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Projecting terrestrial carbon sequestration of the southeastern United States in the 21st century

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Abstract. How terrestrial ecosystems respond to future environmental change in the 21st century is critically important for understanding the feedbacks of terrestrial ecosystems to global climate change. The southeastern United States (SEUS) has been one of the major regions acting as a carbon sink over the past century; yet it is unclear how its terrestrial ecosystems will respond to global environmental change in the 21st century. Applying a process-based ecosystem model (Dynamic Land Ecosystem Model, DLEM) in combination with three projected climate change scenarios (A1B, A2, and B1 from the IPCC report) and changes in atmospheric carbon dioxide, nitrogen deposition, and ozone pollution, we examined the potential changes of carbon storage and fluxes in the terrestrial ecosystems across the SEUS during 2000–2099. Simulation results indicate that SEUS's terrestrial ecosystems will likely continue to sequester carbon in the 21st century, resulting in an increase in total carbon density (i.e., litter, vegetation biomass and soil carbon) from 13.5 kg C/m^2 in the 2000s to 16.8 kg C/m^2 in the 2090s. The terrestrial gross primary production and net primary production will probably continuously increase, while the net carbon exchange (positive indicates sink and negative indicates source) will slightly decrease. The carbon sequestration is primarily attributed to elevated atmospheric carbon dioxide and nitrogen deposition. Forests, including both deciduous and evergreen, show the largest increase in carbon storage as compared with other biomes, while cropland carbon storage shows a small decrease. The sequestered carbon will be primarily stored in vegetation for deciduous forest and in soil for evergreen forest. The central and eastern SEUS will sequester more carbon, while the western portion of the SEUS will release carbon to the atmosphere. The combined effects of climate and atmospheric changes on carbon fluxes and storage vary among climate models and climate scenarios. The largest increase in carbon storage would occur under the A1B climate scenario simulated by the NCAR climate model. Generally, the A1B scenario would result in more carbon sequestration than A2 and B1 scenarios; and the projected climate condition by the NCAR model would result in more carbon sequestration than other climate models.

Key words: carbon flux; carbon storage; climate change; process-based ecosystem model; southeastern United States.

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Introduction

Climate change has been considered as one of the most important environmental threats facing human society, and has drawn attention from both the public and the scientific community (Vitousek et al. 1997, Wofsy 2001, Forster et al. 2007, Heimann and Reichstein 2008). Earth's surface temperature has increased 0.76°C over the past 150 years and is expected to increase 1.5–6.4°C by the end of the 21st century (Solomon et al. 2007). Changes in global precipitation varied among regions over this timeframe. For example, precipitation has generally increased over land north of 30° N over the period 1900 to 2005 but decreased in the tropics since the 1970s (Trenberth et al. 2007). Global precipitation is anticipated to increase approximately 0.5–1% per decade in this century (Solomon et al. 2007). These changes have led to alterations in ecosystem structure and functioning, such as growing season extension (Zhu et al. 2012), carbon release (Piao et al. 2008), and water balance shift (Jung et al. 2010).

Meanwhile, other environmental factors including atmospheric carbon dioxide (CO_2) (Chapin et al. 2008, Langley and Megonigal 2010), nitrogen input through deposition and fertilizer use (Janssens and Luyssaert 2009, Lu et al. 2012, Tian et al. 2012*a*), and ozone pollution (Felzer et al. 2004, Ren et al. 2011), play an important role in changing structure and functioning of terrestrial ecosystems through a complex set of mechanisms (Norby and Luo 2004, Tian et al. 2011*a*). For example, the fertilization effects of elevated CO_2 and nitrogen (N) deposition stimulate plant growth (Cramer et al. 2001, Albani et al. 2006), while ozone pollution reduces plant growth (Felzer et al. 2004). The multiple-factor experiment is an effective tool to study the terrestrial responses to environmental changes (Norby and Luo 2004, Dermody 2006); however, because the establishment of large-scale field experiments is very labor-intensive, time-consuming and expensive, particularly in examining the effects of gradually changed environmental factors over long term periods, process-based ecosystem models are considered more suitable for predicting terrestrial carbon dynamics at large scales (e.g., Melillo et al. 1993, Tian et al. 1998, McGuire et al. 2001).

The southeastern United States (SEUS) has been considered as the largest carbon sink among six major bioclimatic regions of the conterminous US (Schimel et al. 2000, Tian et al. 2010*a*). It has the potential to continuously function as a significant carbon sink in the future because of its large area of young pine forests and increasing area of plantation forest (Turner et al. 1995, Birdsey et al. 2006, Malmsheimer et al. 2008). Whether this potential will be achieved also depends on changes in climate and other environmental changes such as land use and land cover, and atmospheric composition (Wear and Greis 2002, Chen et al. 2006, Tian et al. 2010*a*). The projection of the carbon dynamics in this region, therefore, will be critically important for climate change adaptation and mitigation.

In this study, we applied a process-based terrestrial ecosystem model (Dynamic Land Ecosystem Model, DLEM) to examine how changes in climate and atmospheric chemistry including atmospheric CO_2, N deposition and ozone pollution would affect terrestrial carbon storage and fluxes across the SEUS from 2000 to 2099. The major objectives of this study were: (1) to examine the inter-annual and decadal changes in carbon storage under three projected climate scenarios simulated by four climate models; (2) to investigate the spatial and temporal variations in carbon storage and the underlying controls; (3) to quantify the relative contributions of different biomes to carbon fluxes; and (4) to assess potential uncertainties in carbon fluxes as resulted from different climate change scenarios and prediction models.

Methodology

Study region

The SEUS includes thirteen states: Florida, Georgia, North Carolina, South Carolina, Virginia, Alabama, Arkansas, Kentucky, Louisiana, Mississippi, Oklahoma, Tennessee, and Texas. The elevation of this region ranges from near sea level along the Gulf of Mexico and Atlantic Ocean Coasts to more than 1,800 m in the Appalachian Mountains. Its longitude ranges from 75° W to 100° W, and its latitude ranges from 30° N to 37° N. The summer seasons are relatively long, hot, and humid. The major vegetation types in this region are temperate

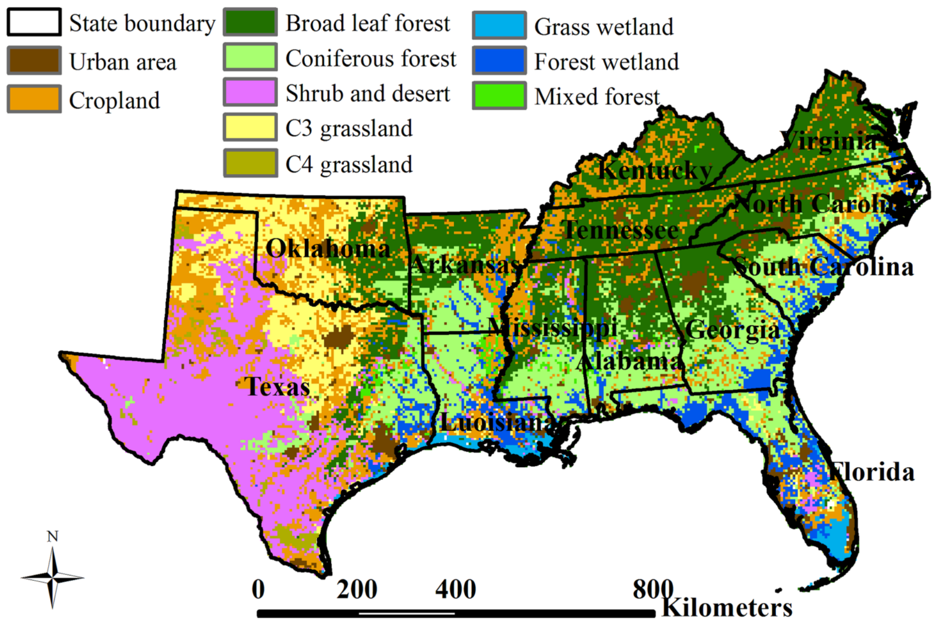

Fig. 1. The boundary and contemporary vegetation of the southeastern United States.

coniferous forest and temperate deciduous forest, grassland, cropland, and shrubland (Fig. 1).

