase in productivity with increasing N fertilization in one time midrotation loblolly pine fertilization were also reported in other studies (Hynynen et al., 1998; Gyawali and Burkhart, 2015). The temporal pattern of ΔFR to one-time midrotation fertilization indicated the FR response reaches its peak around six years of fertilization. Thereafter, the response starts to decrease. Similar results regarding change in productivity due to one time midrotation fertilization were reported in Miller (1981), Hynynen et al. (1998), and Gyawali and Burkhart (2015).

5.5 Conclusion

The objective of this study was to develop a dynamic function for soil fertility (ΔFR) following midrotation fertilization in loblolly pine using intensity of N fertilization, baseline FR, and years since treatment that could be used in the 3-PG model to model fertilizer response. Overall, the results suggest that the effects of midrotation fertilization of N and P on soil fertility is temporary and can be modeled by a Weibull function with two parameters. The change in FR following fertilization follows a temporal pattern that matched the reported loblolly pine growth response following midrotation fertilization. Given the results of this study, it can be concluded that an increase in FR following midrotation fertilization is temporary and FR increases with increasing intensity of N fertilization. The aboveground biomass values generated by 3-PG using FR values from the Weibull function accounted for 80% of the variance in the observed aboveground biomass.

The results of this study show that it is possible to model soil fertility dynamics following midrotation fertilization in the 3-PG model with a unique set of parameters. Tests against independent measurements indicate that the model provides accurate estimates of the soil fertility ratings following midrotation fertilization. The results reported here are applicable to loblolly pine plantations in the southeastern United States of similar age and fertilization intensities as those for the study.

Table 5.1: Location (State, County), latitude / longitude, soil series, average annual precipitation, and average maximum and minimum temperature (^{0}C) for study sites used to model dynamics of soil fertility following midrotation fertilization in loblolly pine plantations using FR in the 3-PG process model

Site	**State, County**	**LAT / LONG**	**Soil Series**	**Precipitation (mm yr $^{-1}$)**	**Temperature max / min**
130101	South Carolina, Lancaster	34.55 /-80.63	Appling	1155.09	32.67/ -0.43
130401	Virginia, King and Queen	37.62/ -76.79	Emporia	1193.07	31.53/-2.08
130901	North Carolina, Brunswick	34.09 /-78.39	Goldsboro	1410.07	32.06/0.81
130903	North Carolina, Cumberland	34.91/ -78.92	Torhunta	1220.26	32.05/-0.39
132605	North Carolina, Bertie	36.21/ -76.95	Leaf	1265.65	31.84/-0.78
132701	Tennessee, Rhea	35.72/ -84.77	Pailo	1421.07	31.06/-2.57
132702	Tennessee, Bradley	35.02/ -84.84	Tasso	1373.32	31.53/-1.81
132802	Arkansas, Howard	34.04/ -94.02	Sacul	1378.52	33.51/-1.01
132805	Arkansas, Polk	34.29/-94.35	Sherles	1462.39	32.14/-2.13
133104	South Carolina, Aiken	33.59/ -81.83	Lakeland	1235.16	33.57/0.10
133105	South Carolina, Greenwood	34.13 /-82.23	Enon	1184.74	33.03/-0.63

Table 5.2: 3-PG parameters and their values for loblolly pine used in this study

	Parameters	Meaning	Unit	Value
1	pFS2	Ratio of foliage:stem partitioning at stem diameter = 2 cm		0.40
2	pFS20	Ratio of foliage:stem partitioning at stem diameter = 20 cm		0.25
3	StemConst	Constant in stem mass diameter relationship		0.10
4	StemPower	Power in stem massvdiameter relationship		2.50
5	pRx	Maximum fraction of NPP to roots		0.40
6	pRn	Minimum fraction of NPP to roots		0.20
7	SLA0	Projected specific leaf area at the beginning of plantation	m^2 Kg^{-1}	6.40
8	SLA1	Projected specific leaf area for mature stand	m^2 Kg^{-1}	4.00
9	tSLA	Age at which SLA is mean of SLA0 and SLA1	year	6.00
10	k	Extinction coefficient for APAR by canopy		0.69
11	fullCanAge	Age at full canopy cover	year	4.00
12	MaxIntcptn	Maximum proportion of rainfall intercepted by canopy		0.20
13	LAImaxIntcptn	LAI for maximum rainfall interception		5.00
14	α_{Cx}	maximum canopy quantum efficiency	molC $molPAR^{-1}$	0.053
15	MaxCond	Maximum canopy conductance	m s^{-1}	0.006
16	LAIgcx	Canopy LAI for maximum canopy conductance		3.00
17	CoeffCond	Defines stomatal response to VPD	$mbar^{-1}$	0.02
18	BLcond	Canopy boundary layer conductance	m s^{-1}	0.10
19	wSx1000	Maximum stem mass per tree at 1000 trees ha^{-1}	kg $tree^{-1}$	235.00
20	thinPower	Power in self thinning law		1.60
21	mF	Fraction of mean foliage biomass per tree on dying trees		0.00

