CALIBRATING THE 3-PG MODEL FOR OPEN POLLINATED AND CLONAL LOBLOLLY PINE STANDS AND EVALUATING THEIR PERFORMANCE ACROSS SPATIAL AND CLIMATIC GRADIENTS IN THE SOUTHEASTERN UNITED STATES

by

CHARLES H BRYARS IV

Under the Direction of Robert Teskey

ABSTRACT

Both projects presented here involved calibrating the 3-PG model. The goal of the first project was to determine if 3-PG could accurately predict growth of loblolly pine (*Pinus taeda*) plantations across a range of sites in the Piedmont and Coastal Plain provinces of Georgia using a fixed physiological parameter set. We hypothesized that because a) many physiological attributes of loblolly pine tend to be very similar across sites, and b) leaf area is highly responsive to fertility but less so to water and other environmental factors, a single physiological parameter set would be suitable for predicting growth across a range of loblolly pine plantations which differed in soil type and silvicultural treatments. The goal of the second project was to determine if the 3-PG model could produce accurate estimates of productivity of two clonal loblolly pine genotypes that exhibit contrasting growth strategies and then to evaluate how the two clones would react to changes in temperature and precipitation. We hypothesized that the broad crown genotype would become water limited with increases in temperature much sooner than the narrow crown genotype due to its increased leaf area of the broad crown genotype.

INDEX WORDS: Process-based model, 3-PG, Loblolly pine, Parameterization, Open pollinated, genotype, Loblolly pine clone

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CHARLES H BRYARS IV

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CHARLES H BRYARS IV

Major Professor: Robert Teskey
Committee: Michael Kane
Christopher Maier

Electronic Version Approved:

Maureen Grasso
Dean of the Graduate School
The University of Georgia
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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

1.1 Purpose of the Study

This project consisted of two studies involving calibration of the 3-PG model. The goal of thie first project was to determine if 3-PG could accurately predict growth of loblolly pine (*Pinus taeda*) plantations across a range of sites in the Piedmont and Coastal Plain provinces of Georgia using a fixed physiological parameter set. We hypothesized that because a) many physiological attributes of loblolly pine tend to be very similar across sites, and b) leaf area is highly responsive to fertility but less so to water and other environmental factors, a single physiological parameter set would be suitable for predicting growth across a range of loblolly pine plantations which differed in soil type and silvicultural treatments. This will allow scientist and mangers to produce accurate predictions of productivity with the 3-PG model with much less effort than previously thought. The goal of the second project was to determine if the 3-PG model could produce accurate estimates of productivity of two clonal loblolly pine genotypes that exhibit contrasting growth strategies and then to evaluate how the two clones would react to changes in temperature and precipitation. We hypothesized that the broad crown genotype would become water limited with increases in temperature much sooner than the narrow crown genotype due to the increased leaf area of the broad crown genotype. Water use efficiency is an important aspect when considering which genotype to plant on a site in order to ensure the health of the stand.

1.2 How This Study is Original

The 3-PG model has been used for a variety of applications. For instance, 3-PG has been used to explore yields and spatial supply of short rotation poplar (*Populus spp.*) and willow (*Salix spp.*) coppice for bioenergy production in the United Kingdom (Aylott, 2008), predict rates of change in soil carbon after afforestation of *Pinus radiata* and *Eucalyptus* plantations in Australia (Paul et al. 2003), model stand volume and leaf area index (LAI) of ponderosa pine (*Pinus ponderosa*) throughout Washington, Oregon, and Northern California (Wulder et al. 2007), explore carbon allocation in clonal *Eucalyptus* plantations in Brazil (Stape et al. 2008), simulate age related changes to carbon allocation in Chinese fir (*Cunninghamia lanceolata*) plantations in southern China (Zhao et al. 2009), and assess the effect of changes in climate on Douglas-fir (*Pssudotsuga menziesii*) productivity in British Columbia (Coops et al. 2010). Several other studies have used 3-PG to estimate productivity over large areas using spatial databases or geographical information systems (GIS); Coops et al (1998), White et al (2000), Coops and Waring (2001), Tickle et al (2001), and Almeida et al (2009).

The 3-PG model has also been used to predict productivity of loblolly pine plantations in the Southeastern United States (Landsberg et al. 2001, Sampson et al. 2006). Our study differs in a number of ways from both the Landsberg et al. (2001) and the Sampson et al. (2006) studies. We calibrated 3-PG using a stand with very high productivity to set the upper limit of the fertility rating. We evaluated the model on a much wider range of sites and stand growth rates. We also used a new parameter calibration tool that we developed to calculate the fertility rating for each site instead of relying on iterative model runs. The physiological parameter sets for the clonal loblolly pine genotypes used in the second study had not been determined for the 3-PG model prior to this study.

CHAPTER 2

A SINGLE PHYSIOLOGICAL PARAMETER SET FOR THE 3-PG MODEL PRODUCED ACCURATE ESTIMATES OF LOBLOLLY PINE GROWTH IN STANDS IN THE COASTAL PLAIN AND PIEDMONT PROVINCES OF GEORGIA, USA[1]

[1] Bryars, C.H., C.A. Maier, Z. Dehai, M. Kane, B.E. Borders, R.O. Teskey. To be submitted to *Forest Ecology and Management*

Abstract

The goal of this project was to determine if 3-PG could accurately predict growth of loblolly pine (*Pinus taeda*) plantations across a range of sites in the Piedmont and Coastal Plain provinces of Georgia using a fixed physiological parameter set. We hypothesized that because a) many physiological attributes of loblolly pine including rates of net photosynthesis, dark respiration, stomatal conductance and specific leaf area tend to be very similar across sites, and b) leaf area is highly responsive to fertility but less so to water and other environmental factors, a single physiological parameter set would be suitable for predicting growth across a range of loblolly pine plantations which differed in soil type and silvicultural treatments. The parameter set was obtained from a combination of published values in the literature and model calibrations developed from a single highly productive stand in the Coastal Plain province in Georgia. Differences in potential productivity among sites were accounted for by only changing the value of the fertility rating and the soil type. The calibrated model was evaluated using observed growth data obtained from a slower growing stand at the same Coastal Plain site as the calibration stand, and three other sites, two in the Piedmont province and one in the Coastal Plain.

The model performed well on all stands and treatments, and accurately estimated stem biomass and diameter growth. However, it did not accurately predict stand density in most cases and tended to overestimate volume. Poor prediction of stand density can be attributed to density-independent mortality, which the model is unable to predict. The overestimated volume was due to an incorrect estimate of wood density. Despite these discrepancies in measured and modeled stem density and volume it is our conclusion that overall the 3-PG model provided an accurate

description of loblolly pine plantation growth and productivity in both the Piedmont and Coastal Plain provinces of the Southeastern US using a single set of physiological parameters.

Keywords: Process-based model, 3-PG, loblolly pine, parameterization.

2.1 Introduction

Loblolly pine is the predominant timber species in the Southeastern United States and is managed on a variety of landtypes using both intensive and extensive silvicultural treatments (Schultz, 1997). Since the second harvest of naturally regenerated stands in the 1920's, productivity of loblolly pine has increased by 700% (Stanturf et al. 2003). Increased productivity can be attributed to changes in silvicultural management regimes including increased fertilization, competition control, and more intensive site preparation, as well as genetic improvement. In addition, climate change (primarily increased atmospheric [CO2]) and increased nitrogen deposition may have also lead to changes in productivity of loblolly pine stands (Groninger et al. 1999, Wertin et al. 2010). For these reasons, a model which can accurately predict plantation productivity and also accommodate changes in environmental conditions and silvicultural treatments would be useful to scientists and managers (Almeida et al, 2004a). The model 3-PG (Physiological Principles Predicting Growth) is a simple process based model that requires parameterization of relatively few physiological attributes and uses simple and readily available weather and site characteristics to produce predictions of stand growth. 3-PG has already been used with a number of tree species, climates, and site conditions throughout the world. It has been used with at least a dozen tree species and species-specific parameter values have been published for several species including; *Eucalyptus grandis* (Almeida et al., 2004a), *Eucalyptus globlulus* (Sands and Landsberg, 2001), *Pinus patula* (Dye, 2001), *Pinus* *ponderosa* (Law et al., 2000)*, Picea sitchensis* (Waring, 2000)*, Acacia mangium* (Booth et al., 2001) *and Dacrydium cupressinum* (Whitehead et al., 2002).

The 3-PG model has been used for a variety of applications. For instance, 3-PG was used to explore yields and spatial supply of short rotation poplar (*Populus spp.*) and willow (*Salix spp.*) coppice for bioenergy production in the United Kingdom (Aylott, 2008), predict rates of change in soil carbon after afforestation of *Pinus radiata* and *Eucalyptus* plantations in Australia (Paul et al. 2003), model stand volume and leaf area index (LAI) of ponderosa pine (*Pinus ponderosa*) throughout Washington, Oregon, and Northern California (Wulder et al. 2007), explore carbon allocation in clonal *Eucalyptus* plantations in Brazil (Stape et al. 2008), simulate age related changes to carbon allocation in Chinese fir (*Cunninghamia lanceolata*) plantations in southern China (Zhao et al. 2009), and assess the effect of changes in climate on Douglas-fir (*Pssudotsuga menziesii*) productivity in British Columbia (Coops et al. 2010). Several other studies have used 3-PG to estimate productivity over large areas using spatial databases or geographical information systems (GIS) (Coops et al. 1998, White et al. 2000, Coops and Waring 2001, Tickle et al. 2001, and Almeida et al. 2009).

The 3-PG model has also been used to predict productivity of loblolly pine plantations in the southeastern United States (Landsberg et al. 2001). The model was calibrated using a twelve-year-old control stand and used to predict growth of fertilized or fertilized and irrigated stands of the same age on the same site by adjusting the fertility rating until the model matched the growth performance of the stands. The model was also used to estimate mean diameter growth of an adjacent experimental genetic trial. This test demonstrated that 3-PG was able to estimate the growth of young loblolly pine plantations with reasonable accuracy. However, the trial was only in its third year of growth so the test was not very robust. Sampson et al. (2006)

combined 3-PG with another process model, SECRETS (Secrets_3-PG), to estimate growth and productivity as well as carbon fluxes for the same stands used in Landsberg et al. (2001). The same calibration approach was used in both studies, but the Sampson et al. data set extended to age 16. They found good agreement between measured growth data and model simulations for a fertilized stand on the same site after calibration. Our study differs in a number of ways from both the Landsberg et al. (2001) and the Sampson et al. (2006) studies. We calibrated 3-PG using a stand with very high productivity to set the upper limit of the fertility rating. We evaluated the model on a much wider range of sites and stand growth rates. We also used a new parameter calibration tool which we developed to calculate the fertility rating for each site instead of relying on iterative model runs (Appendix B).

Our objective was to determine if a single parameter set, developed from a calibration of a single loblolly pine plantation, could be used to accurately predict growth of loblolly pine plantations in other locations. The model was calibrated using a highly productive stand near Waycross, Georgia and then validated against loblolly pine growth data from sites located in Tifton, Athens, and Monticello, Georgia. These sites were chosen because they lie within the Piedmont and Coastal Plain provinces of Georgia and they varied substantially in growth rates due to difference in soil type, climate, and silvicultural treatments. We hypothesized that the physiological and growth characteristics of loblolly pine, especially the high responsiveness of leaf area growth to differences in resource availability and the limited range of response of net photosynthesis and respiration to the same conditions would make it feasible to use a single parameter set in 3-PG to accurately estimate growth of loblolly pine plantations at sites with different soils and climatic conditions.

2.2 Materials and Methods

2.2.1 The 3-PG Model

The 3-PG model is a dynamic, process-based model developed by Landsberg and Waring (1997) that predicts stand growth of plantations or even aged, relatively homogenous stands. The model principally predicts net primary productivity (NPP), the partitioning of biomass to leaves and woody tissue above and below ground, and transpiration on a monthly or annual time step. Net primary productivity is determined using a fixed relationship to gross primary productivity (GPP; NPP/GPP). This assumption eliminates the need to calculate respiration (Waring et al. 1998; Landsberg et al. 2003). 3-PG then uses fixed ratios to allocate NPP to roots, foliage, and stem. The allocation ratio of carbon to roots shifts in relation to site fertility and water availability. Carbon allocation to foliage and stem is determined using allometric relationships (Landsberg and Waring, 1997). Carbon allocated to foliage is adjusted depending on stand age, edaphic and environmental conditions (Landsberg et al. 2003). Stand growth rates are also adjusted for age to compensate for the decline in tree growth rate with age. Stand density is adjusted for density-dependent mortality using the -3/2 thinning law. Soil water balance is calculated using the Penman-Monteith equation to calculate transpiration (Landsberg et al. 2003). The outputs of 3-PG include stand attributes that are useful to land managers for estimating wood production (stem diameter, basal area, volume, stem biomass increment, stand density and mortality) as well as attributes useful to forest scientists such as leaf area index, utilizable radiation, total biomass production, and transpiration. For a more complete description of the model, see Landsberg and Waring (1997).

2.2.2 Site Specific Data

Site-specific climate data required by the model includes monthly mean daily minimum and maximum temperatures, monthly precipitation, and number of frost days per month. These weather data can either be actual observed values if running the model over past time periods or average weather data if running the model for future time periods. Our study used actual monthly weather values as these have been previously observed to produce more accurate predictions (Almeida et al. 2004b). Weather data were available from the National Oceanic and Atmospheric Administration (NOAA) (http://www.ncdc.noaa.gov/oa/ncdc.html). Monthly mean of daily incoming solar radiation is also required by the model and can be calculated from temperature (Bristow and Campbell (1984), Coops et al. 1998) or collected from NASA's Atmospheric Science Data Center website (eosweb.larc.nasa.gov/sse). Other site-specific inputs such as maximum available soil water and a soil texture were determined for each site independently using the NRCS Web Soil Survey website (http://websoilsurvey.nrcs.usda.gov/app/HomePage.htm). Latitude is also a required input (to determine day length), found simply using Google Maps (maps.google.com). The other parameter adjusted from site to site was the fertility rating. The fertility rating is an empirical index that ranks soil fertility on a scale from an optimum value of one to an extremely infertile value of zero. We estimated FR using the parameter calibration tool (Appendix B) and observed DBH and stem biomass data from the most recent ten years of the stand. If know, the initial stem, root, and foliage biomass can be inputs, however, we held these constant at 0.001 tons ha^{-1} each. All other inputs are species physiological parameters, described below.

2.2.3 Study Sites

3-PG was calibrated using one highly productive site on the Coastal Plain near the city of Waycross in Ware County, Georgia (31° 12'50"N latitude, 82°21'18"W longitude) then validated using data collected from two sites in the Piedmont (Athens and Monticello, Georgia) and one site in the Coastal Plain (Tifton, Georgia) (figure 2.1). The Waycross site was chosen as the calibration site because growth rates there were very high for loblolly pine and yearly measurements of stand growth were available. For a complete description of the site see Borders et al. (2004).

There were four silvicultural treatments on all sites; however, for our study we used only the highest intensity treatment (mechanical site preparation, weed control, and fertilization) and the lowest intensity treatment (mechanical site preparation only). The high intensity treatment consisted of annual application of herbicide as needed to control all herbaceous and woody competition and an annual fertilizer amendment as follows: first two growing seasons: 280 kg ha^{-1} DAP + 112 kg ha^{-1} KCl in the spring and 56 kg ha^{-1} of NH_4NO_3 mid-summer. In subsequent growing seasons: 168 kb ha^{-1} NH_4NO_3 early spring. At age 10, 336 kg ha^{-1} NH_4NO_3 + 140 kg ha^{-1} triple super phosphate applied in early spring . At age 11, 560 kg ha^{-1} of NPK (10-10-10) with micronutrients (Super Rainbow, Agrium Inc.) + 168 kg ha^{-1} NH_4NO_3 in early spring. At age 12 onward 336 kg ha^{-1} NH_4NO_3 was applied in early spring. The low intensity treatment consisted of no other treatments following a spot rake, pile, and mechanical bed site preparation, which was the same mechanical site treatment conducted on the high intensity treatment.

Three other sites were used to provide validation data. These sites were located near Athens, Monticello, and Tifton, Georgia and represent a wide range of climatic and edaphic conditions within the native range of loblolly pine (Table 2.1). 3-PG uses one of four soil types (sand, sandy loam, clay loam, and clay) to determine soil water holding capacity. Waycross was classified as a sandy loam, Tifton a clay loam, Monticello a clay, and Athens a clay. All validation sites underwent the same treatments as the Waycross site. Site and treatment effects on seedling survival caused significant differences in age one stem densities across sites. The Waycross high intensity site had 1660 stems ha^{-1} while the Waycross low intensity site had 1690 stems ha^{-1}. The high intensity Monticello site had 1572 trees ha^{-1} while the Monticello low intensity site 1581 stems ha^{-1}. The Athens high intensity site had 1560 trees ha^{-1} and the Athens low intensity site had 1551 stems ha^{-1}. The Tifton high and low intensity sites had 1422 trees ha^{-1} at age one. Dead seedlings were removed and not counted towards the total number of stems planted per hectare. The sites were also established in different years. Waycross was established in 1987, Monticello and Tifton in 1988, and Athens in 1989. All four sites were planted with genetically improved, open pollinated 7-56 1-0 seedlings (North Carolina State University Tree Improvement Cooperative).