Model description

Process-based ecosystem models have long been recognized as an effective tool for examining ecosystem responses to climate change, especially at regional scales (Melillo et al. 1993, Tian et al. 1998, Schimel et al. 2000, Huntzinger et al. 2012). In this study, a process-based DLEM was used to assess the responses of ecosystem carbon fluxes in the SEUS to future environmental changes. The DLEM has been developed and applied to study the effects of environmental stresses including changes in climate, atmospheric composition (CO_2, N deposition, and tropospheric ozone), and land use and land cover in Asia (Ren et al. 2007, Tian et al. 2011*a*, Tian et al. 2011*b*, Xu and Tian 2012) and North America (Zhang et al. 2007, Tian et al. 2010*b*, Xu et al. 2010, Tian et al. 2012*b*, Xu et al. 2012). Here we briefly describe the model structure, major carbon processes, parameterization and evaluation, driving forces, and implementation.

The DLEM simulates daily carbon, nitrogen, and water cycles driven by changes in atmospheric chemistry (including ozone pollution, N deposition and CO_2), climate, and land-use and land-cover types and disturbances (i.e., fire, hurricane, and harvest). A modified Farquhar model is used to simulate gross primary production (GPP) (Farquhar et al. 1980, Collatz et al. 1991, Collatz et al. 1992). The net primary production (NPP) is calculated by subtracting maintenance and growth respiration from GPP. The net carbon exchange (NCE) is calculated by subtracting heterotrophic respiration, methane emission, product decay flux, and fire emission from NPP. The detailed information and model algorithms have been published elsewhere (e.g., Tian et al. 2010*a*, Tian et al. 2011*a*).

Model parameterization and evaluation

Model calibration and evaluation for the DLEM have been conducted for a number of sites and regions across the globe. For example, the DLEM-simulated carbon fluxes have been validated against field observations in China (Liu et al. 2008, Tian et al. 2011*a*, Tian et al. 2011*b*, Lu et al. 2012, Ren et al. 2012) and North America (Xu et al. 2010, Tian et al. 2012*b*). In the SEUS, the DLEM has also been applied to investigate the responses of terrestrial carbon cycles to multiple stresses including changes in climate, atmospheric composition (CO_2, N deposition, and surface ozone), and land use and land cover during 1895–2007 (Tian et al. 2010*a*, Chen et al. 2012, Tian et al. 2012*b*). The comparison between modeled and observed results shows high consistency for evergreen needle-leaf forest, deciduous broadleaf forest, grassland, and cropland. A regional comparison with 138 field observations of NPP was also conducted, and the line was fit with a slope close to 1 and a correlation coefficient of $R^2 = 0.82$. The site-level comparisons for GPP show that the DLEM can capture seasonal variation and magnitude of GPP at all five sites in the study region (Tian et al. 2010*a*, Chen et al. 2012). In this study, we extend our research to include the responses of ecosystem carbon fluxes to future environmental changes. Model parameters are maintained the same as in Tian et al. (2010*a*). The present simulations were conducted from 1895 to 2099 at a spatial resolution of 8 km $\times$ 8 km, while our analyses only focus on the 2000–2099 period.

Model driving forces

Driving forces for the DLEM include a vegetation map, daily climate data, annual atmospheric CO_2, and daily tropospheric ozone concentrations, annual N deposition and other geo-referenced invariant data-including soil bulk density, soil texture and soil pH-at a spatial resolution of 8 km $\times$ 8 km (Tian et al. 2010*a*).

The climate data used include daily precipitation, daily maximum temperature, mean temperature, and minimum temperature during 1895–2099. We have developed the historical climate data from 1895 to 2009 at a spatial resolution of 8 km $\times$ 8 km for the entire SEUS region by integrating the daily climate pattern of the North American Regional Reanalysis (NARR) dataset (http://wwwt.emc.ncep.noaa.gov/mmb/rreanl/) (Zhang 2008). For the future climate dataset (2010–2099), we used the future climate data as predicted by four climate models (GFDL-CM2, GISS-MODEL-E-R, NCAR-CCSM3.0, UKMO-HADCM3) under three greenhouse gas emission scenarios (A1B, A2, and B1; see description below) (Forster et al. 2007). The monthly temperature and precipitation data are based on three greenhouse gas emission scenarios simulated by four climate models (downloaded from the WCRP climate projections-http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections). The detailed techniques for temporal downscaling from monthly to daily and spatial downscaling from 0.5° $\times$ 0.5° to 8 km $\times$ 8 km are described by Maurer et al. (2007). The climate data for simulations include the following variables: daily precipitation and average, maximum and minimum air temperature.

Three future scenarios commonly used in the IPCC report were selected for this study (Forster et al. 2007). The A1B storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Economic development is primarily regionally oriented, and per capita economic growth and technological change are more fragmented and slower than in other storylines. The B1 storyline and scenario family describes a convergent world with the same global population that peaks in mid-century and declines thereafter. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives (www.ipcc.ch).

A standard IPCC CO_2 concentration history dataset (Enting et al. 1994) was used in this simulation. Annual CO_2 concentration for years between 2003 and 2007 was calculated based on the "Global Annual Mean Growth Rate of CO_2" by the Earth System Research Laboratory (ESRL; http://www.esrl.noaa.gov/gmd/ccgg/trends/). For each of the future emission scenarios, the average future CO_2 concentration projections of the IPCC Fourth Assessment Report (IPCC-AR4) were used. The concentration trends of CO_2 under three scenarios are illustrated in Fig. 2D. The three scenarios of atmospheric CO_2 concentration are associated with climate scenarios in simulations. That is to say, the atmospheric CO_2 concentration under the A1B scenario was only included in simulations driven by climate data under the A1B scenario; it is the same for the A2 and B1 scenarios. The N deposition data during 1895–2050 were retrieved from Dentener's global N deposition dataset (Dentener 2006), and we assumed no changes after 2050.