22	mR	Fraction of mean root biomass per tree on dying trees		0.20
23	mS	Fraction of mean stem biomass per tree on dying trees		0.40
24	fracBB0	Branch and bark fraction at stand age 0		0.40
25	fracBB1	Branch and bark fraction for mature stand		0.10
26	tBB	Age at which brak fraction is mean of fracBB0 and fracBB1		15.00
27	gammaFx	Maximum litterfall rate	$month^{-1}$	0.042
28	gammaF0	Litterfall rate at age 0	$month^{-1}$	0.001
29	tgammaF	Age at which litterfall rate is mean of gammaFx and gammaF0		18.00
30	Rttover	Average monthly root turnover rate		0.0168
31	m0	Value of m when FR is zero		0.10
32	fN0	Value of fN when FR is zero		0.50
33	Tmin	Minimum temperature for growth	^0C	4
34	Topt	Optimum temperature for growth	^0C	25
35	Tmax	Maximum temperature for growth	^0C	38
36	kF	Number of days production lost for each frost day		1
37	MaxAge	Maximum stand age used to compute relative age		40
38	nAge	Power of relative age in age modifier		3
39	rAge	relative age to make age modifier 0.5		0.20
40	y	NPP to GPP ratio		0.47

Table 5.3: Summary statistics of stand variables in the control plots of the study sites selected to model dynamics of soil fertility following midrotation fertilization in loblolly pine stands.

Site	n	Max Age	SI (m, age=25)	ABG($Mg\ ha^{-1}$)	Stand density ($stem\ ha^{-1}$)
130101	4	17	18.55	104.01	983 - 1161
130401	2	21	17.50	133.48	1208 - 1540
130901	2	24	18.14	167.27	1166 - 1511
130903	2	22	19.34	168.10	1110 - 1184
132605	2	20	19.14	173.87	1428-1458
132701	4	22	16.92	133.38	1303-1574
132702	2	22	17.69	165.76	1682- 1969
132802	4	16	17.67	105.68	970 - 1046
132805	2	21	17.47	145.70	852 - 867
133104	2	22	17.70	154.01	1360 - 1660
133105	2	24	16.70	137.75	1407 - 1503

Table 5.4: Parameter estimates and fit statistics of FR dynamics model (5.2) following midrotation fertilization

Parameters	Estimates	Standard Error	p-value
α	0.0020679	0.0003107	< 0.0001
β	2.2861918	0.2672600	< 0.0001
γ	8.9277010	0.9507714	< 0.0001
RMSE	0.01596		
R^2	0.73		

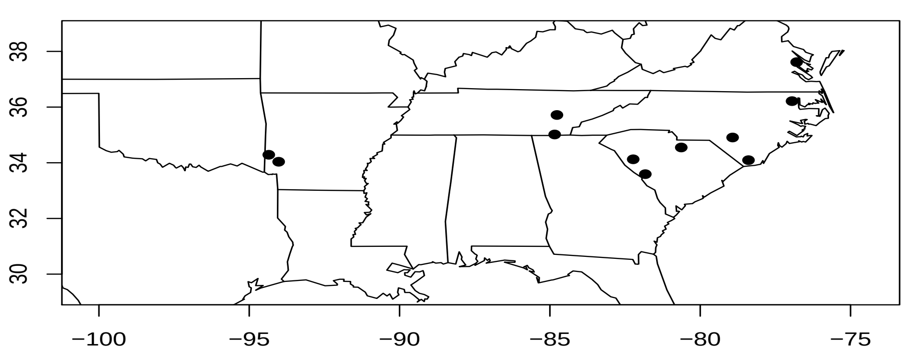

Figure 5.1: Location of study sites used to develop and test dynamics of FR following midrotation fertilization using the 3-PG model

