VALIDATION AND PREDICTION OF WATER USE, STAND DYNAMICS AND GROWTH ATTRIBUTES OF LOBLOLLY PINE PLANTATIONS USING THE 3-PG MODEL UNDER HISTORICAL CLIMATE AND PREDICTED FUTURE CLIMATES IN FOUR LOCATIONS IN THE SOUTHEASTERN USA

by

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(Under the Direction of Robert Teskey)

ABSTRACT

We are using the hybrid process-based model, 3-PG, to understand the production ecology of loblolly pine (*Pinus taeda*) plantations under current and future climate conditions. Existing fertilization x throughfall research installations were utilized to validate the model predictions of leaf area index, water use and productivity at four distinct locations of this species' range. We employed a comprehensive dataset of climate projections to predict the magnitude of changes in productivity and water use at those sites. Results showed that the model could accurately predict productivity and reasonably accurate predictions of water use and leaf area index. Future simulations indicated that colder sites would show a greater increase in productivity and water use compared to warmer sites, as a result of increasing of carbon dioxide concentration [CO2] and average temperature. Water use was predicted to be driven by leaf area index development, regardless of the climate differences between the four sites.

INDEX WORDS: loblolly pine, 3-PG, physiological process-based model, climate change, water use, transpiration, stands dynamics, ecophysiology

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B.S., Federal University of Viçosa, Brazil, 2013

A Thesis Submitted to the Graduate Faculty of The University of Georgia in Partial Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE

ATHENS, GEORGIA

2016

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May 2016

ACKNOWLEDGEMENTS

The research project presented here would have been impossible without my many collaborators, committee members, tree physiology lab mates, and friends and family members. I would first and foremost like to thank my major advisor and committee chair, Dr. Robert Teskey. His challenging and effective mentoring and constructive criticism helped to achieve this memorable degree in the tree ecophysiology field. I am deeply appreciative to him for his friendship, guidance, expertise, and critical thinking lessons, which supported me to further pursue my education and my development as a researcher and as person. I'm grateful to Dr. Mike Kane, for his unwavering support and professional guidance; he is a great teacher and at the same time a very kind person with his door always opened to help. He was a wonderful tutor and I own him for sharing his knowledge regarding intensive forest management and silvicuture of loblolly pine plantations. Thanks also to Dr. Dehai Zhao, who provided statistical expertise, code writing when necessary and for his willingness to help me throughout my project. I'm thankful for their sharing the same research interest and for serving as members of my graduate committee. Special thanks go to Dr. Carlos González-Benecke, even though he was not a member of my committee, he always demonstrate engagement and great disposition to help and generously provided enlightening advice with the 3-PG model, statistical analysis, code writing and data sharing and quality. Thanks also go to Dr. Heather Dinon, who provided invaluable assistance and strong commitment with data quality throughout this research project and to Dr. Eric Ward, who was always prompt to answer questions regarding data interpretation and sharing. It's been a great honor to work together with all of them.

I am extremely grateful to fellow members of the Teskey lab. Dr. Mary Ann McGuire for all the technical support and advisement. My fellow graduate lab mates, including Ying Wang (Maggie), Miles Ingwers, Ryan Thomas, Dr. Josef Urban (Pepa), Dr. Hailan Fan (Hellen) and Dr. Xiu Wei for their support and friendship over the past couple years. Cody Luedtke, Dr. Jinyan Yang, Dr. Josef Urban

(Pepa) and I made a particularly good office team - thank you for your help and suggestions. Particularly, I'm thankful to Dr. Jinyan Yang, and I really appreciate your friendship and help with suggestions during my thesis preparation. You all enriched the quality of my personal life and the science that I accomplished. I am appreciative to many people outside the Teskey lab as well; thank you to Madison Akers and Stan Bartkowiak, and all the members of PINEMAP for your help with my work and for creating a culture of collaboration at PINEMAP.

I would like to thank my parents, Levindo Souza and Marisa Barros, and my sisters Liz and Suhelen Barros for their never-ending consideration and understanding my decision of studying abroad and pursuing my dreams. I miss you all so much at this time. Most importantly, my mom (Marisa Barros) for her never-ending supporting and for providing the best education I could have. I would like to thank my second family in U.S., Sabrina, Penha, Zezé, Eduardo (Dú) and Vinícíus (Vini) without whose unwavering love and support I would have been lost entirely in this endeavor. A special thanks to Sabrina who encouraged and helped me to achieve this Master of Science degree abroad. You are responsible for my career achievements and have an inestimable place in my heart. I would further like to acknowledge everyone who welcomed me with open arms in the beloved city of Athens. I'm grateful to the friendship and care provided by roommate Andrew and his family. My friends Michael, Will D., Daniel, Madison, Chris, Mohammed, Chango, Will A., were great company in after work activities (sorry if I'm missing somebody). Thanks you all for being such good friends during my time in Athens.

This research was possible through support from Pine Integrated Network: Education, Mitigation and Adaptation project (PINEMAP), a coordinated Agricultural Project funded by the USDA National Institute of Food and Agriculture, Award #2011-68002-30185. I wish to thank PINEMAP for funding support and the PINEMAP researchers, graduate students and field crew involved at research sites "Tier III" for the installation, maintenance, data collection and sharing of this study. Finally, I'm extremely grateful and honored for have attended as a graduate student in the Warnell School of Forestry and

Natural Resources. I hope to live up to its prestige. My career will be benefited for this unique opportunity to have attended to one of the greatest schools of Forestry in US.

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CHAPTER 1

INTRODUCTION

1.1 Purpose of the Study

The pine forests in the southeastern US are important economically and also provide many ecosystem services. However, there is increasing concern regarding the amount of water they use and how climate change will affect it. This concern is growing because of an increased demand for water from a growing population and increased urbanization in the region. This project involved using the 3-PG model to simulate water use and productivity of loblolly pine plantations. The project had two parts. The goal of the first part was to determine if the 3-PG model could accurately predict productivity and water use of loblolly pine (*Pinus taeda*) plantations at four widely dispersed locations within the species' range. These sites were located in the states of Virginia (VA), Georgia (GA), Florida (FL) and Oklahoma (OK). We hypothesized that the 3-PG model could accurately predict canopy transpiration, leaf area index and stand growth using a single set of physiological parameters for all four sites. The goal of the second part of the project was to predict transpiration and stand growth over 25-year rotations at the same four sites in mid-century and late-century time periods using twenty climate models and two different Representative Concentrations Pathway (RCP) scenarios. We hypothesized that the productivity and water use of loblolly pine plantations will increase under future climate change scenarios and that the magnitude of this change will vary geographically.

1.2 Unique Aspects of This Study

The 3-PG model has been used to predict the productivity of different plantation species world-wide (Waring, 2000; Landsberg et al., 2003; Esprey et al., 2004; Fontes et al., 2006; Stape et al. 2010). However, the model has been used far less frequently to predict forest water use (Law et al., 2001; Dye, 2001; Dye et al., 2004; Morris et al. 2001; Feikema et al., 2010; Almeida et al., 2007; Almeida and Sands, et al., 2015). Similarly, the 3-PG model has been used a number of times to predict productivity of loblolly pine plantations in the Southeastern US (Landsberg et al., 2001; Sampson et al., 2006; Bryars et al., 2013; Subedi et al., 2015; Gonzalez-Benecke et al., 2016), but it has only been applied in a few studies of loblolly pine water use, and those studies were very limited in scope (Ewers et al., 2001; Sampson et al., 2006; Siqueira et al., 2006). These previous studies of loblolly pine water use did not evaluate the model against independent measurements of canopy transpiration, nor did they assess stand water use in different environments within the loblolly pine range. In our study, we evaluated canopy transpiration and productivity of loblolly pine stands at four experimental sites that spanned the loblolly pine range. These sites were part of the Pine Integrated Network: Education, Mitigation and Adaptation Project (PINEMAP; Will et al., 2015). The sites provided a wide range of climate and soil conditions in which to test model performance. In addition, we used the model for the first time to predict future productivity and water use of loblolly pine plantations under different climate change scenarios. No other studies have applied the 3-PG model to predict future changes in both productivity and water use across a wide range of loblolly pine sites. Exploring potential changes in forest growth due to future changes in climate is a suitable application of process-based models like 3-PG, which have the ability to simulate dynamic forest responses to changes in environmental conditions at different spatial and temporal scales (Almeida et al., 2009; Millar et al., 2007).

The 3-PG model has been used to predict the potential effects of climate change on several tree species, but with different objectives than those of this study (Coops and Waring, 2001; Almeida et al., 2009; Coops et al., 2010; Meason and Mason, 2014; Waring et al., 2014; Coops and Waring, 2011). Also, the climate projections used in the previous studies were derived from either one, or just a few, global circulation models developed in Phase 3 of the Coupled Model Intercomparison Project, which was part of Intergovernmental Panel on Climate Change (IPCC). In this study we used data generated from 20 global circulation models and a new set of emissions scenarios (RCPs) that were from the most recent phase (Phase 5) of the IPCC Coupled Model Intercomparison Project. Climate data for the four sites was downscaled to a local level (6 km by 6 km resolution) from each of the 20 global circulation models for each RCP scenario using the Multivariate Adaptive Constructed Analogs (MACA) statistical method. The use of 20 climate models is unprecedented in studies using 3-PG to predict future forest growth and transpiration. The use of so many models also allowed us to estimate variability due to model uncertainty in climate predictions.

CHAPTER 2

VALIDATION AND PREDICTION OF WATER USE, STAND DYNAMICS AND GROWTH ATTRIBUTES OF LOBLOLLY PINE PLANTATIONS USING THE 3-PG MODEL UNDER HISTORICAL CLIMATE AND PREDICTED FUTURE CLIMATES IN FOUR LOCATIONS IN THE SOUTHEASTERN USA[1]

[1]Souza, B.S.B., C. Gonzalez-Benecke, D. Zhao, M. Kane, H.D. Aldridge and R.O. Teskey. To be submitted to *Forest Ecology and Management*.

ABSTRACT

Southern pine forests have an important role in regional water resources and carbon sequestration. Of particular concern is the potential scarcity of water resources in the future coupled with increased land use and urbanization. In this context, a forest stand process model that integrates climate with physiological processes to predict stand growth and water use could be a useful tool to examine whether climate change will impact water use and productivity of loblolly pine (*Pinus taeda),* the most commercially important tree species in this region. We are using the hybrid process-based model, 3-PG, to understand the production ecology of this species under current and future climate conditions. We hypothesized that the 3-PG model would be able to accurately predict transpiration, leaf area index and stand growth at four sites spanning the species range. We also hypothesized that productivity and water use of loblolly pine plantations will increase under future climate change scenarios and that the magnitude of this change will vary geographically. We used existing fertilizer x throughfall exclusion research installations in Georgia, Virginia, Florida and Oklahoma to examine the performance of the 3-PG model by comparing model predictions of transpiration with estimates of canopy transpiration derived from sap flow measurements, and model predictions of productivity with growth measurements. These sites cover a wide range of climatic and edaphic conditions found on the southeastern region of US. Results showed that the model could accurately predict aboveground biomass, volume inside bark, basal area and quadratic mean diameter. Leaf area index (*LAI*) simulations were accurate for the FL and GA sites, and reasonably accurate for the VA site (RMSE = 0.4, 0.58 and 0.81 m^2m^{-2}, respectively). The bias associated with predicted transpiration ranged from 1% (GA) to 19% (VA). The validated model was then used to simulate water use and stand dynamics under climate change scenarios. We employed twenty climate simulations covering the mid-century and late-century under two distinct Representative Concentration Pathways (RCP). These simulations predicted that water use of loblolly pine would be primarily driven

by *LAI* at all locations and that overall, stand productivity, leaf area index, and water use will increase as the carbon dioxide concentration [CO_2] and average temperature increase. Colder sites would show a greater increase in productivity and water use compared to warmer sites. The 3-PG model appears to be a potentially useful management tool for predicting wood production and water use in loblolly pine plantations locally and regionally under current and future climatic conditions.

INDEX WORDS: loblolly pine, 3-PG, physiological process-based model, climate change, water use, transpiration, stands dynamics, ecophysiology

2.1 INTRODUCTION

The southeastern region of the U.S. encompasses 40% of its total timberland area (Oswalt et al., 2014) and provides approximately 60% of the nation's total wood production (Prestemon and Abt, 2002). The most extensively established and productive pine species in the region is loblolly pine (*Pinus taeda* L.), accounting for 71% of softwood standing volume (Oswalt et al., 2014). Besides its economic relevance, other benefits associated with these forests include a wide range of ecosystem services, including water, wildlife habitat, recreation, carbon sequestration, and soil conservation (Wear et al., 2014). There is likely to be an increase in demand on these ecosystem services due to urbanization and land conversion caused by the growing population in the southeastern U.S. (Kunkel, 2013). Of particular concern is the potential scarcity of water resources. Across the U.S., forested watersheds account for approximately 80 % of the country's freshwater (Kreye et al., 2014).

Mean global air temperature has increased by about 0.8 °C globally since the early 1900s due to climate change (Pachauri and Reisinger, 2007), although for the southeastern U.S. this trend was not significant. Precipitation has shown significant seasonal changes, with an increase in autumn and a decrease in summer. Simulations for the 21st century indicate that future air temperatures in the region will be much higher than those observed in the 20th century. Precipitation will probably increase in the northern and eastern parts of the region and decrease in the southern and western parts of it, although these predictions are associated with great uncertainty (Kunkel, 2013).

