Modeling Repeated Fertilizer Response and One-time Midrotation Fertilizer Response in Loblolly Pine Plantations Using FR in the 3-PG Process Model

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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 (Landsberg & Waring, 1997) 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 variation in observed aboveground biomass in the fertilized plots was described by 3-PG simulated aboveground biomass. We then derived the

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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.

We also developed a dynamic function to model the FR 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 (Δ FR). This was done using an optimization process where the temporal distribution of the Δ FR 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 loblolly pine plantations was described by the 3-PG simulated aboveground biomass.

1. Introduction

1.1 Loblolly Pine Productivity in the Southeastern United States

Nutrient availability is a major factor limiting productivity of loblolly pine plantation in the southeastern United States (Colbert *et al.*, 1990; Albaugh *et al.*, 1998; Jokela & Martin, 2000; Fox *et al.*, 2007). There are three primary reasons behind this. First, previous research that has shown that irrigation has little impact on growth of loblolly pine in the southeastern United States. 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.

Albaugh *et al.* (1998) reported fertilization increased productivity by 188% over four years whereas irrigation only increased productivity by 17% in the Sandhills of North Carolina. Similarly Cobb *et al.* (2008) reported no significant effects of irrigation on growth of loblolly pine whereas fertilization increased productivity by 55%. Second, rainfall exceeds potential evapotranspiration within the natural range of loblolly pine plantation (Allen *et al.*, 1990; Lu *et al.*, 2005). Actual evapotranspiration values in the southeastern United States ranged from 570 to 1050 mm yr⁻¹ whereas rainfall ranges from 1050 to 1825 mm yr⁻¹. Third, the majority of loblolly pine forests in the southeastern United States are located on the soils that are often shallower, rockier, wetter, steeper, sandier, less fertile, eroded, and abandoned agricultural fields (Fox, 2000). About 10 million hectare of the southeastern United States is covered by loblolly pine and many of these forest soils throughout the southeastern United States are nutrient deficient (Jokela, 2004). Because of this, fertilization in loblolly pine plantations has been extended from 81,000 ha in 1990s to over half million ha in 2000s (Fox *et al.*, 2007).

1.2 Fertilization to Ameliorate Nutrient Limitation

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 *et al.*, 1990; Albaugh *et al.*, 1998; Sampson & Allen, 1998; Jokela *et al.*, 2000; Borders & Bailey, 2001; Will *et al.*, 2002; Subedi *et al.*, 2012).

Soil nutrient availability increases following disturbances such as tree harvest, a phenomenon described as the Assart Effect (Burger & Pritchett, 1984; Brais *et al.*, 2002; Fox *et al.*, 2007) 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. Stand demand for nutrients is low during early portions of the rotation and increases through time as tree size increases. Nutrients are tied up in the accumulating forest floor that acts as a sink for nutrients in undisturbed loblolly pine stands (Piatek & Allen, 2001; Kiser & Fox, 2012). 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 & Allen, 2001; Kiser & Fox, 2012). Midrotation fertilization is aimed at ameliorating nutrient deficiency at this stage of stand development.

Soil fertility is a dynamic property of forest soils that varies both spatially across the landscape and temporally during the rotation (Allen *et al.*, 1990; Fox *et al.*, 2007). As a consequence of the temporal pattern of nutrient supply and demand, most southeastern loblolly pine stands develop deficiencies of N and P at some point in the rotation (Allen *et al.*, 1990; Albaugh *et al.*, 1998; Sampson and Allen, 1999; Jokela and Martin, 2000; Will *et al.*, 2002). Loblolly pine plantations in the southeastern United States 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 at this point in the rotation is an important silvicultural practice to minimize nutrient deficiency and improve stand productivity. 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 (Jokela & Stearns-Smith, 1993; Hynynen *et al.*, 1998; Fox *et al.*, 2007; Carlson *et al.*, 2008; Gyawali & Burkhart, 2014). Whereas repeated fertilization produces type 2 response, characterized by a sustained increase in growth and productivity.

Given these circumstances, we are interested in modeling soil fertility response to fertilization. We wanted to model the dynamics of soil fertility following one-time midrotation fertilization with different levels of N and P. Similarly, we wanted to assess how repeated fertilization with N and P would change soil fertility in the southeastern United States.

1.3 Process Based Model 3-PG and Soil Fertility

We used the process based model Physiological Processes Predicting Growth (3-PG) (Landsberg & Waring, 1997) in this study. Details on 3-PG model for loblolly pine can be found on Subedi *et al.* (2015), Gonzalez-Benecke *et al.* (2016) and Bryars *et al.* (2013). Briefly, 3-PG is a canopy carbon balance 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 3PG.

