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Predicting response of fuel load to future changes in climate and atmospheric composition in the Southern United States

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ABSTRACT

The model projected ecosystem carbon dynamics were incorporated into the default (contemporary) fuel load map developed by FCCS (Fuel Characteristic Classification System) to estimate the dynamics of fuel load in the Southern United States in response to projected changes in climate and atmosphere (CO_2 and nitrogen deposition) from 2002 to 2050. The study results indicated that in 2002 the total fuel load of the Southern United States was about 1.15 Pg (1 P = 10^{15}), which will decrease to 1.11 Pg in 2050. The declination of fuel load is mainly due to the climate change, especially the reduced precipitation in 2050, while the effects of elevated CO_2 and nitrogen deposition will increase fuel load. Interactions among all factors will result in 1% reduction in the fuel load in 2050. In response to the spatial heterogeneity in environmental changes, the dynamics of fuel load from 2002 to 2050 vary strongly among the study states. The declined precipitation in the northern inland of the study region may lead to 20% fuel load reduction in Tennessee and Kentucky by the year of 2050, while the elevated precipitation and decreased daily mean temperature in the coastal states, especially in South Carolina, North Carolina, and Virginia, may result in fuel load accumulation. The temporal–spatial variation of the fuel load may be overestimated since the adjustments of forest management regime in response to climate change were not considered in current study.

1. Introduction

The area burned in the Southern US (SUS) is the most in any region of the United States (Stanturf et al., 2002). About 8 million acres of forest, range, and cropland are burned annually. After the fire suppression effort in the first half of the 20th century due to the passage of the Clarke-McNary Act of 1924, prescribed fire gradually became a common practice in the managed forest of the South. Besides prescribed fires, wild fires are also common in this region (Southern Appalachian Man and the Biosphere, 1996). It is expected that future fire emissions will be altered in response to climate change, due in large part to changes in fuel load. Dynamic fuel mapping with high resolution is required for regional fire hazards assessments, fire emission inventory, and air quality maintenance in the 21st century (Stanturf et al., 2003; McKenzie et al., 2006; Arroyo et al., 2008). Recently, a 1-km resolution fuel load map of the conterminous USA was developed based on the 112 fuel beds on the Fuel Characteristic Classification System (FCCS) which was compiled from scientific literature, fuel photo series, fuel data sets, and expert opinions (McKenzie et al., 2007; Ottmar et al., 2007; Riccardi et al., 2007).

Although the FCCS database includes fuel load ranges for each fuel bed type, it does not provide the spatial and temporal (e.g. seasonal) patterns of how the load of a fuel bed type varies in response to the environmental heterogeneity. In reality, ecosystems are dynamic and the heterogeneity of fuel loads is related to the variations in vegetation biomass, mortality rate, and litter decomposition rate, which in turn are responsive to spatial variation in parent material and temporal fluctuation in climate and atmospheric composition (Krasnow et al., 2009; Robinson et al., 2007). Since the FCCS is based on observations and expert knowledge of current ecosystem, it is also unable to predict the dynamics of fuel load caused by the rapid climate changes in the future. Most climate change studies projected considerable rise in temperature and significantly altered spatial and seasonal patterns of precipitation in the Southern US (Sun et al., 2008). According to the Hadley Climate Model, for example, temperature will increase across the Southern US by nearly 1.5 °C by year 2050, and precipitation will increase in the northeast part of the SUS. The changes in climate and atmospheric composition (elevated CO_2 concentration and nitrogen deposition) will have profound impacts on the structure of southern ecosystems, resulting significant changes in regional fuel

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load in the 21st century (McKenzie et al., 2004). As put by McKenzie et al. (2007): "Dynamic fuel mapping is necessary as we move into the future with rapid climatic change ..."

To project the ecosystem's response to environmental changes, process-based ecosystem models have been developed to simulate the dynamics of living or dead organic matter pools in daily or monthly time step. The Dynamic Land Ecosystem Mode (DLEM, Tian et al., 2010), for example, has been used to estimate the impacts of long-term changes in climate and atmosphere on the vegetation biomass, coarse woody debris, litter pools and soil organic matter of a forest ecosystem in the Southern US (Zhang et al., 2007; Tian et al., 2008). The compartments/pools of ecosystem models can be linked to different fuel types (Allaby, 1998; Tian et al., 2005, 2010). Consequently, ecosystem model simulation can provide valuable information of the fuel load dynamic in response to environmental changes. In this study, we combined the DLEM future projections and current FCCS fuel load map to estimate the fuel load of SUS in 2050 and analyze the variations of fuel load pattern in response to changes in climate and atmosphere during the first half of the 21st century.

2. Research method

2.1. Study area

The study region includes 13 southern states: Alabama, Arkansas, Florida, Georgia, Kentucky, Louisiana, Mississippi, North Carolina, Oklahoma, South Carolina, Tennessee, Texas, and Virginia. Fifty-three fuel beds were identified by the FCCS in the SUS (Fig. 1). The largest fuel bed type is loblolly pine – short leaf pine – mixed hardwoods forest, which covers about 175,059 km^2 in SUS. In this study, the fuel load of urban, cropland, and wetlands was not estimated due to the big uncertainties in the fuel loads of these land types (Fig. 1).

We first generated the future climate change dataset under the IPCC (Intergovernmental Panel on Climate Change) A1B scenario (http://www.ipcc.ch/) with climate model. Then, the Dynamic Land Ecosystem Model was driven by spatial explicit (Table 1) to project the spatial and temporal pattern of carbon pools in the SUS with 8 km × 8 km resolution and daily time step for 2002 and 2050. The model generated carbon maps were downscaled to 1 km × 1 km resolution using bilinear interpolation to match the resolution of FCCS fuel load map. Next, the carbon pools were linked to different fuel types to predict the spatial and temporal pattern of fuel loads. The fuel load maps of 2002 and 2050 were generated by integrating the model generated carbon dynamics of fuel beds into the FCCS fuel load map.

