Projecting Climate Change Effects on Forest Net Primary Productivity in Subtropical Louisiana, USA

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Abstract This study projected responses of forest net primary productivity (NPP) to three climate change scenarios at a resolution of 5 km × 5 km across the state of Louisiana, USA. In addition, we assessed uncertainties associated with the NPP projection at the grid and state levels. Climate data of the scenarios were derived from Community Climate System Model outputs. Changes in annual NPP between 2000 and 2050 were projected with the forest ecosystem model PnET-II. Results showed that forest productivity would increase under climate change scenarios A1B and A2, but with scenario B1, it would peak during 2011–2020 and then decline. The projected average NPP under B1 over the years from 2000 to 2050 was significantly different from those under A1B and A2. Forest NPP appeared to be primarily a function of temperature, not precipitation. Uncertainties of the NPP projection were due to large spatial resolution of the climate variables. Overall, this study suggested that in order to project effects of climate change on forest ecosystem at regional level, modeling uncertainties could be reduced by increasing the spatial resolution of the climate projections.

Keywords Climate change · Subtropical forests · Net primary productivity · Pnet-II · Uncertainty · Community Climate System Model 3.0 (CCSM3.0)

INTRODUCTION

To cope with potential future changes in climate, resource managers and policy makers need some means to project the spatial and temporal responses of forest growth to various future climate scenarios. Such predictions are necessary to not only maintain forests but also to enlist forests in mitigating greenhouse gas emissions. Significant increases

of greenhouse gas (GHG) emissions due to industrialization have likely contributed to rapidly changing climate conditions, especially during the last 50 years (IPCC 2007b). The Intergovernmental Panel on Climate Change (IPCC) has developed six greenhouse gas emission scenarios for the twenty-first century labeled A1B, A1F1, A1T, A2, B1, and B2 (Nakicenovic et al. 2000). Scenarios are distinguished by driving forces such as demographic and socio-economic development and technological change. Generally, scenarios B1, A1B, and A2 represent “low,” “medium,” and “high” greenhouse gas emissions in the future, and the approximate carbon dioxide equivalent concentrations in 2100 for the three scenarios are about 600, 850, and 1250 ppm (Nakicenovic et al. 2000). On the basis of these greenhouse gas emission scenarios, global climate change for the twenty-first century has been projected by a number of general circulation models. For instance, global mean surface air temperature has been predicted to rise by 1.8°C (1.1–2.9°C) for the B1 scenario and 4.0°C (2.4–6.4°C) for the A1F1 scenario for the period 2080 to 2099 relative to 1980 to 1999 (Meehl et al. 2007). Furthermore, the projected global warming is expected to cause changes in distribution, intensity, and frequency of precipitation. The precipitation would increase over 20% at most high latitudes, as well as in eastern Africa, central Asia and the equatorial Pacific Ocean for the A1B scenario for the period 2080 to 2099 relative to 1980 to 1999 (Meehl et al. 2007).

The projected climate changes are expected to have wide-ranging effects on natural resources and human societies (IPCC 2007a). For forest ecosystems, Boisvenue and Running (2006) analyzed the effects of climate change on forest productivity between 1950 and 2005 and found a positive response of forest productivity if water and nutrient supplies are not limited. However, Aber et al. (2001) projected that about 20% of current forest area in

the conterminous United States would experience some level of carbon loss if temperature and precipitation were increased by 3.3°C and 23%, respectively, from 2000 to 2099 compared to 1961 to 1990.

Forests exert feedbacks to the climate through carbon cycling and albedo. Currently, U. S. forests as a whole are a net carbon sink (Ciais et al. 1995), sequestering 200 Tg carbon annually from the atmosphere, or 10% of U.S. fossil fuel emissions (Birdsey et al. 2005). However, the forest ecosystems are often perturbed by natural disturbances and management activities. A major disturbance event can shift a forest from a carbon sink to a carbon source. The unpredictability of the intensity and frequency of natural disturbances and the various effects of management practices on forest carbon flux introduce much uncertainty in projecting forest carbon dynamics (Goward et al. 2008; Kurz et al. 2008). Spatially explicit projections of carbon cycling with process-based models that integrate climate and disturbance factors may provide managers and policy makers with better information for future management options.

Using Louisiana as an example in linking an ecosystem model with geographical information systems, this study aims to (1) develop a spatially explicit modeling framework for forest NPP projection; (2) project responses of forest NPP to three commonly used climate change scenarios (IPCC SRES B1, A1B, and A2) at higher spatial resolution of 4,980 m by 4,980 m; and (3) assess uncertainties associated with the NPP projection at the grid and state levels. Global climate models have projected increased temperature and precipitation for Louisiana in the twenty-first century. The forecasted climate changes may have significant effect on forest growth in the state. McNulty et al. (2000) predicted that southern pine productivity in Louisiana would increase by 2.5% between 1990 and 2040, and it would decrease by 6% from 2040 to 2100 under climate change projected by Hadley 2 model with Hadley2Sul¹ run. Results from this study will enable projections of forest carbon dynamics under changing climate at higher resolution than state-wide forecasts.