3-PG relies on a fertility rating (FR) parameter to describe soil nutrient availability with values ranging from 0 to 1. FR is a site-specific parameter 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. FR is also directly involved in the C allocation to the belowground components where higher FR leads to lesser allocation of C to roots (Landsberg & Sands, 2011; Subedi *et al.*, 2015). Complex relationship exists between soil properties and stand productivity

and difficulties associated with measuring physical and chemical properties of mineral soil causes quantification of soil fertility a daunting task (Landsberg *et al.*, 2003; Fontes *et al.*, 2006; Vega-Nieva *et al.*, 2013; Subedi & Fox, 2016). An important limitation of the 3-PG model and several of its variants is that they lack an objective way of determining the FR parameter that links stand productivity to soil fertility. FR has been used as an adjustment factor or determined based on subjective decision of the model developer (Landsberg *et al.*, 2003; Dye *et al.*, 2004). For certain regions in the world this may be a reasonable approach, however, in the southeastern United States where the primary limiting factor for loblolly pine productivity is soil fertility, the objective measurement of soil fertility is necessary. Work by Subedi *et al.* (2015) presented an objective approach to calibrate FR based on site index that can be effectively used to simulate loblolly pine productivity in an unfertilized environment in the southeastern United States. Question remained on the usefulness of 3-PG to model the dynamics or change in soil fertility using FR following fertilization.

One of the objectives of this study was 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. In order to predict changing soil fertility in loblolly pine plantation, an algorithm to account for dynamics in fertility following fertilization is needed. We used data from a series of regional fertilization trials to model the dynamics of FR following a one-time midrotation fertilization and a repeated fertilization of loblolly pine with N and P. The data on one-time midrotation fertilization (Hynynen *et al.*, 1998; Gyawali & Burkhart, 2014) and repeated fertilization beginning in juvenile stage (Albaugh *et al.*, 2015) was used. First, we describe how repeated fertilization affect soil fertility and productivity by altering the FR parameter in the 3-PG model. We hypothesized that repeated fertilization will change soil

fertility permanently and thus lead to a shift in FR for the entire rotation. Second, we modeled the dynamics of soil fertility following one time midrotation fertilization with N and P at three different doses. We hypothesized that the one time fertilization only increased soil fertility temporarily.

2. Methods

2.1 Repeated Fertilization

2.1.1 Study Site Description, Data Collection, and 3-PG Parameterization

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, Table 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 United States (Table 1).

Data from the unfertilized control plots and the fertilization treatment plots receiving $134.4 \text{ kg ha}^{-1} \text{ N} + 13.44 \text{ kg ha}^{-1} \text{ P}$ 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^{2.015} HT^{0.864}, 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.

We used the species specific parameter set developed by Subedi *et al.* (2015) (Table 2). Baseline fertility ratings in the unfertilized plots were derived from site index (SI) using the following equation derived by Subedi *et al.* (2015).

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

2.1.2 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 1 and fertilizer response at age 11. The R² and RMSE values were calculated for a fitted relationship between fertilizer response and aboveground productivity.

2.1.3 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 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 N and P deficiencies. The FR values in each of the biannually fertilized plots of the nine remaining were adjusted to 0.9.

The FR values generated from the above procedure were used as inputs in 3-PG along with species specific parameters from Table 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.

2.2 One-time Midrotation Fertilization

2.2.1 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 (Figure 1, Table 1). 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 1). 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 described in section 2.1.1. 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.

2.2.2 FR Estimation and Validation

Three installations with 12 years of post-fertilization stand growth dataset were randomly 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 2, weather data from www.daymet.org, and FR estimated using equation 1 (Figure 6).

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 & Burkhart, 2014). 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 Δ FR due to fertilization.

$$FR_{\text{fertilized}} = \text{baseline FR} + \alpha N \frac{\gamma}{\beta} \left(\frac{YST}{\beta} \right)^{\gamma-1} e^{\left(\frac{-YST}{\beta} \right)^{\gamma}} \quad (2)$$

The added term to baseline FR represents the dynamics of Δ FR 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 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.

3. Results

3.1 Repeated fertilization beginning juvenile stage

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 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). The R² 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 5). The R² 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 over predicted 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.