2.2. Generate the climate change dataset

Climate change dataset was developed in two steps. First, coarse resolution ($4^\circ \times 5^\circ$) daily climate datasets were generated by the GISS (Goddard Institute for Space Studies) GCM 2 (Global Climate Model) (Rind et al., 1999; Mickley et al., 2004). It had nine vertical layers which extended from surface to 10 hPa. The simulation period spanned from 1950 to 2055 (Mickley et al., 2004). Observed greenhouse gas concentrations were used before year 2000. During the period of 2000–2055, the emissions of CO_2, CH_4, N_2O, and halocarbons followed the A1B scenario (i.e. climate projection based on the assumption of rapid economic growth, low population growth, and moderate resource use with a balanced use of technologies in the future) of IPCC. Ozone and aerosols were fixed at present values in the radioactive scheme.

In the second step, the Penn State/NCAR Mesoscale Model (MM5) was applied to downscale the global climate simulation to a regional domain (36 km × 36 km resolution) (Grell et al., 1994; Leung and Gustafson, 2005). The global simulation results were used to specify initial and lateral boundary conditions for MM5 simulations. MM5 physical schemes used in the simulations include Dudhia shortwave radiation, RRTM longwave radiation, KF convective parameterization, Reisner mixed phase cloud microphysics, countergradient turbulence transport, and OSU land surface model. MM5 used two-way nesting with grid distances of 108 km for outer domain and 36 km for inner domain. There were 23 vertical layers in the sigma coordinate. Hourly meteorological fields such as wind, pressure, and temperature were generated for the inner domain. Finally, with bilinear interpolation, the MM5 outputs were downscaled to 8 km resolution to develop the daily climate inputs (maximum, minimum, and mean temperature, and daily precipitation) required by DLEM. The sources of other inputs required by DLEM were listed in Table 1. All datasets were gridded into 8 km × 8 km resolution maps.

2.3. Calculating fuel load based on the carbon outputs of DLEM

The Dynamic Land Ecosystem Model is a spatial-explicit, process-based terrestrial ecosystem model that simulates daily carbon, water and nitrogen cycles as influenced by changes in atmospheric chemistry (ozone and nitrogen deposition), climate, CO_2 concentration, land-use and land-cover types and disturbances (fire, hurricane, and harvest). Various components and processes simulated in DLEM were described extensively in other studies (Chen et al., 2006; Liu et al., 2007; Ren et al., 2007; Tian et al., 2005, 2008). The effectiveness of the model to simulate the forest landscape in SUS has been tested elsewhere (Tian et al., 2010). For the purpose of regional validation, we compared the state-level model predictions against the forest inventory dataset (http://www.fia.fs.fed.us/) in this study.

By linking the DLEM carbon pools to different fuel types, we calculated the fuel load in the Southeast using the equation developed by Barnard and Brewer (2004):

$$\begin{aligned}\text{Fuel} &= \text{hr1} + \text{hr10} + \text{hr100} \times 0.5 + (\text{hr1000} + \text{hr10k} + \text{hr10kplus}) \\ &\quad \times 0.1 + \text{shrub} \times 0.4 + \text{grass} \times 0.1 \qquad (1)\end{aligned}$$

where shrub and grass are biomass (g/m^2) of shrub and grass; hr1, hr10, hr100, hr1000, hr10k, and hr10kplus denote the mass (g/m^2) of fuel types with 1 h, 10 h, 1000 h, 10,000 h, and more than 10,000 h time lag, respectively. Table 2 shows the definition of each fuel type and their corresponding carbon pools in DLEM. The litter pools of DLEM include dead leaf, bark, small twig, and fragment of branch. We thus assumed the litter pool to be positively correlated to the 1-h fuel (hr1) and 10-h fuel (hr10). The coarse woody debris in DLEM refers to dead wood and large branches. We assumed that coarse woody debris is positively correlated to the fuel types with 100 h or longer time lag.

Based on field observations and expert opinions, FCCS database provides the estimated range (maximum, mean, and minimum values) of fuel load for each fuel type in each of the fuel beds/vegetation types (Riccardi et al., 2007). Through model simulation, we calculated the minimum, mean, and maximum carbon pool sizes for the corresponding fuel types based on Table 2. The actual fuel load in the study region, however, varies both temporally and spatially. To estimate the daily fuel load in each 1-km resolution subregion (i.e. a single grid/pixel in the fuel bed map) of the study area, we assumed that the variations in fuel load is linearly correlated with the variation in carbon pool:

$$\text{Fuel}_{d,g,f,v} - \text{Fuel}_{mean,f,v} = R_{f,v} \times (C_{d,g,f,v} - C_{\text{mean},f,v})$$

or

$$\text{Fuel}_{d,g,f,v} = \text{Fuel}_{\text{mean},f,v} + R_{f,v} \times (C_{d,g,f,v} - C_{\text{mean},f,v})$$