METHODS

PnET-II: A Forest Growth Model

In this study, PnET-II (Aber and Federer 1992) was used to project monthly NPP of forests in the entire state of Louisiana. PnET-II can simulate foliage, wood, and root NPP

by calculating carbon fixed during photosynthesis, allocated to foliage, wood, and roots, and respired from leaf, stem, and roots at a monthly time step (Aber and Federer 1992; Aber et al. 1996). PnET-II assumes that maximum photosynthetic rate is a function of foliar nitrogen concentration and that maximum gross photosynthesis per unit leaf area is 110% of the maximum net photosynthesis. Gross photosynthesis is modified by functions of temperature and the respective direct and indirect effects of soil water stress and vapor pressure deficit on stomatal conductance. To determine whole canopy photosynthesis, the photosynthesis of 50 vertical canopy layers is calculated on the basis of a specific leaf area and light attenuation and summed on a unit ground area basis. The model calculates leaf area index on the basis of soil water holding capacity, species, and local climate.

Modeling Approach

PnET-II projected forest NPP at a spatial resolution of 4980 m by 4980 m for the years between 2000 and 2050 under the three climate change scenarios B1, A1B, and A2. Spatial distribution of forests including deciduous, evergreen, mixed, and woody wetland forests were determined from National Land Cover Data (NLCD) (Multi-Resolution Land Characteristics Consortium 2001). In order to project forest NPP changes across the entire Louisiana, the forest lands were aggregated into 2,711 pixels with size of 4,980 m by 4,980 m. PnET-II was run twice at each pixel, one run with parameters of evergreen forests and another run with parameters of deciduous forests. Then the two sets of model outputs were summarized by multiplying an aerial ratio of evergreen forested land to deciduous forested land in each pixel to compute a composite NPP. If land cover in a pixel was identified as mixed forests by NLCD, a ratio of 60:40 for evergreen and deciduous was assumed (Ollinger et al. 1998). Similarly, a ratio of 75:25 was assumed to calculate the mixed forests NPP for the wetland forests (Rosson 1995; USDA Forest Service 2007). The model run started from 1960 and ended in 2050, and was validated with the modeled results against measurements for the period from 1991 to 2003.

Model Parameters and Data Inputs

The input data sets of PnET-II include climate, forest spatial distribution and attribute parameters, soil water holding capacity, and site attributes, as described below.

Climate Scenarios

Monthly precipitation, mean maximum and minimum temperatures, and solar radiation data were derived from

¹ Hadley2Sul represents one of two runs of the Hadley 2 in prediction of climate change with consideration effects of greenhouse gases and the influence of sulphate aerosols (SUL). Hadley 2 is the Hadley Centre's 2ed coupled Ocean–Atmosphere General Circulation Model.

simulations and predictions by a general circulation model, Community Climate System Model 3.0 (CCSM3.0). CCSM3.0, developed by National Center for Atmospheric Research, USA, is the key component of the National Science Foundation program on climate modeling, analysis and prediction. It simulates and predicts the earth's climate between 1870 and 2100 at a spatial scale of $1.4^\circ \times 1.4^\circ$ by combining comprehensive models of the atmosphere, ocean, sea-ice, and land surface via a centralized coupler. Climate variables for 1870–1999 were simulated by the model with 20C3M experiment, in which the atmospheric carbon dioxide concentrations and other input data were based on historical records or estimates. The climate changes in the period from 2000 to 2100 were predicted by the model under the IPCC GHG emission scenarios A2, A1B, and B1. The atmospheric CO_2 concentration varied from 369 ppm in 2000 to 532, 532, and 488 ppm in 2050 for the three scenarios. Detailed descriptions about annual changes of CO_2 and other GHG concentrations, how CCSM3 designed experiments for simulating climate changes under 20C3M, A2, A1B, and B1 scenarios, and what forces drove the model can refer to CCSM 3.0 IPCC AR4 Simulations (http://www.cgd.ucar.edu/ccr/strandwg/CCSM3_AR4_Experiments.html). In this study, the monthly climate data during 1960–2050 were downloaded from the repository of CCSM3.0 outputs: the Earth System Grid (ESG) and the Eos-Webster. Thirteen pixels that each covered a $96 \text{ km} \times 111 \text{ km}$ ($1.4^\circ \times 1.4^\circ$) space within Louisiana were extracted from the raw dataset covering the entire globe. The 10-year averages of the dataset for Louisiana showed that mean temperature increased by 1.24, 1.35, and 0.97°C for A2, A1b, and B1 scenarios from during 2000–2010 to during 2040–2050, and that monthly precipitation varied 0.33, 0.81, and -0.11 cm from the mean value for the scenarios between the periods.