3.2 Midrotation Fertilization

Figure 7 shows mean change in FR (Δ FR) due to fertilization. The magnitude of Δ FR varied with the rate of N and YST. Δ FR increases with increasing rate of N. The pattern of change is mound shaped and is positively skewed. Results from fitting dynamics of Δ FR following fertilization including parameter estimates, standard error, p-values, RMSE, and R² are shown in Table 3. All parameters were highly significant (p<0.0001). Small RMSE value and a high R² 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 7). 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 7).

3-PG predicted aboveground biomass in the fertilized plots well (Figure 8). Overall, using FR determined from model 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. The intercept of the relationship between observed values of aboveground biomass and modeled values of aboveground biomass had 95% of confidence interval between 5.36 and 17.23.

4. Discussion

Growth increases after fertilization are a result of the increases in soil nutrient availability. The degree of limitation in soil fertility and the timing of limitation will vary with soils, topography, and stage of stand development. During the early stage of stand development, the Assart effect, induced by clearcutting, causes a flush of nutrients that surpassed the demand and many stands do not face nutrient deficiencies until the onset of the stem exclusion stage. It is of crucial importance that modelers recognize that there are different ways in which soil fertility respond to different rates and timing of fertilization. Our study is the first to provide the information on the dynamics of soil fertility following fertilization using process based model systems. Our results confirmed our hypothesis that repeated fertilization leads to permanent increase in soil fertility and one time midrotation fertilization leads to temporary increase in soil fertility.

4.1 Repeated Fertilization and Soil Fertility

Fertilization had a significant positive influence on aboveground productivity. 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 FR 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.* (2011) reported mean annual aboveground biomass increment for 12-year-old intensively managed loblolly pine plantations in the Upper Coastal Plain and Piedmont as $13.6 \text{ Mg ha}^{-1} \text{ yr}^{-1}$ and Borders and Bailey (2001) reported stand volume in the intensively managed loblolly pine plantations in the Lower Coastal Plain as $31.8 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$. Our hypothesis that repeated fertilization with N and P in the southeastern United States eliminates major nutrient deficiency was confirmed in many sites.

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 maximum canopy quantum efficiency (αC_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 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 over prediction by the 3-PG model. Discrepancies in stand density prediction may affect prediction of stand biomass (Pinjuv *et al.*, 2006; Bryars *et al.*, 2013). 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 & Haywood, 1986; Jokela *et al.*, 2000; Martin & Jokela, 2004). 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. Potassium, Ca, Mn, and other micronutrients limit productivity in some locations in the southeastern United States (Jokela *et al.*, 1991; Vogel & Jokela, 2011; Carlson *et al.*, 2014). 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 (Landsberg *et al.*, 2003; Bryars *et al.*, 2013) lacked independent sites for validation. This study had nine sites across the southeastern US for validation of this approach.

4.2 Midrotation Fertilization and Soil Fertility Dynamics

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 United States 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 & Stearns-Smith, 1993; Hynynen *et al.*, 1998; Gyawali & Burkhart, 2014). N fertilization increases the soil mineral N pool and the duration and magnitude of increase depends on the intensity of N fertilization (Mudano, 1986; Carlyle, 1995; Gurlevik *et al.*, 2004). N fertilization increases mineral N initially but the effect diminishes over time (Johnson *et al.*, 1980; Carlyle, 1995). 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; Piatek & Allen, 2001). 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 m³ha⁻¹yr⁻¹ during the first 8 years. The reported growth efficiency for loblolly pine in the southeastern United states is approximately 7.2 m³ha⁻¹yr⁻¹ LAI⁻¹ (Vose & Allen, 1988; Albaugh *et al.*, 1998). 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 Δ FR 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 & Burkhardt, 2014). The temporal pattern of Δ FR 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 Burkhardt (2015).

This study represents the first attempt to model the dynamics of FR following fertilization in the 3-PG model. Our results suggest that the dynamics of FR following fertilization can be modeled and used in the 3-PG model to estimate the growth and productivity of loblolly pine in the southeastern United States. Fertility rating in the 3-PG model is a site specific parameter (Landsberg & Sands, 2011), however, measuring FR has been mostly a subjective approach based on the modeler's judgement. Our approach used a method developed

by Subedi *et al.* (2015) to model baseline FR from site index. This approach to link FR to site index, although makes FR somehow species-specific, takes into account the fact that the variation in site index in any physiographic province that has similar climatic condition is mostly attributed to variation in edaphic factors. So, the inherent limitation on quantifying FR from site index should be recognized.

5. Conclusion

Three major conclusions have emerged from our study. First, the response to fertilization is negatively correlated with baseline soil fertility, soils with inherently high soil fertility respond less to fertilization and soils that are inherently less fertile respond highly to fertilization. Second, repeated fertilization with N and P increases soil fertility permanently throughout the rotation in the southeastern United States. Third, we found the one-time midrotation fertilization temporarily increases soil fertility.