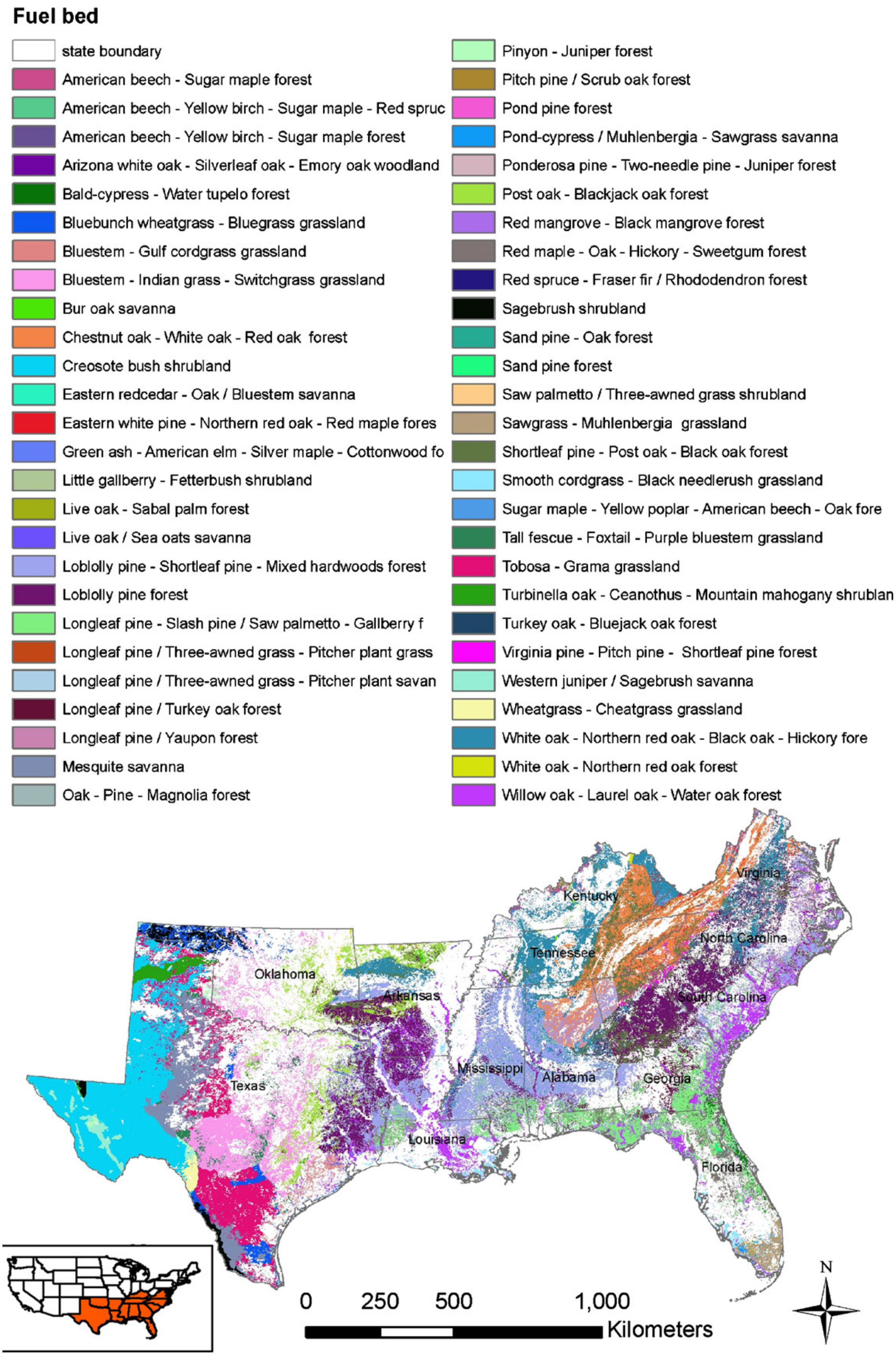

Fig. 1. The fuel beds of the southern United States (adapted from Ottmar et al., 2007; McKenzie et al., 2007 with permission).

Table 1
Data types and sources for model input in the simulation of Southeast U.S.

Data types	Unit	Methods and sources[a]
Vegetation	Categories	The plant physiological parameters were assigned to each vegetation type in the FCCS fuel bed map (Fig. 2) according to the plant functional type (PFT) that composed the fuel bed. Six PFTs were identified: deciduous broad-leaf forest, evergreen broad-leaf forest, coniferous needle-leaf forest, shrubs and scrubs, C3-grass, C4-grass.
Soil clay content Soil-sand content Soil silt content Soil depth Soil acidity Soil bulk density	% % % M pH g/cm^3	Based on the 1-km resolution digital general soil association map (STATSGO map) that was developed by the United States Department of Agriculture (USDA) Natural Resources Conservation (NRC). The texture information of each map unit was estimated using the USDA soil texture triangle (Miller and White, 1998; Miller et al., 2004).
Elevation map Aspect map Slope map	m Degree Degree	Generated from the 7.5-min USGS National Elevation Dataset (NED). Data available online: http://edcnts12.cr.usgs.gov/ned/ned.html
CO_2	ppmv	CO_2 concentrations before 2009 were based on observations by the Earth System Research Laboratory (NOAA/ESRL) (www.esrl.noaa.gov/gmd/ccgg/trends/); CO_2 concentration in 2050 was estimated to be 480 ppmv, based on IPCC A1B scenario (http://www.ipcc.ch/). Linear interpolation was used to estimate CO_2 concentration between 2010 and 2050.
Ozone stress index, AOT40[b]	ppb-h	Spatial interpolation based on records from 181 ozone stations (Felzer et al., 2004). We assumed no changes in ozone stress in the 21st century.
NH_x deposition NO_y deposition	$gN/(m^2$ year) $gN/(m^2$ year)	Date derived from the global nitrogen deposition maps (1993 and 2050) generated by Dentener (2006) using atmospheric chemical model. Linear interpolation was used to develop the annual data between 1993 and 2050. The original coarse resolution ($0.5^\circ \times 0.5^\circ$) datasets were rescaled to 8×8 resolution with bilinear interpolation.