Evapotranspiration (*ET*) in southeastern U.S. varies from 41 to 100% of precipitation (Gholz and Clark, 2002, Powell et al., 2005, Stoy et al., 2006, Sun et al., 2010), and is regulated by physical controls, such as available energy, precipitation distribution, topography and soil properties as well as biological controls, mainly leaf area and canopy conductance. An increase in *ET* is expected to accompany the increase in temperature primarily because of an increase in atmospheric vapor pressure deficit (*VPD*). The expected changes in *ET* suggest that stand water use will increase, and that soil water deficits may occur more frequently, which could reduce the productivity of loblolly pine plantations in portions of the Southeast (Huntington, 2006, Easterling et al., 2000).

Forest management prescriptions may ultimately need to consider stand water use (Johnsen et al., 2013). Thus managing forest plantations to optimize wood production and water use might be the next step in sustainable forest management (Fox, 2000, Millar et al., 2007, Johnsen et al., 2013). In this context, a forest stand process model that integrates climate with physiological processes to predict tree growth and water use could be a useful tool to examine potential productivity. While empirical growth and yield models are easily implemented and require few parameters, they cannot be extrapolated to future climate conditions or different sites. A hybrid process model that has characteristics of a detailed physiological process model and statistical growth and yield model, called 3-PG (Physiological Processes in Predicting Growth), was developed explicitly to address this problem (Landsberg and Waring, 1997). The original version of the 3-PG model had already been used to predict productivity of a loblolly pine plantation in the southeastern United States (Landsberg et al., 2001, Landsberg et al., 2003). More recently, modified versions of the model have been used to predict growth of loblolly pine plantations over a much wider geographic area (Bryars et al., 2013, Gonzalez-Benecke et al., 2016). Bryars et al. (2013) reported that a single set of physiological parameters properly calibrated to loblolly pine plantations at sites in the Piedmont and Coastal Plain provinces of Georgia yielded accurate estimates of biomass and volume growth under different management intensities. Gonzalez-Benecke et al. (2016) reported a regional validation of the 3-PG model across the native range of loblolly pine. That version of the model had improvements in parameter estimates and included some new functions to estimate stand attributes. In both the Bryars et al. (2013) and the Gonzalez-Benecke et al. (2016) studies it was demonstrated that a single set of physiological parameters could accurately predict stand productivity of loblolly pine across a range of edaphic and climate conditions spanning large geographic areas and site conditions.

The 3-PG model has been employed to predict plantation water use of several tree species in contrasting environments, albeit for different purposes. For instance, Dye (2001), (2004) evaluated estimates of canopy transpiration in *Pinus patula* and *Eucalyptus grandis* stands in South Africa, by comparing the model with sap flow measurements and reported that 3-PG underestimated *ET*. In an older mixed-species stand dominated by *Pinus ponderosa* in the Pacific Northwest, Law et al. (2001) reported satisfactory performance of the 3-PG model (bias of -17% and R^2 of 0.59) for predictions of latent heat (evapotranspiration) compared to eddy covariance measurements. They reported that the predictions of 3-PG were within the error range of the flux measurements. In that study, the 3-PG model also performed well when compared to a more complex process model (PnET-II). Feikema et al. (2010) incorporated a more detailed water balance model into 3-PG and used it to predict ET for several *Eucalyptus spp* in plantations ranging in age from 1 to 31 years old in South Australia. In that study, 3-PG provided reasonably accurate predictions and good model performance (R^2 from 0.46 to 0.81 and model efficiency up to 0.8) for daily and monthly time steps, when compared to sap flow measurements. However, the model tended to underestimate *LAI* and transpiration under high sap flow rates. Almeida et al. (2007) used 3-PG to predict water use efficiency and water balance in fast-growing *Eucalyptus grandis* clonal plantations at Southeastern Brazil, and concluded that the predictions from the original version of the 3-PG model were reasonably accurate. Almeida and Sands (2015) compared two versions of the water balance module in 3-PG (the original against a more detailed multilayer water balance module) for short rotation plantations of *Eucalyptus globulus* at southern Australia and Tasmania and *Eucalyptus grandis* in Southeastern Brazil. The improved version required detailed soil profile information to model water balance at a daily resolution, rather than the general soil information and monthly resolution of the original model. However, the original water balance module predicted the total evapotranspiration of rotation within 3% of the more complex water balance module model, which demonstrated that the original water balance module in 3-PG could accurately predict average water use at monthly or yearly time steps.

The 3-PG model has also been used in several water use studies of loblolly pine. For a study in a 13-year old loblolly pine stand in North Carolina US, Ewers et al. (2001), using the original version of 3-PG, found that model accuracy was improved when the maximum canopy conductance term in the model was accurately calibrated. For the same site, Sampson et al. (2006) used a hybrid version of 3-PG (SECRETS-3PG) that had a daily time step and reported a consistent underestimation of stand transpiration on days of low incident photosynthetically active radiation (*PAR*). Siqueira et al. (2006) compared estimates of *ET* for a 22-year old loblolly pine stand at North Carolina US from the original version of 3-PG against *ET* estimates from several more complex models, including SECRETS-3PG and CANVEG-A and PnET II and Biome-BCG. These simulations were not compared with independent measures of water use but it was highlighted that the predictions of water use from the original version of 3-PG were robust, and produced similar predictions to that of the more complex models that used smaller time steps and required much more data for parameterization. However, 3-PG has not been used to predict water use of loblolly pine plantations in different locations in the southeastern US, or to predict water use in future climate scenarios.

In the context of climate change, the 3-PG model has been used to predict changes in productivity of *Pseudotsuga menziesii* Franco var. *glauca* and *P. menziesii* across their geographic ranges in Northwest US and Canada in response to recent changes in climate (Waring et al., 2014) and in future climate scenarios (Coops and Waring, 2001, Coops et al., 2010). It has also been used with *Eucalyptus grandis x* *urophylla* clonal plantations at eastern Brazil to predict the response to elevated atmospheric CO_2 concentrations [CO_2] and climate change scenarios (Almeida et al., 2009). It has been used to evaluate the deployment of alternative species, i.e., *Eucalyptus fastigata* instead of *Pinus radiata* for plantations in New Zealand and *Pinus silvestris* instead of *Picea sitchensis* for plantations in Scotland (Meason and Mason, 2014). The model was also used to estimate potential changes in the distribution of *Pinus contorta* Dougl. in the Pacific Northwest US (Coops and Waring, 2011). However, 3-PG has not been employed to evaluate changes in productivity of loblolly pine plantations in response to climate change.

Recently, Phase 5 of the Coupled Model Intercomparison Project (CMIP5) employed a new set of emissions scenarios to drive global circulation and earth system models, entitled Representative Concentration Pathways (RCPs). These scenarios were developed to represent four radiative forcing pathways for this century, incorporating land use changes and greenhouse gas emissions (IPCC, 2015). We used two RCPs (4.5 and 8.5) to predict the effect of climate change on loblolly pine stand growth and water use (Meinshausen et al., 2011, Moss et al., 2010). This was done by using high-resolution spatially and temporally consistent surface meteorological datasets (Abatzoglou, 2013). A statistical approach called Multivariate Adaptive Constructed Analogs (MACA) was used to provide us with regionally downscaled climate information at a spatial resolution of ~6-km from twenty global climate models from CMIP5 (http://maca.northwestknowledge.net/CMIP5.php). The MACA procedure preserved meteorology patterns and minimized bias associated with complex terrains. It compromises a historical period (1950-2005) and a future climate projection period (2006-2100) for the two RCP scenarios. The RCP 4.5 is a scenario of moderate mitigation (stabilization of emissions by 2050), which envisions that an additional 4.5 W/m^2 of radiative forcing molecules (CO_2, CH_4, etc.) would be introduced into the earth-atmosphere system by 2100 compared to preindustrial conditions (relative to the 1850 climate). In this scenario, the atmospheric CO_2 concentration ([CO_2]) stabilizes around 550 ppm by mid-century. The RCP 8.5 is a scenario of rising emissions, so radiative forcing increases throughout the century to 8.5 W/m^2 by 2100.

This is a "business as usual" scenario which envisions that no further action is taken to reduce emissions. By 2100 in RCP 8.5, atmospheric [CO_2] reaches close to 1000 ppm.

The first objective of this project was to verify the accuracy of 3-PG in predicting water use and productivity in four widely dispersed locations within the loblolly pine range. These sites were located in the states of VA, GA, FL and OK. We evaluated the model's performance by comparing model predictions with empirical inventory data and estimates of canopy transpiration from sap flow measurements. The second objective was to predict water use and stand growth over 25-year rotations at the same four sites at mid-century and the end of the century using the 20 MACA climate data sets and the RCP 4.5 and 8.5 scenarios.

We hypothesized that the 3-PG model would be able to accurately predict transpiration, leaf area index and stand growth at the four sites. We also hypothesized that the productivity and water use of loblolly pine plantations will increase under future climate change scenarios and that the magnitude of this change will vary geographically.

2.2 MATERIALS AND METHODS

2.2.1 The 3-PG model

The 3-PG model is a hybrid process-based model that predicts the growth of even-aged and homogeneous forests, i.e., plantations, at the stand level in monthly time steps. The model uses simplified descriptions of physiological processes that regulate tree growth. It requires monthly weather data, and specific soil and stand information. There has been detailed documentation of model framework, routines, parameters and outputs (Landsberg and Sands, 2010, Landsberg and Waring, 1997, Sands, 2001, Sands and Landsberg, 2002). The model is based on a light-use efficiency function that computes canopy photosynthesis in a series of steps. The amount of photosynthetically active radiation that is absorbed

(*APAR*) by the canopy is calculated from the total incoming solar radiation that is intercepted by the canopy using Beer's Law. Modifiers in the model including *VPD*, available water content in the upper 1 meter of soil, and tree age change *APAR* to utilizable absorbed (*APAR*u). The model also computes the canopy quantum efficiency (α_c) which is altered by a series of growth modifiers (dimensionless factors), which can be multiplicative or additive (temperature, fertility, number of frost days, [CO_2]). Gross primary production (*GPP*) is calculated from α_c, *APAR*u and a carbon-use efficiency ratio (*NPP/GPP*) (Sands, 2001, Waring et al., 1998, Litton et al., 2007). Net Primary Productivity is then allocated to the biomass pools of foliage (*W*f), stem (*W*s) and root (*W*r) using partitioning coefficients (Landsberg and Sands, 2011). Root turnover and foliage abscission are computed and discounted from the corresponding *W*r and *W*f pools.

In 3-PG, a single-layer soil water balance model is used to estimate the water budget in the soil, which simplifies the calculation of water input and output. The 3-PG model uses the Penman-Monteith equation to calculate stand transpiration. Canopy evaporation is computed using canopy interception, *LAI*, and the amount of rainfall. Stand evapotranspiration is calculated by summing canopy transpiration and the evaporation of water from the soil. The difference between throughfall (rain which is not intercepted by the canopy) and stand evapotranspiration increases or decreases the volumetric water content of the soil.

Several parameters useful to forest management are computed in 3-PG. Quadratic mean diameter (*D*q) and basal area (*BA*) are computed from the *W*s pool and stand density, and *LAI* is computed from *W*f and specific leaf area. A management module estimates stem volume, mean annual volume increment from allometric relationships using species-specific coefficients. Mortality in 3-PG is computed by a density-independent and a density-dependent function (Reinecke's self-thinning rule) based on the average single tree stem biomass. Mortality changes stand density and the stand biomass pools. The version of 3-PG used in this project was based on 3-PG_{pjs} version 2.7 developed by Sands (2001) with loblolly pine-specific modifications and parameters (Appendix A) from Gonzalez-Benecke et al. (2016). For a comprehensive explanation of the model version we used, see Gonzalez-Benecke et al. (2016).

2.2.2 Model Validation

The model was validated using data collected from four contrasting sites located in Florida (FL), Georgia (GA), Oklahoma (OK) and Virginia (VA) (Figure 2.1). These sites were part of the Pine Integrated Network: Education, Mitigation, and Adaptation project (PINEMAP, www.pinemap.org), and were used to evaluate the effect of throughfall and fertilization on loblolly pine productivity across a climate gradient (Will et al., 2015). The site-specific climate data required by the 3-PG model, (monthly mean maximum and minimum air temperature, number of frost days per month, monthly mean solar radiation and monthly precipitation), were obtained from US National Oceanic and Atmospheric Administration (https://www.ncdc.noaa.gov/cdo-web/) and from US National Aeronautics and Space Administration Atmospheric Science Data Center portal (https://eosweb.larc.nasa.gov/sse/). The sites ranged in elevation from 14 m (FL) to 1305 m (OK) (Table 2.1). Annual precipitation ranged from 1114 mm at the VA site to 1443 mm at the FL site. Minimum temperature and average solar incoming radiation for January were lowest at the VA site, and highest at the FL site. Average temperature and incoming solar radiation for August were similar across the four sites (Table 2.1). Stand establishment occurred between 2003 and 2008, and all sites had a seed orchard mix of half-sib families, adapted to local conditions. Each stand received vegetation control at the time of planting. The experiment was initiated in 2012, and the experimental design consisted of a randomized block design, replicated four times with throughfall (ambient and an approximate 30% reduction) and fertilization (none and an optimum fertilization level) treatments, arranged as a 2x2 full factorial (Will et al. 2015). Exclusion troughs were installed between tree rows to cover 30% of the ground area. The fertilization treatment consisted of 224 kg ha^{-1} nitrogen, 28 kg ha^{-1} phosphorus, 56 kg ha^{-1} potassium, and a micronutrient blend (6% sulfur, 5% boron, 2% copper, 6% manganese, and 5% zinc), which is a common level of fertilizer applied at midrotation to commercial loblolly pine stands ((Fox et al., 2007, Albaugh et al., 2004). Yearly stand inventory was performed before treatment application in December 2011 and in subsequent years of the study. Projected *LAI* was measured by optical sensors (LAI-2000 plant Canopy analyzer Li-COR Inc., Lincoln, Nebraska).