Site Variables

Latitude, forest types, area percentages of evergreen and deciduous forests, and water holding capacity (WHC) were input variables for each grid point with a size of $4,980 \text{ m}$ by $4,980 \text{ m}$. Forest types and area percentages of each type in each grid point were determined from the National Land Cover Dataset (NLCD) 1992 (Multi-Resolution Land Characteristics Consortium 1992). NLCD was derived from Landsat Thematic Mapper (TM) and Enhanced Thematic Mapper Plus (ETM+) imagery, and four forest types (deciduous, evergreen, mixed, and wetland forests) were classified for square pixels of 30 m on a side. The 30-m square pixels were aggregated into $4,980 \text{ m}$ by $4,980 \text{ m}$ blocks and area percentage of each forest type in each block was computed. At the scale of $4,980 \text{ m}$ by $4,980 \text{ m}$, in Louisiana there were 2,711 forest blocks.

Soil water holding capacity (WHC), the total depth of water that the soil could store within its whole vertical profile, was calculated from Soil Survey Geographic (SSURGO) database. SSURGO is the most detailed level (1:12,000 to 1:163,360) of soil mapping done by the USDA Natural Resources Conservation Service (NRCS). A map unit, defined as polygon on a map, is the fundamental graphic feature in SSURGO spatial data. A single map unit consists of one to three soil components or soil types which are too small or intermixed to represent graphically on a map. Each component has up to six layers to represent soil vertical profile, and soil physical and chemical properties of each layer or horizon were surveyed and stored in multiple relational tables. In Louisiana, soil water holding capacity across all map units ranged from 88 to 24 cm. For a given map unit, the WHC was computed by the equation below (Soil Survey Staff 2004; California Soil Resource Lab 2006):

$$\text{WHC} = \sum_i^3 \left((\text{compct_r}_i / 100) \times \sum_j^6 ((\text{hzdepb_r}_{ij} - \text{hzdept_r}_{ij}) \times \text{awc_r}_{ij}) \right) / \sum_i^3 (\text{compct_r}_i / 100)$$

where i is number of component in each map unit, j is number of horizon layer across a component profile, compct_r is area percentage of each component in a map unit, hzdepb_r is distance from the top of the soil to the base of the soil horizon, hzdept_r is the distance from the top of the soil to the upper boundary of the soil horizon, and awc_r is the amount of water that an increment of soil depth, inclusive of fragments, can store that is available to plants. It is expressed as a volume fraction, and is commonly estimated as the difference between the water contents at 1/10 or 1/3 bar (field capacity) and 15 bars (permanent wilting point) tension and adjusted for salinity and fragments.

Forest Parameters

In total, 36 parameters are required to run the PnET-II model. However, not all of them change with forest stands (Aber et al. 1995). In this study, four forest parameters were selected to represent changes in forest stand properties. They included the intercept and the slope of relationship between foliar N concentration, maximum net photosynthesis rate, foliage retention time, and specific leaf weight. Initial setting of the parameters for a model run was based on the published values by Ellsworth and Reich (1992), Maier et al. (2008), Reich et al. (1995), Springer et al. (2005), and Tang et al. (2004).

Model Validation

Model validation is a critical step for model applications. In this study, the USDA Forest Service's National Forest Inventory and Analysis (FIA) data released in 1992 and 2006 were used to determine how accurate PnET-II was in predicting forest NPP in Louisiana. The FIA data is composed of 6,589 plots within Louisiana. Each plot is 1 acre in size and represents 6,000 acres of land. From the FIA data sets, the forest carbon in 1991 and 2003, and yearly mortality and removals between 1991 and 2003 for each plot were derived. The mortality and removals were losses of carbon owing to mortality and removals including harvests between these two inventories. PnET-II was validated for Louisiana forests with an assumption that apparent biomass increment projected by PnET-II should equal to the biomass changes derived from FIA dataset as the equation below showed:

$$y = x_0 - x_1 + x_2$$

where y is the projected NPP by PnET-II for the years from 1991 to 2003, x_0 and x_1 are the carbon in 2003 and 1991, and x_2 is the carbon losses owing to removals and mortality.

To protect privacy, the coordinates of FIA plots were fuzzed within 1.6 km of the exact plot location and up to 20% of the private plot coordinates were swapped with another similarly private plot within the same parish (a territorial unit equivalent to a county in other U.S. states). Our validation was conducted at parish level. Within each parish, even though coordinates of individual FIA plots were swapped and fuzzed, summarization of forest attributes at the parish level is not affected by the hidden location of the plots (USDA Forest Service 2007).