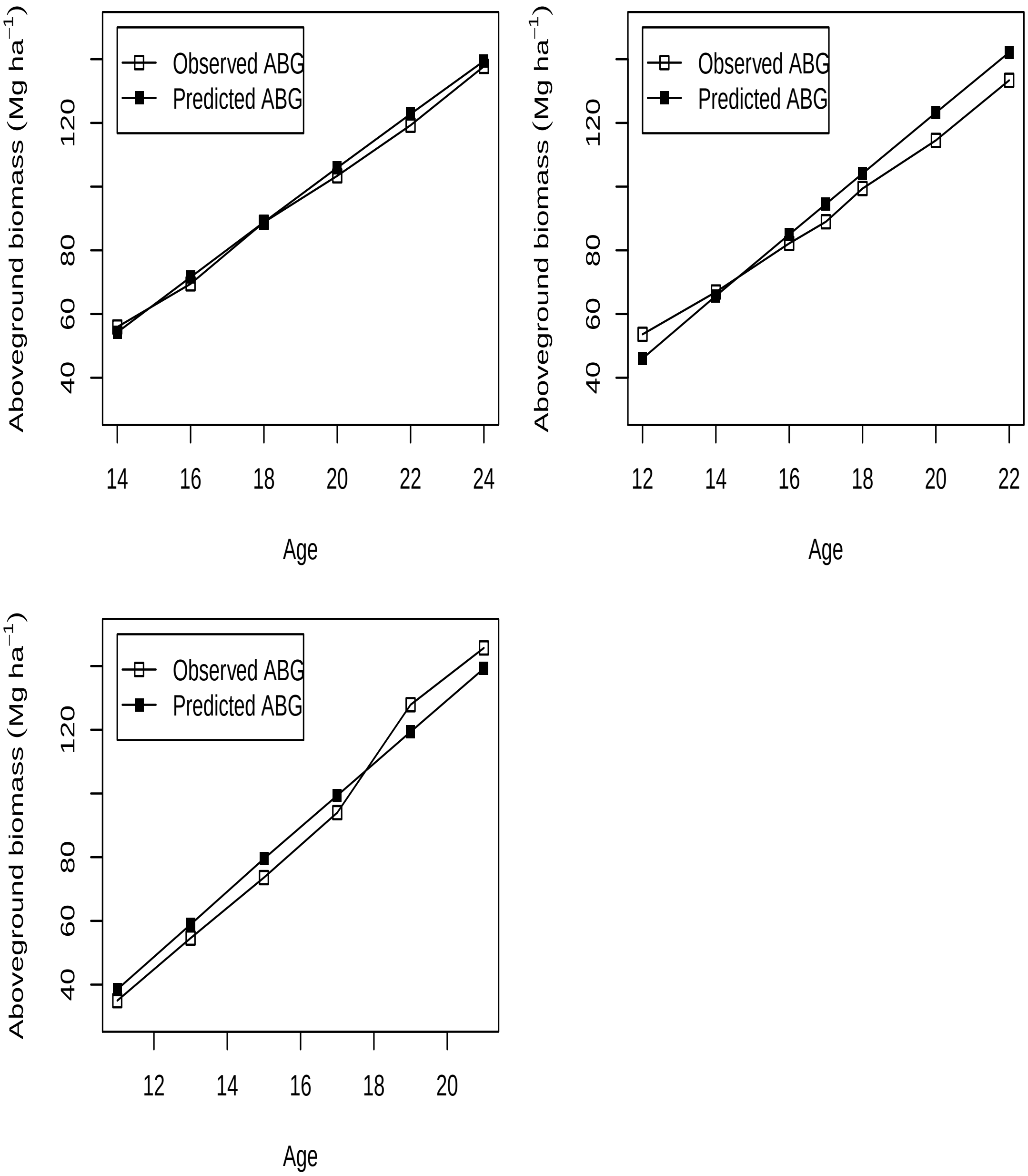

Figure 5.2: Relationship between observed aboveground biomass and predicted Aboveground biomass in the calibration sites (Top left: Greenwood, South Carolina; top right: Rhea, Tennessee; and bottom :Polk, Arkansas) used to develop the model to predict dynamics of FR following midrotation fertilization.