Transpiration estimates were obtained at the tree level from stem sap flow measurements, using Granier-style thermal dissipation probes (TDP) (Bartkowiak et al., 2015, Ward et al., 2015). Sap flow was converted to the sap flux density of the instrumented trees, and then multiplied by tree sapwood area to yield sap flow, which is an estimate of tree-level transpiration. Since five trees were equipped with TDPs in each plot, to estimate transpiration on a ground area basis the sap flow values were averaged across the sample trees, divided by measurement plot area and multiplied by the ratio of plot sapwood area-to-average sapwood area of the sap flow trees (Bartkowiak et al., 2015). Water use predictions of 3-PG were evaluated by comparing them to the independent measurements of sap flow.

The 3-PG model requires specifying the site fertility rating (FR) and the initial biomass of the stand. The fertility rating was computed using site index at age-base 25 years (SI_{25}), and the equation of Gonzalez-Benecke et al. (2016). Initial biomass at the start of the model runs was estimated using site-specific tree height, dbh, stocking and age information and the above- and below-ground biomass equations reported in (Gonzalez-Benecke et al., 2014). To mimic the throughfall exclusion treatment for validation runs, the precipitation input in the model was reduced by 30%. Site-specific and stand initialization data of the four Tier III sites used for validation runs were summarized in Table 2.2.

2.2.3 Climate change simulations

To model stand growth under climate change scenarios at a local scale, a high-resolution spatially- and temporally-consistent surface meteorological dataset is required to statistically downscale current and future climate scenarios for specific sites (Abatzoglou and Brown, 2012). The Multivariate Adaptive Constructed Analog (MACA) statistical approach was used to compile climate data from 20 Global

Climate Models (Appendix B) for the four study sites with a 6x6 km resolution at a monthly time step. These provided the climate conditions for the four sites for the period from 1950 to 2098. This dataset was employed as an input for running the 3-PG model and was split into three 25-year rotation length periods: 1980-2004, representing the Baseline period, and 2043-2067 and 2074-2098 representing future climate projections. For each site, two climate pathway scenarios were used, RCP 4.5 and RCP 8.5 (Figure 2.2).

The MACA simulations indicated a consistent increase in yearly average temperature across the four sites in both future time periods under the two RCPs compared to the Baseline period (Table 2.3). Across the four sites, mean temperature increases in years 2074 to 2098 ranged between rom +2.11 °C to +2.63 °C under RCP 8.5 and from +4.0 °C to +4.92 °C under RCP 8.5. The OK site displayed the largest increases, followed by VA, GA and FL. Frost days are predicted to decrease substantially. For late-century period under RCP 8.5, the FL site would have the largest reduction (up to 68%), followed closely by OK and GA sites (61% and 60%, respectively) and VA site (50%). Precipitation was generally predicted to increase, or stay the same, in the simulations, with the largest increases in GA and VA, of 5 and 9%, respectively. The only site expected to have a decrease in precipitation was OK, and only at the end of the century under RCP 8.5.

For the climate change simulations we employed the same set of species parameters, as well as the site-specific data that were used for the validation runs, with exception of stand density for the VA site, which was set to 1400 trees hectare^{-1} and the initial values of component biomass (*W*r, *W*f and *W*s), which were all assigned the value of 0.001 ton ha^{-1} to simulate planting all of the sites with the same seedlings for the climate change scenarios. The model was run using monthly weather data, and the output was yearly. For each future period, the actual or estimated [CO_2] in the atmosphere (http://tntcat.iiasa.ac.at/RcpDb/dsd?Action=htmlpage&page=welcome) was represented in the model by the average value for the respective period. The [CO_2] for RCP 4.5 was 354 ppm (1980-2004), 496 ppm (2043-2067) and 533 ppm (2074-2098). The [CO_2] for RCP 8.5 was 354 ppm (1980-2004), 571 ppm

(2043-2067) and 807 ppm (2074-2098). For each site, and each RCP, we ran the model 20 times with each of the 20 MACA climate datasets simulating 25 year rotations. We averaged the predicted values of stand transpiration (E_G), *ET*, *LAI*, *D*q, *BA*, *AGB (*Aboveground biomass), *WUE* (water use efficiency – *AGB*/E_G), stand volume inside bark (*VIB*) and accumulated mortality (Accumulated mortality was the difference of stand density at age 1 and stand density at age 25) from the 20 MACA model runs in order to define the variation in response to likely future climates, and to capture the uncertainty related to model predictions.

2.2.4 Statistical Analyses

Model performance test statistics used for evaluating the model predictions were: root mean square error (RMSE), absolute bias (Bias), mean absolute error (MAE), and coefficient of determination (R2). Statistical analyses followed an unbalanced data design and were computed using SAS (version 9.4, Cary, NC, USA). A general linear model was used to perform an analysis of variance (ANOVA, Proc GLM) for the climate change simulations. Multiple comparisons of the end of rotation values for EG, ET, LAI, Dq, BA, AGB, VIB and Mortality for the four sites, the three simulation periods, and the 2 RCPs were made using the least squares means method (LSMEANS statement). The multiple comparison adjustment for the p-values and confidence limits were performed by Bonferroni tests (ADJUST=BON) with a significance threshold of p=0.05. Curve fits were performed using Sigmaplot (version 11.0, SPSS Inc., CA, USA).

2.3 RESULTS

2.3.1 Validation of the 3-PG Model

As indicated by the statistical measures (Table 2.4) and scatter plots (Figure 2.3), the model predictions of *AGB*, *VIB*, *BA*, *D*q across the four validation sites were generally in good agreement with measured values. For example, the coefficient of determination showed that *AGB*, *VIB*, *BA*, *D*q estimations were highly correlated with measured values, with R^2 values ranging from 0.68 to 0.98 (Table 2.4). There were differences in model performance among the sites. For the OK and VA sites, there was a tendency of the model to under-estimate *D*q (bias of +10%) and *BA* (bias of +21%). The predictions for the GA and FL sites tended to over-estimate VIB (bias of -14% and -12%). The predictions of *AGB* were also over-estimated for GA (bias of -20%) and OK (bias of -11%) sites. The model accuracy for predicting *AGB* and *VIB* was highest for the OK site (lowest RMSE and MAE) and lowest for the GA and FL sites although the R^2 for *AGB* and *VIB* was 0.96 for the FL site and 0.84 for the GA site.

For *LAI* predictions, the model showed the highest accuracy for the FL site (year 2013 data) with the RMSE of 0.4 m^2 m^{-2} and MAE of 0.31 m^2 m^{-2}, and the lowest Bias (0.06 m^2m^{-2}). For the GA site, the model prediction had a reasonable RMSE of 0.58 m^2 m^{-2} and MAE of 0.45 m^2 m^{-2} but a small R^2 (0.21). The simulations for the VA site yielded a small R^2 (0.21) associated with the highest RMSE (0.81 m^2 m^{-2}), MAE (0.72 m^2 m^{-2}) and Bias (-0.72 m^2 m^{-2}).

Model performance was satisfactory for predicting average annual transpiration across the sites (Figure 2.3, Table 2.4), with an average bias of +3.45 mm H_20 (GA) to –61.9 mm H_20 (VA) (Table 2.4). That represents a difference between the measured transpiration values and the predicted transpiration of 1% to 19%. The model under-estimated transpiration for the VA and OK sites compared to the transpiration data collected in 2013, and over-estimated transpiration for OK site compared to the data collected in 2014 (Figure 2.3). Both visual comparisons and the performance statistics indicated a lower accuracy (higher RMSE and MAE) in treatment-level predictions for the GA site, followed by the OK site, implying an inability of the 3-PG model to completely capture the treatment differences at those sites (Figure 2.3).

2.3.2 Climate Change Simulations

We found substantial differences between Baseline and RCP 4.5 and 8.5 simulations for *AGB*, *VIB*, *BA*, *D*q, *LAI* and E_G (Table 2.5). Both RCP scenarios produced an increase in predicted growth in mid- and late-century rotations. The RCP 8.5 scenario produced greater increases in *D*q, *BA*, *AGB*, *VIB*, *LAI* and E_G than the RCP 4.5 scenario. The magnitude of the increase in growth and water use was different across the four sites and depended on when the rotations started (Figure 2.4). The model predicted an increase in productivity and water use under climate change scenarios that was greater in the coolest site than in the warmer sites (Figure 2.5). The predicted increase in *ET* and growth was greatest at the VA site under both RCP scenarios, with the maximum gain under the RCP 8.5, followed by the GA, OK and FL sites, respectively (Figure 2.4). For the warmest site (FL), there was no difference in *AGB* and *BA* when comparing the two future periods (2043 and 2074) under the two RCPs scenarios, but growth was higher than the Baseline prediction for both scenarios (Table 2.5).

The 3-PG model predicted a strong correlation between *LAI* and transpiration across all sites and the two RCP scenarios up to an *LAI* of 3 (Figure 2.6). At *LAI* > 3 the relationship plateaued, and transpiration did not increase further with an increase in *LAI*. Leaf area index explained 98% of the variation in predicted water use (R^2 = 0.98, p=0.001) with no variation among sites or treatments. Among sites, the highest LAI and transpiration for the Baseline scenario were predicted for the FL site (3.2 m^2 m^{-2}, 846 mm H_20), followed by GA, OK and VA sites, respectively (Table 2.5). The potential changes in *LAI* and transpiration predicted at the end of the century for the four sites under RCP 8.5 indicated that the VA site would have the largest increase in *LAI* and transpiration (+0.79 m^2 m^{-2}, +272 mm H_20), followed by the GA, OK and FL sites. Water use efficiency (*WUE*) for the Baseline scenario ranged from 0.304 to 0.208 tons ha^{-1}/ mm H_20 at the OK and VA sites, respectively. Under climate change scenarios, the model predicted no significant changes for the OK and FL sites, while, significant increases in *WUE* are expected for the VA and GA sites under both RCPs.

Comparing predicted *LAI*, *ET* and precipitation for each year of the rotation between the baseline period (1980 to 2004) and the end of the century period (2074 to 2098) under the RCP 8.5 scenario indicated that *LAI* will reach a plateau at about 8 years into the rotation for the GA and FL sites (Figure 2.7). At the VA and OK sites the plateau was predicted to be later (Figure 2.8). After maximum *LAI* was achieved, annual *ET* approached, but did not exceed, annual precipitation at the FL and OK sites. At the VA site annual *ET* was substantially below annual precipitation for all years in the simulation.

The simulations for the Baseline scenario predicted that productivity (*AGB, VIB, BA*, *D*q, *LAI*) would be highest for the FL site, intermediate for GA and OK sites, and lowest for VA site. *AGB* and *VIB* were predicted to be 256 tons ha^{-1} and 405 m^3 ha^{-1} $year^{-1}$, respectively, for the FL site, whereas they were approximately 30% lower for OK and GA sites and 80% lower for the VA site (Table 2.5). However, the predictions at both RCPs scenarios for the mid- and end-of-century periods predicted the smallest increases in productivity for the FL site (~7%) and the largest increases for the VA site (190%), with intermediate responses for the OK and GA sites (23% and 34%, respectively). The model predicted that the difference in *AGB* and *VIB* will be reduced from 30% to 20% in GA and OK sites and from 80% to 50% at the VA site, compared to that of the FL site. This pattern of predicted site productivity indicated that there may be less difference in plantation productivity across the region in the future.

Under both climate change scenarios the only reduction in any growth variable was *BA* (up to -3.6 m^2 ha^{-1}) for the FL site, despite having the highest predicted *D*q, because of high mortality (Figure 2.9). The VA site displayed the lowest value of *D*q, and predictions indicated that under future climate conditions, it would not have any additional mortality over a 25 year rotation compared to the Baseline scenario. Under the Baseline scenario mortality was highest for FL site (775 trees ha^{-1}), 50% lower for GA and OK sites (379 trees ha^{-1}) and 75% lower for the VA site (189 trees ha^{-1}).

Across the four sites, the ratio of *ET*/Precipitation for the last year of the rotation was predicted to increase compared to baseline by 81% at the VA site, 25% at GA site, 22% at the OK site, and 11% at the FL site (Table 2.6). As there was no apparent increase or decrease in precipitation in the MACA simulations (Table 2.3) the change in the *ET*/Precipitation ratio was mainly attributed to *LAI* development and an increase in *VPD*. Although the *ET*/Precipitation ratio increased for all four sites between the baseline and either RCP scenario, in no case did the ratio increase above 0.78. Total stand water use (sum of *ET* for the 25 year rotation) was predicted to increase in both RCP 4.5 and 8.5 scenarios (Figure 2.10). Comparing the Baseline scenario with the RCP 8.5 scenario at the end of the century, total stand water use was predicted to increase for the FL site from 19,678 to 22,454 mm H_20, which is an increase of 14% (Table 2.6). For the other sites, the increases in *ET* were much greater: 32% at the OK site, 50% in GA site, and 160% at the VA site. Total *ET* for a 25 year rotation at the end of the century under RCP 8.5 was 22,454, 17,246, 16,150 and 11,239 mm H_2O for the FL, GA, OK and VA sites, respectively.