[a] All model inputs were developed into spatial maps with 8 km × 8 km resolution.
[b] AOT40 is the accumulated dose over a threshold of 40 ppb during daylight hours.

where $\mathrm{Fuel}_{mean,v,f}$ is the default/mean fuel load of fuel type f in fuel bed/vegetation type v as estimated by FCCS. $\mathrm{Fuel}_{d,g,v,f}$ is the fuel load of day d in simulation grid g. $C_{\mathrm{mean},f,v}$ and $C_{d,g,f,v}$ are the corresponding carbon pools, respectively. $\mathrm{Fuel}_{d,g,v,f} - \mathrm{Fuel}_{mean,v,f}$ is the variation of fuel load from the FCCS default value, while $C_{\mathrm{mean},f,v} - C_{\mathrm{mean},f,v}$ is the variation of carbon pool from the regional mean value as simulated by the DLEM model. $R_{f,v}$ is the correlation coefficient that converts the carbon density to fuel load. We calculated $R_{f,v}$ by comparing the range of fuel load against the range of carbon pool:

$$\begin{cases} R_{f,v} = \dfrac{\mathrm{Fuel}_{\max,f,v} - \mathrm{Fuel}_{\mathrm{mean},f,v}}{C_{\max,f,v} - C_{\mathrm{mean},f,v}}, & (C_{d,g,v,f} \geq C_{\mathrm{mean},v,f}) \\ R_{f,v} = \dfrac{\mathrm{Fuel}_{\min,f,v} - \mathrm{Fuel}_{\mathrm{mean},f,v}}{C_{\min,f,v} - C_{\mathrm{mean},f,v}}, & (C_{d,g,v,f} \geq C_{\mathrm{mean},v,f}) \end{cases} \tag{3}$$

where $\mathrm{Fuel}_{\max,f,v}$ and $\mathrm{Fuel}_{\min,f,v}$ are the maximum and minimum fuel load values reported by the FCCS database. $C_{\max,f,v}$ and $C_{\min,f,v}$ are the corresponding carbon pools derived from model simulation.

The fuel load of 2050 was estimated based on the carbon dynamics from 2002 to 2050.

$$\mathrm{Fuel}_{2050,d,g,v,f} = \mathrm{Fuel}_{2002,d,g,v,f} \times \frac{C_{2050,d,g,v,f}}{C_{2002,d,g,v,f}} \tag{4}$$

2.4. Scenario design

To analyze the impacts of climatic and atmospheric changes in CO_2 and nitrogen deposition on the fuel load of SUS from 2002 to 2050. We designed the following five scenarios.

Baseline_2002: DLEM was driven by the climate and atmospheric dataset in 2002;
Climate_2050: DLEM was driven by the climate of 2050, other inputs are same to Baseline_2002. This scenario was used to project the impacts of climate change on future fuel load;
CO2_2050: Only CO_2 concentration changed from 2002 to 2050, other inputs are same to Baseline_2050. This scenario was used to project the impacts of CO_2 change on future fuel load;

Table 2
Description of fuel types and their corresponding pools in the Dynamic Land Ecosystem Model (DLEM).

Fuel type	Description[a]	Corresponding pools in DLEM
1-h time lag	Dead fuels consisting of herbaceous plants or roundwood less than one-quarter inch in diameter. Also included is the uppermost layer of liter on the forest floor.	Litter pool
10-h time lag	Dead fuels consisting of roundwood in the size range of one quarter to 1 in. in diameter and very roughly, the layer of litter extending from just below the surface to three quarters of inch below the surface.	
100-h time lag	Dead fuels consisting of roundwood in the size range of 1–3 in. in diameter and, very roughly, the forest floor from three quarters of an inch to 4 in. below the surface.	Coarse woody debris
≥1000-h time lag	Dead fuels consisting of roundwood 3–8 in. in diameter or the layer of the forest floor more than about 4 in. below the surface or both.	
Grass	Aboveground part of herbaceous plants.	Aboveground grass biomass
Shrub	Scrub vegetation and stands of tree species that do not produce merchantable timber.	Aboveground shrub biomass

[a] Based on the National Fire-Danger Rating System (Deeming et al., 1977).