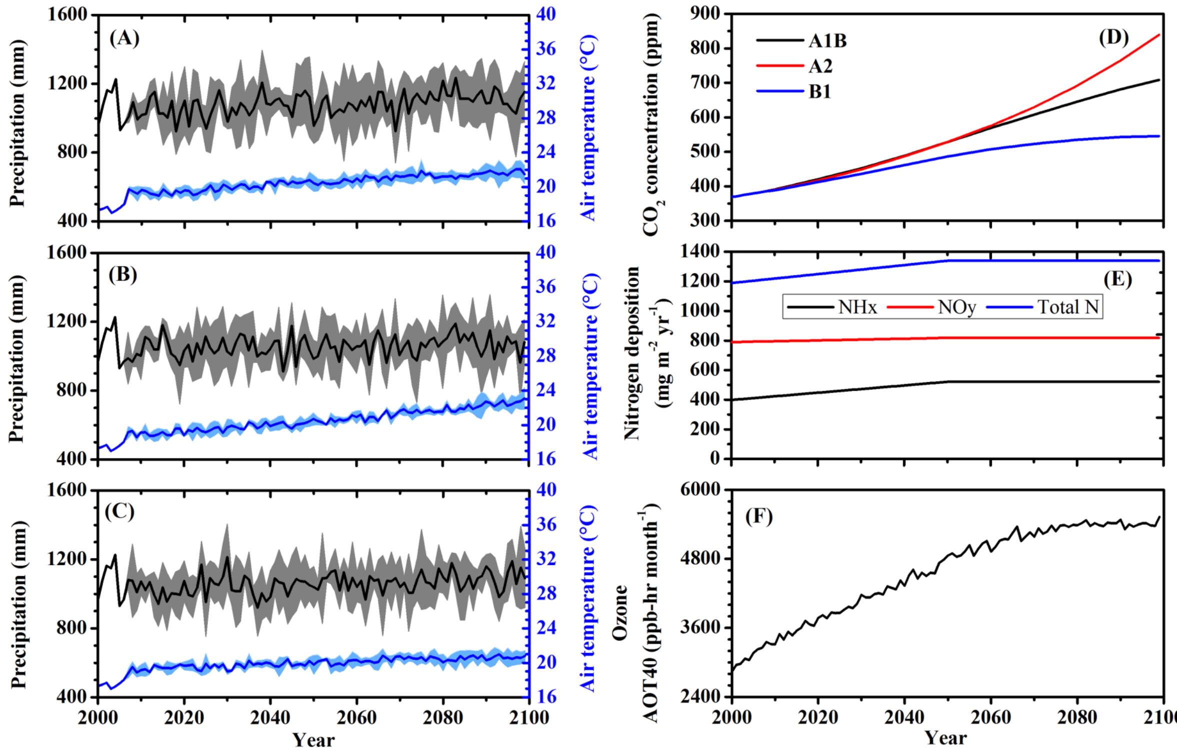

Fig. 2. Temporal variations of climate variables, atmospheric CO_2 concentration, N deposition, and ozone pollution from 2000 to 2099: (A) air temperature and precipitation under A1B scenario; (B) air temperature and precipitation under A2 scenario; (C) air temperature and precipitation under B1 scenario; (D) elevated atmospheric CO_2 under three scenarios; (E) N deposition rate; (F) projected ozone pollution. Shadow indicates range of one standard deviation among four single models: GFDL, Geophysical Fluid Dynamics Laboratory; GISS, Goddard Institute for Space Studies; NCAR, National Center for Atmospheric Research; UKMO, United Kingdom Met Office.

The ozone effect within DLEM is calculated as a function of the AOT40 index. The AOT40 is defined as the accumulated dose over a threshold of 40 ppb during daylight hours (Felzer et al. 2004). In DLEM, we used an accumulation period of 30 days back-trajectory as the tropospheric ozone concentration. For the historical dataset, we developed a spatially explicit dataset of historical changes in the AOT40 index by extracting the data from the global ozone dataset developed by Felzer et al. (2004). For the future dataset (1995–2099), we used the AOT40 datasets generated from the MIT-IGSM, along with the MIT-IGSM predicted climatology (Felzer et al. 2004). For our study scenarios, we used the dataset of MIT-IGSM to produce ozone emissions for the period 1995–2099 and latitudinal band ozone for the period 1977–2099.

Base maps of soil properties and vegetation

The eleven base maps used in the model provide basic information of the location, topology, soil, and natural vegetation of the study region (Zhang 2008). Elevation, slope, and aspect maps were derived from the 7.5 minute USGS National Elevation Dataset (http://edcnts12.cr.usgs.gov/ned/ned.html). Soil datasets (acidity, bulk density, depth to bedrock, soil texture represented as the percentage content of clay, sand, and silt) were derived from the 1 km resolution digital general soil association map (STATSGO map) developed by the United States Department of Agriculture (USDA) Natural Resources Conservation Service, while the texture information of each map unit was estimated using the USDA soil texture triangle (Miller and White 1998). Our contemporary vegetation map shows the distribution of four natural plant functional groups of SEUS before human disturbances (Fig. 1), derived from GLC2000 at a resolution of 1 km (Bartholome and Belward 2005). We reclassified the potential vegetation into ten general plant functional groups and replaced the cropland and urban area in the GLC2000 with the potential vegetation types from Ramankutty and Foley (1998). Water bodies were excluded from the vegetation map (Fig. 1). All of these input data were aggregated and re-projected to a spatial resolution at 8 km × 8 km.

Model implementation

The model simulations include three stages: an equilibrium simulation, a 3000-year spin-up run, and a transient simulation. First, the model was run with long-term average climate data for the period 1901–1930, with the 1895 levels of atmospheric CO_2 concentration, tropospheric ozone, N deposition, and potential vegetation map to reach equilibrium state. The equilibrium state is defined as the absolute value of annual net carbon exchange (net balance of carbon dioxide and methane fluxes), is less than 0.1 g C/m^2, the change in the soil water pool is less than 0.1 mm, and the difference in the soil mineral nitrogen content and N uptake is less than 0.1 g N/m^2 among consecutive years. After the equilibrium simulation, a spin up of 3000 years was then applied using the climate data as described above and cropland and urban distribution in 1895 to generate the initial conditions of January 1, 1896. Finally, the model was run in transient mode, where the simulated carbon fluxes were driven by the time-series of multiple environmental changes from 1896 to 2009 and from 2010 to 2099 with projected climate scenarios. For the simulations of 2010–2099, the models were driven by climate data, atmospheric CO_2, N deposition, tropospheric ozone pollution, vegetation distribution, while land use and cover change and nitrogen fertilizer application were kept unchanged at the levels of 2009. We started the simulation in the year 1895 in order to capture the legacy effects of changes in land conversion, climate, nitrogen, ozone, and atmospheric CO_2. We focused our analysis on ecosystem carbon storage and fluxes from 2000 to 2099. Totally twenty-four simulations were set up, of which twelve were driven by climate data (4 models × 3 climate scenarios), elevated atmospheric CO_2, N deposition, and ozone pollution. The other twelve simulations were driven by climate scenario only (4 models × 3 climate scenarios), in this case the 2010–2099 data of elevated atmospheric CO_2, N deposition, and ozone pollution were kept constant at the level of 2009. The simulations were carried out with the climate data from four single models (GFDL, GISS, NCAR, and UMKO) and three climate scenarios (A1B, A2, and B1, see previous description for detailed) while the model-averaged results under each scenario are reported.