2.2.4 Physiological Parameter Estimation, Calibration, and Validation

3-PG was calibrated by comparing measured data from a single stand with modeled data and then manipulating model parameters so that the model's output fit the measured data. 3-PG was then validated by modeling growth on sites not used for calibration by comparing modeled growth to observed values. In our study, we used stem biomass, diameter at breast height (DBH), stem volume outside bark, and stand density data from the Waycross high intensity site as our calibration data. Initial parameter estimates were constrained by published information when available (Table 2.2). When parameter values were not known, or when values ranged widely from report to report, we used parameter estimates which best recreated the growth of the calibration plantation (Table 2.2). Site specific parameters were adjusted for the climate, soils, planting density, and fertility of each site. Simple linear regressions were performed to determine the relationship between modeled and measured values.

2.3 Results

On the calibration site the model was able to accurately estimate stem biomass, diameter at breast height (DBH), volume outside bark (VOB), and stem density over the 23 year measurement period (figure 2.2). Measured and modeled DBH and stem density values at age 24 were, respectively, 24.5 and 26.3 cm for DBH and 1048 and 1077 stems ha^{-1} for stem density. 3-PG estimates were in near perfect agreement with measured stem biomass through year 23 as well. At age 23 the stand had 361 tons ha^{-1} of stem biomass while the model predicted 354 tons ha^{-1}. Volume was only recorded up to year 15. Year 15 values for measured and modeled VOB (figure 2.2C) were 449 and 457 m^3 ha^{-1}. Linear regression was used to compare modeled and measured values. R-squared values for all linear regression analyses on the calibration plot were $\geq$0.97 (figure 2.2).

Low intensity treatment plots had lower productivity than the high intensity plots in all of the stands used for model validation. On average, stem biomass at the final year of measurement on low intensity plots was 58% less on the Coastal Plain sites and 50% less on Piedmont sites than in the corresponding high intensity sites. However, 3-PG was able to accurately estimate growth of these stands. At age 21, measured and modeled values of stem biomass were 184 and 170 tons ha^{-1} for the low intensity plot at Waycross (Figure 2.3). Similarly, the model predicted DBH extremely well at age 21 with measured and modeled values of 16.8 and 15.2 cm, respectively. At years <8 DBH was slightly overestimated and slightly underestimated at years >14, however the error remains low. VOB was consistently overestimated at all ages <12 however the predicted VOB growth curve corresponded well to the measured data (figure 2.3C).

Stand density was the worst predicted output on the Waycross control site with measured and modeled values at year 21 of 1048 and 1639 stems ha^{-1}, respectively (figure 2.3D). All modeled outputs were regressed against their measured counterparts and produced R-squared values >0.97 except for the stand density output which produced an R-squared value of 0.675.

At the other Coastal Plain site (Tifton, GA) measured values were only available to age 14. Measured and modeled stem biomass on the high intensity Tifton site were nearly congruent at ages >12 but diverged somewhat between ages 7 and 10. In the last year of measurement, measured and modeled stem biomass values were 192 and 194 m^3 ha^{-1} respectively, producing an R-squared value of 0.925 (figure 2.4A). Modeled DBH mirrored the observed DBH growth curve, although there was a consistent under-prediction producing a discrepancy of 3.5 cm at the point where the predicted value was furthest from the observed value (figure 2.4B). Volume was very well estimated by the model on this site. Modeled VOB values very nearly matched those measured throughout the years measured (figure 2.4C). Stem density was poorly predicted on the Tifton high intensity site with year 14 values for measured and modeled stem density being 1066 and 1373 stems ha^{-1} respectively (figure 2.4D).

On the Tifton low intensity site, all outputs examined were modeled well by 3-PG (figure 2.5). At age 14, measured and modeled stem biomass were 161 and 163 tons ha^{-1} (figure 2.5A). Values for stem biomass were slightly over-predicted at ages <10. Modeled and measured DBH values were very similar at age 14, 18 and 16.8 cm, respectively. DBH values were slightly over-predicted at ages <9 and slightly under predicted at ages >9 (figure 2.5B). VOB on the Tifton low intensity site was well predicted at age 14 with a measured value of 286 m^3 ha^{-1} and a modeled value of 303 m^3 ha^{-1}, however all values previous to age 14 were over-predicted.

Stocking was predicted well throughout the study period. 3-PG slightly over-predicted stocking, by only seven stems ha^{-1} at age 14 (figure 2.5D).

The two Piedmont sites (Monticello and Athens) outperformed the two Coastal Plain sites (Waycross and Tifton) in stem biomass production on both high intensity and low intensity sites except at the Waycross high intensity site which outperformed the Monticello high intensity site. High and low, intensity treatments on the Piedmont sites were on average seven percent more productive in terms of measured stem biomass than Coastal Plain sites of the same age though their average DBH values were very similar. 3-PG was able to simulate this change in productivity with location. Stem biomass was extremely well predicted by the model on the Monticello high intensity site (figure 2.6A). DBH was under-predicted by 3-PG. Measured and modeled DBH values at age 21 were 24.5 and 21.3 cm, respectively (figure 2.6B). Volume was very well predicted on this site with values at ages >10 being nearly identical (figure 2.6C). Stem density was again the most poorly predicted output examined. At age 21, measured and modeled stem density were 998 and 1329 stems ha^{-1}, respectively (figure 2.6D).

Measured stem biomass values on the Monticello low intensity site had an irregular growth curve which led to over-predicted modeled values at ages <15 and under-predicted at ages >18 (figure 2.7A). Modeled DBH values closely followed the measured values throughout the life of the study (figure 2.7B). At age 21 measured and modeled values for DBH were 18.2 and 17.1 cm and produced an R-squared value of 0.988 when measured and modeled values were regressed. Once again, modeled VOB values followed the growth curve of measured values but were over-predicted early in the life of the stand and were most accurate near the last year of measurement (figure 2.7C). Stem density was well predicted on the Monticello low intensity site. Despite the irregular curve produced by measured values over the timeframe of the study the model was able to accurately predict stand density values consistently, producing an R-squared value of 0.889 (figure 2.7D).

Stem biomass, DBH, and volume on the Athens high intensity treatments were accurately predicted by the 3-PG model (figure 2.8). At age 13 measured and modeled VOB were 348 and 389 m^3 ha^{-1}, measured and modeled and measured DBH were 19.8 and 18.3 cm, and measured and modeled stem density were 1343 and 1376 stems ha^{-1}. Again, the model consistently over-predicted VOB while matching the slope of the measured values (figure 2.8D). Despite that, a linear regression of the measured and modeled values produced an R-squared of 0.996 indicating that variability of the measured values was accounted for by the modeled values.

Stem biomass values on the Athens low intensity site were slightly over-predicted until the final year of measurement (figure 2.9A) however measured and modeled values at the final year of measurement were both 130 tons ha^{-1}. Modeled DBH values were over-predicting at ages <8 and under-predicting at ages >10. Measured and modeled values for DBH at age 13 were 16.4 and 14.7 cm, a difference of only 1.7 cm. VOB was initially over-predicted but due to the steeper growth curve of this site, measured VOB values reached the levels of modeled values by year 13 when measured and modeled values were 221 and 238 m^3 ha^{-1} (figure 2.9C). Stand density was over-predicted by 3-PG. At age 13, measured and modeled stand density was 1442 and 1504 stems ha^{-1}, respectively (figure 2.9D).

2.4 Discussion

The 3-PG model was able to produce accurate estimates of loblolly pine stand growth, similar to other studies (Almeida et al., 2004a, Sands and Landsberg, 2001, Dye, 2001, Law et al., 2000, Waring, 2000, Booth et al., 2001, Whitehead et al., 2002). Landsberg et al. (2001) produced evidence that 3-PG could produce accurate estimates of loblolly pine growth however that study was calibrated and validated within a single locale, and used the same weather data for both the calibration and validation sites. Our study expanded on that result and demonstrated that a single parameter set can produce accurate estimates of loblolly pine stand growth across a large area. We hypothesized that a single physiological parameter set would accurately predict growth of loblolly pine plantations growing at different rates due to differences in silvicutural regime, soil type, and climate. The only changes we made in the model from site to site were the fertility rating, weather conditions, soil type and initial planting density. Our tests indicated that this method may be a reasonable way to use the model across a range of site and climatic conditions. This result was likely produced because many physiological attributes of loblolly pine, most notably, rates of net photosynthesis, dark respiration, stomatal conductance, and specific leaf area appear to change little across sites and climatic conditions. Growth appears to be much more dependent on leaf area development and the quantity of solar radiation intercepted by the plantation than on changes in the rates or efficiencies of specific physiological processes (Albaugh et. al. 2004b, Samuelson et al. 2004). It has been shown in a number of studies that leaf area index (LAI) of loblolly pine increases with increased site fertility and that loblolly pine plantation growth is strongly tied to the fertility of the site and whether supplemental fertilization was applied (Borders et al. 2004, Landsberg et al. 2001, Albaugh et al 2003, Jokela et al 2004). This information allowed us to hypothesize that a single parameter set could produce accurate estimates of loblolly pine growth across a wide range of areas with only the fertility rating changed from site to site. Our approach suggests that it is not necessary to develop a unique parameter set for each location where 3-PG is applied to estimate productivity of plantation-grown loblolly pine.

3-PG's comparatively poor predictions of volume in our simulations can be attributed to an incorrect value for wood density in the parameter set. Despite the good predictions of volume on the calibration site, on some of the low intensity sites it was overestimated, indicating an adjustment needs to be made. An increased wood density value was found to produce more accurate predictions of volume by reducing the over predictions of volume while leaving the other outputs unaffected. This systematic overestimation of volume on low intensity sites may reflect the trend observed by Love-Meyers et al. (2009) which indicated loblolly and slash pine (*Pinus elliottii*) latewood had a lower specific gravity in the two to three years following fertilization. Schimleck et al. (2008) observed lower specific gravity of loblolly pine stems receiving annual fertilization relative to those not receiving fertilization further supporting the extrapolation that since the high intensity treatments received an annual fertilizer addendum their specific gravity, and therefore wood density, were lower than that of the low intensity treatment plots which received no fertilization. This accounts for the differences in the accuracy of volume predictions on high and low intensity sites. A valuable addition to the 3-PG model would be a modifier to adjust wood density for the effects of growth rate.

Other sources of error are the model's inability to predict stochastic events causing non-density related individual tree mortality such as lighting strikes, insect attack, drought, and disease outbreak, and the use of average rather than actual weather data. The largest discrepancies we found in our use of 3-PG were in predictions of stand density over time. The poor prediction of stand density was due to 3-PG being unable to predict density- independent mortality events. This inaccuracy in predicting stand density values has been previously observed (Pinjuv et al., 2006). Previous studies have also noted the tendency of the model to produce less accurate predictions when average monthly weather data is used rather than actual monthly weather data. (Almeida et al. 2004b). Average weather data is unable to account for discrete events in time such as drought and therefore tend to provide less accurate results than actual weather data. We used actual monthly weather data in the simulations presented here. However, runs with average weather data were also made, and greater errors were observed in the model's predictions.

Despite the model's encouraging performance in this study an important limitation that hinders its use as a practical forest management tool is the estimation of the fertility rating. We developed a parameter calibration tool to determine the fertility rating that allowed us to determine an appropriate fertility rating value using the past nine or ten years of stem growth data. This approach required information on stand average DBH and stem biomass. DBH is a relatively common forestry measurement, however estimates of stand biomass are more difficult to obtain, and limits the usefulness of the approach. For a complete description of the parameter calibration tool see appendix B. Landsberg et al (2001) and Sampson et al. (2006) calibrated the fertility rating for each loblolly pine site based on iterative simulations until model outputs agreed with observed data. This differs from our study in both the site quality used for calibration and the method with which site fertility was calibrated. Our study used a highly productivity site for calibration and assigned it the highest possible FR rather than using a low productivity site and assigning it the lowest possible FR. It appears that either approach will allow 3-PG to produce accurate estimates of growth and productivity. Similar to our approach, Stape et al. (2004) scaled fertility ratings using one highly productive site which was assigned a value of one. All other sites were assigned a fertility rating based on a comparison to the initial, highly fertile site. An unbiased independent method of estimating the fertility rating would greatly enhance the utility of the model.

2.5. Conclusion

The model was capable of producing accurate estimates of loblolly pine productivity across a wide environmental gradient and on different soil types when the species parameters were held constant and only the fertility rating parameter was manipulated. This indicates that 3-PG may not need to be parameterized for each site where is it used, although additional testing is required over a larger geographic range before this can be confirmed. 3-PG is unable to predict stochastic events and therefore predictions of stand stem density tend to be overestimated in stands that experience density independent mortality.

Tables and Figures

Table 2.1: Average monthly weather data for Waycross, Athens, Tifton, and Monticello, Georgia.

Month	Average Temperature °C								Frost Days (<0°C)				Average Precipitation (mm)			
	Waycross		Athens		Tifton		Monticello		Waycross	Athens	Tifton	Monticello	Waycross	Athens	Tifton	Monticello
	max	min	max	min	max	min	max	min								
January	21.8	6.8	12.4	1.7	15.8	4.4	14.2	2.0	10.4	10.9	11.1	14.7	117.7	119.5	143.5	129.9
February	24.0	8.8	14.9	3.3	17.9	5.8	16.6	2.9	6.0	6.9	7.7	11.0	75.5	116.8	93.3	107.1
March	27.3	11.5	18.3	6.0	21.1	8.8	20.5	5.8	2.1	3.8	3.7	5.0	93.9	129.9	128.5	126.0
April	30.8	14.3	22.8	9.5	24.5	11.8	24.3	9.3	1.1	0.2	0.2	1.2	42.1	88.0	68.2	86.0
May	35.0	19.3	27.2	14.6	28.9	16.4	28.0	14.0	0.0	0.0	0.0	0.0	39.4	72.4	54.4	58.0
June	37.3	23.5	30.4	18.9	31.2	20.0	30.6	18.5	0.0	0.0	0.0	0.0	135.0	134.1	106.4	95.7
July	38.6	25.4	32.7	21.2	32.8	21.6	32.5	20.9	0.0	0.0	0.0	0.0	149.4	125.6	120.9	126.3
August	37.8	25.2	31.5	20.5	32.3	21.2	31.7	20.0	0.0	0.0	0.0	0.0	146.5	103.2	76.8	84.6
September	35.3	22.4	28.2	16.9	30.0	18.9	28.8	16.7	0.0	0.0	0.0	0.0	98.1	111.3	107.4	94.4
October	30.9	15.2	23.3	10.6	25.6	13.0	24.3	10.4	0.5	0.2	0.2	0.9	78.6	91.9	80.9	92.3
November	27.3	11.3	17.8	5.5	20.7	8.1	19.2	5.2	3.4	3.9	3.8	6.1	45.6	85.5	67.9	85.5
December	22.5	7.1	12.7	2.1	16.1	4.4	14.1	1.6	9.5	10.2	10.9	14.3	39.8	84.7	83.2	85.8

Table 2.2. 3-PG Species Parameters for *Pinus taeda*. See Appendix A for explanation of notes.