2.4 DISCUSSION

2.4.1 Validation of the 3-PG Model

The four Tier III sites varied substantially in climate, soils and growth rate. Our simulations showed good agreement between predictions from the 3-PG model and empirical measurements made at the four sites, supporting our first hypothesis. The 3-PG model produced accurate predictions of annual stand growth, canopy transpiration and leaf area index at all four sites using a single set of parameters. However, the model provided better predictions at some sites than at others. For example, there was a consistent underestimation of *D*q, *BA*, *VIB* and *AGB* for the VA site and of *D*q and *BA* for the OK site. Particularly for the VA site, the model may not be accurately representing the potential for loblolly pine to photosynthesize after frost events. Law et al. (2001) noted that for *Pinus ponderosa* stands, positive net photosynthetic rates can occur on overcast days after nights of subfreezing temperatures, which is prevented in the current parameterization of the model.

The version of the 3-PG model we used was that of Gonzalez-Benecke et al. (2016). Consistent with their observations, we found that the model was able to produce accurate estimates of loblolly pine stand growth at widely dispersed sites across the geographic range of the species. Gonzalez-Benecke et al. (2016) made several improvements to the 3-PG model including the additions of more accurate functions for estimating the FR term, the development of canopy cover, density-independent and dependent mortality, LAI, transpiration and carbon allocation for loblolly pine plantations.

Despite the simplicity of the water balance sub-model, across the three sites for which transpiration estimates were available, the model was able to produce reasonable predictions of annual average canopy transpiration. Feikema et al. (2010) and Almeida et al. (2007) reported that an underestimation of LAI caused the model to underestimate water use for *Eucalyptus grandis* and *Eucalyptus globulus*. The improved function for estimating LAI in this version of the model was likely an important reason for the accurate estimates of transpiration for the sites used in this study.

2.4.2 Climate Change Simulations

Our study demonstrated that the 3-PG model can be used to assess the impact of future climate change scenarios on loblolly pine water use and stand growth across its native range. Our second hypothesis that productivity and water use of loblolly pine plantations will increase under future climate change scenarios was supported by our model simulations. Moreover, this study suggested that there will be an increase in productivity across the native range of loblolly pine, but the magnitude of the increase will vary geographically, with cooler areas having relatively greater increases in productivity and water use than warmer areas.

The 3-PG model computes stand transpiration using the well-known, and widely used, Penman-Monteith equation. Predicted yearly canopy transpiration increased linearly with LAI, with a strong and similar correlation across the four sites under all climate change and baseline scenarios. This suggested the transpiration is directly regulated principally by LAI, despite the different environmental conditions of different sites. A linear relationship between transpiration and LAI has been observed in other studies. Feikema, et al. (2010) reported a linear relationship between daily canopy transpiration and LAI for *Eucalyptus globulus* ($R^2 = 0.43$) and *Eucalyptus nitens* ($R^2 = 0.69$), suggesting an increase in transpiration rates were associated with development of LAI and sapwood area. Granier et al. (2000) proposed that the linear relationship was primarily due to increases in canopy conductance associated with increases in LAI. Our simulations produced a saturation of canopy transpiration at LAI = 3 m^2 m^{-2}, which may have been due to the value of LAI in the model for maximum canopy conductance (LAIgcx = 3). We will need more information about transpiration of loblolly pine at LAI>3 to determine if the model is accurately predicting transpiration for loblolly pine at LAI>3. However, Granier et al. (2000) noted that as LAI increases, transpiration can level off due to an increase in self-shading of the lower canopy by upper canopy leaves.

The predictions for mid and end-century precipitation under the 20 climate scenarios (MACA outputs), indicated that water availability may be sufficient to meet the water demand of loblolly pine plantations across the region. However, this does not consider other uses of precipitation, including ground water recharge and stream flow, or ecosystem services, which may be impaired if water use increases in loblolly pine stands in the Southeast in the future. Understanding the tradeoff between water use and productivity of intensively managed loblolly is important in the southeastern U.S. region where demand for water is increasing (Johnsen et al, 2014).

Across the four sites, for the baseline and end-of-century simulations under RCP 8.5, as stand age increased, predicted *ET* followed the pattern of stand development of LAI. Similar to our findings, Stoy et al. (2006) reported a strong biological control (LAI and canopy conductance) and climatic control of

ET for a mature loblolly pine stand in North Carolina. In young and old loblolly pine plantations at the same site at North Carolina, the old stand had little variation in annual *ET* while the young stand showed more variability over time, which was attributed to a stable LAI in the older stand and a developing LAI in the younger stand (Sun et al., 2010, Domec et al., 2012). Available latent energy is the principal driver of *ET* in the Southeast (Gholz and Clark, 2002; Stoy, et al. 2006). Hennessey et al. (1992) and Will et al. (2005) concluded that the climate pattern within the native range of loblolly pine exerts an influence on leaf area development, which affects radiation interception which, in turn, affects transpiration and wood production. Notably, *ET* was not affected by variation in annual precipitation in our simulations, indicating that there is, on average, adequate precipitation to meet the water use needs of loblolly pine plantations.

Our analyses indicated that in the future *AGB*, *VIB*, *BA*, *D*q, *LAI* and $E_{G,}$ will increase at the four locations under either RCP scenario. However the amount of increase will vary with climate. The model predictions indicate that cool sites will benefit more in the increased productivity than warm sites from future climate conditions. For the VA site, mortality was not altered under climate change conditions, and the model predicted substantial increases in growth at that site. Under RCP 8.5, the GA site was predicted to yield more wood than the OK site at the end-century period, and the FL would have higher mortality, but more volume in the remaining trees. These results suggest there will be differences in stand development in the future, at least in some parts of the region.

Understanding the tradeoff between water use and productivity is critical for modeling growth of intensively managed loblolly pine plantations in a region where demand for water is increasing (Johnsen et al, 2014). Overall, under both a moderate mitigation scenario and a business as usual scenario, all the sites will have an increase in the total amount of water consumed during the rotation. The expected increases under RCP 8.5 compared to Baseline scenario, are 14% at the FL site, 32% at the OK site, 50% at the GA site and 160% at the VA site. For the RCP 8.5 and end of century case, the stand established at the FL site was predicted to consume up to 100% more water than a stand established at the VA site, but because the increase in water use is so much greater at VA, OK and GA sites, the potential for future problems is greater at those sites than at the FL site.

For hotter and wetter sites in Southeast Brazil, Almeida et al. (2009) predicted (using 3-PG) that there would be an overall increase in *WUE* in short-rotation *Eucalyptus grandis x urophylla* plantations under climate change scenarios, which they attributed to decreases in stomatal conductance in response to increases in [CO_2]. Contradictory to our simulations, the authors suggested that those plantations will use the same amount of water, but produce more biomass, in climate change scenarios. Our simulations indicated that concomitant with increases in productivity, loblolly pine stands will also increase their water use. The stomata of loblolly pine and other gymnosperms have little, or no, response to [CO_2], which explains the difference between the results of Almeida et al. (2009) and those of our study. Although we predict that overall water use will increase in loblolly plantations, we also predict that *WUE* will often increase, and that the change in *WUE* will vary across the region. For example, our simulations predicted that the driest site of the four we studied (OK) will have the highest *WUE* among the four sites under both Baseline and future climate change scenarios, but no changes in this ratio are expected under future scenarios at that site. The sites with the lowest ET/Precipitation ratio (VA and GA) are predicted to have especially large increases in WUE.

Our model simulations are the most comprehensive to date because we used 20 MACA climate simulations which provided a comprehensive prediction of the future climate at each of the four sites. Using only one global climate model output (Hadley III) Huang et al. (2011) predicted a similar pattern of response for loblolly pine plantations in the region, i.e., a greater increase in growth in cooler portions of the species range. However, that modelling effort predicted a decrease in productivity in warmer portions of the range, which we did not predict. This was likely due to the use of the Hadley III global climate model in the Huang et al. (2011) study. That model predicts greater increases in temperature in the future compared to most global climate models. Wang et al. (2011) used the PnET-II model and outputs from 10 global climate models predicted for three IPCC climate scenarios, to predict forest growth in Louisiana.

They reported that growth would increase in two of the three scenarios examined. In agreement with our findings, they also concluded that net primary productivity was primarily a function of temperature and not precipitation.

2.5 CONCLUSIONS

Our study demonstrated that the 3-PG model has the ability of accurately predict water use across a wide range of sites, and in agreement with previous studies, we also found that 3-PG accurately predicted loblolly pine plantation productivity. This study was the first to use the 3-PG model to predict water use of loblolly pine plantations under future climate scenarios, or over entire rotations. This study indicates that productivity and water use will increase across the region, but that the increase will vary geographically. The highest increases will be in cooler sites, and smallest in warmer sites. The model also predicted that water use of loblolly pine would be primarily driven by LAI at all locations within the range. We conclude that 3-PG could be a useful tool for regional analysis and evaluation of effects of future climate scenarios on stand productivity across a wide range of loblolly pine sites.

Forest plantations in temperate regions are managed over time frames spanning decades. The 3-PG model allows analysis of water use and growth for entire rotations and multiple growth cycles under current and potential future climates, making in powerful tool for analyzing trends in growth and water use as the climate changes. The use of twenty global circulation models and two RCP scenarios in this study has provided the most robust prediction of future changes in growth and water use of loblolly pine plantations to date. Incorporating a large number of global circulation models into our simulations allowed us to constrain the variability in climate predictions. Our simulations indicate that climate change has the potential to increase water use and productivity under the scenario of a drastic reduction of human-related GHG emissions (RCP 4.5) as well as the scenario of a massive increase in GHG emissions (RCP 8.5).

We were encouraged by the model performance in estimating water use and productivity. Southern pine forests have a crucial role in regional water resources and carbon sequestration. The 3-PG model appears to be a potentially useful management tool for both regional and local assessments of wood production and water use in loblolly pine plantations.

FIGURES AND TABLES

Table 2.1. Summary of climate data for the four sites used for model validation. The values are 30-year averages of the U of Idaho Gridded Surface Meteorological Dataset. Abbreviations: Annual Preci, Annual Precipitation; Annual Temp, Annual Temperature; Min Temp, Minimum Temperature; Max Temp, Maximum Temperature; Min Rad, Minimum Radiation; Max Rad, Maximum Radiation. *Monthly Average for January; **Monthly Average for August.

State	County	Physiographic Regions	Latitude/Longitude	Elevation (m)	Annual Preci. (mm)	Annual Temp. (°C)	*Min Temp. (°C)	**Max Temp. (°C)	*Min Rad (MJ m^{-2} day^{-1})	**Max Rad (MJ m^{-2} day^{-1})	Number of Frost Days
Florida	Taylor	South Coastal Plain	30°12′ N 83°52′ W	13.7	1443	20.22	4.37	33.47	10.827	24.582	22
Georgia	Taliaferro	Piedmont	33°37 N 82°47′ W	150.0	1149	16.95	0.16	33.06	9.320	24.497	56
Oklahoma	McCurtain	Upper Coastal Plain	34°01′ N 94°49′ W	125.0	1305	16.93	-0.96	34.54	8.686	24.720	62
Virginia	Buckingham	Piedmont	37°27′ N 78°39′ W	125.0	1114	13.59	-3.79	31.51	7.893	23.441	98

Table 2.2. Summary of site-specific and stand initialization data used for model validation and simulations. Symbols: SD, Stand Density (trees ha^{1}); SI_{25}, Site Index at base age = 25 years; FR, Fertility rating; [CO_2], average atmospheric carbon dioxide concentration in air; Max ASW, Maximum available soil water in upper 1m soil layer; Min ASW, Minimum available soil water in upper 1m soil layer; WFi, Initial foliage biomass (ton ha^{-1}); WSi, Initial stem biomass; WRi, Initial root biomass. Values in parenthesis represent standard error of the mean; * indicates measured in November 2015; ** indicates estimated using the equations in Gonzalez-Benecke et al. (2015).

State	Date Planted	Stand Age*	SD* (trees ha^{1})	SI_{25} (m)	FR**	Soil Texture	[CO_2] µmol mol-1	Max ASW (mm)	Min ASW (mm)	WFi** (tons ha^{-1})	WSi** (tons ha^{-1})	WRi** (tons ha^{-1})
Florida	2003/12	12	1720 (15.2)	26.5	0.76	Fine Sand	386.78	240	80	6.05(0.1)	60.50(0.8)	13.96(0.2)
Georgia	2006/1	9.8	1380 (61.1)	23.2	0.65	Clay Loam	388.82	600	300	3.34(0.12)	13.98 (1.85)	3.65(0.45)
Oklahoma	2008/1	7.8	1610 (24.8)	23.4*	0.53	Fine Sandy Loam	390.81	600	300	4.20(0.05)	28.53 (0.1)	6.27(0.03)
Virginia	2003/3	12.7	790 (16.4)	20.9	0.57	Silty Clay Loam	385.78	460	200	3.61(0.04)	7.87(0.44)	2.08(0.1)

Table 2.3. Summary of the annual mean air temperature, precipitation and number of frost days predicted from 20 Global Climate Models for the study sites located in Florida (FL), Georgia (GA), Oklahoma (OK) and Virginia (VA). The data were downscaled using MACA for a past Baseline period and two future time periods. For future projections, two Representative Concentration Pathways (RCP), 4.5 and 8.5, were used. Values in parenthesis indicate the standard error for the 20 climate model weather simulations (MACA).