Sensitivity Analysis

Sensitivity analysis is an investigation of importance of the imprecision or uncertainty in model inputs in modeling process. It describes how much the model output values are affected by changes in model input values. Aber and others (1996) assessed sensitivity of the PnET-II model to a set of parameters by an increase of 10% of each parameter value. They found that gross carbon exchange (GCE) was more sensitive to foliage N concentration and slope of the relationship between maximum net photosynthesis rate and foliage nitrogen concentration followed by daily maximum net photosynthesis as fraction of early morning instantaneous rate, and specific leaf weight. In this study, sensitivity of these four parameters was analyzed by Monte Carlo simulation to propagate model uncertainty. The simulation involves a large number of iterations with parameters determined by probability distribution functions, usually normal distribution

(Smith and Heath 2001). Normal distributions of the input parameters for sensitivity analysis were generated with an assumption that standard deviation was 10% of the mean value of the parameters. A total 100 values for each parameter were generated. Sensitivity of four climate inputs including maximum and minimum temperature, precipitation, and solar radiation were simulated. For each climate variable, the monthly input was the data during 2000–2050 subtracting or adding the mean stand deviation of the monthly climate data between 1970 and 2000.

RESULTS

Temporal Changes in NPP

The model predicted parish-wide NPP well (Fig. 1a). The projected NPP rates were compared with the apparent biomass increment between 1991 and 2003, and the result showed a strong agreement as indicated in the result comparison with a slope of 0.9 (Fig. 1b). The mean NPP difference between the prediction and validation in Louisiana parishes (i.e., counties) was 0.9 Tg, with a standard deviation of 4.9 Tg (Fig. 1c). Two of the 59 parishes showed higher, positive differences of 12.8 and 17.5 Tg, indicating great under predictions of NPP changes in the counties.

Temporally, among the three scenarios, the projected annual NPP rates fluctuated widely over the years (Fig. 2a). However, the overall NPP trend was still evident as shown by difference of the 10-year average NPP between the period of 2011 to 2050 and 2001 to 2010 (Fig. 2b) and the accumulated annual mean NPP (Fig. 2c). The annual NPP displayed a wide range of difference among the three scenarios during 2000 to 2020, but afterward, the values converged. In particular, the annual NPP showed a peak of $1,286 \text{ g m}^{-2}$ in 2012 for B1 scenario, a trough of 807 g m^{-2} in 2006 for A1B, and a trough of 786 g m^{-2} in 2019 for A2. Compared to the mean NPP rate during 2001 to 2010 (Fig. 2b), the mean NPP rates of the remaining years showed that for the B1 scenario, the mean NPP between 2011 and 2020 was higher than the mean between 2001 and 2010. After 2020, the NPP increased slightly, but the mean values at the 10-year period from 2021 through 2050 still were lower than during 2001 to 2010. For A1B and A2 scenarios, the 10-year mean values showed overall increasing trends. The accumulated annual mean NPP (Fig. 2c) also showed a difference among the three scenarios with an obviously higher accumulated NPP for B1 than for the A1B and A2 scenarios. For both the A1B and A2, the accumulated values were similar. Results of one-way ANOVA analysis showed that the mean NPP values of the three scenarios during 2000 to 2050 were significantly

Fig. 1 (a) Predicted NPP during 1991–2003 by PnET-II, (b) validation of PnET-II with independent data derived from FIA dataset at parish (county) level, where y is the predicted NPP, x_0 and

x_1 are the biomass carbon in 2003 and 1991, and x_2 is the carbon losses owing to removals and mortality, and (c) NPP difference between the validation and prediction

different ($P = 0.0097$). Tukey's test revealed that mean NPP of B1 scenario was significant different from those of A1B and A2 scenarios. However, no significant difference was found between mean NPPs of the A1B and A2 scenarios.

Spatial Change in NPP

Across Louisiana, the projected 10-year average NPP during periods of 2001–2010, 2021–2030, and 2041–2050 showed a distinctly increasing trend from North to South but small changes from East to West (Fig. 3). A total of 11 climate grids (non-forest grids 1 and 2 were not included) as shown in the NPP map for A1B during 2001–2010 were distributed over three latitude zones (Fig. 3; Table 1). From one latitude zone to adjacent one, the average NPP rate changed considerably. For instance, from North to South, mean NPP changed from 532 to 878 g m⁻² year⁻¹, and then to 1,598 g m⁻² year⁻¹. In contrast, among climate

pixels within a latitude zone, NPP rates appeared homogeneous from one pixel to next one (Table 1). For example, for latitude zone 1, mean NPP ranged from 1,570 to 1,635 g m⁻² year⁻¹ across the time periods and climate scenarios. Within a climate pixel, forests NPP were projected at a resolution of 4,980 m by 4,980 m. NPP at this spatial level, regardless of time periods and climate scenarios, varied slightly with a minimum standard deviation of 0.2 g m⁻² year⁻¹ in climate pixel number 13 for A1B scenario during 2041–2050, and a maximum standard deviation of 91 g m⁻² year⁻¹ in climate pixel number 8 for A2 scenario during 2021–2030.