3-PG symbol	Description	Parameter value	Units	Sources (Ref.) & Comments (Notes)
Allometric relationships & partitioning				
pFS2	Ratio of foliage:stem partitioning at stem diameter = 2 cm	0.4	-	Note 1
pFS20	Ratio of foliage:stem partitioning at stem diameter = 20 cm	0.25	-	Note 1
StemConst	Constant in stem mass *v* diameter relationship	0.1	-	Note 2
StemPower	Power in stem mass *v* diameter relationship	2.5	-	Note 2
PRx	Maximum fraction of NPP to roots	0.4	-	Ref. [1, 2, 13]
PRn	Minimum fraction of NPP to roots	0.2	-	Ref. [1, 2, 13]
Temperature modifier				
Tmin	Minimum temperature for growth	4	°C	Ref. [4]
Topt	Optimum temperature for growth	25	°C	Ref. [20]
Tmax	Maximum temperature for growth	38	°C	Ref. [20]
Frost modifier				
kF	Number of days production lost for each frost day	1	Days	Ref. [19]
Age modifier				
MaxAge	Maximum stand age used to computer relative age	35	years	Note 3
nAge	Power of relative age in f_{age}	3	-	Note 3
rAge	Relative age to give $f_{age} = 0.5$	0.2	-	Note 3
Litterfall & root turnover				
gammaFx	Maximum litterfall rate	0.042	$Month^{-1}$	Ref. [8]
gammaF0	Litterfall rate at $t = 0$	0.001	$Month^{-1}$	Ref. [8]
tgammaF	Age at which litterfall rate has median value	18	month	Ref. [8]
Rttover	Average monthly root turnover rate	0.0168	per month	Ref. [11]
Conductance				
MaxCond	Maximum canopy conductance	0.006	$m\ s^{-1}$	Ref. [17, 23]
LAIgcx	Canopy LAI for maximum canopy conductance	3	-	Note 4
CoeffCond	Defines stomatal response to VPD	0.025	$mbar^{-1}$	Ref. [18, 23]
BLcond	Canopy boundary layer conductance	0.1	$m\ s^{-1}$	Ref. [7, 10]
Fertility effects				
m0	Value of m when $FR = 0$	0.1	-	Ref. [2, 6]
fN0	Value of f_N when $FR = 0$	0.5	-	Ref. [2, 6]

Stem mortality				
wSx1000	Maximum stem mass per tree at 1000 trees/ha	235	kg $tree^{-1}$	Ref. [25]
thinPower	Power in self thinning law	1.7	-	Note 5
mF	Fraction of mean foliage biomass per tree on dying trees	0	-	Note 6
mR	Fraction of mean root biomass per tree on dying trees	0.2	-	Note 6
ms	Fraction of mean stem biomass per tree on dying trees	0.4	-	Note 6
Canopy structure and processes				
SLA0	Specific leaf area at stand age 0	6.4	m^2 kg^{-1}	Ref. [21]
SLA1	Specific leaf area for mature aged stands	6	m^2 kg^{-1}	Ref. [23]
tSLA	Age at which specific leaf area = ½(SLA0+SLA1)	4	years	Ref. [5]
k	Extinction coefficient for absorption of PAR by canopy	0.57	-	Note 7 Ref. [12, 14, 16]
fullCanAge	Age at full canopy cover	2	years	Ref. 5
MaxIntcptn	Maximum proportion of rainfall intercepted by canopy	0.2	-	Ref. [7, 15, 16]
LAImaxIntcptn	LAI for maximum rainfall interception	5	-	Note 8
Alpha	Canopy quantum efficiency	0.0485	mol C mol PAR^{-1}	Note 9
Branch & bark fraction				
fracBB0	Branch and bark fraction at stand age 0	0.4	-	Ref. [5]
fracBB1	Branch and bark fraction for mature aged stands	0.1	-	Ref. [3, 13]
TBB	Age at which branch and bark fraction =½(fracBB0+fracBB1)	15	-	Ref. [3, 13]
Various				
Y	Ratio NPP/GPP	0.47	-	Ref. [9, 22]
Density	Basic density	0.5 ton/m^3	tons m^{3-1}	Note 10
volRatio	Ratio Vob/Vib	1.25	-	Note 11

Reference key: [1]Albaugh et al. (1998), [2]Albaugh et al. (2004), [3]Baldwin et al. (1998), [4]Boyer, W.D. (1970), [5]Burkes et al. (2003), [6]Gebauer et al. (1996), [7]Kelliher et al. (1992), [8]Kinerson et al. (1977), [9]Maier et al. (2004), [10]Martin et al. (1999), [11]Matamala et al. (2003), [12]McNulty et al. (1996), [13]Schultz, R.P. (1997), [14]Sinclair and Knoerr (1982), [15]Stogsdill and Wittwer (1989), [16]Sun et al. (2000), [17]Swank et al. (1972), [18]Tang et al. (1999), [19]Teskey et al. (1987), [20]Teskey and Will (1999), [21]Tyree et al. (2009) [22]Waring et al. (1998), [23]Will et al. (2001), [24]Will and Teskey (1997), [25]Samuelson et al. (2010)..

Figure 2.1: Map of study sites used in parameterization and validation of the 3-PG model.

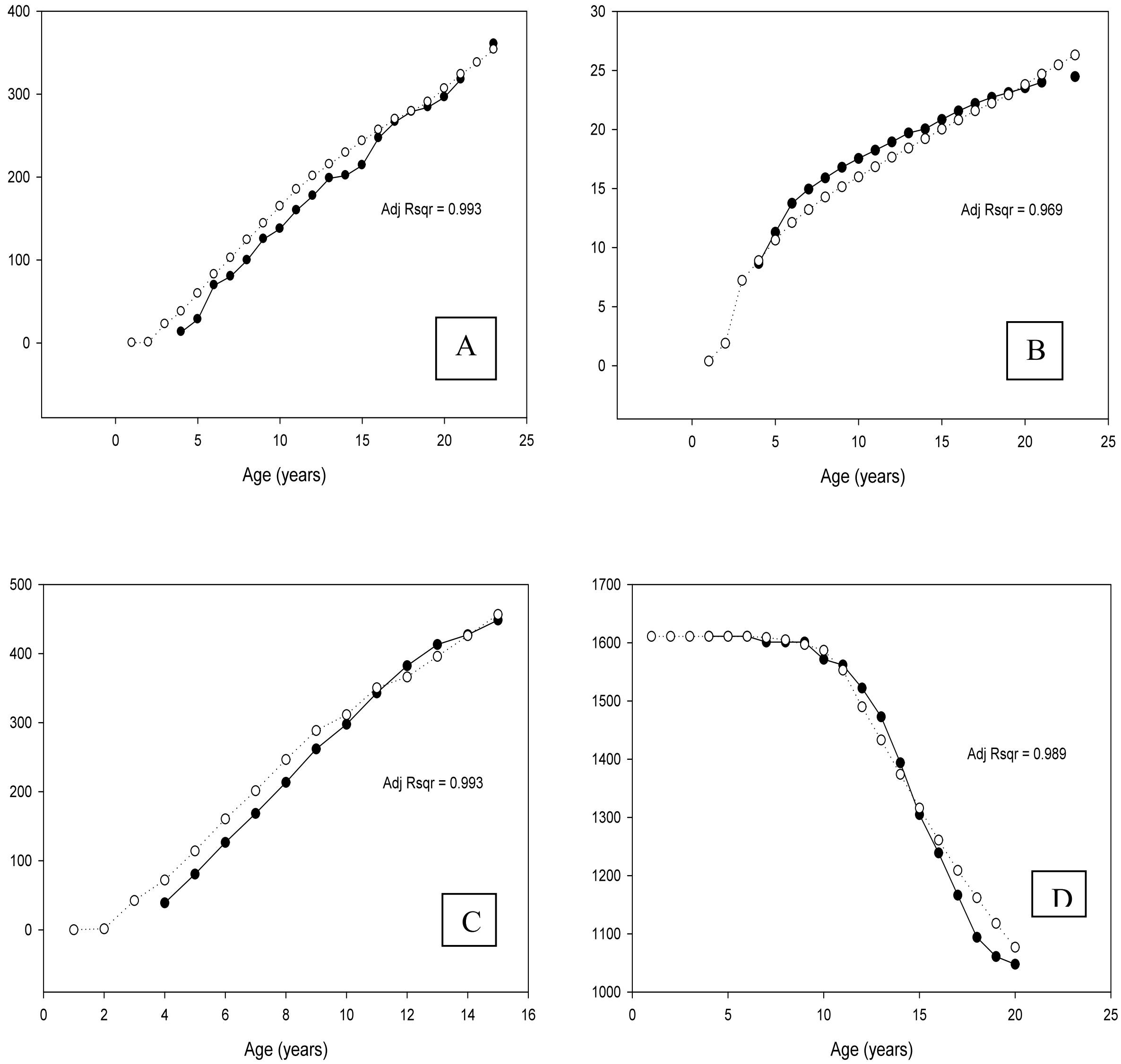

Figure 2.2: Measured (filled circle) vs. modeled (unfilled circle) stem biomass (A), diameter at breast height (DBH) (B), volume outside bark (C), and stocking (D) on the Waycross high intensity site.

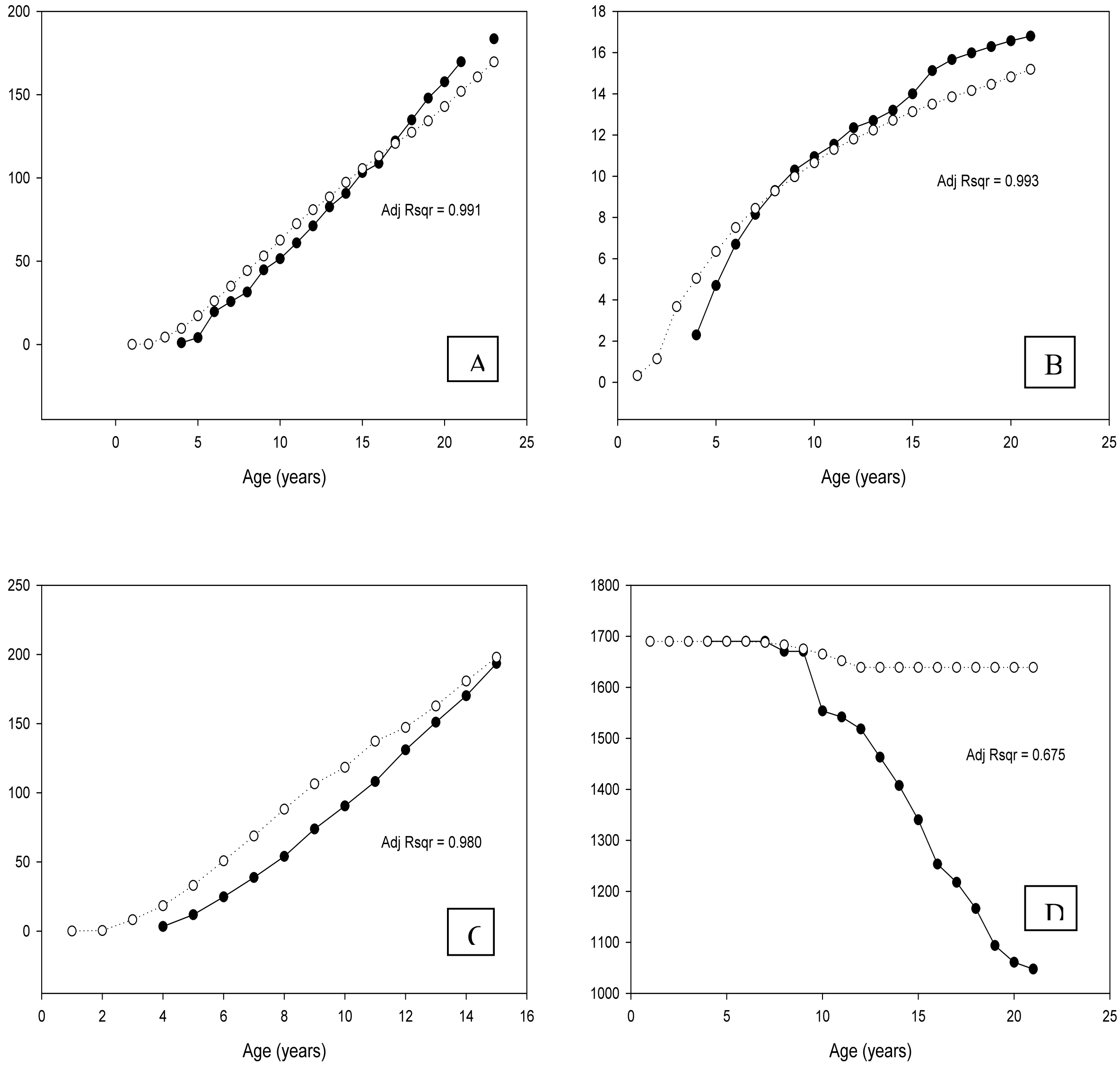

Figure 2.3: Measured (filled circle) vs. modeled (unfilled circle) stem biomass (A), diameter at breast height (DBH) (B), volume outside bark (C), and stocking (D) on the Waycross low intensity site.

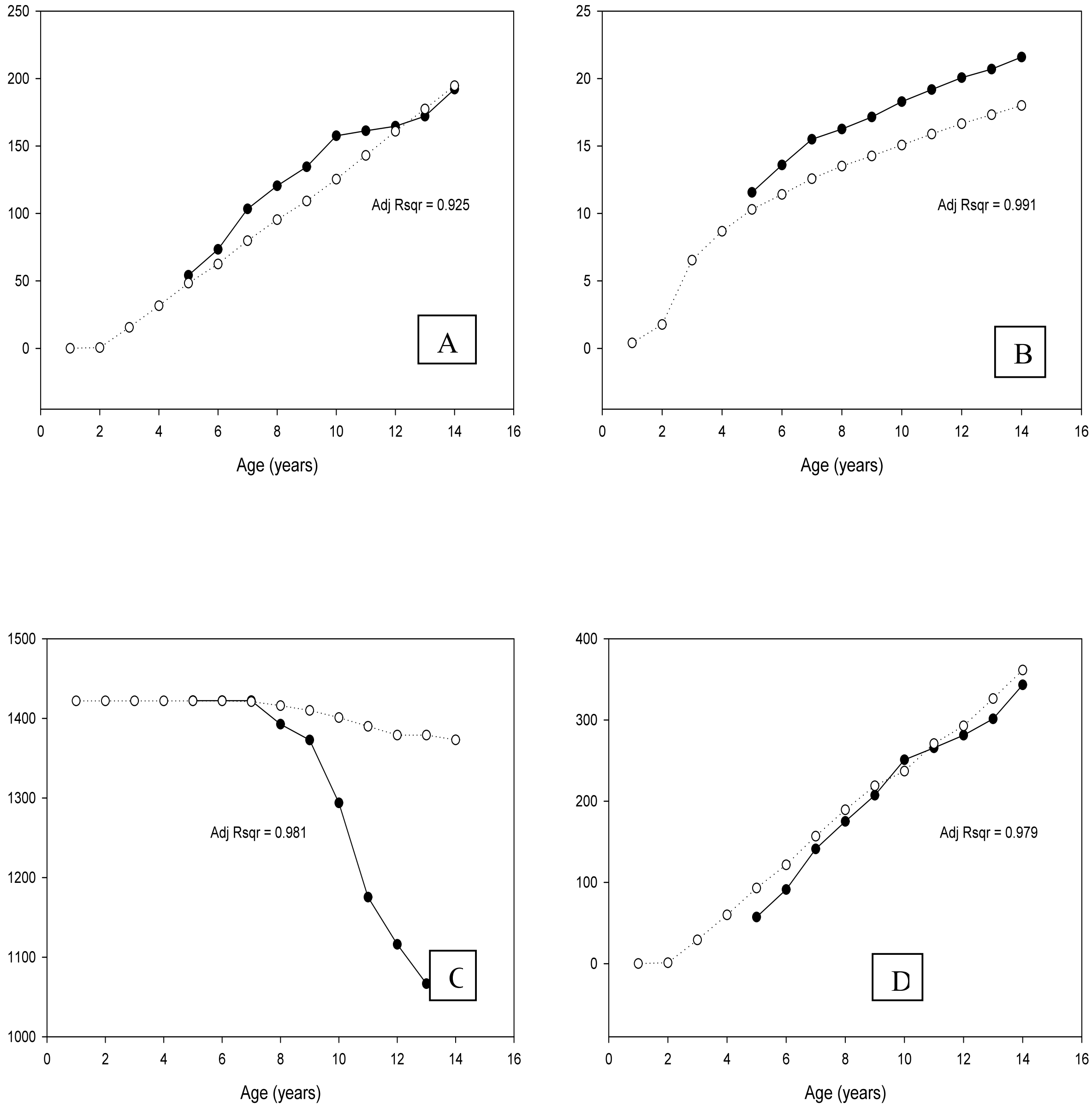

Figure 2.4: Measured (filled circle) vs. modeled (unfilled circle) stem biomass (A), diameter at breast height (DBH) (B), volume outside bark (C), and stocking (D) on the Tifton high intensity site.

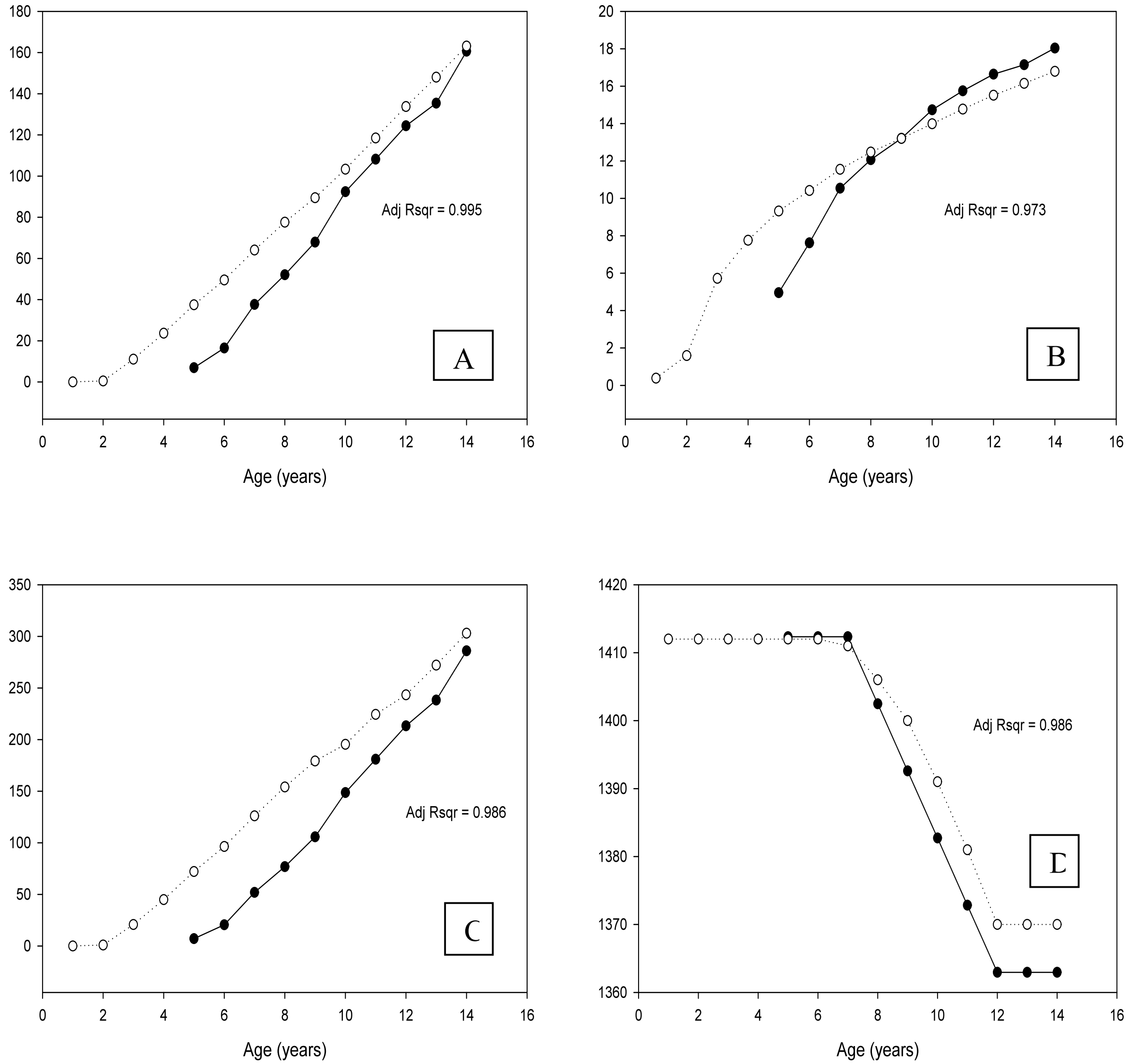

Figure 2.5: Measured (filled circle) vs. modeled (unfilled circle) stem biomass (A), diameter at breast height (DBH) (B), volume outside bark (C), and stocking (D) on the Tifton low intensity site.