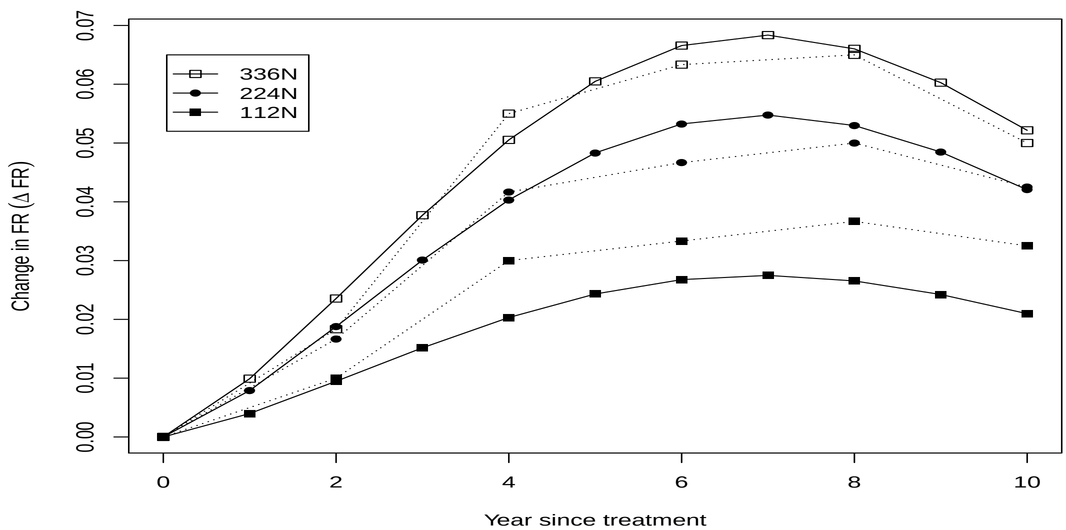

Figure 5.3: Comparison of adjusted FR values from calibration sites (dotted lines) and predicted FR values (solid lines) from 2 parameter Weibull function for various levels of midrotation treatment. 336 N, 224 N, and 112 N denoted 336 Kg N + 56 Kg P ha^{-1}, 224 Kg N + 56 Kg P ha^{-1}, and 112 Kg N + 56 Kg P ha^{-1}, respectively.

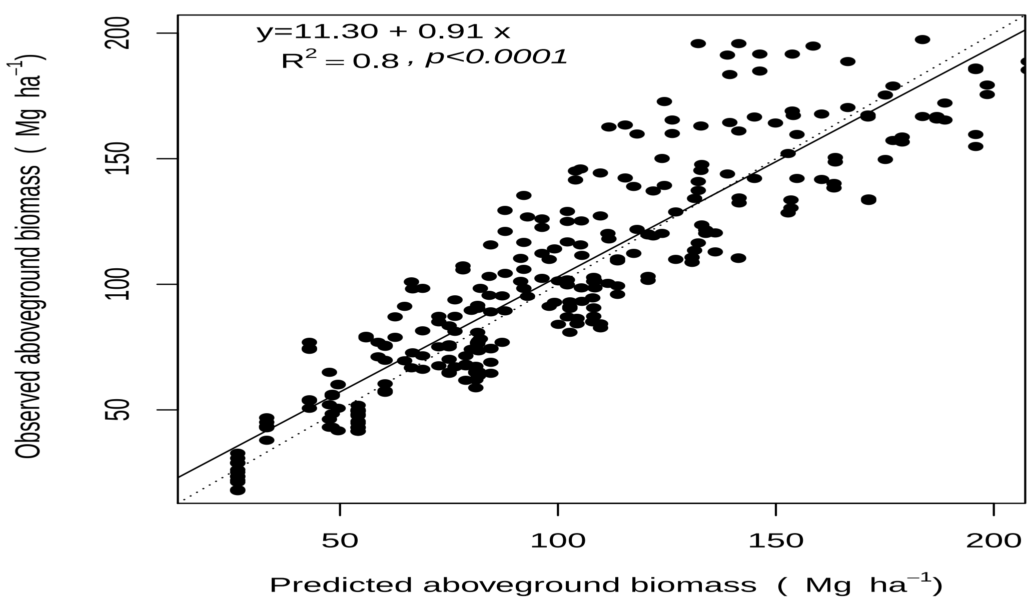

Figure 5.4: The relationship between observed aboveground biomass and predicted aboveground biomass in fertilized plots using 3-PG model using the FR values generated from model 5.2 in the validation sites of the midrotation fertilization.