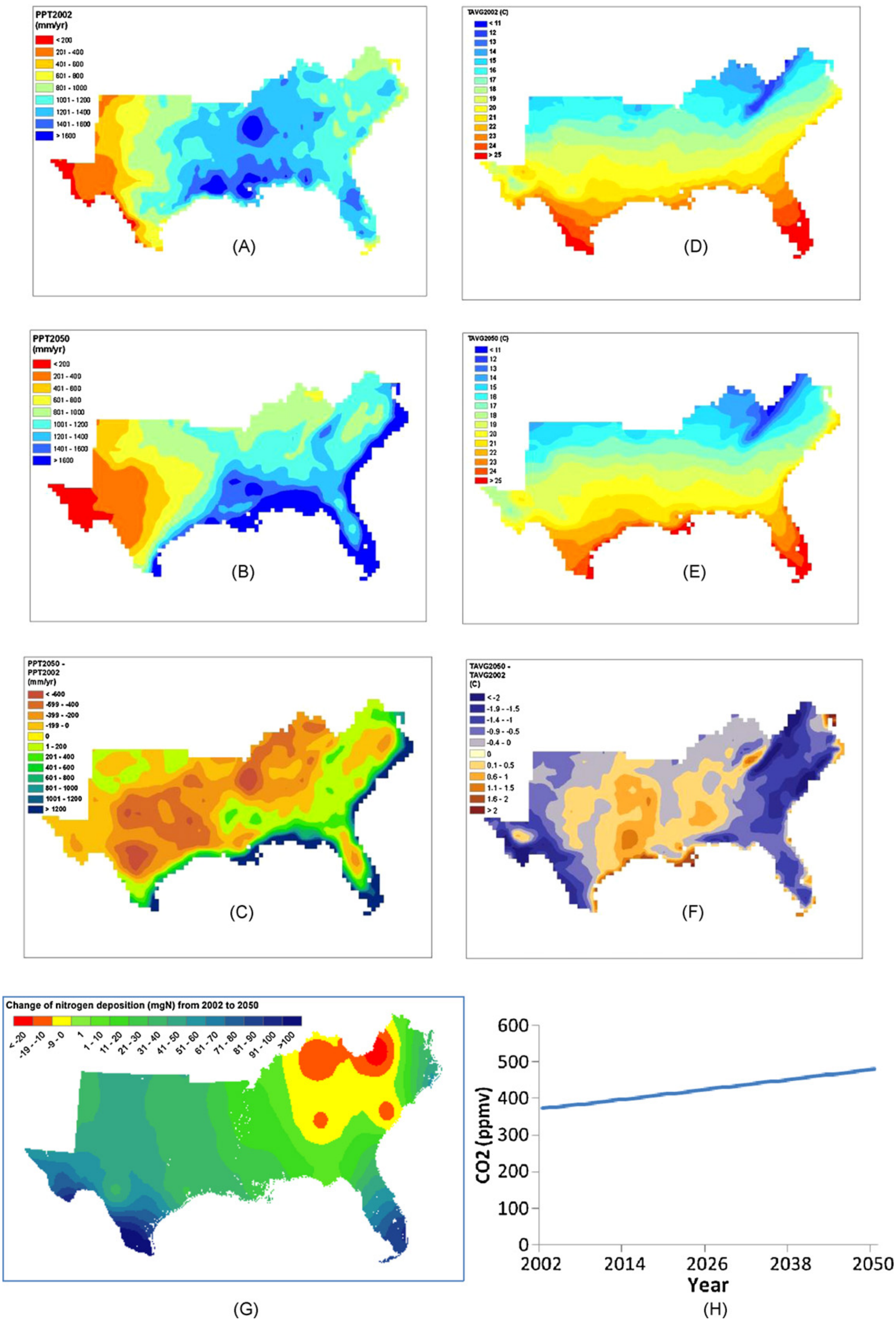

Fig. 2. The temporal–spatial pattern of environmental changes from 2002 to 2050 in the Southern United States. (A) Annual precipitation (mm/year) in 2002, (B) annual precipitation (mm/year) in 2050, (C) changes in precipitation (calculated as precipitation 2050 – precipitation 2002); (D) annual average daily temperature (°C) in 2002, (E) annual average daily temperature (°C) in 2050; (F) changes in temperature (calculated as temperature 2050 – temperature 2002); (G) change of nitrogen deposition from 2002 to 2050 (based on Dentener, 2006); (H) annual changes in CO_2 concentration (ppmv) from 2002 to 2050. We assume no spatial heterogeneity of atmospheric CO_2.

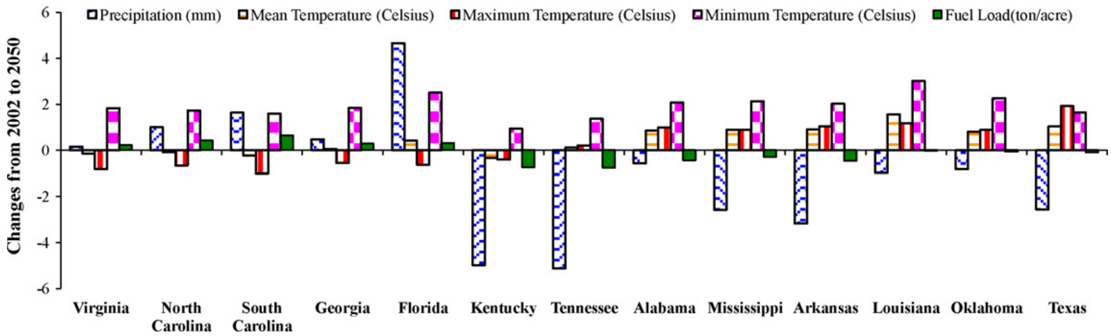

Fig. 3. The changes in climate and predicted fuel load in the southern states from 2002 to 2050.

NDEP_2050: Only nitrogen deposition rate changed from 2002 to 2050, other inputs are same to Baseline_2050. This scenario was used to project the impacts of change in nitrogen deposition on future fuel load;

Combine_2050: DLEM was driven by climate in 2050 and by changes in atmosphere composition (CO_2 and nitrogen deposition) from 2002 to 2050. This scenario provided the future projection of the fuel load in SUS.

We also assessed the impacts of interactions of environmental factors (climate, CO_2 and nitrogen deposition) on future fuel load using the following equation:

$$\text{Interaction} = \text{Combine\_2050} - \frac{\text{Climate\_2005} + \text{CO2\_2050} + \text{NDEF\_2005}}{3} \quad (5)$$

3. Results and discussion

3.1. Changes in climate and atmosphere from 2002 to 2050

From 2002 to 2050, the regional annual precipitation was predicted to decrease about 10% (114.97 mm), while annual average, maximum and minimum air temperature were projected to increase 0.52, 0.66, and 1.90 °C, respectively. The spatial pattern of climate, especially the precipitation, was predicted to change significantly from 2002 to 2050 (Fig. 2A, B, D, E). The mean daily air temperature was projected to decrease in the east-coastal states from Virginia to Georgia, while rising in the western and central parts of the study region (Figs. 2F and 3). A state-level analysis shows that the minimum daily temperature will increase significantly in all southern states (Fig. 3). Higher night-time temperature will accelerate the decomposition of detritus pools and enhance plant respiration rate, thus resulting in reduced fuel load in 2050. Precipitation was predicted to increase in the eastern, lower central and upper western parts of the SUS, especially the coastline region (Fig. 2C). Previous research indicated that the productivity and biomass of southern forest are sensitive to the variation of annual precipitation (McNulty et al., 1996). We therefore expect that the ecosystems which will experience increased precipitation will have higher fuel production. The increased moisture, however, may also alter the fuel bed condition and reduce the fire risk. The arid ecosystems in the west part of the study region were projected to experience higher temperature and lower precipitation in 2050, which will exacerbate the severity of the drought stress and inhibit fuel production.