Results

Changes in climate and atmospheric chemistry during 2000-2099

Precipitation and temperature have been projected to change substantially in the SEUS over the study period (Fig. 2). Overall, air temperature shows continuously increasing trends under the three scenarios, with the highest increase under the A2 climate scenario, followed by the A1B climate scenario, and the lowest under the B1 climate scenario. The projected precipitation has essentially no trend from 2010 to 2099, with very high inter-annual variations for all three climate scenarios (Fig. 2A–C). The atmospheric CO_2 concentration continuously increases with the largest increase under the A2 scenario, and the smallest under the B1 scenario (Fig. 2D). The N deposition rate shows a slight increasing trend from 2000 to 2050, while it is assumed constant after 2050 due to the lack of data (Fig. 2E). The ozone pollution shows a substantial increasing trend, and the average AOT40 index is projected to be doubled from 2000 to 2099 (Fig. 2F).

Large spatial variations for these environmental factors and their change trends are also found (Fig. 3). The largest increase in N deposition occurs in the southwestern SEUS (>300 mg/year), while the smallest increase occurs in the eastern coastal region (0∼300 mg/year). The ozone pollution has the largest increase in the northwest and the southeast (>500 ppb-hr/month), while the smallest increase is in the western SEUS (<400 ppb-hr/month). The projected precipitation increases in the northeast and decreases in the southwest. The A2 scenario has the largest decrease in precipitation while the

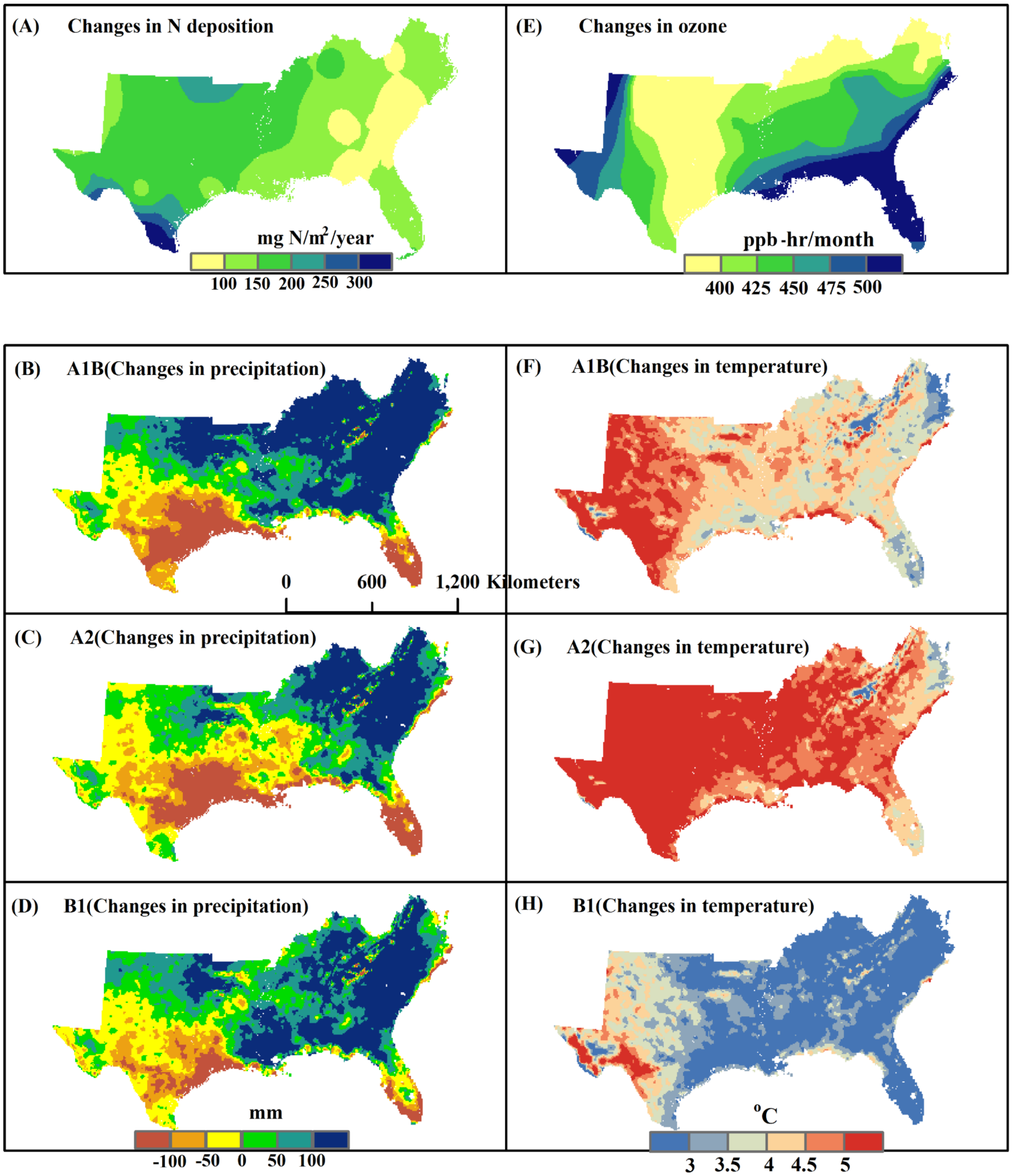

Fig. 3. Spatial variations of changes in climate variables, atmospheric CO_2 concentration, N deposition, and ozone pollution from the 2000s to the 2090s: (A) N deposition change; (B) changes in precipitation under A1B scenario; (C) changes in precipitation under A2 scenario; (D) changes in precipitation under B1 scenario; (E) ozone pollution change; (F) changes in temperature under A1B scenario; (G) changes in temperature under A2 scenario; (H) changes in temperature under B1 scenario.

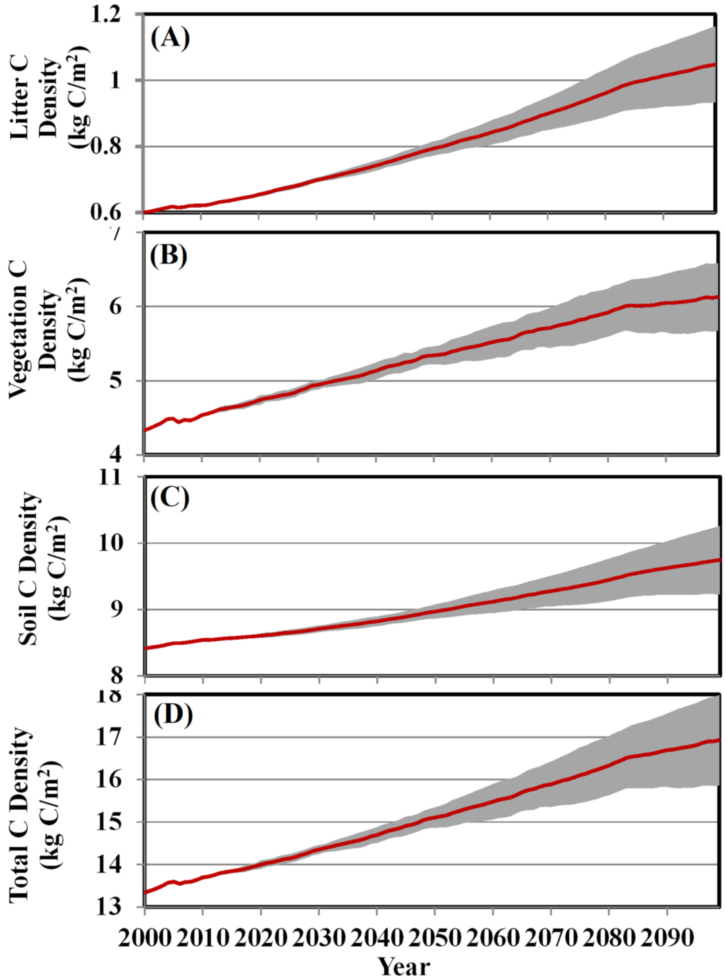

Fig. 4. Temporal variation of changes in C storage across the southeastern US from 2000 to 2090: (A) change in litter carbon; (B) change in vegetation carbon; (C) change in soil carbon; (D) change in total carbon.