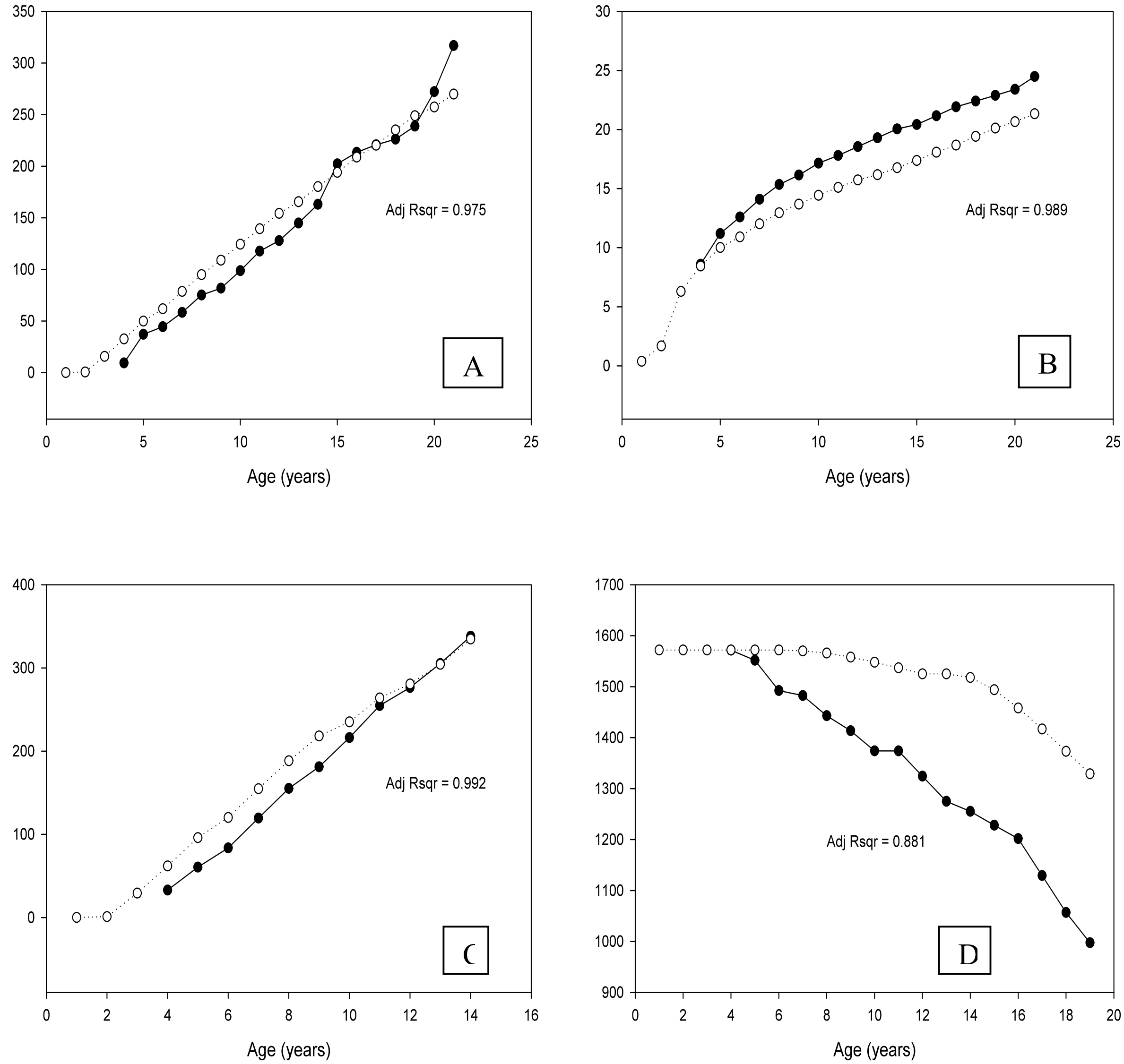

Figure 2.6: Measured (filled circle) vs. modeled (unfilled circle) stem biomass (A), diameter at breast height (DBH) (B), volume outside bark (C), and stocking (D) on the Monticello high intensity site.

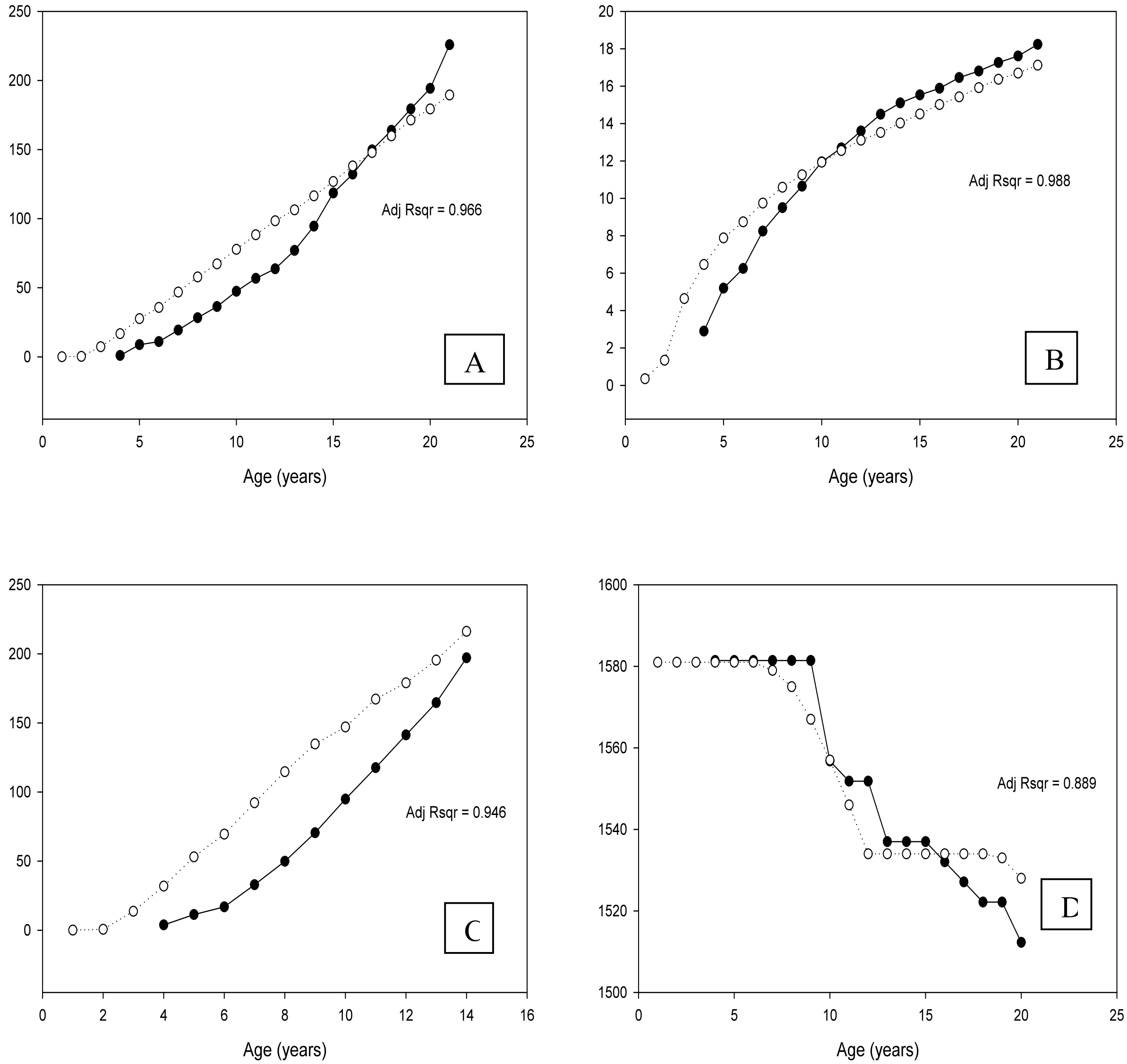

Figure 2.7: Measured (filled circle) vs. modeled (unfilled circle) stem biomass (A), diameter at breast height (DBH) (B), volume outside bark (C), and stocking (D) on the Monticello low intensity site.

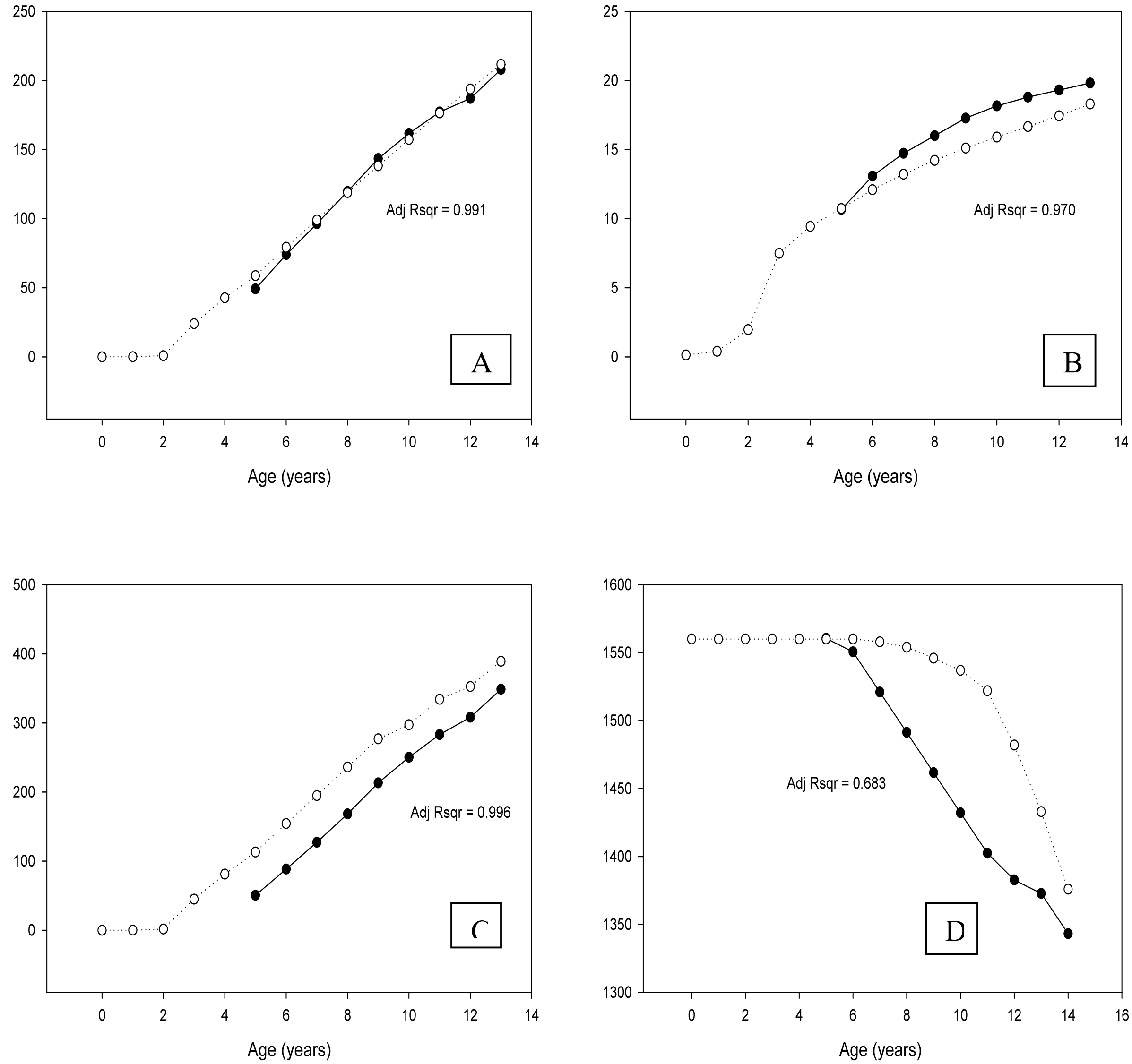

Figure 2.8: Measured (filled circle) vs. modeled (unfilled circle) stem biomass (A), diameter at breast height (DBH) (B), volume outside bark (C), and stocking (D) on the Athens high intensity site.

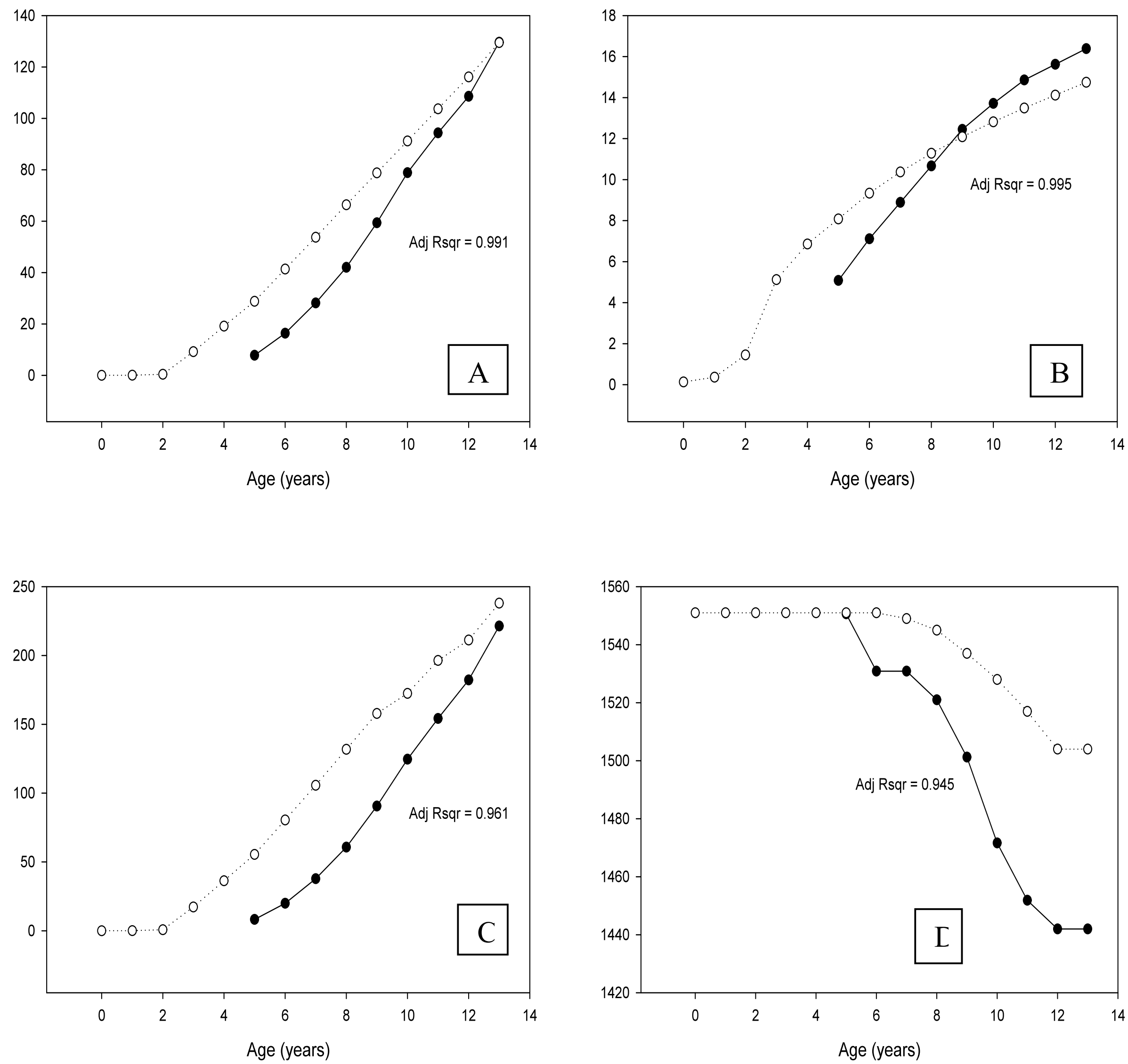

Figure 2.9: Measured (filled circle) vs. modeled (unfilled circle) stem biomass (A), diameter at breast height (DBH) (B), volume outside bark (C), and stocking (D) on the Athens low intensity site.