Climate variable	**FL**		**GA**		**OK**		**VA**	
Temperature								
Baseline								
1950-2004	20.10	(0.34)	16.94	(0.36)	16.96	(0.39)	13.81	(0.38)
RCP 4.5								
2043 - 2067	21.81	(0.37)	18.83	(0.40)	19.08	(0.43)	15.90	(0.43)
2074 - 2098	22.21	(0.38)	19.28	(0.41)	19.59	(0.45)	16.36	(0.44)
RCP 8.5								
2043 - 2067	22.44	(0.39)	19.50	(0.42)	19.84	(0.44)	16.62	(0.44)
2074 - 2098	24.10	(0.43)	21.34	(0.47)	21.88	(0.49)	18.51	(0.48)
Precipitation								
Baseline								
1950-2004	1431	(61.14)	1168	(44.59)	1268	(55.98)	1103	(32.36)
RCP 4.5								
2043 - 2067	1451	(65.14)	1200	(48.92)	1271	(66.08)	1154	(40.68)
2074 - 2098	1494	(67.89)	1228	(48.07)	1263	(63.60)	1169	(38.16)
RCP 8.5								
2043 - 2067	1469	(65.51)	1235	(46.45)	1273	(64.11)	1173	(39.74)
2074 - 2098	1431	(70.57)	1234	(53.94)	1223	(65.64)	1203	(42.74)
Frost Days								
Baseline								
1950-2004	22	(1.88)	54	(2.65)	62	(2.36)	95	(2.75)
RCP 4.5								
2043 - 2067	15	(1.52)	37	(2.42)	43	(2.32)	72	(3.19)
2074 - 2098	12	(1.58)	33	(2.52)	40	(2.39)	67	(3.31)
RCP 8.5								
2043 - 2067	12	(1.46)	32	(2.66)	37	(2.56)	65	(3.43)
2074 - 2098	7	(1.25)	22	(2.55)	24	(2.56)	47	(3.61)

Table 2.4. Comparisons between mean observed, or measured, value ($\overline{O}$) and the mean predicted from the 3-PG model ($\overline{P}$) for four sites. Variables compared were: AGB, above-ground biomass (t ha^{-1}); VIB, stand bole volume inside bark (m^3 ha^{-1}); BA, stand basal area (m^2 ha^{-1}); Dq, quadratic mean diameter (cm); LAI, mean projected leaf area index (m^2 m^{-2}); E_G, Annual transpiration (mm H_2O). Other symbols: n is number of observations; RMSE is root of mean square error (same unit as observed value); Bias is absolute bias (observed - predicted; same unit as observed value); MAE is Mean absolute error; R2 is coefficient of determination. Values in parenthesis are percentages relative to observed mean. Measurements not available indicated by (-).

Variable	Location	$\overline{O}$	$\overline{P}$	*n*	RMSE	Bias	MAE	R^2
AGB	FL	95.5	93.9	64	5.05 (5.3)	1.6 (1.7)	3.84	0.96
	GA	30.1	36.32	64	8.72 (28.9)	-6.23 (-20.7)	7.55	0.84
	VA	39.73	40.64	64	5.51 (13.8)	0.9 (2.28)	4.81	0.86
	OK	18.71	20.81	48	2.45 (13.08)	-2.04 (-10.9)	2.28	0.98
VIB	FL	133.5	149.23	64	17.19 (12.8)	-15.63 (-11.7)	15.65	0.96
	GA	46.99	53.64	64	12.19 (25.9)	-6.65 (-14.1)	10.13	0.84
	VA	66.62	63.77	64	11.08 (16.6)	4.44 (6.51)	8.87	0.86
	OK	27.43	28.17	48	5.38 (19.62)	-0.72 (2.65)	3.96	0.91
BA	FL	28.38	30.22	64	2.35 (8.3)	-1.83 (-6.4)	1.88	0.91
	GA	14.87	14.26	64	2.28 (15.3)	0.61 (4.1)	1.64	0.81
	VA	17.86	14.80	64	4.30 (31.1)	3.05 (17.1)	3.054	0.84
	OK	12.60	9.37	48	3.72 (20.9)	3.23 (25.5)	3.29	0.90
Dq	FL	14.3	15.0	64	1.0 (7.0)	-0.83 (-5.82)	0.84	0.83
	GA	11.4	11.45	64	0.8 (7.0)	-0.04 (-0.33)	0.63	0.90
	VA	16.99	15.63	64	1.67 (9.8)	1.36 (8.01)	1.03	0.82
	OK	9.56	8.55	48	1.31 (13.8)	1.01 (10.54)	1.39	0.68
LAI	FL	3.58	3.67	4	0.4 (16.5)	0.06 (2.3)	0.31	0.59
	GA	2.64	2.44	32	0.58 (21.9)	-0.19 (-7.2)	0.45	0.21
	VA	2.33	1.61	12	0.81 (34.7)	-0.72 (-30.1)	0.72	0.22
	OK	-	-	-	-	-	-	-
E_G	FL	-	-	-	-	-	-	-
	GA	605.89	602.45	16	164.9 (27.2)	3.45 (0.56)	128.4	0.52
	VA	321.23	383.15	4	73.83 (22.9)	-61.9 (-19.3)	61.90	0.39
	OK	351.56	396.3	32	90.16 (25.6)	-44.7 (-11.9)	81.73	0.23

Table 2.5. Summary of model predictions for four sites for baseline and different scenarios for the 25th year of a rotation. Abbreviations and symbols are: *AGB*, above-ground biomass (t ha^{-1}); *VIB*, mean bole volume inside bark (m^3 ha^{-1}); *Mortality*, Accumulated mortality for one rotation (trees ha^{-1}); *BA*, stand basal area (m^2 ha^{-1}); *D*q, quadratic mean diameter (cm); *LAI*, mean projected leaf area index (m^2 m^{-2}); *T*, annual transpiration (mm of H_2O y^{-1}); *WUE*, water use efficiency (*AGB/T*); Base, Baseline period. The second column in each simulation period corresponds to the total change in the predicted value compared to the Baseline period. * indicates that no difference in mortality from the Baseline prediction was expected for VA site. Different letters denote significant difference (p=0.05) within each site.

Variable	Site	Base	Period 2043 - 2067				Period 2074 - 2098			
			4.5		8.5		4.5		8.5	
AGB	FL	256.9 ^{a}	270.1 ^{c}	+13.2	272.7 ^{c}	+15.8	272.5 ^{c}	+15.6	273.7 ^{c}	+16.8
	GA	171.2 ^{a}	195.8 ^{b}	+24.6	222.0 $^{c\,d}$	+50.8	218.9 ^{c}	+47.7	229.9 ^{d}	+58.7
	OK	178.0 ^{a}	213.9 ^{b}	+35.9	219.3 ^{b}	+41.3	217.5 ^{b}	+39.6	218.2 ^{b}	+40.2
	VA	58.8 ^{a}	109.2 ^{b}	+50.6	124.7 ^{d}	+66.3	118.9 ^{c}	+60.2	149.7 ^{e}	+91.7
VIB	FL	405.8 ^{a}	426.7 ^{b}	+20.9	430.7 ^{c}	+24.8	430.2 ^{c}	+24.4	432.6 ^{c}	+26.8
	GA	270.5 ^{a}	305.6 ^{b}	+35.1	351.3 ^{cd}	+80.9	346.4 ^{c}	+75.9	364.1 ^{d}	+93.7
	OK	281.5 ^{a}	338.9 ^{b}	+57.4	347.5 ^{b}	+65.9	344.5 ^{b}	+63.0	345.9 ^{b}	+64.4
	VA	91.7 ^{a}	171.8 ^{b}	+80.3	196.4 ^{d}	+105.2	187.3 ^{c}	+95.5	236.4 ^{e}	+145.9
Mortality	FL	775.0^{a}	930.4^{b}	+155.40	953.5^{c}	+178.50	952.3^{c}	+177.30	953.3 ^{c}	+178.30
	GA	379.5^{a}	410.5^{a}	+31.00	487.8^{b}	+108.30	474.5^{b}	+95.00	525.2 ^{c}	+145.70
	OK	379.0^{a}	394.5^{b}	+15.50	426.4^{d}	+47.40	410.4^{c}	+31.40	467.3 ^{e}	+88.30
	VA*	189.5	-	-	-	-	-	-	-	-
BA	FL	46.8 ^{a}	43.9 ^{b}	-2.9	43.4 ^{b}	-3.4	43.4 ^{b}	- 3.3	43.2 ^{b}	- 3.6
	GA	42.7 ^{a}	47.5 ^{b}	+4.8	48.0 ^{b}	+5.3	47.8 ^{b}	+5.1	48.3 ^{b}	+5.6
	OK	43.6 ^{a}	48.2 ^{b}	+4.7	48.4 ^{b}	+4.8	48.4 ^{b}	+4.9	47.5 ^{b}	+3.9
	VA	22.4 ^{a}	32.8 ^{b}	+8.9	35.6 ^{d}	+11.1	34.6 ^{c}	+10.3	39.7 ^{e}	+14.6
***D*q**	FL	30.9 ^{a}	34.6 ^{b}	+3.7	35.4 ^{cd}	+4.4	35.3 ^{c}	+4.3	35.8 ^{d}	+4.8
	GA	23.0 ^{a}	25.5 ^{b}	+2.5	26.2 ^{c}	+3.2	25.9 $^{d\,c}$	+2.9	27.0 ^{d}	+3.9
	OK	23.2 ^{a}	24.6 ^{b}	+1.4	25.1 ^{c}	+1.9	24.9 ^{c}	+1.7	25.5 ^{c}	+2.3
	VA	16.7 ^{a}	20.2 ^{b}	+4.9	21.0 ^{d}	+6.0	20.7 ^{c}	+5.6	22.2 ^{e}	+7.6
LAI	FL	3.2 ^{a}	3.39 ^{c}	+0.19	3.44 $^{d\,c}$	+0.24	3.48 ^{d}	+0.28	3.31 ^{b}	+0.11
	GA	2.16 ^{a}	2.36 ^{b}	+0.2	2.61 ^{c}	+0.45	2.61 ^{c}	+0.45	2.60 ^{c}	+0.44
	OK	2.15 ^{a}	2.41 ^{b}	+0.26	2.47 ^{b}	+0.32	2.52 ^{b}	+0.37	2.40 ^{b}	+0.25
	VA	1.10 ^{a}	1.59 ^{b}	+0.55	1.74 ^{d}	+0.7	1.68 ^{c}	+0.64	1.89 ^{e}	+0.85
E_G	FL	846.8 ^{a}	861.6 ^{b}	+14.8	892.6 ^{dc}	+45.8	870.6 ^{bc}	+23.9	882.2 ^{d}	+35.4
	GA	597.7 ^{a}	728.4 ^{b}	+130.7	745.2 ^{b}	+147.5	733.5 ^{b}	+135.7	769.9 ^{c}	+172.2
	OK	600.9 ^{a}	687.2 $^{a\,b}$	+86.4	708.9 ^{b}	+108.0	717.0 ^{b}	+116.1	719.7 ^{b}	+118.8
	VA	283.9 ^{a}	442.2 ^{b}	+164.0	491.9 ^{d}	+213.7	471.5 ^{c}	+193.4	556.7 ^{e}	+277.6
WUE	FL	0.302 ^{a}	0.313 ^{a}	+0.011	0.312 ^{a}	+0.010	0.304 ^{a}	+0.002	0.310 ^{a}	+0.008
	GA	0.255 ^{a}	0.266 ^{ab}	-	0.280 ^{bc}	+0.026	0.279 ^{b}	+0.024	0.288 ^{bc}	+0.033
	OK	0.304 ^{a}	0.328 ^{a}	+0.024	0.322 ^{a}	+0.018	0.312 ^{a}	+0.008	0.322 ^{a}	+0.018
	VA	0.208 ^{a}	0.247 ^{b}	+0.039	0.252 ^{b}	+0.044	0.254 ^{b}	+0.046	0.269 ^{c}	+0.061

Table 2.6. Precipitation and evapotranspiration simulated for either the 25th year of a rotation (*) or summed for the whole rotation length (25 years) in four sites under Baseline and climate change conditions (RCP 4.5 and 8.5). Abbreviations are: Prec, Annual Precipitation (mm H_20 y^{-1}); T, Annual Transpiration (mm H_20 y^{-1}); ET, Annual Evapotranspiration (mm H_20 y^{-1}); ET/P, Ratio of evapotranspiration to precipitation; ∑ET, total evapotranspiration for a whole rotation; ∑Prec, total precipitation for a whole rotation.