A1B scenario has the largest increase. Compared to precipitation, air temperature change shows more substantial differences among climate scenarios. The A2 scenario predicts the highest air temperature across the entire SEUS (most areas with >5°C increases), while the A1B scenario projects an increase of >5°C in the west and relatively lower increases in the east (<4°C). The B1 scenario predicts a temperature increase <3°C for most areas (Fig. 3).

Temporal variation of carbon storage and fluxes from 2000 to 2099

The simulation results show that climate and atmospheric changes could largely alter terrestrial carbon storage and fluxes across the SEUS from 2000 to 2099 (Figs. 4 and 5, Table 1). Over the study period, the carbon storage in litter, vegetation and soil show continuously increasing trends with relatively small uncertainties among climate scenarios and climate models (Fig. 4). The total carbon storage (i.e., litter + vegetation + soil carbon) in terrestrial ecosystems across the SEUS is predicted to increase from 13.5 kg C/m^2 in the 2000s to 16.8 kg C/m^2 in the 2090s, which is a 24% increase (Table 1). Approximately 50% of the increase is due to increases of vegetation biomass. Carbon storage in litter will increase from 0.6 kg C/m^2 in the 2000s to 1.0 kg C/m^2 in the 2090s, vegetation carbon will increase from 4.4 kg C/m^2 in the 2000s to 6.1 kg C/m^2 in the 2090s, and the soil carbon storage is projected to

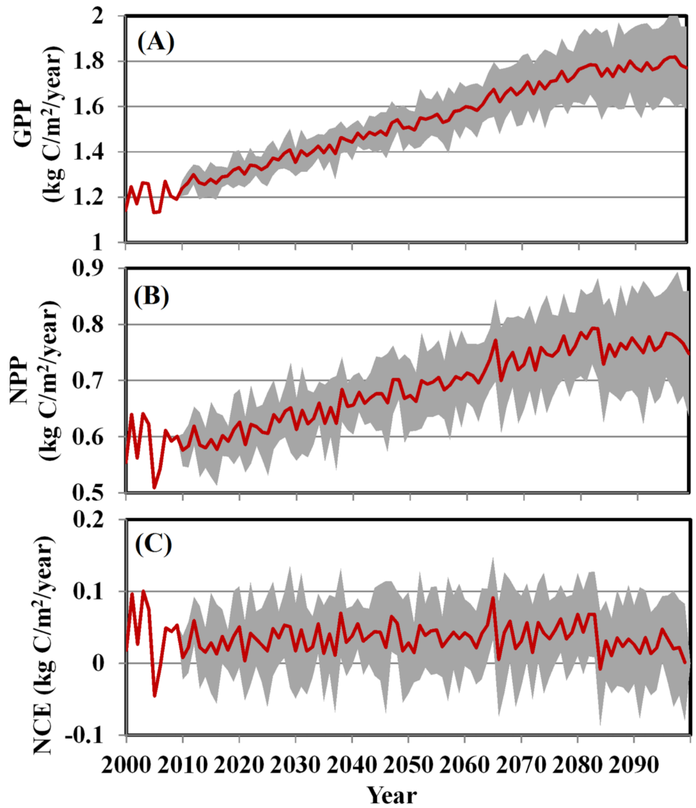

Fig. 5. Temporal variations of major C fluxes from 2000 to the 2090: (A) change in gross primary production; (B) change in net primary production; (C) change in net carbon exchange. Positive indicates sink while negative indicates source.

increase from 8.5 kg C/m^2 in the 2000s to 9.7 kg C/m^2 in the 2090s.

For the carbon fluxes, GPP and NPP are simulated to continuously increase, while the simulated NCE would slightly decrease from 2000 to 2099. Carbon fluxes show substantial inter-annual variations over the study period (Fig. 5). Although the terrestrial ecosystems will continuously act as a carbon sink (Figs. 4 and 5), the strength of the sink will become smaller at the end of the 21st century in the SEUS (Fig. 5). The decadal average shows that the NCE will decrease from 0.04 kg C/m^2/year in the 2000s to 0.02 kg C/m^2/year in the 2090s, with a 43% decrease (Table 1). The GPP is simulated to increase from 1.2 kg C/m^2/year in the 2000s to 1.8 kg C/m^2/year in the 2090s, and the NPP will increase from 0.6 kg C/m^2/year in the 2000s to 0.8 kg C/m^2/year in the 2090s. The decreases in NCE from the 2000s to 2099s are primarily due to faster increases in ecosystem heterotrophic respiration compared to those of NPP (Fig. 5).

Table 1. Changes of carbon fluxes and storage from 2000s to the 2090s (percentage changes shown in parentheses.)

Variable	2000s	2090s	Change
GPP (kg C m^{-2} yr^{-1})	1.2	1.8	0.6 (49)
NPP (kg C m^{-2} yr^{-1})	0.6	0.8	0.2 (30)
NCE (kg C m^{-2} yr^{-1})	0.04	0.02	−0.02 (−43)
Litter C (kg C m^{-2})	0.6	1.0	0.4 (68)
Vegetation C (kg C m^{-2})	4.4	6.1	1.7 (37)
Soil C (kg C m^{-2})	8.5	9.7	1.2 (14)
Total C (kg C m^{-2})	13.5	16.8	3.3 (24)

Spatial distribution of carbon storage and fluxes and their changes

The simulated carbon storage and fluxes across the SEUS and their changes from the 2000s to the 2090s show substantial spatial heterogeneities