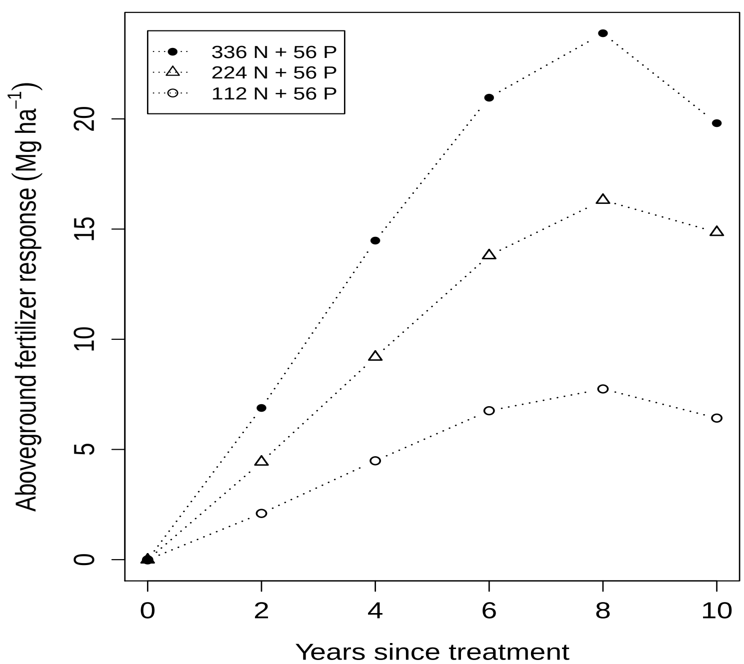

Figure 5.5: 3-PG predicted average aboveground fertilizer response curves in the validation sites plotted against years since treatment for various levels of fertilization treatments.

References

Akers, M. K., Kane, M., Zhao, D., Teskey, R. O., and Daniels, R. F. (2013). Effects of planting density and cultural intensity on stand and crown attributes of mid-rotation loblolly pine plantations. *For. Ecol. Manage.*, 310:468 – 475.

Albaugh, T. J., Allen, H. L., Dougherty, P. M., Kress, L. W., and King, J. S. (1998). Leaf area and above- and belowground growth responses of loblolly pine to nutrient and water additions. *For. Sci.*, 44:317–328.

Allen, H. L. (1987). Forest fertilizers: nutrient amendment, stand productivity, and environmental impact. *J. For.*, 85:37–46.

Allen, H. L., Dougherty, P. M., and Campbell, R. G. (1990). Manipulation of water and nutrients -practice and opportunity in southern U.S. pine forest. *For. Ecol. Mange.*, 30:437–453.

Brais, S., Paré, D., Camiré, C., Rochon, P., and Vasseur, C. (2002). Nitrogen net mineralization and dynamics following whole-tree harvesting and winter windrowing on clayey sites of northwestern Quebec. *For. Ecol. Manage.*, 157:119–130.

Bryars, C., Maier, C., Zhao, D., Kane, M., Borders, B., Will, R., and Teskey, R. (2013). Fixed physiological parameters in the 3-PG model produced accurate estimates of loblolly pine growth on sites in different geographic regions. *For. Ecol. Manage.*, 289:501–514.

Burger, J. A. and Pritchett, W. L. (1984). Effects of clearfelling and site preparation on Nitrogen mineralization in a southern pine stand. *Soil Sci. Soc. Am. J.*, 48:1432–1437.

Carlson, C. A., Fox, T. R., Allen, H. L., and Albaugh, T. J. (2008). Modeling mid-rotation fertilizer response using the age-shift approach. *For. Ecol. Manage.*, 256:256–262.