CHAPTER 3

PARAMETERIZATION OF THE 3-PG MODEL FOR USE WITH TWO CLONAL LOBLOLLY PINE GENOTYPES THAT EXHIBIT CONTRASTING GROWTH PATTERNS AND EVALUATION OF THEIR PERFORMANCE UNDER ALTERED CLIMATE REGIMES[2]

[2] Bryars, C.H., C.A., Maier, R.O. Teskey. To be submitted to *The Southern Journal of Applied Forestry*

Abstract

Forest management practices and genetic planting stock are changing rapidly to increase plantation productivity and increase economic return. Genetically improved, clonal Loblolly pine (*Pinus taeda*) planting stock are being used by land managers in plantation establishment more frequently. With the advent of commercially available clonal seedlings, managers will be able to select genotypes for specific products. Some genotypes are suited for bioenergy production, with high growth rates and aggressive branching patterns, while others are suited to sawtimber production with a decreased rotation length. The goal of this project was to determine if the 3-PG model could produce accurate estimates of productivity of two clonal loblolly pine genotypes that exhibit contrasting growth strategies and then to evaluate how the two clones would react to changes in temperature and precipitation. We hypothesized that despite the differences in allocation patterns of the two genotypes the 3-PG model would be able to produce accurate estimates of DBH and stem, root, and foliage biomass due to the flexible nature of the model. We also predicted that increased temperatures would result in increased water demand by both genotypes and that clone 32 would become water limited sooner than clone 93 due to its higher increased leaf area relative to clone 93.

The model was calibrated using two fast growing loblolly pine clones that exhibit contrasting morphological and physiological characteristics. Data was collected from an established field study located in Cross, SC. The observed data was used to parameterize the 3-PG model so that it could accurately predict growth rates and productivity of two clonal loblolly pine genotypes that exhibit contrasting growth strategies. After calibration, the 3-PG model was then validated using data from Jericho and Haven, SC which had previously established plantations of the same two genotypes. Despite the differences in allocation patterns of the two

genotypes, the 3-PG model was able to produce accurate estimates of DBH and stem, root, and foliage biomass due to the flexible nature of the model. Successful parameterization of the model for each clonal genotype allowed us to simulate their performance for the entire length of a rotation (assumed 30 years) and under altered climate regimes likely to occur in the next 100 years (Solomon et al. 2007). The full rotation predictions indicated that clone 32 outperformed clone 93 in DBH and had a much higher set primary productivity than clone 93 while stem biomass and volume outside bark were very similar between the clones. Simulations under altered climate regimes indicated that transpiration was correlated to temperature change. Productivity of both clones was inversely correlated to temperature change. Clone 32 had a temperature by precipitation decrease interaction. As temperature increased, reductions in precipitation caused further reductions in productivity. Neither clone responded to simulated increases in precipitation. We conclude that the 3-PG model can be a useful tool for evaluating clonal loblolly pine growth and water use in the current climate and to evaluate potential changes in productivity due to changes in temperature and precipitation regimes.
Keywords: Process-based model, 3-PG, parameterization, genotype, loblolly pine clone.

3.1 Introduction

Loblolly pine (Pinus taeda) provides ca 16% of the world's annual timber supply, and grows on nearly 24 million ha of plantation and natural forest in the southeastern United States. 12 million ha are in plantations on a variety of landtypes, managed using both intensive and extensive silvicultural treatments (Schultz, 1997, Wheeler and Neale, 2004). Forest management practices and genetic planting stock are changing rapidly to further increase plantation productivity and economic return. Since the second harvest of naturally regenerated stands in the 1920's productivity of loblolly pine has increased by 700% (Stanturf et al. 2003). These increases in productivity can be attributed to changes in silvicultural management regimes including increased fertilization, competition control, and more intensive site preparation, as well as genetic improvement. Additional volume gains of 10–30% may be possible with selective breeding, and gains of 50% or more may be attained by using a combination of clones and intensive silviculture (Allen et al. 2005, Martin et al. 2005, McKeand et al. 2006). With these projected gains it is probable that implementation of clonal planting stock will become more widespread. With increasing emphasis on site-specific management there is a need to determine how genotypes will react and perform on each site (Fox 2000). A model parameterized for specific genotypes could be used to evaluate which genotypes are best suited to a site as well as the effects of different silvicultural regimes, weather events, and competition on clonal stands.

In addition to continued advancements in the silvicultural practices and further genetic improvement, changes in greenhouse gas concentrations may also lead to changes in productivity of loblolly pine stands through shifts in weather patterns and changes in the concentration of carbon dioxide in the atmosphere (Groninger et al. 1999, Wertin et al. 2010). A model which can accurately predict clonal plantation productivity and also accommodate changes in environmental conditions and silvicultural treatments would be useful for examining the potential changes in growth that may be caused by climate change and shifting weather patterns. Forest managers and planners are turning to process based models to reduce the risks associated with industrial wood production and for explanations of the causes of variation and probable effects of changing conditions (Almeida et al. 2004a). 3-PG (Physiological Principles Predicting Growth) is a simple, process based model that requires parameterization of relatively few physiological attributes and uses simple, and readily available, weather and site characteristics to produce predictions of stand growth. 3-PG has already been used with a number of tree species, climates, and site conditions throughout the world. It has been used with at least a dozen tree species. Species-specific parameter values have been published for several species including *Eucalyptus grandis* (Almeida et al., 2004A), *Eucalyptus globlulus* (Sands and Landsberg, 2001), *Pinus patula* (Dye, 2001), *Pinus ponderosa* (Law et al., 2000), *Picea sitchensis* (Waring, 2000), *Acacia mangium* (Booth et al., 2001), *Pinus taeda* (Landsberg et al 2001), and *Dacrydium cupressinum* (Whitehead et al., 2002).

The 3-PG model has been used for a variety of applications. For instance, 3-PG has been used to explore yields and spatial supply of short rotation poplar (*Populus* spp.) and willow (*Salix* spp.) coppice for bioenergy production in the United Kingdom (Aylott, 2008), predict rates of change in soil carbon after afforestation of *Pinus radiata* and *Eucalyptus* plantations in Australia (Paul et. al. 2003), model stand volume and leaf area index (LAI) of ponderosa pine (*Pinus ponderosa*) throughout Washington, Oregon, and Northern California (Wulder et. al. 2007), explore carbon allocation in clonal Eucalyptus plantations in Brazil (Stape et. al. 2008), simulate age related changes to carbon allocation in Chinese fir (*Cunninghamia lanceolata*) plantations in southern China (Zhao et. al. 2009), and assess the effect of changes in climate on Douglas-fir (*Pseudotsuga menziesii*) productivity in British Columbia (Coops et. al. 2010). Several other studies have demonstrated the use of 3-PG over large areas using spatial databases or geographical information systems (GIS)(Coops et al. 1998, White et al. 2000, Coops and Waring 2001, Tickle et al. 2001, Almeida et al. 2009). The 3-PG model has also been used to predict productivity of loblolly pine plantations in the Southeastern United States (Landsberg et al. 2001, Sampson et al. 2006, Bryars et al. Chapter 1).

Our objective was to define two parameter sets, one for each of two genotypes of loblolly pine for which we had data available and then to evaluate the changes in productivity associated with changes in temperature and precipitation. The two contrasting clones (clones AA93 and AA32) were developed by ArborGen and are both highly productive. The two different genotypes were chosen because they exhibit contrasting growth characteristics. Clone 93 is a narrow crown clone with small diameter branches, while clone 32 has a broad and aggressive branching patter, Experimental results show that both clones have similar stem growth rates, but clone 93 carries 15-25% less leaf area index than clone 32 (Maier, unpublished observations). Clone 93 has a high growth efficiency, lower nitrogen requirements (Tyree et al. 2009) and maintains lower fine root biomass during early stand development (Prichard et al. 2010) than clone 32. These two genotypes represent a large amount of genetic variation and so are a good test of capabilities of 3-PG for modeling clonal growth. We hypothesized that despite the differences in allocation patterns of the two genotypes the 3-PG model would be able to produce accurate estimates of DBH and stem, root, and foliage biomass due to the flexible nature of the model. We also predicted that increased temperatures would result in increased water demand by both genotypes and that clone 32 would become water limited sooner than clone 93 due to the increased leaf area relative to clone 93. Data for the calibration plantation was obtained from an established field study (Agenda 2020 Cross Carbon Study) located near Cross, SC. Once the parameter set was defined, it was validated using data from established plantations in Jericho and Haven, SC. These sites were chosen because they both contained established plantations of the same two genotypes and there were several years of DBH growth data available.

3.2 Materials and Methods

3.2.1 The 3-PG Model

The 3-PG model is a dynamic, process-based model developed by Landsberg and Waring (1997) that predicts stand growth of plantations or even aged, relatively homogenous stands.

The model principally predicts net primary productivity (NPP), the partitioning of biomass to leaves and woody tissues above and belowground and transpiration. Net primary productivity is determined using a fixed relationship of gross primary productivity (GPP) to NPP. This assumption eliminates the need to calculate respiration (Waring et al, 1998; Landsberg et al, 2003). 3-PG then uses fixed ratios to allocate NPP to roots, foliage, and stem. The allocation ratio of carbon to roots shifts in relation to site fertility and water availability. Carbon allocation to foliage and stem are determined using allometric relationships (Landberg and Waring, 1997). Carbon allocated to foliage is adjusted depending on stand age, edaphic and environmental conditions (Landsberg et al., 2003). Stand growth rates are also adjusted for age to compensate for the decline in tree growth rate with age. Stand density is adjusted for density-dependent mortality using the -3/2 thinning law. Soil water balance is calculated monthly using the Penman-Monteith equation to determine transpiration (Landsberg et al., 2003). The outputs of 3-PG include stand attributes that are useful to land managers for estimating wood production (stem diameter, basal area, volume, stem biomass increment, stand density and mortality) as well as attributes useful to forest scientists such as leaf are index, utilizable radiation, total biomass production, and transpiration. For a more complete description of the model see Landsberg and Waring (1997).

3.2.2 Study Sites

The 3-PG model was calibrated using data from the Cross Carbon Study located near Cross, SC (33.2 N, 80 W) (Figure 3.1). The Cross Carbon Study site is a study of the performance of clone 32 and 93 in a wide variety of silvicultural treatments. The site was planted in January 2005 in three blocks containing 273 seedlings of either clone 93 or clone 32 planted at a density of 1280 stems ha^{-1}. The site received four levels of silviculture treatment

(Tyree et al. 2009), however only the control plot data was used for the parameterization of 3-PG. The control treatment consisted of shearing and bedding following local commercial operations on the previous rotation. Six years of DBH and four years of stem, foliage, and root biomass data were available from the Cross site. After calibration, the model was then used to predict growth on another site in order to evaluate if the parameter set was accurate. Validation sites were located near the towns of Jericho (N 32.7343 W 80.3156) and Haven, SC (N 32.78503 W 80.2613). There were eleven years of DBH data available from the Haven and Jericho sites for validation.

3.2.3 Site Specific Data

Site-specific climate data required by the model includes monthly mean daily minimum and maximum temperatures, monthly precipitation, and number of frost days per month. These weather data can either be actual observed values if running the model over past time periods or average weather data if running the model for future time periods. This study used average monthly weather values rather than monthly actual weather data from a (weather station name) near Monck's Corner, SC about xx kilometers from the Cross site.. These weather data are available from the National Oceanic and Atmospheric Administration (NOAA) (http://www.ncdc.noaa.gov/oa/ncdc.html). Monthly mean daily incoming solar radiation is also required by the model and can be calculated from temperature (Bristow and Campbell, 1984, Coops et al. 1998) or collected from NASA's Atmospheric Science Data Center website (eosweb.larc.nasa.gov/sse). Latitude is also a required input (to determine day length); this can be found simply using Google Maps (maps.google.com). In this study monthly averages of minimum and maximum temperatures, frost days, precipitation, and incoming solar radiation were used (table 3.1). Monthly averages were used to make the changes in temperature and precipitation regimes easier to conduct.

The fertility rating was adjusted for each site. The fertility rating is an empirical index that ranks soil fertility on a scale from an optimum value of one to an extremely infertile value of zero. Each fertility rating value was calculated by the model using the parameter calibration tool and observed DBH and stem biomass data. The fertility rating for all stands was set to a value of 0.7. The parameter calibration tool (Appendix B) was unable to calibrate the fertility rating of the site due to the nature of the calibration tool coupled with the limited number of years of data available for this study. The parameter calibration tool was only able to use one year of data to determine the fertility rating. Rather than assign a fertility rating based on one year of data the fertility rating was set at 0.7 to indicate moderate-high site fertility. Initial planting stock characteristics are required by 3-PG. Clone 93 foliage biomass at age one was 0.0033863 tons ha^{-1}, root biomass was 0.002963 tons ha^{-1}, and stem biomass was 0.001284 tons ha^{-1}. Clone 32's initial biomass was; foliage 0.003597944 tons ha^{-1}, root 0.002822 tons ha^{-1}, and stem 0.000945 tons ha^{-1}. 3-PG uses one of four soil types (sand, sandy loam, clay loam, and clay) for each site to determine soil texture and water holding capacity. Data describing the site's soil texture were found for each site independently using the NRCS Web Soil Survey website (http://websoilsurvey.nrcs.usda.gov/app/HomePage.htm). Monck's Corner, Haven, and Jericho were all classified as having a sandy loam soil. All other inputs are species physiological parameters, described below.

3.2.4 Planting Stock and Measured Data

Clonal seedlings were obtained from ArborGen. As mentioned, both clones are among the most productive genotypes available; however they have different biomass allocation patterns. Clone differences in standing biomass and allocation were apparent at age 4. Total stand biomass (foliage+stem+branch+root) was significantly greater in clone 32 than 93 (clone 93=30.4 tons ha^{-1}, clone 32=35.6 tons ha^{-1}; p=0.03 figure 3.2). Measurements through age four indicate that clone 32 carried 32% more branch biomass than clone 93 (clone 93=3.15 tons ha^{-1}, clone 32=4.66 tons ha^{-1}; p=0.004, figure 3.3). Clone 32 had about 15% more foliage biomass than clone 93, but the difference were only marginally significant (clone 93=4.20 tons ha^{-1}, clone 32=4.92 tons ha^{-1}, p=0.09, figure 3.3). Clone 32 had more stem and root biomass than clone 93, but these differences were not statistically significant (Stem: clone 93=11.7 tons ha^{-1}, clone 32=13.6 tons ha^{-1}, p=0.13; Root: clone 93=11.4 tons ha^{-1}, clone 32=12.4 tons ha^{-1}, p=0.14, figure 3.3). Aboveground wood biomass (stem and branch) was greater for clone 32 than clone 93 (C93=14.9, C32=18.2, p=0.049). At age 4, clone 32 allocated 13.1% of total biomass to branches compared to 10.4% for clone 93. However, clone 93 allocated 37.5% of total to roots compared to 34.8% in clone 32. Both clones allocated a similar percentage of biomass to foliage and stem, devoting approximately 14 and 38% of total biomass for foliage and stems, respectively (Christopher Maier, personal communication, 2011). Validation data was obtained from trees of each clone harvested in years 2, 3, and 4 (n=43). All harvest trees were within one standard deviation of the treatment plot mean stem diameter at breast height. Biomass allocated to each portion of the tree and DBH were recorded.

3.2.5 Physiological Parameter Estimation

Initial parameter estimates were constrained by published information when available (Table 3.2). When parameter values were not known, or when values ranged widely from report to report, we used parameter estimates which best recreated the growth of the calibration plantation (Table 3.2). Initial parameter values were set to those of 7-56 open pollinated loblolly pine determined in Bryars (2011). Foliage to stem partitioning ratios at a diameter of 2cm and 20 cm were increased for both clones from the open pollinated values of 0.35 and 0.25 to 0.4 and 0.3 for each clone. This change was made to allocate a greater portion of carbon assimilation into foliage rather than the stem. Ratio of carbon allocated to the roots was also increased for both clones with clone 32 receiving a slightly larger increase to reflect the observed greater root biomass than clone 93 (Pritchard et al. 2010, Maier unpublished data). The mass to diameter parameters were reduced for both clones to reflect lower mass relative to the diameter likely caused by a decreased density of the wood. Clone 32's mass to diameter relationship was reduced slightly more so than clone 93's. Specific leaf areas were set using information from Tyree et al. (2009) and then adjusted until modeled leaf biomass values matched measured values. The amount of precipitation which evaporated from the canopy was slightly increased for clone 32 to reflect the greater leaf area of that genotype. Density was slightly lowered for both clones to reflect a lower wood density relative to open pollinated loblolly pine. Both of these density adjustments were made to reflect the increased amount of less dense early wood present in clonal loblolly pine genotypes (Bettinger et al. 2009).

The alpha parameter was also lowered for each clone. This parameter essentially defines the photosynthetic efficiency of the foliage. Clone 32 was lowered more than clone 93 due to the larger leaf area likely indicating that the foliage was not as efficient per unit area. It is counter intuitive that the photosynthetic efficiency parameter would be lowered for clonal genotypes relative to open pollinated pine. This may be due to an over-estimation of the fertility rating which was unable to be calibrated using the model's parameter calibration tool due to the relatively few years of stem biomass data available. For a complete list of parameters adjusted, see table 3.2.