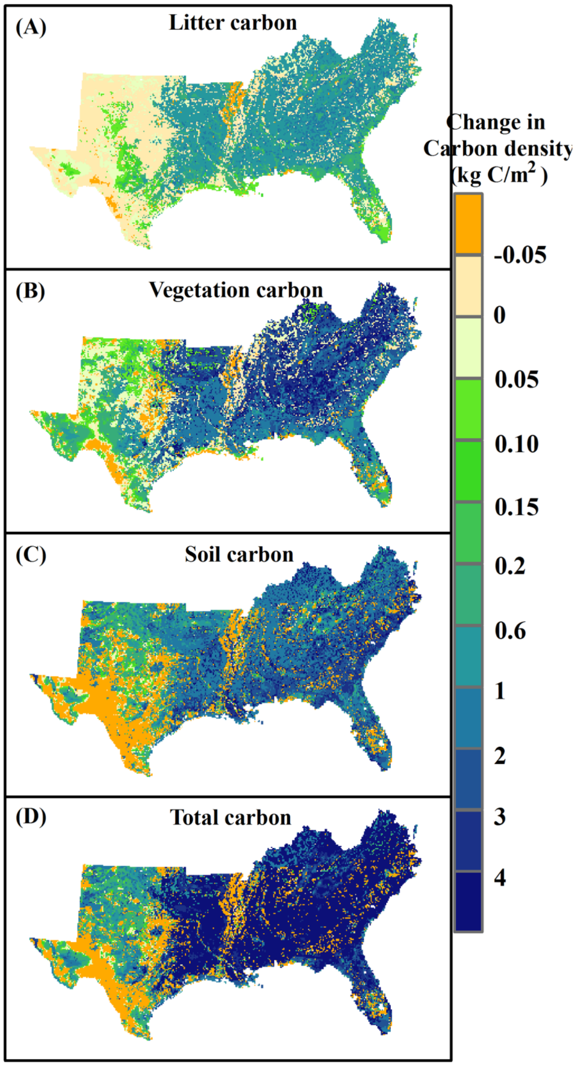

Fig. 6. Spatial variation of changes in C storage across the southeastern US from 2000s to the 2090s: (A) change in litter carbon; (B) change in vegetation carbon; (C) change in soil carbon; (D) change in total carbon.

(Figs. 6–8, Table 1). Litter carbon decreases slightly in the western SEUS, while it increases in the central and eastern SEUS. Vegetation carbon shows an increasing trend in most areas, yet a decreasing trend in small areas of the western SEUS is seen. Soil carbon also increases in most areas, while it decreases in some areas in the southwest. The total carbon storage shows a slight decrease in some areas of the central SEUS, while it increases in most other areas in the SEUS (Fig. 6).

GPP, NPP, and their changes show large spatial variations from the 2000s to the 2090s (Figs. 7 and 8). The simulated GPP is usually less than 0.8 kg C/m^2/year near the western boundary of SEUS; while it is generally higher than 1.2 kg C/m^2/year in the 2000s and is higher than 1.8 kg C/m^2/year in the 2090s in the central and eastern SEUS. With a similar spatial pattern, the simulated NPP is usually less than 0.4 kg C/m^2/year in the western SEUS, while it is generally higher than 0.6 kg C/m^2/year in the 2000s and is higher than 0.9 kg C/m^2/year in the 2090s in the central and eastern SEUS. Changes in GPP and NPP from the 2000s to the 2090s are quite consistent, showing decreases in the western SEUS, and increases in the central and eastern SEUS (Figs. 7C and 8C).

Carbon fluxes of major biomes

The simulated results indicate large variation in the responses of various biomes to future environmental changes. Both deciduous and evergreen forests show large increases, grassland and shrubland show small increases, while cropland shows a decrease in carbon storage from the 2000s to the 2090s. The carbon storage in the deciduous forest shows a 42.2% increase from 14.7 kg C/m^2 in the 2000s to 20.9 kg C/m^2 in the 2090s, the evergreen forest shows a 23.2% increase from 22.0 kg C/m^2 to 27.1 kg C/m^2, the grassland shows a 4.5% increase from 12.4 kg C/m^2 to 12.9 kg C/m^2, and shrubland shows no change at 10.4 kg C/m^2, while cropland shows a 3.8% decrease from 5.8 kg C/m^2 to 5.5 kg C/m^2 (Fig. 9). Most of the carbon is sequestered in the vegetation for the deciduous forest (57% of total carbon increase), and in the soil for evergreen forest (50% of total carbon increase) (Fig. 9).

Since the forest accounts for more than half of the land area, the largest potentials for carbon sequestration in forest indicate that the SEUS may continuously serve as a strong carbon sink in the 21st century, though the carbon sink strength is projected to decrease.

Carbon fluxes under different climate scenarios and prediction models

The simulated carbon fluxes vary substantially among climate scenarios and climate models. Over the study region, the simulation driven by

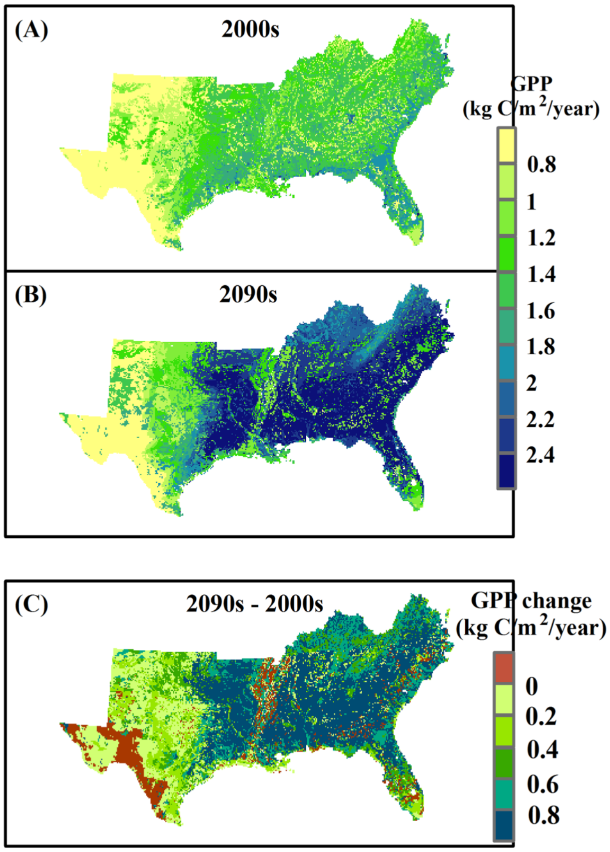

Fig. 7. Spatial distribution of GPP across the southeastern US in the (A) 2000s and (B) 2090s and (C) its changes from 2000s to the 2090s.

NCAR-climate conditions under the A1B scenario has the largest increase in carbon storage, with a 38% increase from the 2000s to the 2090s, while the simulation driven by GFDL-climate conditions under A2 scenario has the smallest increase in carbon storage, with a 16% increase from the 2000s to the 2090s (Fig. 10).

Overall, climate and atmospheric change together would result in the average increases in carbon storage for the four GCMs by 25% under A2 scenario, 21% under B1 scenario, and 27% under A1B scenario from the 2000s to the 2090s. For the three future scenarios, the average increases of total carbon storage would be 17% for GFDL, 29% for GISS, 32% for NCAR, and 20% for UKMO.

Discussion

Comparison with other studies

The simulated spatial patterns of carbon storage and fluxes in the recent decade are consistent with our previous studies (Chen et al. 2006, Tian et al. 2012*a*), showing larger carbon sinks in the central and eastern than the western SEUS. This study simulated a large potential of carbon sequestration in the SEUS, which is consistent with other studies, using inversion models or the inventory method (Pacala et al. 2001, Pan et al. 2011, Hayes et al. 2012). The strong carbon sink in forest is also consistent with a recent finding that global forests are a large and persistent carbon sink (Pan et al. 2011).