Carlyle, J. C. (1995). Nutrient management in a *Pinus radiata* plantation after thinning: the effect of nitrogen fertilizer on soil nitrogen fluxes and tree growth. *Can. J. For. Res.*, 25:1673– 1683.

Colbert, S. R., Jokela, E. J., and Neary, D. G. (1990). Effects of annual fertilization and sustained weed control on dry matter partitioning, leaf area, and growth efficiency of juvenile loblolly and slash pine. *For. Sci.*, 36:995–1014.

Dalla-Tea, F. and Jokela, E. J. (1991). Needlefall, canopy light interception, and productivity of youg intensively managed slash and loblolly pine stands. *For. Sci.*, 37:1298–1313.

Fox, T. R., Allen, H. L., Albaugh, T. J., Rubilar, R., and Carlson, C. A. (2007). Tree nutrition and forest fertilization of pine plantations in the southern United States. *South. J. Appl. For.*, 31:5–11.

Gonzalez-Benecke, C., Gezan, S., Albaugh, T., Allen, H., Burkhart, H., Fox, T., Jokela, E., Maier, C., Martin, T., Rubilar, R., and Samuelson, L. (2014). Local and general above-stump biomass functions for loblolly pine and slash pine trees. *For. Ecol. Manage.*, 334:254 – 276.

Gurlevik, N., Kelting, D. L., and Allen, H. L. (2004). Nitrogen mineralization following vegetation control and fertilization in a 14-year-old loblolly pine plantation. *Soil Sci. Soc. Am. J.*, 68:272281.

Gyawali, N. and Burkhart, H. E. (2015). General response functions to silvicultural treatments in loblolly pine plantations. *Can. J. For. Res.*, 45:252–265.

Hynynen, J., Burkhart, H. E., and Allen, H. (1998). Modeling tree growth in fertilized midrotation loblolly pine plantations. *For. Ecol. Manage.*, 107(13):213 – 229.

Johnson, D. W., Edwards, N. T., and Todd, D. E. (1980). Nitrogen mineralization, immobilization, and nitrification following urea fertilization of a forest soil under field and laboratory conditions. *Soil Sci. Soc. Am. J.*, 44:610–616.

Jokela, E. J. and Martin, T. A. (2000). Effects of ontogeny and soil nutrient supply on production, allocation, and leaf area efficiency in loblolly and slash pine stands. *Can. J. For. Res.*, 30(10):1511–1524.

Jokela, E. J. and Stearns-Smith, S. C. (1993). Fertilization of established souther pines stands: effects of single and split Nitrogen treatments. *South. J. Appl. For.*, 17:135–138.

Kiser, L. C. and Fox, T. R. (2012). Soil accumulation of nitrogen and phosphorus following annual fertilization of loblolly pine and sweetgum on sandy sites. *Soil Sci. Soc. Am. J.*, 76:2278–2288.

Landsberg, J. J., Johnson, K. H., Albaugh, T. J., Allen, H. L., and McKeand, S. E. (2001). Applying 3-PG, a simple process-based model designed to produce practical results, to data from loblolly pine experiments. *For. Sci.*, 47:43–51.

Lu, J., Sun, G., McNulty, S. G., and Amatya, D. M. (2005). A comparison of six potential evapotranspiration methods of regional use in the southeastern united states. *J. Am. W. Res. Ass.*, 33:354–374.

McCrady, R. L. and Jokela, E. J. (1995). Growth phenology and crown structure of selected loblolly pine families planted at two spacings. *For. Sci.*, 42:46–57.

Miller, H. G. (1981). Forest fertilization: some guiding concepts. *Forestry*, 54:157–167.

Mudano, J. E. (1986). Assessment of soil Nitrogen availability following Nitrogen and Phosphorous fertilization of a loblolly pine stand. Master's thesis, North Carolina State University, Raleigh, NC.

Piatek, K. B. and Allen, H. L. (2001). Are forest floors in mid-rotation stands of loblolly pine (*Pinus taeda*) a sink for nitrogen and phosphorus? *Can. J. For. Res*, 31:1164–1174.

Reich, P. B., Grigal, D. F., Aber, J. D., and Gower, S. T. (1997). Nitrogen mineralization and productivity in 50 hardwood and conifer stands on diverse soils. *Ecology*, 78:335–347.