3.2.6 Evaluation of Performance under Altered Climate Regimes

Once a parameter a set was found and validated for each genotype their performance under altered climate regimes was modeled. Altered climate regimes were based on predictions of temperature and precipitation pattern changes in the Southeastern region of North America from the IPCC (Solomon et al. 2007). Altered regimes included an increase in temperature of 2 or 4°C, a decrease in precipitation of 200 mm year^{-1} evenly distributed through all months, an increase in precipitation of 200 mm year^{-1} evenly distributed through all months, and all combinations of these potential changes. Each genotype's performance was evaluated under these altered climate regimes with a simulated 30-year rotation at the Cross site. Performance was evaluated using predicted DBH, volume outside bark, stem biomass, and annual transpiration.

3.3 Results

On the calibration site, the model accurately estimated stem biomass, root biomass, foliage biomass, and DBH of clone 93 for all years measured (figure 3.4). DBH was recorded to age six while biomass measurements were only to age four. Values for modeled and measured DBH at age 6 were identical at 13.6 cm (figure 3.4A). Measured and modeled stem biomass at age 4 were 17.7 and 17.5 tons ha^{-1} (figure 3.4B). Measured and modeled root biomass at age 4 were 11.4 and 10.9 tons ha^{-1} (figure 3.4C), while measured and modeled foliage biomass values were 3.8 and 4.0 tons ha^{-1} (figure 3.4D) indicating good agreement between observed and simulated values. Linear regression was used to compare measured and modeled values. R-squared values for all linear regression analysis for clone 93 on the calibration plot were all $\geq$0.92 (figure 3.4).

Modeled values for clone 32 also closely matched the calibration plot data. At age 6 measured and modeled DBH values were 14.1 and 13.7 cm respectively (figure 3.5A). Measured and modeled stem biomass at age 4 were 17.9 and 16.8 tons ha^{-1} (figure 3.5B). Measured and modeled root and foliage biomass were also in close proximity to each other. Measured root biomass was 12.7 tons ha^{-1} while the modeled value was 12.3 tons ha^{-1} (figure 3.5C). Modeled foliage biomass was identical to its measured counterpart at 4.7 tons ha^{-1} at age 4 (figure 3.5D).

3-PG was also able to estimate growth of both clones reasonably well on the validation sites of Haven and Jericho. DBH was recorded on the Haven and Jericho sites up to age 11. At age 11 the DBHs of clones 93 and 32 were slightly over-predicted by 3-PG on the Haven site. Measured and modeled DBH of clone 93 at age eleven on the Haven site were 17.8 and 19.2 cm respectively. Measured and modeled DBH values on the Haven site for clone 32 were 18.6 and 20.3 cm. 3-PG more accurately predicted DBH of clone 93 on the Jericho site, producing a difference between measured and modeled values of only 0.3 cm (figure 3.6). The DBH of clone 32 was well predicted on the Jericho validation site as well, measured and modeled DBH values were 19.2 and 19.9 cm respectively (figure 3.7).

Values for DBH, VOB, basal area, stem biomass, root biomass, foliage biomass, net primary production (NPP), transpiration, absorbed photosynthetically active radiation (APAR), and stand stocking for both clones at year 30 are displayed in table 3.3. At age thirty clone 93 exceeds clone 32 in VOB and stem biomass. Clone 32 exceeds clone 93 in DBH, basal area, root biomass, foliage biomass, NPP, transpiration, and APAR at age 30. Figure 3.8 shows the performance of the two clones over the course of a thirty-year rotation. Clone 93 and clone 32 are predicted to perform similarly as far as stem biomass and volume outside bark while clone 32 exceeds the predicted values of clone 93 in DBH and NPP.

The effect of altered climate regimes varied between the two genotypes (table 3.4). Predicted volume produced by clone 93 at year 30 was inversely related to temperature (table 3.4) with an increase in temperature of 4°C resulting in a decrease in volume of 20.1% compared to ambient conditions. Predicted transpiration increased with increased temperatures. However, changes in precipitation had no effect on predicted volume growth or transpiration (table 3.4). Like clone 93, Clone 32 had an inverse relationship between temperature and predicted volume. A temperature increase of 4°C resulted in a decrease in volume growth of 15.9% at age 30. Unlike clone 93, changes in precipitation did have an effect on predicted volume growth of clone 32. At temperatures above ambient conditions, decreases in precipitation resulted in further decreases in volume production below that caused by temperature increases alone. In addition to clone 32's the 14.9% decrease in volume production with a 4°C increase in temperature, a reduction of precipitation of 200mm a year caused volume production to drop to 23.8% of its value at ambient conditions. Predicted transpiration rates of clone 32 increased with increased temperature but did not change with variations in precipitation (table 3.4). A simulated increase in precipitation of 200 mm had no effect on volume production of either genotype.

3.4 Discussion

We hypothesized that despite the differences in carbon partitioning of the two genotypes the 3-PG model would be able to produce accurate estimates of DBH and stem, root, and foliage biomass due to the flexible nature of the model. Our analysis indicates that the 3-PG model was able to produce accurate estimates of DBH and stem, root, and foliage biomass of young stands of two clonal genotypes of loblolly pine with different carbon allocation patterns. This result is similar to that of studies of *Euclyptus* clones (Dye et al. 2004, Stape, 2002). The 3-PG parameter set developed for open pollinated loblolly pine parameter set (Bryars et al. Chapter 1) was used for the initial simulations. However, several parameters were changed to match clonal growth characteristics.

Increased temperatures resulted in decreased volume production of both clones, indicating that current temperatures are near optimum or above optimum in Monck's Corner, SC. This suggests that further increases in temperature will cause decreases in productivity of loblolly pine stands near Monck's Corner, SC. This extrapolation is supported by predictions made by Presad et al. (2007) who predict decrease in productivity of loblolly pine with increasing temperatures. Clone 93 exceeded the productivity of clone 32 under all scenarios except the plus four degrees Celsius and plus four degree Celsius and 200mm year^{-1} increase in precipitation. The simulations also indicate that increased temperatures will cause increased water demand due to higher rates of transpiration in elevated temperature scenarios. As would be expected, clone 32 has higher predicted transpiration rates due to the higher leaf area of clone 32 relative to clone 93 (table 3.4). Reduction in amount of precipitation had a greater effect on clone 32 than on clone 93, which was unaffected by decreases in precipitation of 200mm year^{-1} (table 3.4). This seems to indicate that with increased temperatures water will become more limited for clone 32, reducing its productivity. Despite higher rates of transpiration with increased temperatures, clone 93 did not become water limited as volume production did not decrease with precipitation decreases, even in elevated temperature scenarios (table 3.4). For this reason sites being considered for planting of this genotype should be carefully evaluated to ensure that tree water demand will be met so that maximum productivity can be achieved.

Further research into clonal planting stock should select individuals with a higher optimum growth temperature and water use efficiency to prepare for future climates

Table 3.3 and figure 3.8 indicate that both clones are strong performers throughout a full rotation. Clone 32 exceeds the DBH growth and NPP of clone 93 easily as the stand ages. Clone 93 exceeded clone 32's stem biomass and VOB at the end of an assumed 30 year rotation by a narrow margin. Since no data was used in calibration past year six the potential for error in these predictions is high. When interpreting all results it is important to consider is that the model was calibrated using only three years of biomass data and only six years of DBH data. Parameterization ideally would be carried out using measured values over the life of the stand. For this reason, predictions made by the 3-PG model for clones 93 and 32 using the parameter sets described here may be inaccurate for stand of older ages.

The fertility ratings of Haven and Jericho were assumed to be 0.7. However, the overestimations of DBH values on the Haven site seem to indicate that a lower value should be assigned to the site. This is an example of how important an accurate fertility rating is to the 3-PG model.

3.5 Conclusions

The 3-PG model is able to produce accurate predictions of DBH and stem, foliage, and root biomass for young stands of loblolly pine clonal genotypes 93 and 32. As stands of these two genotypes continue to age 3-PG's ability to predict their growth should be continued to be evaluated to ensure that predictions remain accurate in older stands. 3-PG's simulations indicate that increased temperatures will result in decreased productivity of both clone 93 and 32 in Monck's Corner, SC. Changes in precipitation in the range of +200mm to -200mm a year appeared to have no effect on volume production of clone 93. However clone 32 was predicted to transpire more water due to a higher leaf area, which resulted in a prediction of water stress occurring earlier in clone 32 than clone 93 as temperature increases and/or precipitation decreases. The much larger predicted increase in water use of clone 32 compared to clone 93, and the similarity in their aboveground productivity, indicates that water use efficiency is much lower in clone 32 than 93 and may be an important factor to consider when selecting clones for planting.

Tables and Figures

Table 3.1: Average monthly weather data for Cross, Haven, and Jericho, SC.

	Average Temperature °C				Average Precip (mm)		Solar Radiation (Mj/m/day)		Frost Days (<0°C)	
	Monck's Corner		Haven/Jericho		Monck's Corner	Haven/ Jericho	Monck's Corner	Haven/ Jerico	Monck's Corner	Haven/ Jericho
Month	Max	Min	Max	Min						
Jan	18.1	6.4	15.3	3.2	41.3	67.9	9.4	9.4	13	11
Feb	19.1	7.0	16.9	4.2	63.4	66.7	11.6	11.6	8	6
Mar	24.2	11.0	21.2	8.3	67.0	86.2	15.6	15.6	2	2
Apr	29.1	14.0	25.0	12.0	44.0	63.7	20.2	20.2	0	0
May	32.3	19.6	28.6	17.0	78.4	80.2	21.6	21.6	0	0
Jun	36.9	24.4	31.6	21.4	120.9	148.9	21.1	21.1	0	0
Jul	37.6	25.7	32.6	22.7	114.4	176.0	20.6	20.6	0	0
Aug	37.1	25.4	32.0	23.0	146.5	189.8	18.4	18.4	0	0
Sep	34.1	22.3	29.5	20.1	101.2	124.0	16.1	16.1	0	0
Oct	29.1	16.4	25.3	13.9	84.3	107.3	13.9	13.9	0	0
Nov	24.3	11.2	21.1	8.4	44.0	54.2	10.8	10.8	2	1
Dec	20.5	7.9	16.4	4.2	84.6	81.3	9.1	9.1	8	9

Table 3.2: 3-PG Species Parameters for an open pollinated family (756) and clones 93 and 32 of *Pinus taeda*. See Appendix A for explanation of notes.

3-PG symbol	Description	Parameter Value 7-56 Loblolly Pine	Parameter Value Clone 93	Parameter Value Clone 32	Units	Sources (Ref.) & Comments (Notes)
Allometric relationships & partitioning						
pFS2	Ratio of foliage:stem partitioning at stem diameter = 2 cm	0.4	0.35	0.4	-	Note 1
pFS20	Ratio of foliage:stem partitioning at stem diameter = 20 cm	0.25	0.25	0.3	-	Note 1
StemConst	Constant in stem mass *v* diameter relationship	0.1	0.07	0.07	-	Note 2, Ref. [1]
StemPower	Power in stem mass *v* diameter relationship	2.5	2.45	2.35	-	Note 2, Ref. [1]
PRx	Maximum fraction of NPP to roots	0.4	0.43	0.45	-	Ref. [2, 3, 14]
PRn	Minimum fraction of NPP to roots	0.2	0.3	0.35	-	Ref. [2, 3, 14]
Temperature modifier						
Tmin	Minimum temperature for growth	4	4	4	ºC	Ref. [5]
Topt	Optimum temperature for growth	25	25	25	ºC	Ref. [21]
Tmax	Maximum temperature for growth	38	38	38	ºC	Ref. [21]
Frost modifier						

kF	Number of days production lost for each frost day	1	1	1	Days	Ref. [20]
Age modifier						
MaxAge	Maximum stand age	35	30	30	years	Note 3
nAge	Power of relative age in f_{age}	3	3	3	-	Note 3
rAge	Relative age to give $f_{age} = 0.5$	0.2	0.2	0.2	-	Note 3
Litterfall & root turnover						
gammaFx	Maximum litterfall rate	0.042	0.042	0.03	$Month^{-1}$	Ref. [9]
gammaF0	Litterfall rate at $t = 0$	0.001	0.001	0.001	$Month^{-1}$	Ref. [9]
tgammaF	Age at which litterfall rate has median value	18	18	24	month	Ref. [9]
Rttover	Average monthly root turnover rate	0.0168	0.0168	0.0175	$Month^{-1}$	Ref. [12]
Conductance						
MaxCond	Maximum canopy conductance	0.006	0.006	0.006	$m\ s^{-1}$	Ref. [18, 24]
LAIgcx	Canopy LAI for maximum canopy conductance	3	3	3	-	Note 4
CoeffCond	Defines stomatal response to VPD	0.025	0.035	0.025	$mbar^{-1}$	Ref. [19, 24]
BLcond	Canopy boundary layer conductance	0.1	0.1	0.1	$m\ s^{-1}$	Ref. [8, 11]
Fertility effects						
m0	Value of m when $FR = 0$	0.1	0.1	0.1	-	Ref. [3, 7]
fN0	Value of f_N when $FR = 0$	0.5	0.6	0.6	-	Ref. [3, 7]
Stem mortality						

wSx1000	Maximum stem mass per tree at 1000 trees/ha	235	10000	10000	kg $tree^{-1}$	Ref. [26]
thinPower	Power in self thinning law	1.7	1.2	1.2	-	Note 5
mF	Fraction of mean foliage biomass per tree on dying trees	0	0	0	-	Note 6
mR	Fraction of mean root biomass per tree on dying trees	0.2	0.2	0.2	-	Note 6
ms	Fraction of mean stem biomass per tree on dying trees	0.4	0.4	0.2	-	Note 6
Canopy structure and processes						
SLA0	Specific leaf area at stand age 0	6.4	7	7	m^2 kg^{-1}	Ref. [22]
SLA1	Specific leaf area for mature aged stands	6	4.6	5	m^2 kg^{-1}	Ref. [24]
tSLA	Age at which specific leaf area = ½(SLA0+SLA1)	4	6	6	years	Ref. [6]
k	Extinction coefficient for absorption of PAR by canopy	0.57	0.57	0.57	-	Note 7 Ref. [13, 15, 17]
fullCanAge	Age at full canopy cover	2	6	4	years	Ref. 5
MaxIntcptn	Maximum proportion of rainfall intercepted by canopy	0.2	0.2	0.25	-	Ref. [8, 15, 17]
LAImaxIntcptn	LAI for maximum rainfall interception	5	5	5	-	Note 8
Alpha	Canopy quantum efficiency	0.0485	0.047	0.039	mol C mol PAR^{-1}	Note 9
Branch & bark fraction						

fracBB0	Branch and bark fraction at stand age 0	0.4	0.4	0.4	-	Ref. [6]
fracBB1	Branch and bark fraction for mature aged stands	0.1	0.1	0.1	-	Ref. [4, 14]
TBB	Age at which branch and bark fraction =½(fracBB0+fracBB1)	15	15	15	-	Ref. [4, 14]
Various						
Y	Ratio NPP/GPP	0.47	0.47	0.47	-	Ref. [10, 23]
Density	Basic density	0.5 ton/m^3	0.47	0.47	tons m^{3-1}	Note 10
volRatio	Ratio Vob/Vib	1.25	1.25	1.25	-	Note 11

Reference key: [1]Bettinger et al. (2009), [2]Albaugh et al. (1998), [3]Albaugh et al. (2004), [4]Baldwin et al. (1998), [5]Boyer, W.D. (1970), [6]Burkes et al. (2003), [7]Gebauer et al. (1996), [8]Kelliher et al. (1992), [9]Kinerson et al. (1977), [10]Maier et al. (2004), [11]Martin et al. (1999), [12]Matamala et al. (2003), [13]McNulty et al. (1996), [14]Schultz, R.P. (1997), [15]Sinclair and Knoerr (1982), [16]Stogsdill and Wittwer (1989), [17]Sun et al. (2000), [18]Swank et al. (1972), [19]Tang et al. (1999), [20]Teskey et al. (1987), [21]Teskey and Will (1999), [22]Tyree et al. (2009), [23]Waring et al. (1998), [24]Will et al. (2001), [25]Will and Teskey (1997), [26]Samuelson et al. (2010).

Table 3.3: Comparison of modeled clone 93 and 32 diameter at breast height (DBH), volume outside bark (VOB), basal area, stem biomass, root biomass, foliage biomass, net primary production (NPP), transportation, and absorbed photosynthetically active radiation (APAR) at year 30 on the Cross site using average monthly weather data.

Output	Units	Clone 93	Clone 32
DBH	cm	35.4	40.4
VOB	m^3 ha^{-1}	1225	1173
Basal Area	m^2 ha^{-1}	111	144
Stem Biomass	Tons ha^{-1}	558	534
Root Biomass	Tons ha^{-1}	73	77
Foliage Biomass	Tons ha^{-1}	9.5	14.7
NPP	Tons ha^{-1} $year^{-1}$	38.8	39.2
Transpiration	mm $year^{-1}$	486	542
APAR	mol m^{-2} $year^{-1}$	12040	13090

Table 3.4: Modeled volume outside bark ($m^3 ha^{-1}$) and annual total transpiration (mm $year^{-1}$) of clones 93 and 32 under altered climate regimes at age 30.