The finding that climate change alone could not lead to a substantial carbon sequestration is consistent with other studies (Schimel et al. 2000, Cramer et al. 2001, Albani et al. 2006), indicating

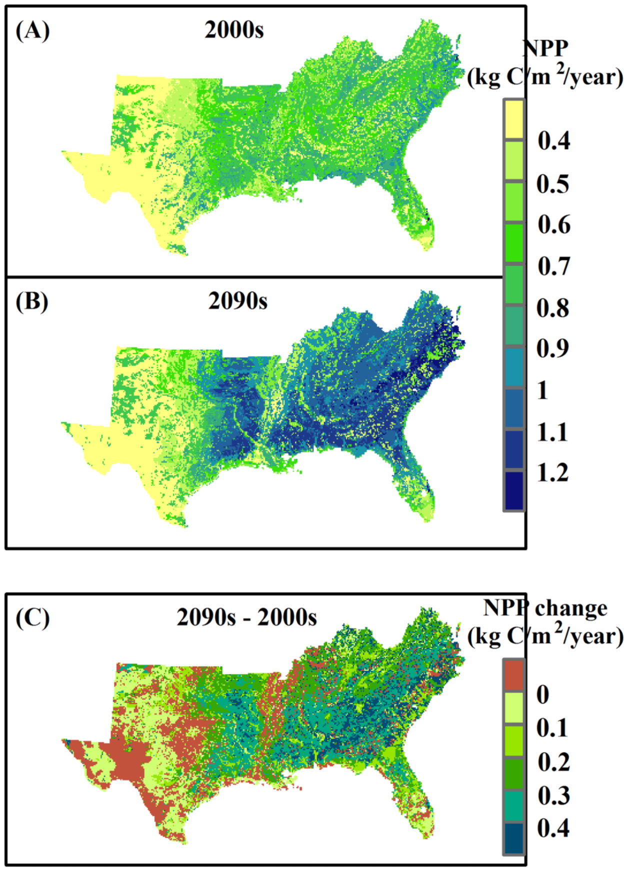

Fig. 8. Spatial distribution of NPP across the southeastern US in the (A) 2000s and (B) 2090s and (C) its changes from 2000s to the 2090s.

that the nitrogen input as well as elevated atmospheric CO_2 are the key drivers for enhanced carbon sink strength in this region (Pinder et al. 2012). For example, a recent study found that climate variability makes a minor contribution to the long-term carbon storage and fluxes in the 21st century (Albani et al. 2006). Albani et al. (2006) also reported that forest

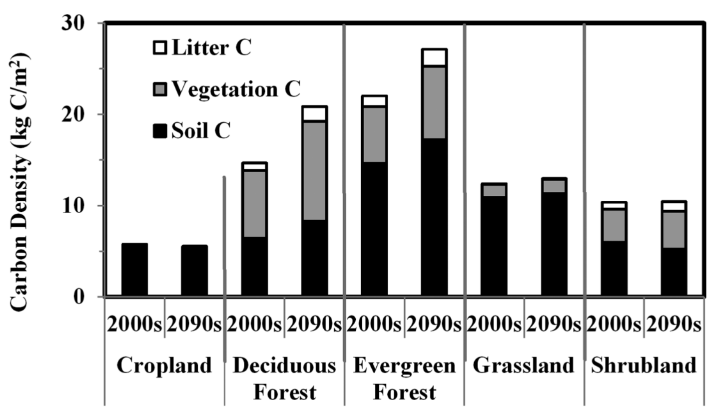

Fig. 9. Biome-level contribution to the C sequestration across the southeastern US from 2000s to the 2090s.

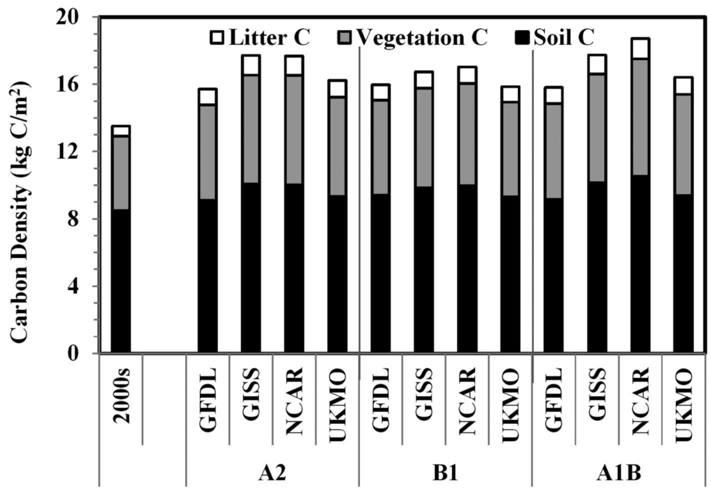

Fig. 10. Modeled temporal variation of changes in C storage across the southeastern US from 2000 to 2090 solely driven by projected climate: (A) change in litter carbon; (B) change in vegetation carbon; (C) change in soil carbon; (D) change in total carbon.

regrowth is the key mechanism driving continuous carbon sequestration (Albani et al. 2006), thus the relatively young forests in the study area will act as a strong carbon sink for a long time period. This study also found the negative effect of ozone pollution on carbon sequestration, which has been supported by a number of previous studies (Felzer et al. 2004, Ren et al. 2007).

Controls on carbon storage and fluxes

Temperature and precipitation as well as other environmental factors including nitrogen and elevated CO_2 could affect ecosystem functioning such as carbon fluxes at scales from stomata to regional (Farquhar et al. 1980, Melillo et al. 1993, Cramer et al. 2001, Thornton et al. 2002, Zeng et al. 2005). Over the time period of 2010–2099, we find that climate change contributes less to the increase in total carbon storage (Fig. 11D), as compared with elevated atmospheric CO_2 and N deposition (Fig. 4D). This is consistent with a previous study based on a multi-model analysis (Cramer et al. 2001). In that study, they reported that the global NPP continuously increased through the 2090s and attributed the increase to the CO_2 fertilization effect (Cramer et al. 2001), which is consistent with our conclusion. The precipitation had short-term impacts, but did not play an important role in the long-term changes in carbon fluxes over the SEUS.

Overall, considering climate change only, the carbon storage in litter, vegetation, and soil will increase before the 2050s and then decline; the total carbon storage will be slightly higher in the 2090s than the 2000s, but much smaller than in the 2050s. Therefore, the carbon sequestration in the study region is primarily attributed to elevated atmospheric CO_2 and nitrogen deposition; the ozone pollution has negative effects while the climate change has very small positive effects on carbon storage over the study period.

Carbon sequestration at biome level

This study concludes that forests have the highest potential to sequester more carbon than other biomes in the 21st century. Grasslands and shrublands will act as very small carbon sink, while cropland will act as a small carbon source. The SEUS has usually contributed to more than 60% of wood supply of the entire U.S. (Adams et al. 2006). The frequent harvest for wood products creates a young forest age structure, and these young forests have been reported to act as strong carbon sinks (Albani et al. 2006).