Richter, D. D., Markewitz, D., Heine, P. R., Jin, V., Raikes, J., Tian, K., and Wells, C. G. (2000). Legacies of agriculture and forest regrowth in the nitrogen of old-field soils. *For. Ecol. Manage.*, 138:233–248.

Sampson, A. and Allen, H. L. (1999). Regional influences of soil available water and climate, and leaf area index on simulated loblolly pine productivity. *For. Ecol. Manage.*, 124:1–12.

Sampson, D. A. and Allen, H. L. (1998). Light attenuation in a 14-year-old loblolly pine stand as influenced by fertilization and irrigation. *Trees*, 13:80–87.

Sampson, D. A., Amatya, D. M., Lawson, C. D. B., and Skagg, R. W. (2011). Leaf area index (LAI) of loblolly pine and emergent vegetaion following a harvest. *Trans. Am. Soc. Agr. Biol. Eng.*, 54:2057–2066.

Samuelson, L. J., Marrianne, F. G., Stokes, T. A., and Coleman, M. D. (2008). Fertilizaton not irrigation influences hydralulic traits in plantation-grown loblolly pine. *For. Ecol. Manage.*, 255:3331 – 3339.

Snowdon, P. (2002). Modeling type 1 and type 2 growth responses in plantations after application of fertilizer or other silvicultural treatments. *For. Ecol. Manage.*, 163:229–244.

Vose, M. and Allen, H. L. (1988). Leaf area, stemwood growth, and nutrition relationships in loblolly pine. *For. Sci.*, 34:547–563.

Will, R. E., Barron, G. A., Burkes, E. C., Shiver, B., and Teskey, R. O. (2001). Relationship between intercept radiation, net photosynthesis, respiration, and rate of stem volume growth of *Pinus taeda* and *Pinus elliottii* stands of different densities. *For. Ecol. Manage.*, 154:155–163.

Will, R. E., Munger, G. T., Zhang, Y., and Borders, B. E. (2002). Effects of annual fertilization and complete competition control on current annual increment, foliar development, and growth efficiency of different aged *Pinus taeda* stands. *Can. J. For. Res*, 32:1728–1740.

Chapter 6

Conclusion

Soil fertility is an important component of forest ecosystem, yet evaluating soil fertility remains one of the least understood aspects of forest science. The overall goal of this dissertation was to estimate the soil fertility rating (FR) to be used in the process-based model 3-PG. Up to now, the use of FR in 3-PG has been mostly confined as an adjustment factor to fit predicted productivity from 3-PG to observed productivity. This dissertation explored ways to estimate FR and improve the existing methods of FR estimation. The southern United States has millions of acres of loblolly pine plantations, representing a vast area of land that varies greatly in terms of soil fertility. Soil fertility is the most limiting factor for loblolly pine productivity in the southeastern United States. Quantification of soil fertility would provide a unique opportunity to study soil fertility gradients across the landscape and provides a basis for implementing site specific forest management practices.

Quantification of soil fertility in forested ecosystems has important implications for modeling forest productivity. Knowledge of soil fertility is equally important for making fertilization decisions and estimating fertilizer response. A key question arising from previous research is how can site index, a widely used indicator of site quality in forested ecosystem, be used as a potential tool for soil fertility estimation. Specifically, site index is a realized measure of site quality that is affected by not just soil fertility but a variety of edaphic and climatic factors including soil moisture and temperature. However, previous studies on loblolly pine have suggested that soil moisture is not a strong determinant of productivity in the southeastern US as this region receives fairly well distributed rainfall through out the year and annual precipitation exceeds potential evapotranspiration.

This study was designed to test the potential of using site index to estimate FR for use in the 3-PG model. The data used in the analyses came from two distinct designed field experiments. First, the remeasurement data collected from a loblolly pine fertilization trial established in the early to mid 1990s as an incomplete factorial design of nutrient dose and application frequency to evaluate the rates and frequencies of fertilization to optimize growth and fertilizer use efficiency. Second, the remeasurement data collected from a designed experiment in midrotation loblolly pine stands to evaluate the intensity of fertilization on the productivity of loblolly pine due to one-time fertilizer application of N and P. The data were collected from stands across the natural range of loblolly pine in the southeastern United States. Climatic data required for the 3-PG model were obtained from the daymet data set provided by Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC).