Site	Period	RCP	Prec.	T	ET	ET/P	∑ ET	∑ Prec.
FL	1980 - 2004	Baseline	1476	846	1031	0.70	19678	35775
	2043 - 2067	4.5	1449	861	1055	0.73	21665	36280
	2043 - 2067	8.5	1613	892	1108	0.69	22048	36739
	2074 - 2098	4.5	1523	870	1079	0.71	22089	37357
	2074 - 2098	8.5	1378	882	1075	0.78	22454	35777
GA	1980 - 2004	Baseline	1213	598	700	0.58	11520	29269
	2043 - 2067	4.5	1188	728	819	0.69	13554	30069
	2043 - 2067	8.5	1269	745	886	0.70	16020	31011
	2074 - 2098	4.5	1263	733	870	0.69	15622	30739
	2074 - 2098	8.5	1217	770	893	0.73	17246	30912
OK	1980 - 2004	Baseline	1194	600	754	0.63	12180	31819
	2043 - 2067	4.5	1232	687	852	0.69	14955	31726
	2043 - 2067	8.5	1326	708	887	0.67	15558	31947
	2074 - 2098	4.5	1192	717	895	0.75	15369	31469
	2074 - 2098	8.5	1159	720	897	0.77	16150	30593
VA	1980 - 2004	Baseline	1100	241	349	0.32	4310	27596
	2043 - 2067	4.5	1133	405	535	0.47	7955	28961
	2043 - 2067	8.5	1232	455	595	0.48	9156	29440
	2074 - 2098	4.5	1194	434	572	0.48	8663	29316
	2074 - 2098	8.5	1164	519	670	0.58	11239	30142

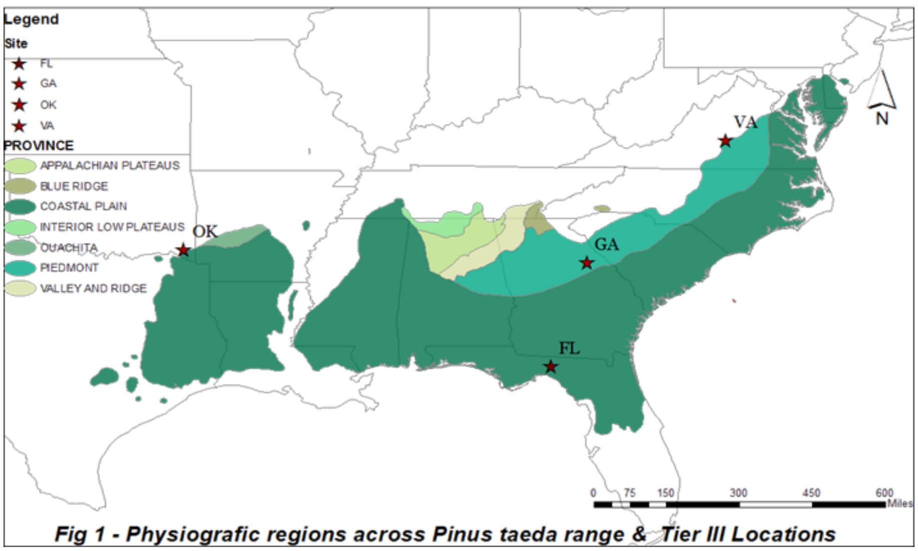
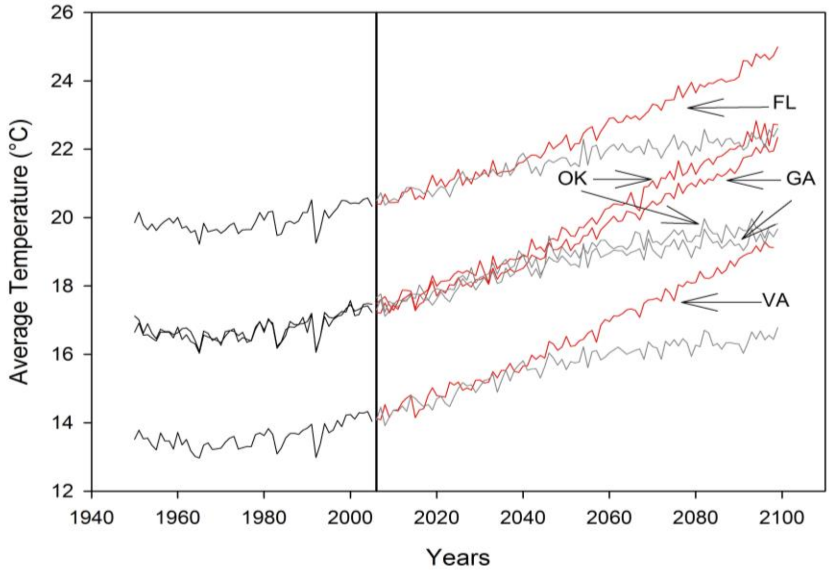


Figure 2.1. Locations of the Tier III sites (red star) across the loblolly pine native range (green shaded area) and the respective physiographic division of the Southeast U.S. (scale color).



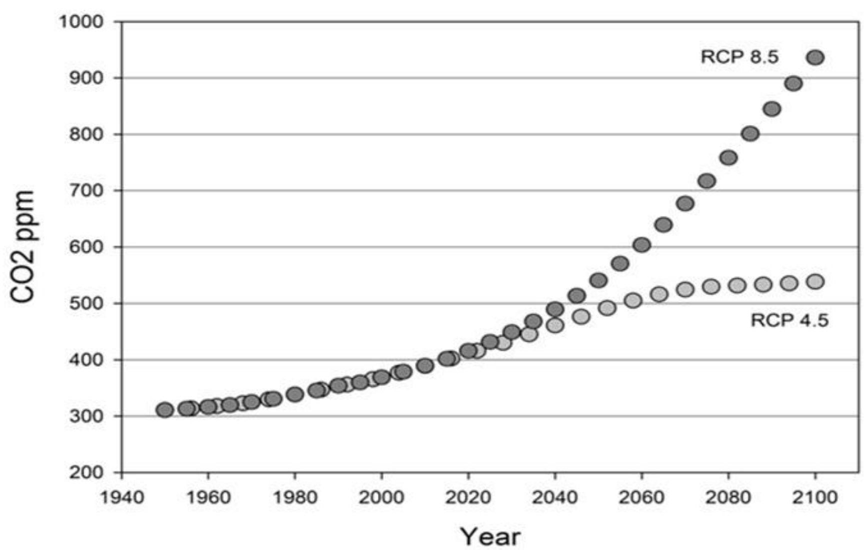


Figure 2.2. Upper graph: Observed and expected average annual air temperature at the four Tier III sites for two Representative Concentration Scenarios (RCPs) 4.5 (grey line) and 8.5 (red line) with the vertical line representing the end of baseline period (2004). Lower graph: Observed and expected atmospheric carbon dioxide concentration (CO_2) for the two representative concentration pathway scenarios, RCP 4.5 and RCP 8.5.

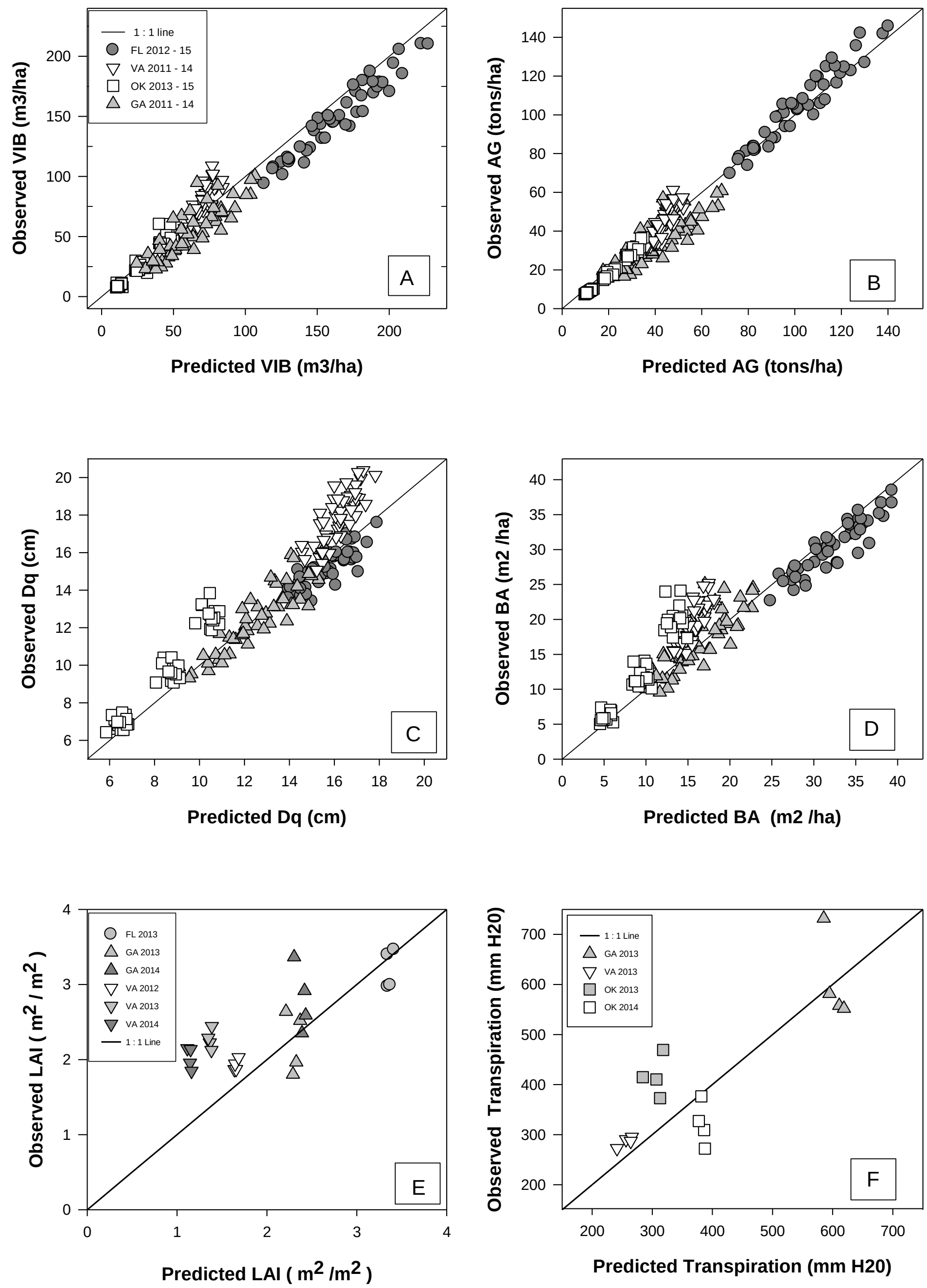


Figure 2.3. Model validation using data from the four Tier III sites. Predicted (simulated by 3-PG) versus observed values of A) quadratic mean diameter (Dq); B) stand basal area (BA); C) volume inside bark (VIB); D) aboveground biomass (AGB); E) peak leaf area index (LAI); F) transpiration. Symbols shown in Figures A, B, C, D, represent the four replications of the four treatments imposed on each of the four sites (16 symbols per year). Symbols shown in Figure E and F represent the average of the four replicates for each of the treatments at each site.

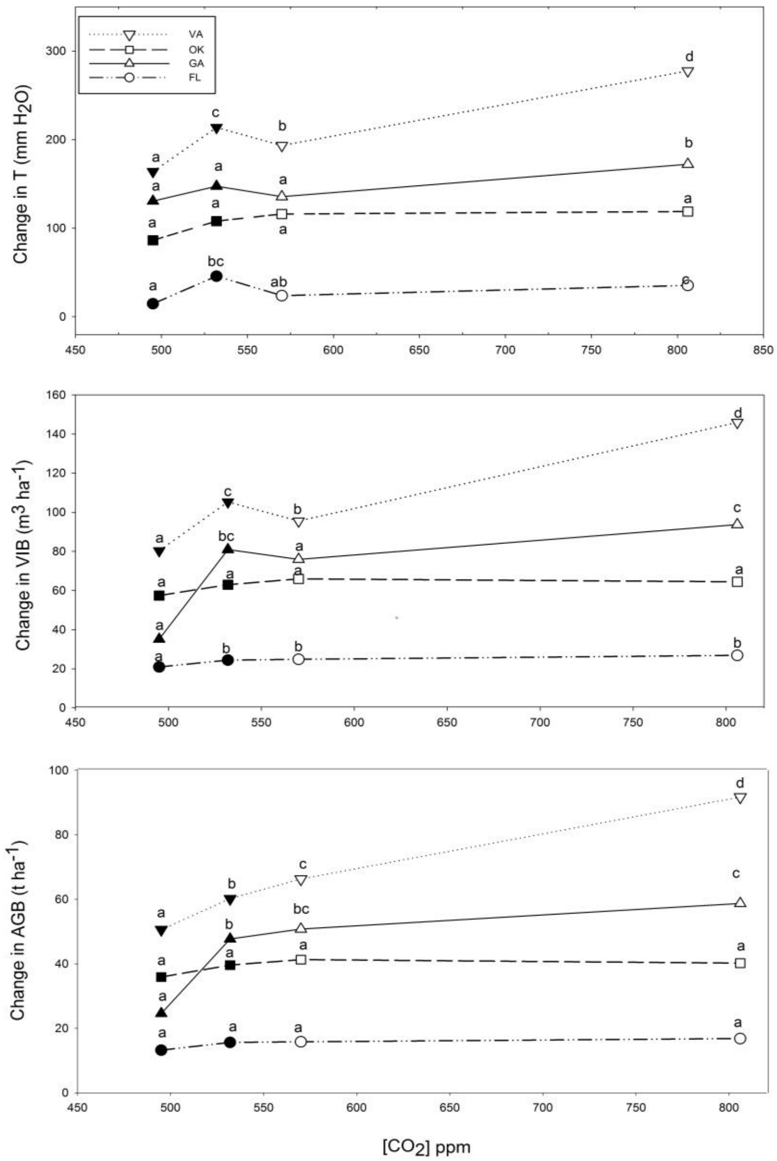


Figure 2.4. Change in canopy transpiration (T), Stand Volume Inside Bark (VIB) and Aboveground biomass (AGB) plotted against the mean carbon dioxide concentration ($[CO_2]$) expected in the two future simulation periods (2043-2067, 2074-2098) compared with baseline period (1980-2004) for each RCP (4.5, filled symbol and 8.5, open symbol) at the four sites, Virginia (inverted triangle), Oklahoma (square), Georgia (triangle) and Florida (circle). Different letters denote statistical significance (p=0.05).