A global three-dimensional chemistry-transport model (TM3) simulation (Dentener, 2006) projected that the average annual atmospheric nitrogen deposition in SUS might increase from 1.2 g N/m^2 to 1.3 g N/m^2 from 2002 to 2050 (Fig. 2G). The changes, however, will not be homogenous. The west part of Virginia, Kentucky, and South Carolina were projected to experience reduced nitrogen deposition, while other part of the study region, especially Texas and Florida, will have higher nitrogen deposition by year of 2050. Based on the IPCC A1B projection, the CO_2 concentration was predicted to increase from 373 ppmv in 2002 to 480 ppmv in 2050 (Fig. 2H). Higher nitrogen and CO_2 input will generally enhance the productivity and biomass of the ecosystem, resulting in fuel load accumulation in SUS (Wear and Greis, 2002).

3.2. Changes of fuel load from 2002 to 2050

Our study result showed that the total fuel load of the SUS is currently (2002) about 1.15 Pg. The mean fuel load density is about 2.12 ton/acre. The north part of the study region has high fuel load density, while the lowest fuel load is found in the arid ecosystems in the west part of the study region (Fig. 4). Kentucky has the highest fuel load of 3.86 ton/acre, followed by Tennessee (3.62 ton/acre). Texas has the lowest fuel load of 0.61 ton/acre. According to the model projection, the SUS fuel load will decline by about 4% in 2050. The spatial pattern of fuel load in 2050 will differ from the pattern in 2002 (Fig. 4). The northeastern part of the study region (North Carolina, Virginia, and South Carolina) will have the highest fuel load density, while the fuel load density of Kentucky and Tennessee will drop to the 5th and 8th places. Fuel load was predicted to decrease in the central part of the study region (decline by 0.77 and 0.74 ton/acre for Tennessee and Kentucky respectively), while will increase in the northeast-coastal states of the study region (increase by 0.65 and 0.43 ton/acre in South Carolina and North Carolina, respectively). We did not observe declined fuel load in response to the decreased nitrogen input in Virginia, Kentucky and South Carolina. The fuel load of Southern Texas and Florida, however, was projected to increase significantly possibly due to the effect of increased nitrogen deposition in 2050. In general, the spatial pattern of fuel load change is quite similar to the climate changes, indicating the dominant effect of climate on the dynamic of fuel load in SUS during the study period (2002–2050; Fig. 2C and F).

3.3. Contribution of individual factors to the fuel load dynamic

Single factor experiments (Fig. 5) indicated that from 2002 (Baseline_2002) to 2050 (CO2_2005, NDEP_2005) the regional fuel load may increase by 9% and 1% in response to elevated CO_2 concentration and atmospheric nitrogen deposition respectively. Free-Air CO_2 Enrichment (FACE) experiments suggested that the ecosystem productivity response positively to the elevated CO_2 (Norby et al., 2005). In the Southern US, forest growth is also stimulated by nitrogen deposition, although the effect may decline through time due to nitrogen saturation (Aber and Magill, 2004; McNulty et al., 2005). Other factors unchanged, higher productivity will lead to higher biomass and litter production, thus resulting in fuel load accumulation.

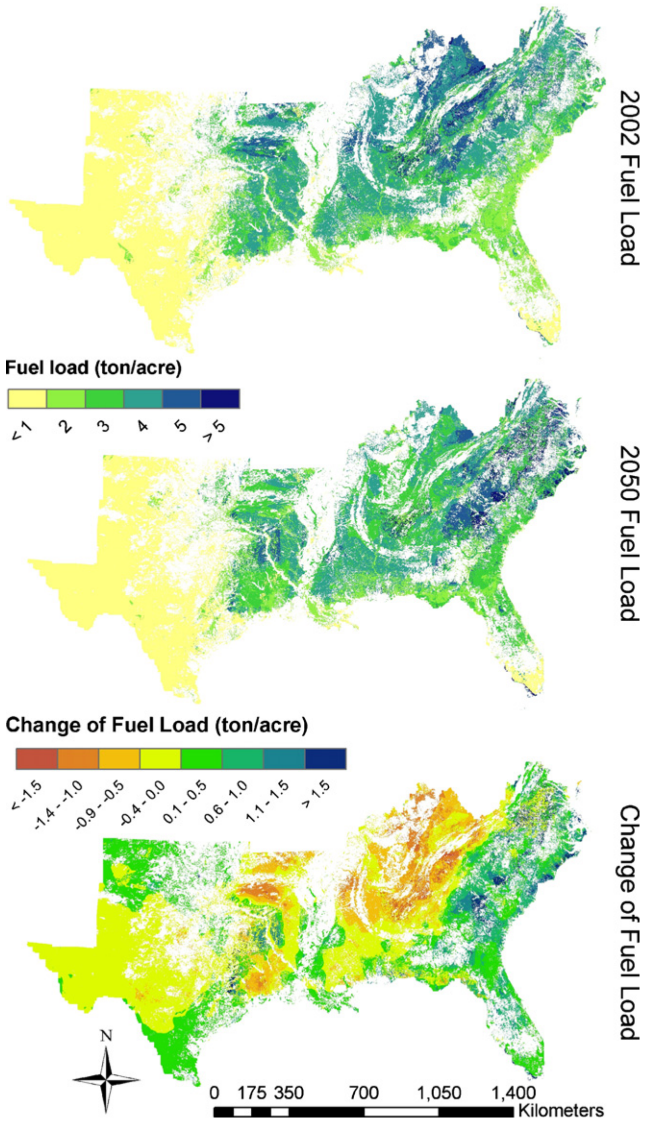

Fig. 4. Changes of fuel load from 2002 to 2050 in the Southern United States.