Sensitivity Analysis

Sensitivity analysis of the four forest parameters showed that the PnET-II model was more sensitive to foliar N concentration and slope of the relationship between maximum net photosynthesis and foliar N concentration than to

Fig. 2 (a) Projected annual NPP in Louisiana during 2000 to 2050 by the three climate change scenarios of A1B (blue), A2 (green), and B1 (red), (b) difference of the 10-year average NPP between the period of 2010 to 2050 and 2000 to 2010, and (c) accumulated annual mean NPP

daily maximum net photosynthesis as fraction of early morning instantaneous rate and specific leaf weight (Fig. 4; Table 2). Relative to the mean NPP of 1033, 988, and 985 g m⁻² year⁻¹ projected by PnET-II without Monte Carlo simulation for B1, A2, and A1B scenarios, the projected mean NPP through sensitivity analysis presented a change from -0.5 to 6.9% across all scenarios and parameters. The coefficient of variations of NPP simulated by Monte Carlo approach varied from -36.6 to 195.1% as compared to standard deviations of 87, 95, and 82 g m⁻² year⁻¹ for B1, A2, and A1B scenarios without the simulation. The analysis of percentage changes by the parameters, regardless of the emission scenarios, showed that percentages of the projected mean NPP rates varied from 5.8 to 6.6% for foliar N concentration and slope of the relationship between maximum net photosynthesis and foliar N concentration. In contrast, for daily maximum net photosynthesis as fraction of early morning instantaneous rate and specific leaf weight, percentages of the projected

mean NPP rates were relatively stable at -0.6% of the mean. On the other hand, coefficients of variation of the parameters were 173.9 and 172.2% for the first two parameters and were 34.3 and -41.4% for the later parameters, respectively.

Sensitivity analysis of four climate variables—mean maximum and minimum temperature, precipitation, and radiation—showed that the PnET-II model was more sensitive to the temperature than to the precipitation (Fig. 5; Table 3). In terms of the percentage change in NPP during 2000–2050 relative to the mean NPP (985 g m⁻² year⁻¹) for A1B scenario projected by PnET-II without Monte Carlo simulation, the opposite signs of the percentages for mean maximum temperature were identified as compared to the remaining parameters. This indicated a negative effect of increasing mean maximum temperature on NPP, with a positive response of NPP on rising mean minimum temperature, precipitation, and radiation. For the entire state of Louisiana, particularly, increasing max temperature

Fig. 3 Mean NPP during the 10-year period of 2001–2010, 2021–2030, and 2041–2050 for the three climate change scenario groups. The spatial resolution of the maps is 4,980 m by 4,980 m and the grid overlaid on the maps are climate pixel with a size of 1.4° by 1.4°

could reduce mean NPP by 16% during 2000–2050. Small changes in temperature in the future could result in high variability in forest NPP.

DISCUSSION

Temporal Effects of Climate Change on NPP

The modeling results of this study suggest that projected forest NPP in Louisiana will differ with the various

greenhouse gas emission scenarios. The differences, however, may not be the direct result of divergent atmospheric CO₂ concentrations. The rate of photosynthetic carbon assimilation is a function of the bulk concentration of CO₂ in the atmosphere, stomatal conductance, environmental factors, such as radiation and temperature. Elevated CO₂ increases internal CO₂ concentration, increasing water use efficiency, and apparent light-use efficiency (Drake et al. 1997). Enhanced nutrition can significantly amplify the effects of elevated CO₂ on carbon gain and biomass increment (Winter et al. 2001) while nutrient deficiencies

Table 1 Mean and standard deviation of NPP ($\text{g m}^{-2} \text{ year}^{-1}$) during the three periods by latitude zones and the three climate change scenarios

Zone #	Latitude	GRID # ^a	2001–2010			2021–2030			2041–2050			NPP by latitude
			A1B	B1	A2	A1B	B1	A2	A1B	B1	A2	
1	29.4–30.8	3, 4, 5, 6	1570 ± 35	1612 ± 22	1617 ± 34	1635 ± 22	1572 ± 28	1590 ± 19	1574 ± 20	1631 ± 25	1586 ± 19	1598 ± 25
2	30.8–32.2	7, 8, 9, 10	723 ± 32	916 ± 40	805 ± 36	899 ± 42	886 ± 36	895 ± 45	906 ± 43	929 ± 38	943 ± 40	878 ± 39
3	32.2–33.0	11, 12, 13	477 ± 15	596 ± 18	527 ± 16	513 ± 10	565 ± 10	512 ± 9	494 ± 8	521 ± 10	578 ± 11	532 ± 12
NPP by time and climate scenarios			934 ± 27	1051 ± 27	994 ± 29	1027 ± 25	1018 ± 25	1010 ± 25	1003 ± 24	1039 ± 24	1046 ± 23	

^a This is the climate grid number as indicated on the upper-left corner sub-figure in Fig. 3

limit photosynthetic responses to elevated CO_2 at least to some degree (Saxe et al. 1998). Without competition, elevated CO_2 typically increases leaf area, leaf mass, and branches (Tissue et al. 1997; Saxe et al. 1998). PnET-II Matlab version cannot simulate direct effects of CO_2 on photosynthesis because the maximum net photosynthetic rate is solely a function of foliar nitrogen concentration. As the site and tree physiological conditions were set constant in the simulations, the projected differences in NPP among the three scenario are due to differences in minimum and maximum temperature, precipitation, and solar radiation.