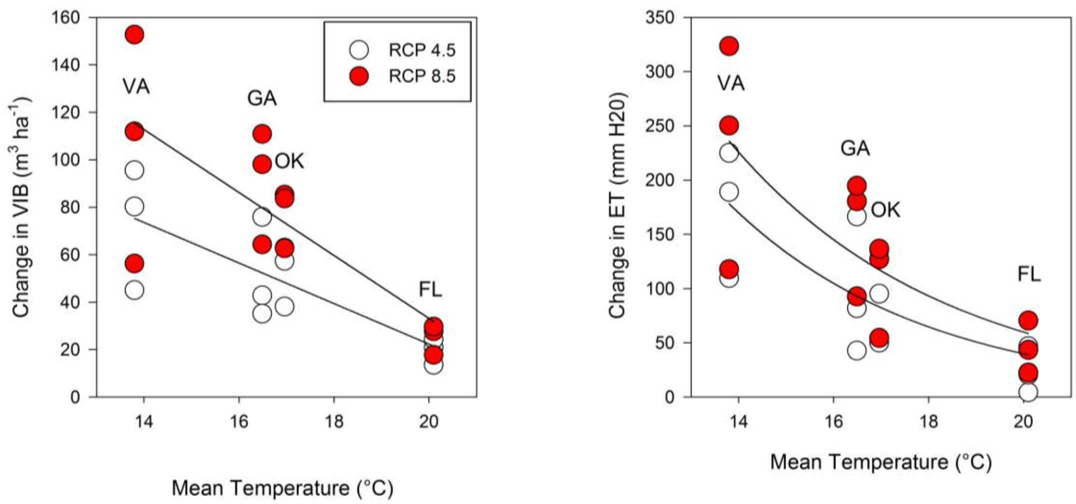


Figure 2.5. Change in evapotranspiration (ET) and in Stand Volume Inside Bark (VIB) at year 2098 compared to year 2004 for two Radiative Concentration Pathways (4.5, open dot and 8.5, red dot) compared with the mean annual temperature of the Baseline period.

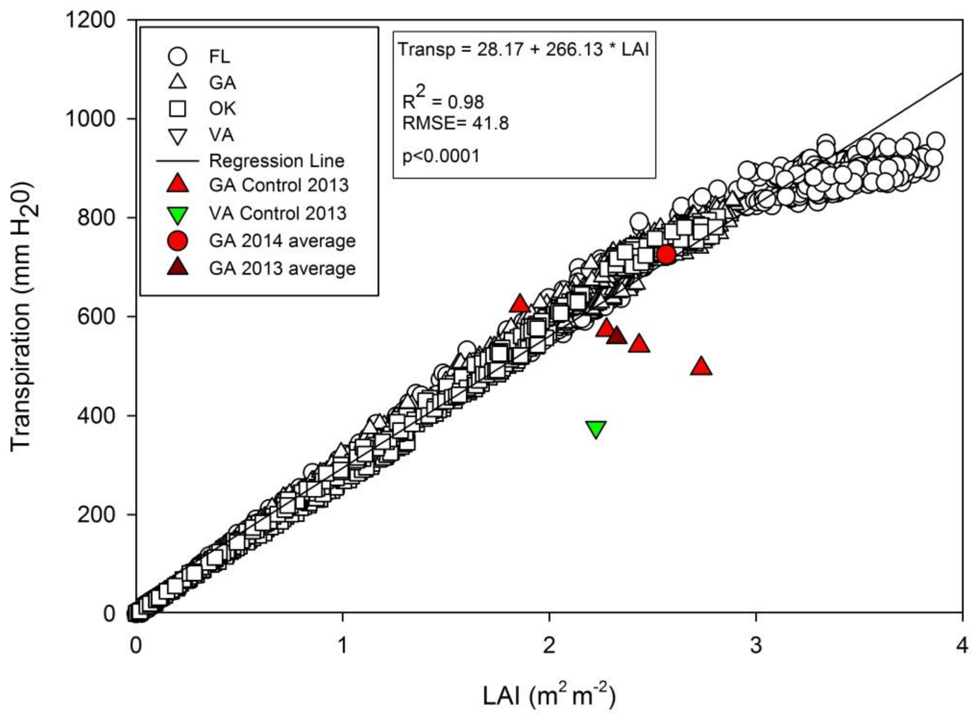


Figure 2.6. The predicted relationship between leaf area index (LAI) and transpiration for the four sites, for the Baseline and RCP 4.5 and 8.5 scenarios for each year of the three simulation time periods used in this study:1980 to 2004, 2043 to 2067 and 2074 to 2098 (unfilled symbols). Colored symbols represent measured values from Control plots at the GA and VA sites as well as the average transpiration from all four treatments at the GA site.

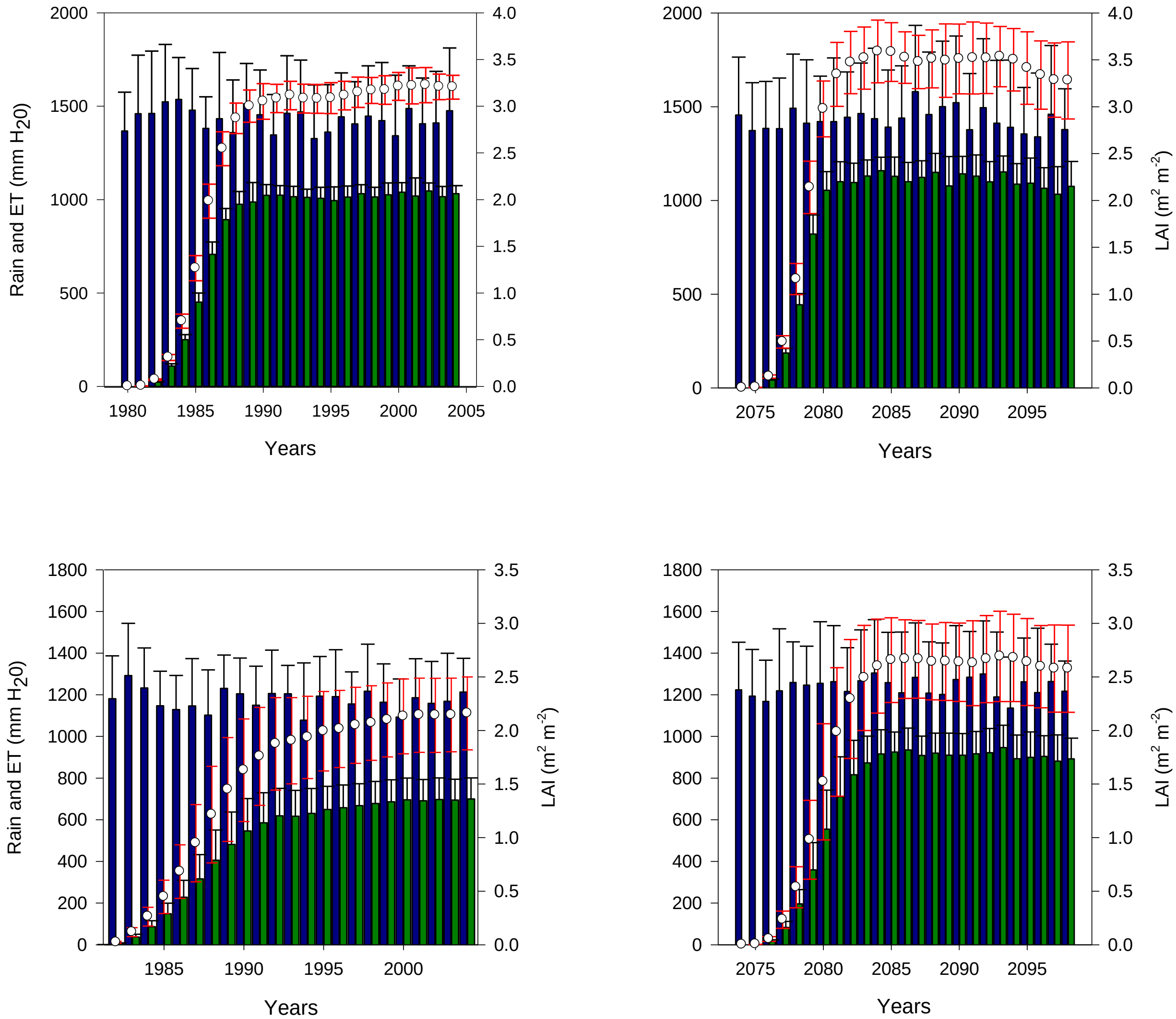


Figure 2.7. A comparison of leaf area index (LAI, triangle), evapotranspiration (ET, grey bar) and rainfall (Rain, black bar) for the FL (upper) and GA (lower) sites, simulated for each year of the Baseline (1980-2004, left) and at the end of the century (2074-2098, right), for the RCP 8.5 scenario. Error bars represent the standard deviation (1± SD).

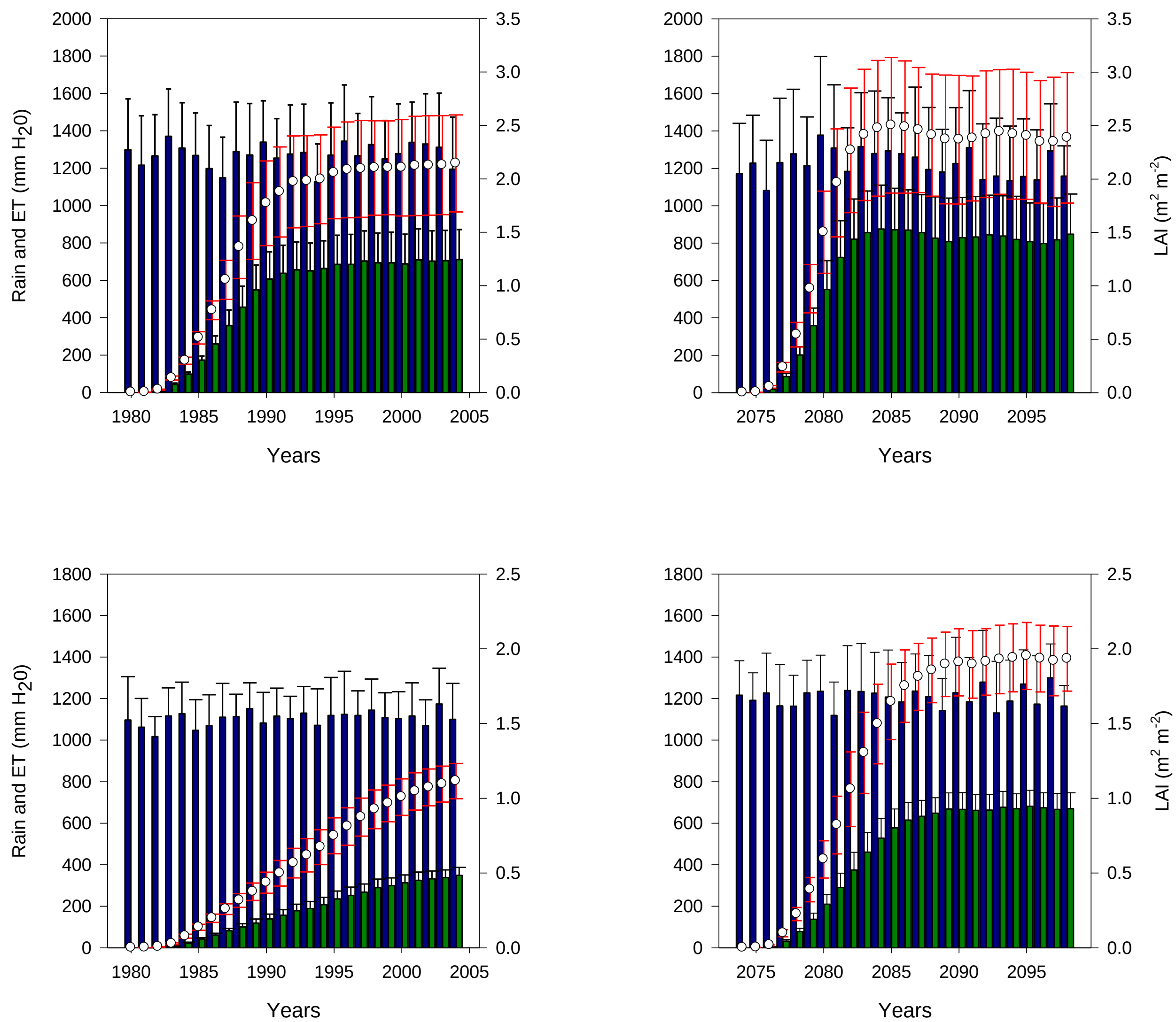


Figure 2.8. A comparison of leaf area index (LAI, triangle), evapotranspiration (ET, grey bar) and rainfall (Rain, black bar) for the OK (upper) and VA (lower) sites, simulated for each year of the Baseline (1980-2004, left) and at the end of the century (2074-2098, right), for the RCP 8.5 scenario. Error bars represent the standard deviation (1± SD).