The reason that grasslands and shrublands will act as very small carbon sinks is that grasslands and shrublands usually receive less precipitation but with higher inter-annual climate variability than forested ecosystems. These two ecosystems

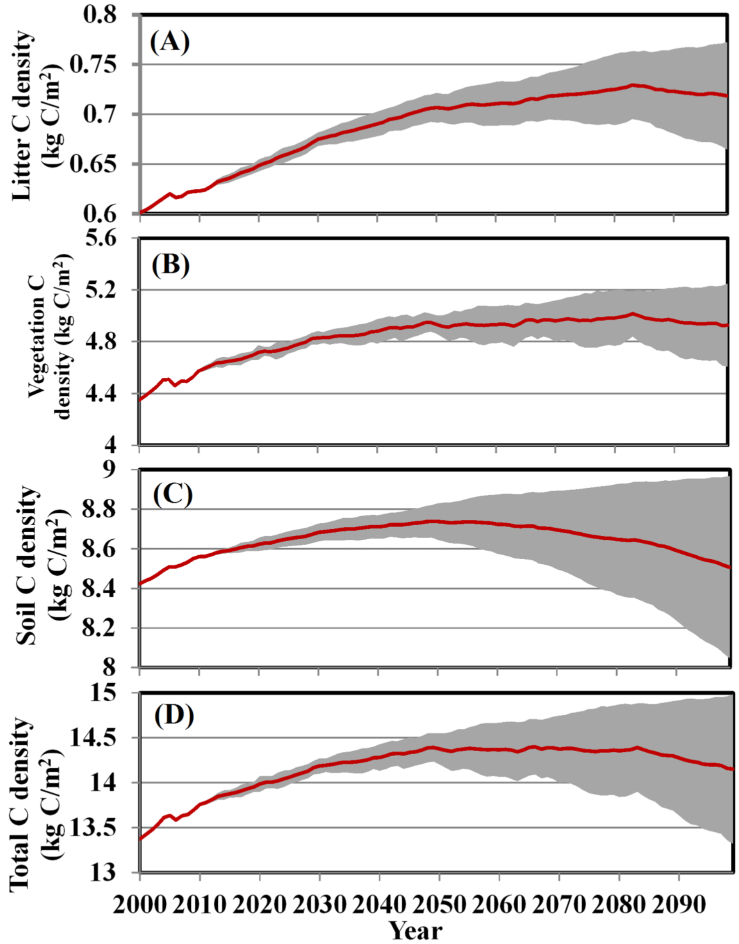

Fig. 11. Change in C sequestration across the southeastern US from 2000s to the 2090s under three climate scenarios as simulated by four climate models: (A) A2 climate scenario; (B) B1 climate scenario; (C) A1B climate scenario. Climate model abbreviations are: GFDL, Geophysical Fluid Dynamics Laboratory; GISS, Goddard Institute for Space Studies; NCAR, National Center for Atmospheric Research; UKMO, United Kingdom Met Office.

are primarily distributed in the western SEUS and no significant increase in precipitation is projected for this region (Fig. 3C, E, G). Meanwhile, this study found that cropland will be a small carbon source in the 21st century. This is because the carbon sink in croplands is solely calculated from the changes of soil carbon, and the crop yield which will be removed and utilized by human society is not taken into account as a carbon sink component.

Carbon dynamics among climate scenarios and climate models

Carbon storage is simulated to increase from the 2000s to the 2090s, which is consistent across climate scenarios and climate models. However, this study does show large discrepancies in magnitude of carbon storage change among climate scenarios and climate models (Fig. 10). Also, the carbon storage differences among the climate scenarios are not consistent with the future policy scenarios. For example, the A2 scenario features the highest elevated CO_2 concentration which has a fertilization effect on vegetation growth; however the greatest simulated carbon sequestration occurs under the A1B scenario. This indicates the complicated mechanisms for terrestrial ecosystems in assimilating carbon from the atmosphere (Heimann and Reichstein 2008). It also indicates that the regional case is not absolutely consistent with global projections (Callaghan et al. 2004, McGuire et al. 2006). More regional studies on carbon dynamics under projected climate scenarios are needed for regional policy making and scientific advance (Wofsy and Harriss 2002).

Uncertainties and research needs

This study examined the effects of future environmental changes on carbon fluxes over the SEUS in the 21st century. Information generated from this study would be helpful for policymakers targeting better management of the terrestrial ecosystems in the SEUS. Like any other projection study, there are some uncertainties in this study that need to address in future research, particularly the accuracy of model driving forces and modeling mechanisms in simulating changes in ecosystem structure and function. Specifically, for this study, several uncertainties need to be considered when interpreting the results. First, the land use and land cover may evolve under the projected climate change as predicted by a number of dynamic global vegetation models (Kittel et al. 2000, Cramer et al. 2001). But many other factors such as policy may influence land use change and cause uncertainty in the projection. Second, this version of the DLEM only considers the dominant vegetation type in each grid cell. But due to the high spatial heterogeneity of vegetation, no uniform land surface exists. Considering mixed vegetation types would be a great improvement in ecosystem carbon and water flux estimation. Third, terrestrial ecosystems are facing more environmental changes than those considered in the current study, for example, insect outbreaks and disease. However, the availability of these datasets is limited for this study. Fourth, the statistical downscaling approach has been used in preparing climate data in this study. Even though it has been confirmed that the statistical downscaling method could generate data with quite good quality (Liang et al. 2006, Kim et al. 2007), the data might still need to be improved, especially for the southern boundary region and the mountain region (Xue et al. 2007). Finally, the acclimation of ecosystems to temperature and precipitation changes is one of the major mechanisms by which plants will adjust to environmental stresses (Stirling et al. 1997, Oechel et al. 2000). The effects of projected changes in temperature and precipitation estimated in this study might be overestimated if we take plant acclimation into account. It would be more accurate and precise if several of these shortcomings could be overcome in future work.

Conclusions

Through a modeling analysis with support of projected climate data predicted by four climate models under the three climate scenarios, the study reports the projected spatial and temporal changes in carbon storage and fluxes across the SEUS region resulting from the combined impacts of climate and atmospheric changes. The key findings are (1) the terrestrial ecosystems in the SEUS will likely be continuously sequestering carbon in the 21st century; (2) the carbon sequestration is primarily caused by elevated atmospheric CO_2 and nitrogen deposition; (3) the terrestrial GPP and NPP probably will continuously increase, while NCE will slightly decrease through the 2090s; (4) forests will be the major contributor to the continuous carbon sink, while croplands will be a very small carbon source in the 21st century; (5) the central and eastern SEUS will sequester carbon, while the southwestern part will release carbon to the atmosphere; (6) the A1B scenario favors more carbon sequestration than the A2 and B1 scenarios; and the projected climate condition by the NCAR model is more favorable for carbon sequestration than the other three climate models.

This study, focusing on the projection of carbon dynamics in the SEUS, is among the first attempts to assess carbon storage and fluxes and their changes across the SEUS during the 21st century. The findings obtained through this study will provide fundamental information for policymakers to adapt to and mitigate climate change impacts. For example, the large and persistent carbon sink in forest ecosystems will be convincing evidence for continuous forestation in this area. Given that land use and land cover change are not considered in this study, future effort is needed to investigate the impacts of projected land use and land cover change in the 21st century.

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