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578 Figure 1: Location of study sites used to develop and test dynamics of fertility rating following one-time
579 midrotation fertilization with N and P (●) and repeated biannual fertilization with N and P (*) using the 3-
580 PG model. (Note: Two repeated biannual fertilization sites in the Coastal Plain of Georgia are very close
581 to each other.)

Figure 2: Aboveground biomass (Mg ha^{-1}) in biannually fertilized and control plots at Berkeley, South Carolina (left) and Marengo, Alabama (right).

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

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597 Figure 4: The relationship between observed aboveground biomass (Mg ha⁻¹) and 3-PG predicted
 598 aboveground biomass (Mg ha⁻¹) on two sites where repeated fertilization with N and P did not increase
 599 growth. Solid lines represent linear fit between observed and predicted values and dotted lines represent
 600 the 1:1 line between observed and predicted values.

Figure 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. Solid lines represent linear fit between observed and predicted values and dotted lines represent the 1:1 line between observed and predicted values.

Figure 6: Relationship between observed aboveground biomass and 3-PG 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 fertility rating (FR) following midrotation fertilization.

Figure 7: 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 8: The relationship between observed aboveground biomass and predicted aboveground biomass in fertilized plots using 3-PG model using the FR values generated from model 2 in the validation sites of the midrotation fertilization. Solid lines represent linear fit between observed and predicted values and dotted lines represent the 1:1 line between observed and predicted values.

637 Table 1: Location (State, County), physiographic province, latitude / longitude, soil series, average annual
638 precipitation (mm yr⁻¹), and average maximum and minimum temperature (°C) for study sites used to
639 calibrate fertility rating in the biannually fertilized plots (installations begin with 18) and one time
640 midrotation plots (installations begin with 13).

Installations	State, County	Lat / Long	Soil series	Precipitation (mm yr ⁻¹)	Temperature
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
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

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644 Table 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		0.4
2	pFS20	Ratio of foliage: stem partitioning at stem diameter = 20 cm		0.25
3	StemConst	Constant in stem mass diameter relationship		0.1
4	StemPower	Power in stem mass diameter relationship		2.5
5	pRx	Maximum fraction of NPP to roots		0.4
6	pRn	Minimum fraction of NPP to roots		0.2
7	SLA0	Projected specific leaf area at the beginning of plantation	m ² Kg ⁻¹	6.4
8	SLA1	Projected specific leaf area for mature stand	m ² Kg ⁻¹	4
9	tSLA	Age at which SLA is mean of SLA0 and SLA1	year	6
10	k	Extinction coefficient for APAR by canopy		0.69
11	fullCanAge	Age at full canopy cover	year	4
12	MaxIntcptn	Maximum proportion of rainfall intercepted by canopy		0.2
13	LAImaxIntcptn	LAI for maximum rainfall interception		5
14	αC_x	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
17	CoeffCond	Defines stomatal response to VPD	Mbar ⁻¹	0.02
18	Blcond	Canopy boundary layer conductance	m s ⁻¹	0.1
19	wSx1000	Maximum stem mass per tree at 1000 trees ha ⁻¹	kg tree ⁻¹	235
20	thinPower	Power in self thinning law		1.6
21	mF	Fraction of mean foliage biomass per tree on dying trees		0
22	mR	Fraction of mean root biomass per tree on dying trees		0.2
23	mS	Fraction of mean stem biomass per tree on dying trees		0.4
24	fracBB0	Branch and bark fraction at stand age 0		0.4
25	fracBB1	Branch and bark fraction for mature stand		0.1
26	tBB	Age at which brak fraction is mean of fracBB0 and fracBB1		15
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
30	Rttover	Average monthly root turnover rate		0.0168
31	m0	Value of m when FR is zero		0.1
32	fN0	Value of fN when FR is zero		0.5
33	Tmin	Minimum temperature for growth	⁰ C	4
34	Topt	Optimum temperature for growth	⁰ C	25
35	Tmax	Maximum temperature for growth	⁰ C	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		0.2
40	y	NPP to GPP ratio		0.47

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646 Table 3: Parameter estimates and fit statistics of fertility rating dynamics model (equation 2) following
 647 midrotation fertilization.

Parameters	Estimates	Standard Error	p-value
α	0.0020679	0.003107	<0.001
γ	2.2861918	0.267260	<0.001
β	8.9277010	0.950771	<0.001
RMSE	0.01596		
R^2	0.73		

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