Despite the positive effect of atmospheric change, the overall fuel load of the SUS would decrease from 2002 to 2050 due to the negative effect of climate change. The effect of climate (Climate_2050 vs. Baseline_2002; Fig. 5) was projected to reduce the fuel load of SUS by about 12%. Except for the coastal regions, most of the southern states were projected to experience declined precipitation and prolonged drought in 2050 (Fig. 2C). Previous studies indicated that the productivity of southern ecosystem was dominated by precipitation (Zhang et al., 2007; Wear and Greis, 2002). Our climate model predicted 10% declination of annual precipitation of SUS during the first 50 years of the 1st century. A state-level analysis revealed that the precipitation generally dominated the fuel load dynamics (Fig. 3). Reduced precipitation will always result in decreased fuel load, while increased fuel load will be found in the states that were projected to experience higher precipitation.

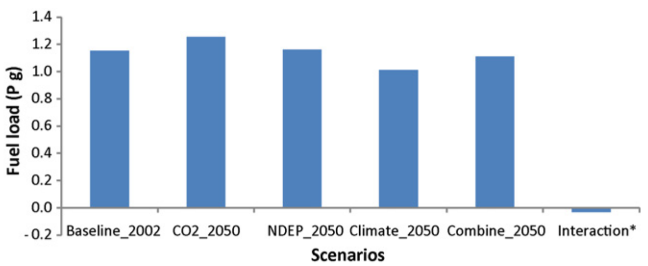

Fig. 5. Model projected fuel load of the Southern US under different scenarios. Baseline_2002 and Combine_2050 scenarios estimated the fuel load of 2002 and 2050, respectively. CO2_2050, NDEP_2050, and Climate_2050 are single factor experiments that investigate the individual impact of elevated CO_2, nitrogen deposition, and climate change on regional fuel load respectively. Interaction evaluated the effects of interactions among multiple environmental factors on fuel load. Interaction = Combine_2050 − (Climate_2050 + CO2_2050 + NDEP_2050)/3.

The changes in temperature will modify the magnitude of the fuel load dynamics. For example, while the precipitation was predicted to decrease in large areas of Virginia (Fig. 2C), the reduced mean and maximum daily temperature (Figs. 2 and 3) may enhance the accumulation of fuel load possibly due to reduced respiration/decomposition rate and water stress (as the result of decreased evapotranspiration rate under lower temperature). Although Florida may experience the largest increase in precipitation, it was also projected to experience warmer climate which will enhance the decomposition of ecosystem fuel load. Therefore, the highest increase of fuel load will be found in South Carolina, which was projected to have the second largest increase in precipitation, and the most significant decrease in daily maximum temperature ($-1\,^{\circ}$C) (Fig. 3).

The accumulated results of single factor experiments indicated 3% declination of fuel load. The multiple stress scenarios (Combine_2005), however, projected 4% declination of fuel load. Environmental factors usually do not operate independently, but rather often interact to produce combined impacts on ecosystem functioning. For example, a plants' response to elevated atmospheric CO_2 or nitrogen input can be limited by soil water deficiency (Norby and Luo, 2004). It is possible that the stimulating effect of rising CO_2 and elevated nitrogen deposition in the future will be inhibited by the impacts of declined precipitation in the SUS. According to our analysis, the interactions among multiple environmental changes will have negative effects (−1%) on the dynamics of fuel load in SUS.

3.4. Implications for the environmental managements in the southern states

Private forest is the major land-use type in the Southeast (Wear and Greis, 2002). Prescribed fire is widely applied in the southern forest plantations for fuel load and weed control. Fire emission threatens the regional air quality. Our study indicated that in response to the climate change, the spatial pattern of forest fuel load may be altered significantly in the first 50 years of the 21st century. In Tennessee and Kentucky, the forest fuel load may decline by 20% by the year of 2050, leading to significantly reduced fire emission. In contrast, the fuel load of South Carolina which is in adjacent to Tennessee was predicted to increase by 23%, implying elevated air pollution due to fire emission in 2050. The fuel load in the central and west part of the study region (Arkansas, Mississippi, Texas; Fig. 4) was predicted to decrease in 2050. However, the elevated temperature (Fig. 2F) and declined annual precipitation (Fig. 2C) in these areas may enhance the risk of wildfire. We therefore expect increased frequency of wildfire with decreased fire intensity due to lower fuel load density in these regions in 2050.

3.5. Validation and uncertainties

This study was based on the fuel load map of the Fuel Characteristic Classification System and the carbon dynamics estimated by DLEM. The FCCS was compiled and calculated using the best available data which has a well-documented scientific foundation (Riccardi et al., 2007). The DLEM has been validated and applied to study the ecosystem carbon dynamics in response to long-term climate changes in the SUS (Zhang et al., 2007; Tian