The major objectives of this research were to estimate soil fertility to be used in the process-based model 3-PG using site index and physical and chemical properties from A-horizon. In the four previous chapters, four specific objectives were addressed:

i. Use site index for the *a priori* prediction of FR that could be used as a set rather than a tunable parameter (see chapter 2)

ii. Understand the potential of using soil physical and chemical properties of the A-horizon to estimate FR values (see chapter 3)

iii. Assess FR in the repeated fertilized plots and derive relationship between fertilizer response and baseline FR in the control plots (see chapter 4)

iv. Model dynamics of FR (ΔFR) following midrotation fertilization of N and P across various intensities of N fertilization (see chapter 5)

The findings from this dissertation research illustrate the phytocentric and geocentric approach of soil fertility estimation. We also developed ways to adjust FR values when stands received one time midrotation fertilization of N and P with various intensities of N and repeated fertilization of N and P. We derived five conclusions from this research:

1. FR can be accurately estimated *a priori* from site index and used in 3-PG to accurately predict the growth and stocking of loblolly pine across the southeastern US with a single parameter set.

2. Strong correlation was found between site index values in the study sites and site index values archived in Soil Survey and Geographic Database (SSURGO). Our work on Kemper County, Mississippi, showed that 3-PG has the potential to estimate loblolly pine productivity using the FR values estimated using the site index values from the SSURGO database.

3. Multivariate regression methods are the most useful method to model soil fertility from physical and chemical properties of the A-horizon. Multicollinearity was a severe problem in the ordinary least square method of multiple linear regression due to high degree of correlation among soil physical and chemical properties. Partial least square regression selected N, Ca, Mg, C, and sand percentage as the significant predictor of soil fertility.

4. An inverse relationship was observed between fertilizer response and baseline fertility ratings in the control plots. The 3-PG model for stands repeatedly fertilized with N and P can be adapted by adjusting FR to 0.9.

5. Midrotation fertilization of N and P had temporary effects on soil fertility improvement and can be modeled by a Weibull function with two parameters. Dynamics of soil fertility (ΔFR) following midrotation fertilization can be modeled with intensity of N fertilization, year since treatment, and baseline FR values of the control plots. Increase in ΔFR following midrotation fertilization is temporary and depends in intensity of N fertilization.

A number of research questions are unanswered and deserve further attention:

a. Assart effect: Considerable temporal variation in nutrient supply, especially N, is prevalent in sandy Spodosols of the southeastern United States due to assart effect. The assart effect causes relatively short-lived pulse of N during the early phase of stand development as the forest floor and logging debris decompose. Temporal dynamics of nutrient availability as stands develop on sandy soils deserves further attention.

b. Soil nutrient capital: The soil nutrient data available in this research was collected during the juvenile stage. Availability of soil nutrient data during various stages of stand development would give an indication of temporal variation in soil nutrient capital.

c. Buffering capacity: This study measured soil nutrient quantity to explain the variability in FR. Measuring quantity does not guarantee the capacity of the soil to replenish depleted nutrients, the buffering capacity.

d. Mortality: The 3-PG model was found to be inadequate to model mortality especially in fertilized plots. In addition to canopy quantum efficiency and carbon partitioning, the effect of FR was clearly evident on tree mortality in several locations. Greater stand differentiation due to higher soil fertility needs further attention.

e. Competing vegetation: Heavy competition from woody and herbaceous plants following fertilization might decrease the growth response in fertilized plots and contribute to the over-prediction in the 3-PG model. Effect of fertilizer induced competition and its potential impact on soil fertility deserves further attention.

An enhanced understanding of soil fertility can be an effective means for modeling forest growth and decision making on site specific forest management practices. This study contributes to the greater body of knowledge of soil fertility evaluation. Models developed in this study will be useful to predict regional productivity of loblolly pine across the southeastern United States using the 3-PG model. A future consideration will be to understand the temporal dynamics of soil fertility especially in the sandy Spodosols. We expect soil fertility diminishes greatly in the sandy Spodosols of the southeastern United States thus causing substantial disparity between stand demand of nutrients and soil supply of nutrients during the early stage of stand development. A robust understanding of stand differentiation due to fertilization will be very important to accurately model growth and stocking of loblolly pine.