In Louisiana, for scenario B1, the 10-year mean precipitation between 2001 and 2050 projected by CCSM3.0 shows a decreasing trend with the highest mean occurring during 2001–2010 and the lowest mean during 2011–2020 (Fig. 6a). This precipitation trend is opposite to the NPP trend over the same time interval (Fig. 2b). In contrast, for scenarios A1B and A2, the 10-year mean precipitation between 2001 and 2050 displayed an overall increasing trend, corresponding to the increasing trends of projected NPP for the scenarios during the same interval. Though precipitation obviously affects NPP, sensitivity analysis indicated only small effects on projected NPP with ± 1 standard deviation in precipitation. One reason for this relative insensitivity of projected NPP to precipitation in this analysis is that one standard deviation of annual precipitation corresponds to only 0.67% of the normal annual mean precipitation about 1,500 mm in Louisiana (Fig. 5c; Table 3).

The sensitivity analysis indicates that compared to precipitation, temperate change exerts more influence on NPP than precipitation. Increasing mean monthly maximum temperature one standard deviation of the monthly maximum temperature during 1970–1999 (yearly average 2.6°C) would decrease NPP by 16%, and increasing mean monthly minimum temperature one standard deviation of the monthly minimum temperature during 1970–1999 (yearly average 1.9°C) would increase NPP by 15% (Fig. 5a, b). The maximum temperature in Louisiana during 2000–2050 would increase slightly, particular for A1B and A2 scenarios (Fig. 6b). Meanwhile, PnET-II also projected overall rising trends of NPP for both scenarios. In terms of sensitivity analysis, increasing maximum temperature should lead to a decline NPP. However, in our study, the projected increasing maximum temperatures still correspond to a rise in NPP. This is contrary to the result from another PnET-II simulation by McNulty et al. (1996), but is similar with the results of Campbell et al. (2009) and Tian et al. (2010). McNulty et al. (1996) pointed out that increasing monthly minimum and maximum temperature by 2°C , NPP of loblolly pine forests decreased 30% in the Florida site. This could be that the projected maximum temperature change (about 1, 0.3, and 0.7°C for A1B, A2,

Fig. 4 Monte Carlo sensitivity analysis of PnET-II to parameters of (a) foliar N concentration, (b) slope of the relationship between maximum net photosynthesis and foliar N concentration, (c) daily maximum net photosynthesis as fraction of early morning instantaneous rate, and (d) specific leaf weight in predicting forest NPP in Louisiana. Solid black line represents PnET prediction without

application of Monte Carlo simulation. Solid blue, green and red lines represent average values of the predicted NPP by iterating PnET-II 100 times for the climate change scenarios of A1B, A2, and B1, respectively. The dashed lines display one standard deviation (s) of the mean NPP in corresponding to the scenario groups

and B1; Fig. 6b) in Louisiana did not alter as much as McNulty et al. assumed. We think the slight increasing temperature in Louisiana during 2000–2050 does not rise to a level to limit forest growth but may increase photosynthesis rates to an optimum as suggested by Saxe et al. (2001).

Minimum temperature has also been projected to increase in Louisiana for 2000–2050 under the three climate scenarios (Fig. 6c), implying a longer growing season. There are many possible definitions of growing-season length, but the most common definition is the number of days between the last occurrence of a minimum temperature of 0°C in the spring and the first in the fall (Brinkmann 1979). Growing season not only has a profound effect on

many processes related to forest growth, such as photosynthesis, respiration, nutrient availability, soil moisture, and evapotranspiration, but also controls bud break in spring and senescence and dormancy in fall (Campbell et al. 2009). In PnET-II, the timing of leaf out and the earliest time at which foliar senescence occur are determined by total accumulated growing degree days calculated as all mean temperatures above 0°C (Aber et al. 1996). Minimum and maximum temperatures are also used in the model to calculate leaf respiration and photosynthesis and vapor pressure deficit, and determine monthly leaf area display. Therefore, projected increasing NPP could be due simply to longer growing seasons as Campbell et al. (2009).