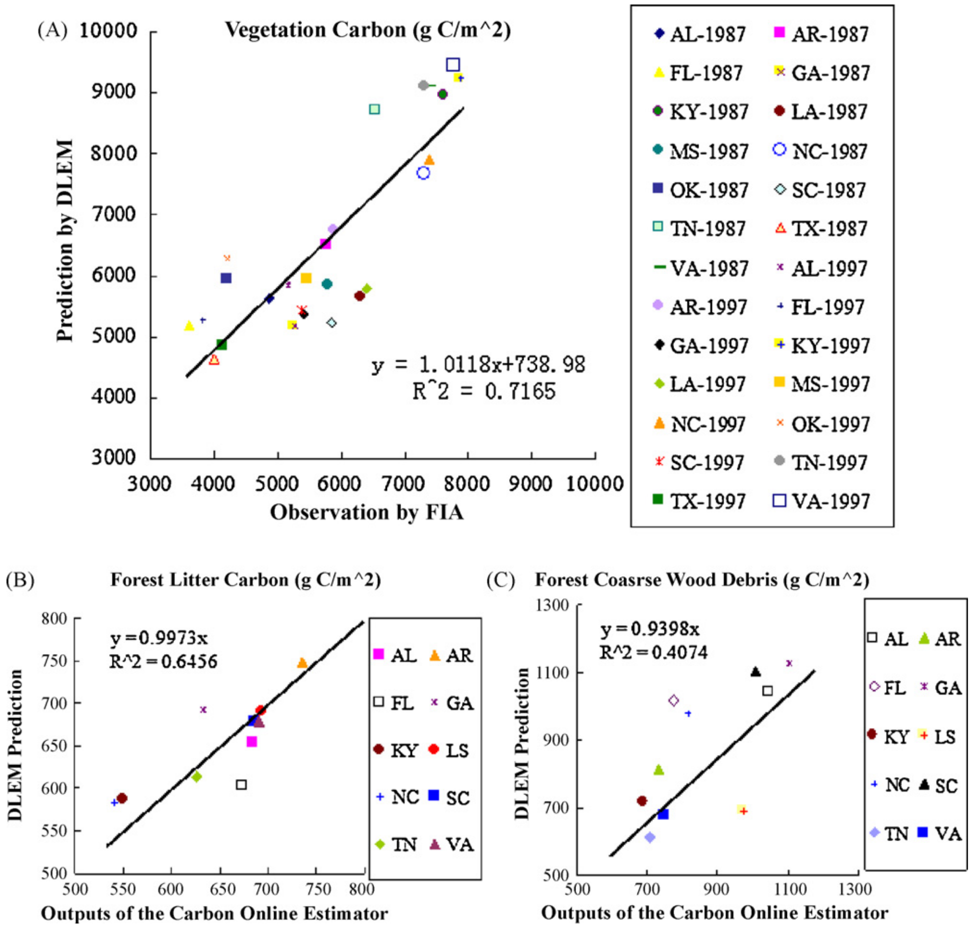

Fig. 6. Comparing the state average carbon density of forest ecosystems as simulated by DLEM simulated against the assessments based on forest inventory database (FIA; www.fia.fs.fed.us/). (A) Vegetation carbon density based on inventory data in 1987 and 1997 (Birdsey and Lewis, 2003); (B) and (C) litter carbon density and coarse woody debris density, respectively, based on the Carbon Online Estimator (COLE; http://ncasi.uml.edu/COLE/cole.html).

et al., 2010). For the purpose of regional validation, we compared the model simulated state-level mean carbon density of the southern ecosystem against the reported value based on forest inventory dataset (http://www.fia.fs.fed.us/). The comparisons (Fig. 6) showed that the carbon pools (vegetation, litter, and coarse woody debris) simulated by DLEM matched well with the results derived from the forest inventory database (Birdsey and Lewis, 2003; http://ncasi.uml.edu/COLE/cole.html). The spatial heterogeneity of vegetation carbon (Fig. 6A) and litter carbon (Fig. 6B) among the southern states were also captured by the DLEM simulation. However, DLEM tends to underestimate (with a slope of 0.93) the carbon density of coarse woody debris which is related to the fuel type with time lag larger than 100 h (Fig. 6C).

In this study, we gridded all model inputs to 8 km × 8 km resolution, assuming homogeneous environmental conditions in each simulation unit (grid). After the model simulation, we used bilinear interpolation to spatially downscale the model outputs to 1 km × 1 km resolution to match the FCCS fuel bed map. This scale transformation, although was necessary for improving the computational efficiency in regional simulation, could underestimate the spatial heterogeneity in the fuel load distribution. This is because (1) the gradient of many environment factors such as soil texture may not show a linear pattern, and (2) the interactions among multiple environmental factors (e.g. feedbacks among vegetation, climate, and soil) are usually nonlinear. The approach, however, should have relatively small impact on our estimation of the temporal dynamic of fuel load.

Uncertainties may also be caused by our assumption of unchanged ecosystem management regime from 2002 to 2050. We did not consider the impacts of fuel load management by human in response to climate changes. However, it was reported that resource managers generally limit fuel consumption to 2–6 ton/acre in the southern forest (Stanturf et al., 2002). The frequency of prescribed fire is actively adjusted according to the forest fuel load. Therefore, the actual variations of fuel load between 2002 and 2050 may be less significant than the model predictions.

In addition, uncertainty in fuel load prediction may be also caused by large discrepancies in climate projection among climate models (IPCC 2007). It is clearly needed to consider multiple climate model scenarios in future research.

4. Conclusions

The productivity and accumulation of fuel load are controlled by multiple environmental stresses on the southern ecosystem. Considering the temporal–spatial heterogeneity of major environmental drivers, our study assessed that in 2002 the total fuel load of the SUS was about 1.15 Pg, which will decrease to 1.11 Pg in 2050. The declination of fuel load is mainly due to the climate change, especially the reduced precipitation in 2050. Factorial analysis indicate that the climate change alone will reduce the fuel load by 12%, elevated CO_2 and nitrogen deposition will increase fuel load by 9% and 1%, respectively. Interactions among all factors will result in 1% reduction in the fuel load in 2050.

Future changes in climate and atmosphere will be uneven in SUS. The complex interactions among multiple environmental stresses further complicate the spatial pattern of the fuel load dynamics. Dynamic fuel load mapping approaches like this study are required as we move into the future under rapid environmental changes.

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