Treatment	Volume Outside Bark		Transpiration	
	Clone 93	Clone 32	Clone 93	Clone 32
Ambient	1225	1173	486	542
+2C	1125	1103	508	574
+4C	968	987	529	605
+200mm	1225	1173	486	542
-200mm	1225	1164	486	542
+2C, +200mm	1125	1103	508	574
+2C, -200mm	1125	1062	508	574
+4C, +200mm	968	987	529	605
+4C, -200mm	968	894	529	571

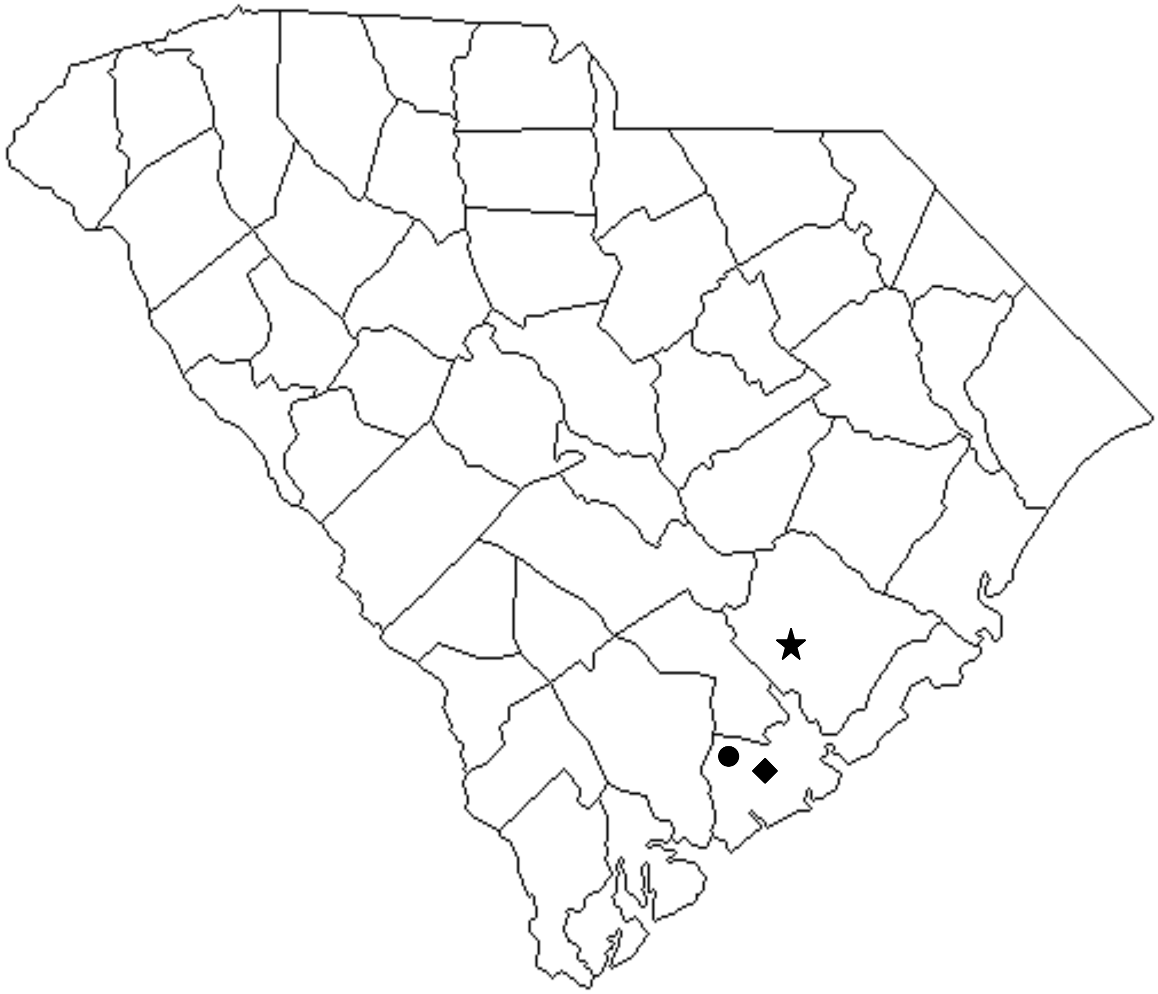

Figure 3.1: Map of South Carolina showing the sites used for calibration and validation of the 3-PG model for clones 93 and 32. The star represents Cross, the diamond, Jericho, and the circle Haven.

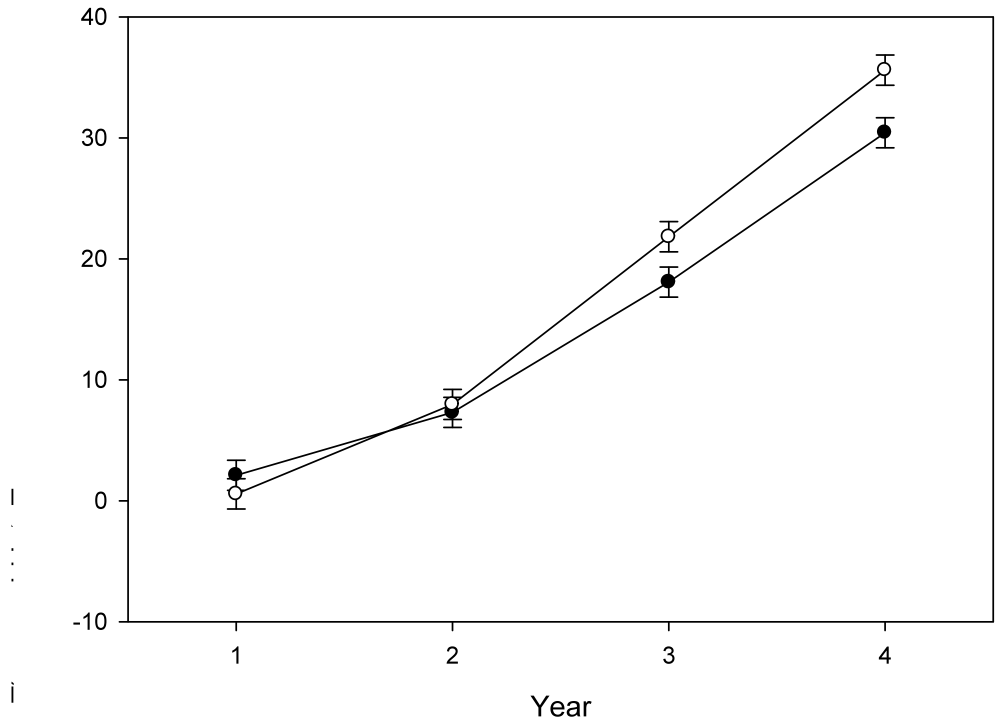

Figure 3.2: Total biomass of clone 93 (closed circle) and clone 32 (open circle) through age four at Cross, SC.

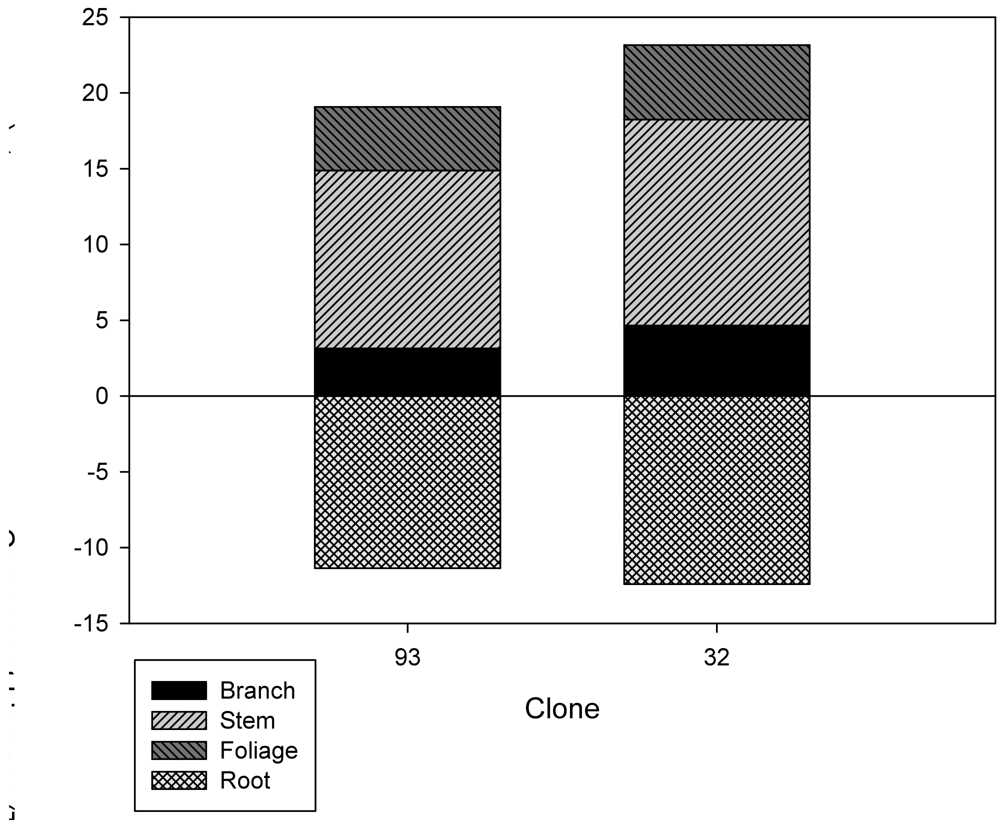

Figure 3.3: Allocation of biomass to branch, stem, foliage, and roots of clones 32 and 93 at age four on Cross, SC.

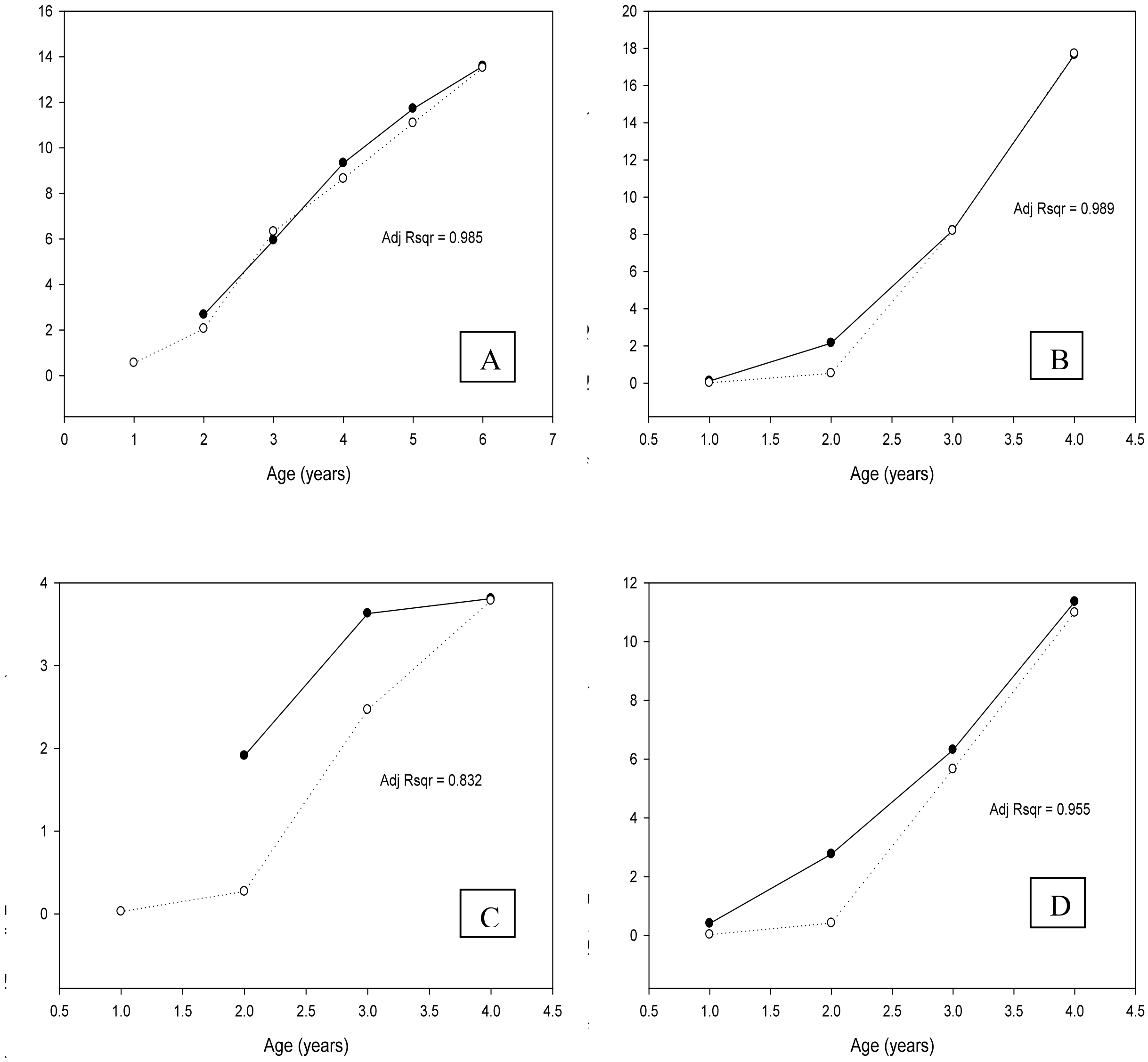

Figure 3.4: Measured (filled circle) vs. modeled (unfilled circle) diameter at breast height (DBH) (A), stem biomass (B), foliage biomass (C), and root biomass (D) for clone 93 at Cross.

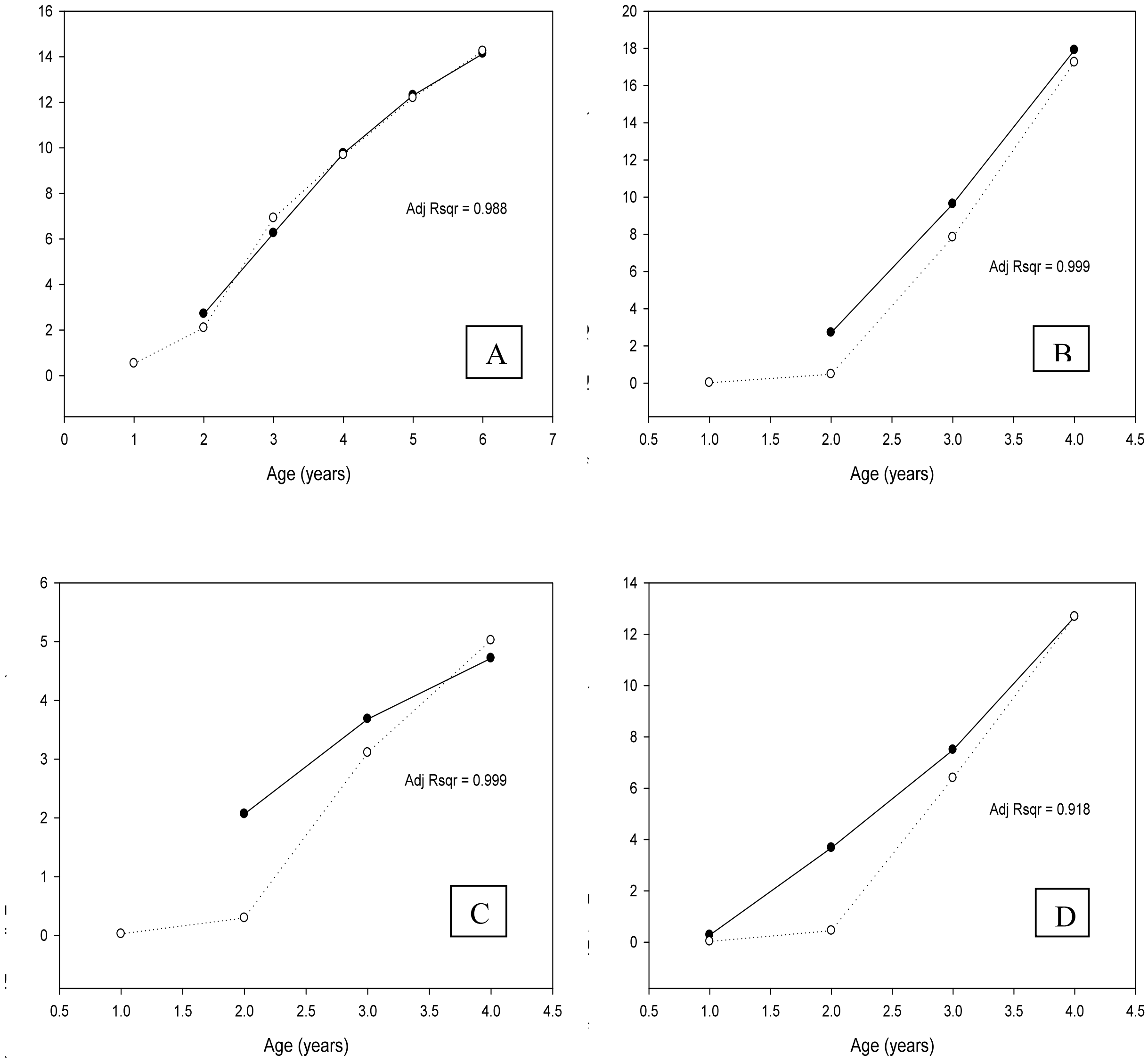

Figure 3.5: Measured (filled circle) vs. modeled (unfilled circle) diameter at breast height (DBH) (A), stem biomass (B), foliage biomass (C), and root biomass (D) for clone 32 at Cross.