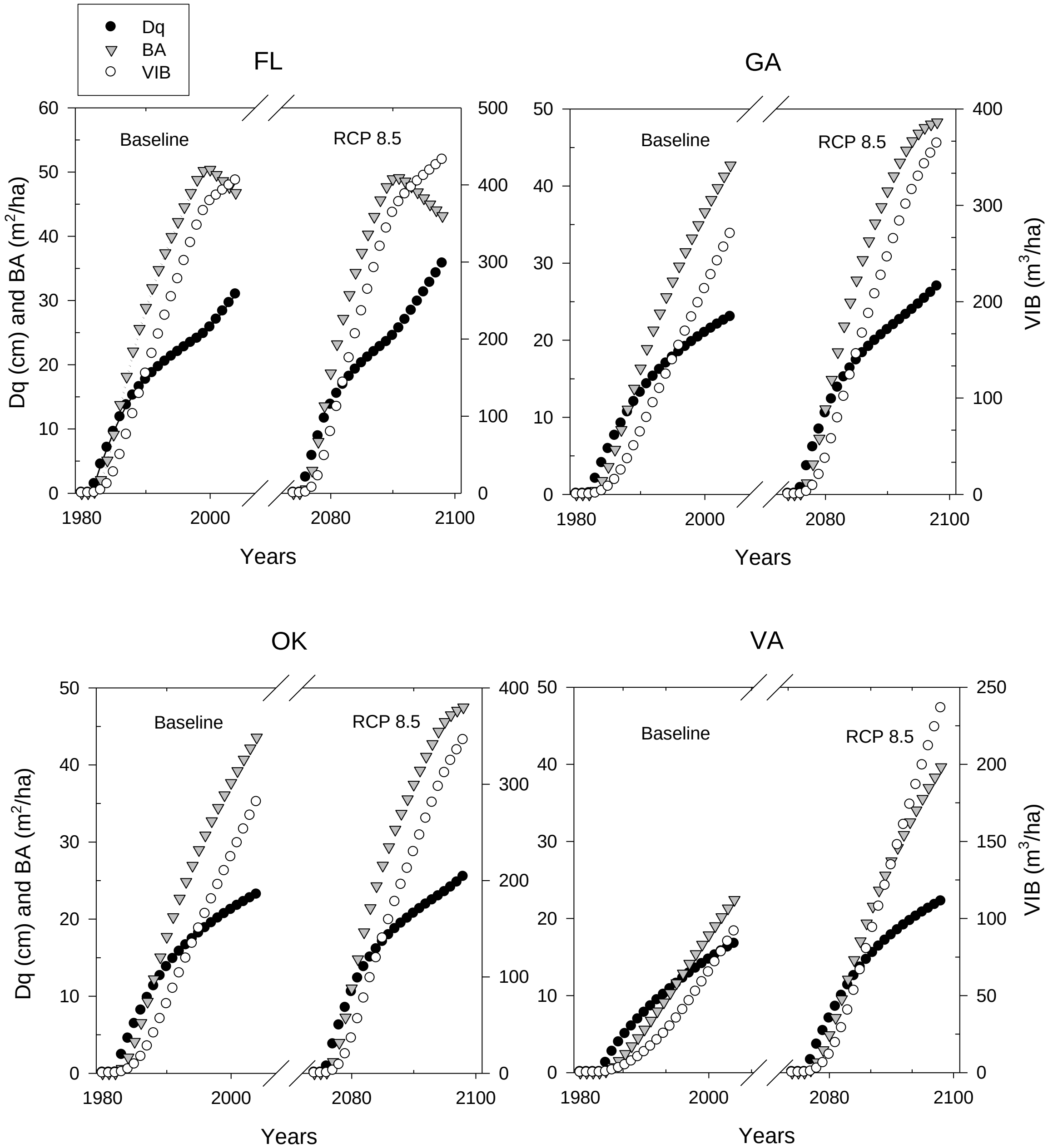


Figure 2.9. A comparison of the stand dynamics over a 25 year rotation, for the Baseline (1980 -2004) and a future period (2074-2098) under RCP 8.5 for the four sites in GA, OK, FL and VA. Quadratic mean diameter (Dq, open circle), basal area (BA, inverted triangle) and Stand Volume Inside Bark (VIB, filled circle).

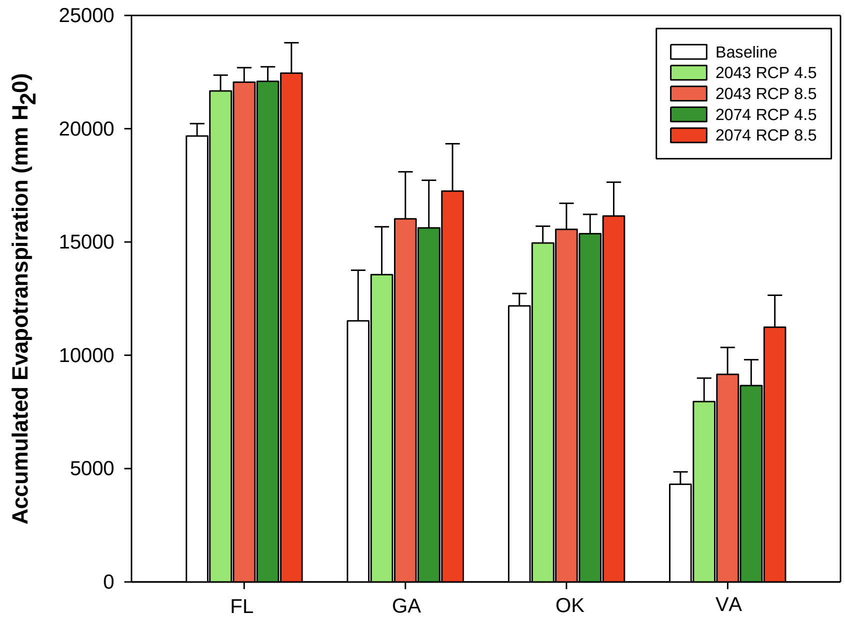


Figure 2.10. A comparison of total water use for the entire rotation (ET summed for all years) for the Baseline (base) (1980-2004) and RCP 4.5 and 8.5 scenarios at the end of century (2074-2098).

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APPENDICES

Appendix A. Description of the 3-PG parameters and values that were used in this study.

Meaning / Comment	3-PG symbol	Unit	Value	Sources
Biomass partitioning and turnover				
Allometric relationships & partitioning				
Constant in the Foliage:stem partitioning ratio relationship	pFSC	-	0.406	
Power of Age in the Foliage: stem partitioning ratio relationship	pFSAge	-	0.311	1
Power of Dq in the Foliage:stem partitioning ratio relationship	pFSD	-	-0.288	1
Intercept in the Dq v. stem mass relationship	a11Ws	-	-3.707*	1
Constant in the Dq v. stem mass relationship	a1Ws	-	54.449*	1
Power in the Dq v. stem mass relationship	n1Ws	-	0.253*	1
Power of Age in the Dq v. stem mass relationship	n2Ws	-	0.037*	1
Power of Nha in the Dq v. stem mass relationship	n3Ws	-	-0.306*	1
Maximum fraction of NPP to roots	pRx	-	0.40	2
Minimum fraction of NPP to roots	pRn	-	0.20	2
Needlefall, litterfall, litter decay & root turnover				
Maximum needlefall rate	γFx	month^{-1}	0.157	1
Month at which needlefall rate has maximum value	tγFx		11	1
Average yearly decay rate of litter		year^{-1}	0.15	1
Needlefall to litterfall ratio at age 0	NF_0	-	0.733	1
Needlefall to litterfall ratio for mature stands	NF_1	-	1.0	1
Age at which Needlefall to litterfall ratio = (□0+□□1)/2	Age_{NLR}	year	21.5	1
Average monthly root turnover rate	γR	month^{-1}	0.0168	2
NPP & conductance modifiers				
Temperature modifier (fT)				
Minimum temperature for growth	Tmin	ºC	4	2
Optimum temperature for growth	Topt	ºC	25	2
Maximum temperature for growth	Tmax	ºC	38	2
Frost modifier (fFrost)				
Days production lost per degree celcius below zero on frost day	kF	Day	0.178	1
Soil water modifier (fSW)				
Moisture ratio deficit for fq = 0.5	SWconst	-	0.7	2
Power of moisture ratio deficit	SWpower	-	9	2
Fertility effects				
Value of 'm' when FR = 0	m0	-	0	3
Value of 'fNutr' when FR = 0	fN0	-	0.3	3
Power of (1-FR) in 'fNutr'	fNn	-	1	3
Age modifier (fAge)				
Maximum stand age used in age modifier	MaxAge	year	200	4
Power of relative age in function for fAge	nAge	-	1.5	4
Relative age to give fAge = 0.5	rAge	-	0.5	4
Stem mortality & self-thinning				
Mortality rate for large t	γNx	%/year	0.392	1
Seedling mortality rate (t = 0)	γN0	%/year	2.320	1
Age at which mortality rate has median value	tγN	year	10.853	1
Shape of mortality response	nγN	-	1	1
Max. stem mass per tree @ 1000 trees/hectare	wSx1000	kg tree^{-1}	230	1

Power in self-thinning rule	thinPower	-	1.174	1
Fraction mean single-tree foliage biomass lost per dead tree	mF	-	0	2
Fraction mean single-tree root biomass lost per dead tree	mR	-	0.2	2
Fraction mean single-tree stem biomass lost per dead tree	mS	-	0.4	2
Canopy structure and processes				
Specific needle area (σ)				
Specific needle area at age 0	σ0	$m^2\ kg^{-1}$	5.529	1
Specific leaf area for mature leaves	σ1	$m^2\ kg^{-1}$	3.875	1
Age at which specific needle area = (σ0+σ1)/2	tσ	year	5.971	1
Light interception				
Extinction coefficient for absorption of PAR by canopy	k	-	0.57	2
Constant in the CanCover relationship	aCan	-	0.258	1
Power of BA in the CanCover relationship	nCanBA	-	0.688	1
Power of Age in the CanCover relationship	nCanAge	-	-0.198	1
Maximum proportion of rainfall evaporated from canopy	MaxIntcptn	-	0.2	2
LAI for maximum rainfall interception	LAImaxIntcptn	-	5	2
Production and respiration				
Canopy quantum efficiency	α_c	molC $molPAR^{-1}$	0.053	4
Ratio NPP/GPP	Y	-	0.47	2
Canopy Conductance (gc)				
Minimum canopy conductance	MinCond	$m\ s^{-1}$	0	3
Maximum canopy conductance	MaxCond	$m\ s^{-1}$	0.0118	1
LAI for maximum canopy conductance	LAIgcx	-	3	2
Defines stomatal response to VPD	CoeffCond	mb^{-1}	0.0408	1
Canopy boundary layer conductance	BLcond	$m\ s^{-1}$	0.1	2
Wood and stand properties				
Branch and bark fraction (pBB)				
Branch and bark fraction at age 0	pBB0	-	1.198	1
Branch and bark fraction for mature stands	pBB1	-	0.235	1
Age at which pBB = (pBB0+pBB1)/2	tBB	year	1.737	1
Wood basic specific gravity				
Minimum basic density - for young trees	ρ0	-	0.358 **	1
Maximum basic density - for older trees	ρ1	-	0.482 **	1
Age at which rho = (rhoMin+rhoMax)/2	tRho	year	7.054 **	1
Stem height				
Constant in the Dq v. height relationship	aH	-	0.230 ***	1
Power of Dq in the Dq v. height relationship	nHD	-	0.91 ***	1
Power of Age in the Dq v. height relationship	nHAge	-	0.261 ***	1
Power of Nha in the Dq v. height relationship	nHN	-	0.110 ***	1
Volume Ratio				
Constant in the bole volume ratio relationship	aVR	-	1.232	1
Power of VIB in the bole volume ratio relationship	nVRVi	-	-0.017	1
Power of Nha in the bole volume ratio relationship	nVRN	-	0.025	1
Power of Age in the bole volume ratio relationship	nVRAge	-	-0.030	1

References: 1: Gonzalez-Benecke et al, 2015; 2: Bryars et al. 2013; 3: Gonzalez-Benecke et al., 2014a; 4: Sampson et al., 2001.

Appendix B: List of the global climate models used in this study.

Model Name	Country of Origin	Developing Agency
bcc-csm1-1	China	Beijing Climate Center, China Meteorological Administration
bcc-csm1-1-m	China	Beijing Climate Center, China Meteorological Administration
BNU-ESM	China	College of Global Change and Earth System Science, Beijing Normal University, China
CanESM2	Canada	Canadian Centre for Climate Modeling and Analysis
CCSM4	USA	National Center of Atmospheric Research, USA
CNRM-CM5	France	National Centre of Meteorological Research, France
CSIRO-Mk3-6-0	Australia	Commonwealth Scientific and Industrial Research Organization/Queensland Climate Change Centre of Excellence, Australia
GFDL-ESM2M	USA	NOAA Geophysical Fluid Dynamics Laboratory, USA
GFDL-ESM2G	USA	NOAA Geophysical Fluid Dynamics Laboratory, USA
HadGEM2-ES	United Kingdom	Met Office Hadley Center, UK
HadGEM2-CC	United Kingdom	Met Office Hadley Center, UK
inmcm4	Russia	Institute for Numerical Mathematics, Russia
IPSL-CM5A-LR	France	Institut Pierre Simon Laplace, France
IPSL-CM5A-MR	France	Institut Pierre Simon Laplace, France
IPSL-CM5B-LR	France	Institut Pierre Simon Laplace, France
MIROC5	Japan	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies,and Japan Agency for Marine-Earth Science and Technology
MIROC-ESM	Japan	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies
MIROC-ESM-CHEM	Japan	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies
MRI-CGCM3	Japan	Meteorological Research Institute, Japan
NorESM1-M	Norway	Norwegian Climate Center, Norway