Table 2 Monte Carlo sensitivity analysis of the PnET-II model to four forest parameters in predicting forest NPP in Louisiana

Parameter	Climate scenarios	Mean and <i>s</i> of NPP ^a (g m ⁻² year ⁻¹)	Changes in mean NPP ^b (%)	Changes in <i>s</i> of the NPP ^c (%)	Mean NPP change by the parameters (%)	Mean <i>s</i> change by the parameters (%)
Foliar N concentration	A1B	1044 ± 242	6.0	195.1	5.8	173.9
	B1	1090 ± 242	5.5	178.2		
	A2	1045 ± 236	5.8	148.4		
Amaxb ^d	A1B	1053 ± 243	6.9	187.8	6.6	172.2
	B1	1098 ± 243	6.3	179.3		
	A2	1053 ± 237	6.6	149.5		
Amaxfrac ^e	A1B	978 ± 120	-0.7	46.3	-0.6	34.3
	B1	1028 ± 118	-0.5	35.6		
	A2	981 ± 115	-0.7	21.1		
Specific leaf weight	A1B	978 ± 52	-0.7	-36.6	-0.6	-41.4
	B1	1028 ± 52	-0.5	-40.2		
	A2	983 ± 50	-0.5	-47.4		

^a Mean and standard deviation (*s*) of the NPP predicted by iterating 100 times of the PnET-II with parameters generated by Monte Carlo analysis for all cells in Louisiana for the 2000–2050 period. The parameters were generated with an assumption of normal distribution and 10% of the mean value of the parameters as standard deviation

^b Percentage of the mean NPP relative to the mean of 1033, 988, and 985 g m⁻² year⁻¹ projected by PnET-II without Monte Carlo simulation for B1, A2, and A1B scenarios

^c Percentage of the *s* relative to the mean *s* of 87, 95, and 82 g m⁻² year⁻¹ projected by PnET-II without Monte Carlo simulation for B1, A2, and A1B scenarios

^d Slope of the relationship between maximum net photosynthesis and foliar N concentration

^e Daily maximum net photosynthesis as fraction of early morning instantaneous rate

Uncertainties in Spatial Estimation of NPP

Spatial variations of projected NPP by PnET-II over the years of 2001 through 2050 indicated a notable dependence of NPP on climate data input for Louisiana (Fig. 3). The projection using climate data at the pixel size of 1.4° by 1.4° resulted in a high NPP changes (about 533 g m⁻² year⁻¹) from one latitudinal climate zone to the next. In contrast, within each climate zone, the standard deviation of NPP for all pixels was relatively low, about 39 g m⁻² year⁻¹. The smaller change of NPP within each climate zone and the large change of NPP between the climate zones suggest a dominant control of climate factors in NPP projection with PnET-II. Louisiana has some very different geomorphological and soil conditions (Zhong and Xu 2009). Because local site conditions including soil water holding capacity can also play a dominant role in forest stand growth, it remains unclear how critical site factors would be in the PnET-II modeling if the climate projections are downscaled at a finer resolution.

Sensitivity analysis revealed that NPP was most sensitive to foliar N concentration, slope of the linear relationship between maximum net photosynthesis and foliar N concentration, and daily max net photosynthesis as fraction of early morning instantaneous rate. However, in this study, values of these three parameters were kept

unchanged for all pixels across the entire state due to the lack of such local data for the various tree species comprising Louisiana forests. Therefore, the effects of spatial variation in these parameters on the spatial patterns of NPP are unknown.

In addition to the inherent uncertainties of large scale of climate projections and the lack of variation in N concentration within a species grouping, other assumptions may affect NPP projections within the state, for instance, land-use changes and changes in forest types. Sohngen and Brown (2006) indicated that there may be a shift of pine plantations in this region being converted to hardwood-forest lands in the future. Zaehle et al. (2006) demonstrated the importance of changes in the age structure of forests in simulating forest NPP at large scales. Peng and Apps (1999) reported that enhanced N mineralization caused by increased decomposition rates was an important factor contributing to the increases of simulated NPP in a boreal forest ecosystem. Wang and Xu (2009, 2010) reported that Hurricane Katrina and Rita severely damaged forests in southeast Louisiana in 2005. In further studies, these factors, particularly hurricane disturbance to forest ecosystem, could be incorporated into future modeling exercises.

Due to the complexity of large scale modeling and uncertain accuracy of below-ground information with the FIA data, our study excluded simulation of possible root

Fig. 5 Sensitivity analysis of the PnET-II model to climate inputs of A1B scenario of (a) maximum and (b) minimum temperature, (c) precipitation, and (d) radiation in prediction of NPP in Louisiana. Solid black line represents PnET NPP prediction with raw CCSM3

climate data. Red and blue lines represent NPP predicted by adding or subtracting A1B climate variables one standard deviation (s) of the corresponding climate variable data in 1970–2000

Table 3 Sensitivity analysis of the PnET-II model to climate inputs of A1B scenario in prediction of NPP in Louisiana