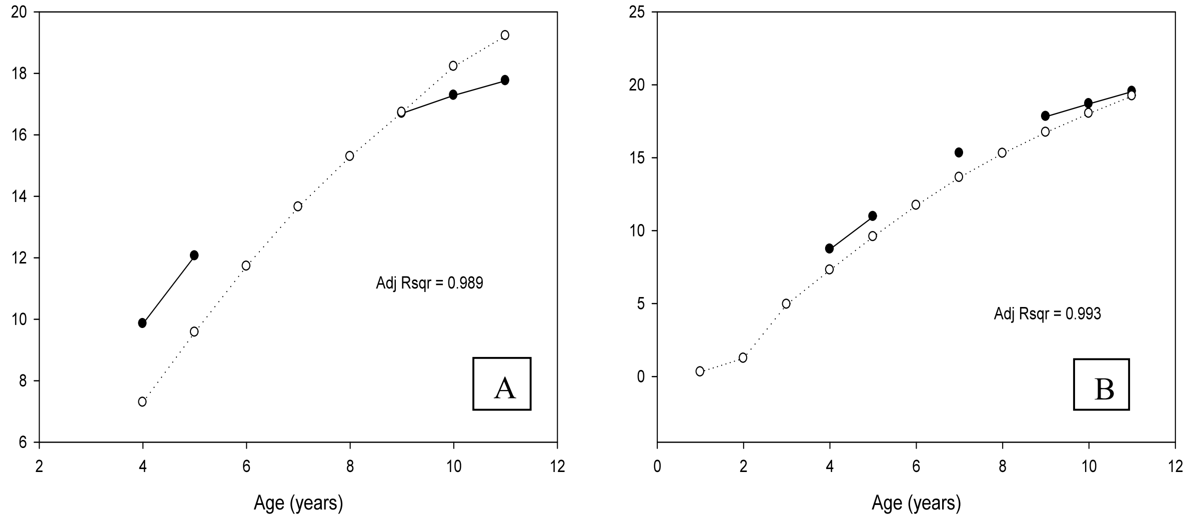

Figure 3.6: Measured (filled circle) vs. modeled (unfilled circle) diameter at breast height (DBH), for clone 93 on the validation sites of Haven (A) and Jericho (B).

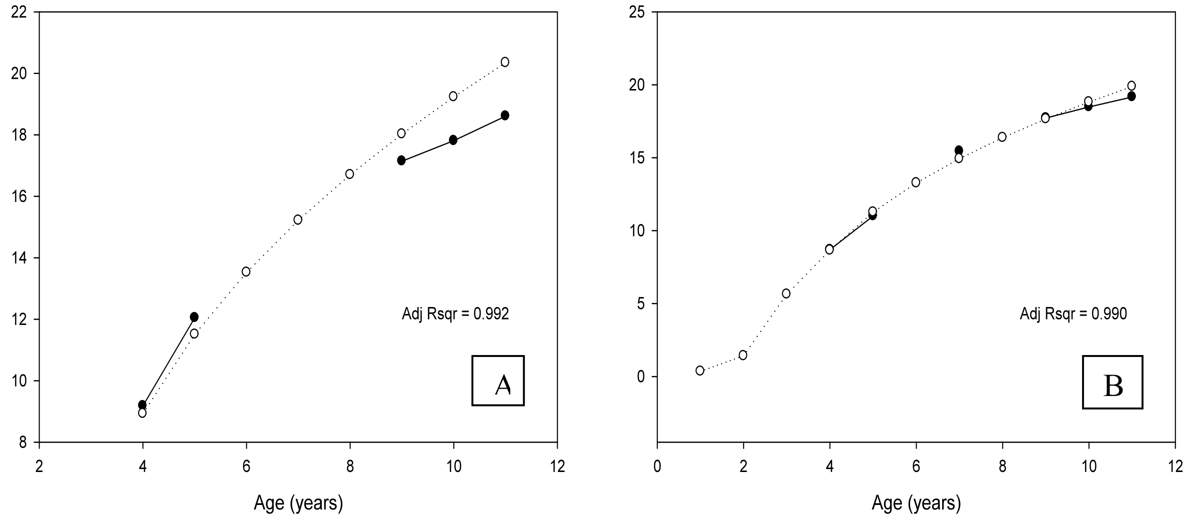

Figure 3.7: Measured (filled circle) vs. modeled (unfilled circle) diameter at breast height (DBH), for clone 32 on the validation sites of Haven (A) and Jericho (B).

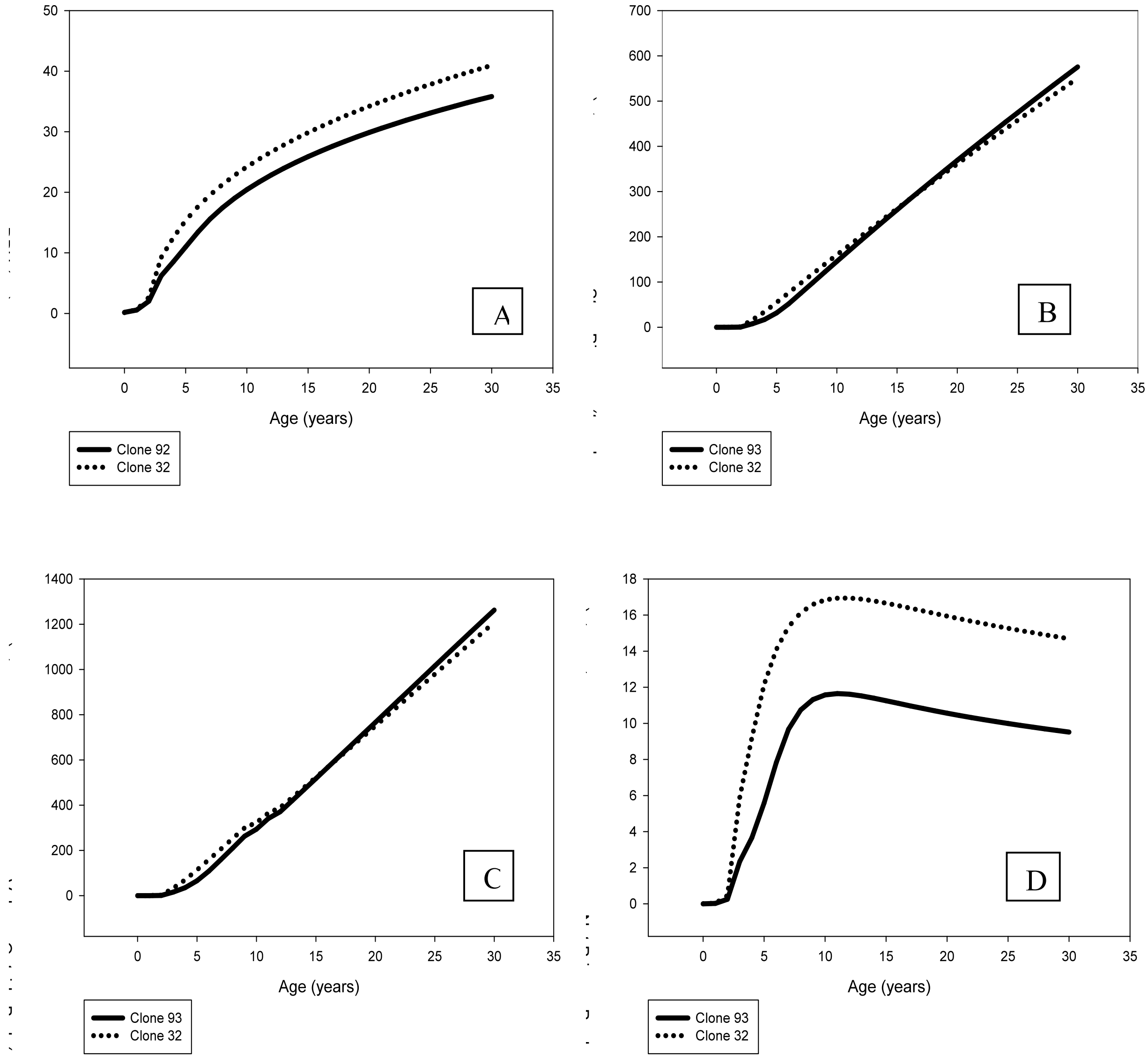

Figure 3.8: A comparison of clones 93 and 32 modeled diameter at breast height (DBH) (A), stem biomass (B), volume outside bark (VOB) (C), and net primary productivity (D) at age 30 on the Cross site using average monthly weather data.

CHAPTER 4

4. Conclusions

4.1 Chapter 1

The model was capable of producing accurate estimates of loblolly pine productivity across a wide environmental gradient and on different soil types when the species parameters were held constant and only the fertility rating parameter was manipulated. This indicates that 3-PG may not need to be parameterized for each site where is it used, although additional testing is required over a larger geographic range before this can be confirmed.

4.2 Chapter 2

The 3-PG model is able to produce accurate predictions of DBH and stem, foliage, and root biomass for young stands of loblolly pine clonal genotypes 93 and 32. As stands of these two genotypes continue to age 3-PG's ability to predict their growth should be continued to be evaluated to ensure that predictions remain accurate in older stands. 3-PG's simulations indicate that increased temperatures will result in decreased productivity of both clone 93 and 32 in Cross, SC. Changes in precipitation in the range of +200mm to -200mm a year appeared to have no effect on volume production of clone 93. However clone 32 was predicted to transpire more water due to a higher leaf area, which resulted in a prediction of water stress occurring earlier in clone 32 than clone 93 as temperature increases and/or precipitation decreases. The much larger predicted increase in water use of clone 32 compared to clone 93, and the similarity in their aboveground productivity, indicates that water use efficiency is much lower in clone 32 than 93 and may be an important factor to consider when selecting clones for planting.

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APPENDICES

Appendix A:

Notes about Parameter Estimates:

(Numbers correspond to the note numbers in table 2.2 and 3.2)

Note 1. pFS2 and pFS20 are ratios of partitioning coefficients for foliage and stem (η_f / η_s) at average stem diameter at breast height (avDBH) at 2 cm and 20 cm, respectively. Specific values for these terms were not available from the literature, so we rearranged equations solving for η_f / η_s and used data from CAPPS growth plots to provide estimates of pFS2 and pFS20. First, copying equations (10) and (12) in Landsberg and Waring (1997) here:

$$dw_f/d_t = dW/d_t \times \eta_f - \gamma_f \times w_f \qquad (1)$$

$$dw_s/d_t = dW/d_t \times \eta_s - \gamma_s \times w_s \qquad (2)$$

where η_f and η_s represent carbon allocation coefficients for foliage and stem, γ_f and γ_s represent litterfall and stem mortality rates, dw_f/d_t and dw_s/d_t represent the rates of growth in foliage and stem biomass, dW/d_t represents the net rate of dry biomass production of a tree.

Then, rewrite (1) and (2) as follows:

$$dW/d_t \times \eta_f = dw_f/d_t + \gamma_f \times w_f \qquad (3)$$

$$dW/d_s \times \eta_s = dw_s/d_t + \gamma_s \times w_s \qquad (4)$$

(3) divided by (4), we get (5):

$$\eta_f / \eta_s = (dw_f/d_t + \gamma_f \times w_f) / (dw_s/d_t + \gamma_s \times w_s) \qquad (5)$$

Since dw_f/d_t, dw_s/d_t and γ_s can be calculated from real data, and γ_f is assumed to be 0.5, we can calculate η_f / η_s using (5). In Table 2.2, values of pFS2 and pFS20 are mean values of η_f / η_s at avDBH at 2 cm and 20 cm, respectively, for 12 loblolly pine plantations. These values were considered a baseline and were adjusted iteratively until agreement between measured and modeled data was achieved.

Note 2. StemConst and StemPower were determined empirically and iteratively using the growth data from CAPPS datasets and the calibrate function in 3-PG+.

Note 3. There is evidence that trees have increased resistances to the transport of water and materials as they grow larger and older, which decreases their ability to gain carbon and grow, but there is little information on this topic for loblolly pine that could be used to determine the parameters *Max age*, *nAge* and *rAge*. Because of this we initially set Max age to 200 to make the age modifier non-functional. However, when examining the modeled results for the Waycross site, it was evident that 3-PG was predicting a higher rate of growth in older stands than was exhibited in the actual measured data. Therefore values for *Max age*, *nAge* and *rAge* were estimated to account for this discrepancy.

Note 4. We used a sensitivity analysis to estimate *LAIgcx*. A value of 3 constrains *gcmax* to less than 0.006, which is supported by published information (19, 24). *LAIgcx* and *gcmax* are also affected by low values of FR. At FR < 0.2, gcmax was reduced if *LAIgcx* was above 3. So based on considerations, and a lack of published information, *LAIgcx* of 3 was our best estimate.

Note 5. Stand mortality is calculated from the –3/2 thinning law, which would imply that the best value of *thinPower* would be –1.5 (entered as a positive number in 3-PG). Unfortunately the mortality function in 3-PG+ does not account for stochastic events that cause mortality in loblolly pine stands, other than size-related mortality. In many instances mortality was occurring sooner than predicted by the –3/2 thinning law approach, so a slightly more negative value was used for *thinPower* which had the effect of initiating mortality slightly sooner.

Note 6. Values for *mF*, and especially *mR*, are not readily available. However, 3-PG is not very sensitive to the actual value of *mF* and *mR*, so depending on your objectives, determining the specific values may not be critical. For example, changing *mF* from 0 to 1 affects foliage biomass and LAI, but has almost no effect on any other result, except that *mF* of 0, compared to 1, decreases the number of remaining trees slightly. Similarly, changing *mR* from 0 to 1 affects root biomass and total biomass, but has almost no effect on any other output. However, changing *mS* from 0 to 1 has a large effect on almost all output variables, but only after stand mortality begins. We assumed that the trees that died in the plantation would be suppressed, and that canopy leaf biomass was not significantly altered by their death, and the trees had only 20% of the root mass and 40% of the stem mass of the average tree in the stand. These values are simple approximations and should be changed if the user has better information on mortality in the stands to be modeled.

Note 7. There are published values for k for loblolly pine stands. However, these estimates vary a great deal, and some are only approximations. 3-PG simulations are sensitive to the value of this parameter, therefore we decided to estimate k from measured values of LAI and intercepted radiation made at Waycross (Coastal plain) and Eatonton (Piedmont) sites. Data from a total of forty plantations were used in this analysis. The stands were of different ages and levels of management intensity from minimal to high. The k value also varied in these stands, from 0.47 to 0.89, and we used the mean of all stands (0.57) for the 3-PG parameter.

Note 8. The LAI for maximum interception of precipitation was assumed to be 5.

Note 9. The model is very sensitive to *alpha*, canopy quantum efficiency. This represents the maximum canopy quantum efficiency, which is then constrained by environmental and tree conditions. Based on leaf level information we selected an approximate alpha of 0.045 and then made iterative adjustments until good agreement between measured and modeled data was achieved at a value of 0.0435. There is a large amount of uncertainty about this estimate, and because of the sensitivity of the model to *alpha* if a more accurate value is available, it should be substituted in place of the current estimate.

Note 10. Basic density represents the average wood density of the entire tree. The estimate we used in 3-PG is based on an average of loblolly pine wood density measurements by Alex Clark, USDA Forest Service (Personal communication). It should be noted that in 3-PG, changing the value of wood density only affects volume, and not biomass estimates.

Note 11. The ratio of outside bark volume to inside bark volume, *volRatio*, was calculated from direct measurements (unpublished data). This ratio may vary depending on the genetic make-up of the stand and growing conditions.

Appendix B:

Additions to the Model:

A sensitivity analysis module was added to the model allowing the user to assess the relative sensitivity of any parameter to changes. Single or multiple parameters can be evaluated at the same time, and output variables to be evaluated are user selected. Another valuable addition to the model is the parameter calibration module. The parameter calibration tool allows the user to find the optimum value for up to three unknown parameters using observed site data. 3-PG finds the value by iteratively using different values within the range of potential values until the one is found that results in the best agreement between measured and modeled values. This study used the new parameter calibration tool to determine the appropriate FR value for each site. To do so we used the most recent nine to ten years of stem biomass and DBH values.

There were also some modifications made to 3-PG's original programming code. Times of planting and stand initiation are now assumed to be at the start of the calendar month instead of the end of it. One parameter was added to the species parameter page, volRatio. This parameter is the ratio of total stem+branch volume to the inside bark volume in order to describe the combined volume of wood and bark. An output parameter "vob" now predicts volume outside of bark. The leaf area index (LAI) function was also changed by adding a new modifier to stem biomass (WS) in order to correct 3-PG's computation of LAI. Previously, due to the incorrect calculation of LAI the LAI value changed inversely with WS. The modifier is only employed when the stand age is greater than the maximum age (MaxAge). The modified estimation of WS is WS=WS-mS*delStems*(WS/Stemno)*(**StandAge-MaxAge)^0.6**, with the boldfaced part being the added new age modifier.

In the fertilization section of the silvicultural events module (newly added to 3-PG) a duration option was added. This allows the user to control the length of time that fertilization increases the site's FR value. The competition module is also a new addition to the model. This module takes advantage of the canopy quantum efficiency (molC/molPAR) by adjusting the efficiency in varying degrees for each of the four competition levels (none, low, medium, and high). An additional modification involves the initial growth efficiency of seedlings. The original 3-PG model did not estimate initial growth well. Actual seedling growth is greater than the model could estimate and still provide reasonable estimates as stands matured. To compensate for this we added a percentage increase for WF, WR, and WS in the first three years to increase modeled seedling growth. After year three the model reverts to the original biomass equations. We also manipulated the model's wood density function calculations. In the original model wood density was a single value for the entire run length of the model. In our modified version of 3-PG wood density changes with age to allow for more accurate predictions of volume, which is calculated using wood density and biomass.