Climate inputs	Input changes ^a	Mean NPP during 2000–2050 ($\text{g m}^{-2} \text{ year}^{-1}$)	NPP changes ^b (%)	Mean of the percentage changes by parameters (%)
Max. Temp.	+2.6°C	831	–15.6	17.1
	–2.6°C	1,167	18.5	
Min. Temp.	+1.9°C	1,137	15.4	12.3
	–1.9°C	895	–9.1	
Precipitation	+20.3 mm	1,057	7.3	6.0
	–20.3 mm	938	–4.8	
Radiation	+58.7 $\mu\text{moles m}^{-2}$	1,061	7.7	4.3
	–58.7 $\mu\text{moles m}^{-2}$	994	0.9	

^a PnET-II runs with monthly climate data. The values reported here are mean of monthly one standard deviation of the corresponding climate variable data in 1970–2000

^b Percentage change of mean NPP during 2000–2050 relative to the mean of $985 \text{ g m}^{-2} \text{ year}^{-1}$ predicted by PnET-II without Monte Carlo simulation for A1B scenario

Fig. 6 Changes in 10-year (a) mean precipitation, and (b) maximum, and (c) minimum temperatures relative to the mean values between 2001 and 2010 by the climate change scenario groups

system responses to the climate change scenarios. Other studies have suggested that carbon assimilation of woody plants can be substantially enhanced in response to increasing atmospheric CO₂ (Norby et al. 1999; Sholtis et al. 2004). However, researchers argued whether the stimulation in photosynthesis would result more in above-ground biomass increment (Drake et al. 1997; Korner et al. 2005) or would lead more to increased carbon allocation to roots (Hattenschwiler et al. 1997; Matamala et al. 2003; Norby et al. 2004). In any case, it seems plausible to conclude that increased litter buildup and soil organic matter in Louisiana forests can be expected with increased greenhouse emissions in the future.

In order to reduce uncertainties of NPP over space, two steps may be required. First, the input data of climate projections need to be downscaled at finer spatial scales. For instance, for historical climate inputs, 4 km by 4 km climate data have been created using the PRISM (Parameter-elevation Regressions on Independent Slopes Model) climate mapping system. Second, given the importance of parameters in spatial forecasting with ecosystem model, the uncertainty caused by parameterization should be minimized through generating spatial layers of the parameters

at fine spatial scales. In some cases, using hyperspectral remotely sensed data to generate spatial parameter layers, such as foliar N concentration, is possible (Ollinger and Smith 2005). However, the strength of the relationship between foliar nitrogen and photosynthesis varies by species too. Furthermore, in some cases, such an approach is impracticable because of often limited availability of hyperspectral data. Therefore, as an alternative solution, spatial layers of the parameters may be generated by incorporating remotely sensed data (e.g., hyperspectral airborne data), improved inventory data (e.g., FIA data for forest attributes and SSURGO for soil attributes), field investigations and long-term records with geospatial techniques, such as k-nearest neighbors, segmented regression, and geospatial statistics. The generated spatial data layers will represent variations of vegetation parameters at local scale. Particularly, it would be a better choice for heterogeneous landscape that has various vegetation types. Even though it is possible to derive values of some parameters, such as foliar N concentration, for each species at the landscape level, determination of the values for broad forest groups of deciduous, evergreen, mixed, and woody wetland forests may be more applicable for applications.

The reason is that the relationship of photosynthesis with foliar N concentration may highly vary when individual species or narrow species groupings are compared, but a positive linear trend should be clearly viewed across a broad range of species (Peterson et al. 1999).

CONCLUSION

This modeling study projected changes in net primary productivity of Louisiana forests in response to three climate change scenarios (A1B, A2, and B1) for the period from 2000 through 2050. Using Louisiana as an example, we developed a spatially explicit modeling framework for forest NPP projection, which demonstrated the credibility of geographic information systems in assisting the projection and spatial analysis of forest NPP at finer scales of resolution. Beyond development of the modeling system, the study yielded insight into forest NPP responses to future climate change in a subtropical region. The modeling results showed that forest NPP would positively respond to the medium (A1B) and high (A2) greenhouse gas emissions (CO₂ concentration of 850 and 1,250 ppm in the atmosphere in 2100, respectively). The response of Louisiana forests NPP to the low greenhouse gas emission (B1, CO₂ concentration of 600 ppm in the atmosphere in 2100) was mixed: an initial increase through 2018 followed by a sharp decrease through 2030 before a relatively stable period through 2050. According to PnET-II, forest NPP appears to be primarily a function of temperature. The uncertainty of NPP over the space was noticeably related to spatial variation of climate variables and spatial resolution of the variables. The results gained from this study imply that if Louisiana forests could be a carbon sink in the future as they serve currently, changes in heterotrophic respiration, soil nutrients, and disturbances from natural and human forces should be considered along with NPP changes for profiling Louisiana forest's potential in carbon sequestration and climate mitigation.

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