Drought in the Southern United States over the 20th century: variability and its impacts on terrestrial ecosystem productivity and carbon storage

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Abstract Drought is one of the most devastating natural hazards faced by the Southern United States (SUS). Drought events and their adverse impacts on the economy, society and environment have been extensively reported during 1895–2007. Our aim is thus to characterize drought conditions in the SUS and explore the impacts on terrestrial ecosystem function (i.e., net primary productivity (NPP) and net carbon exchange (NCE)). Standard precipitation index (SPI) was used to characterize drought intensity and duration, and a process-based ecosystem model was used to explore the relationship between drought and ecosystem function. Combining overall information on growing-season SPI, drought area and duration, we concluded there was no significant change in drought conditions for the SUS during 1895–2007. However, increased drought intensity was found for many areas in the east, resulting in significant decreases in NPP for these areas, with the largest decrease up to 40% during extreme droughts. Changes in precipitation patterns increased C emissions of 0.16 Pg (1 Pg=10^{15} g) in the SUS during 1895–2007. The west (dry region) acted as a C sink due to increased precipitation, while the east (water-rich region) acted as a C source due

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to increased drought intensity. Both NPP and NCE significantly increased along a gradient of declining drought intensity. Changes in precipitation resulted in C sources in forest, wetland, and cropland ecosystems, while C sinks in shrubland and grassland ecosystems. Changes in air temperature could either enhance or reduce drought impacts on NPP and NCE across different vegetation types.

1 Introduction

A widespread increase in precipitation is projected by most global climate models (GCMs) for the majority of the North American continent, except the Southern and Southwestern U.S. and Mexico (IPCC 2007; CENR 2008; Karl et al. 2009), and it is likely that water distribution among different terrestrial ecosystems will become more variable. Drought means water deficiency at the land surface, while water availability at land surface is mainly controlled by the balance between precipitation and evapotranspiration (ET) (Ji and Peters 2003). Although droughts are generally associated with decreased precipitation, increased rainfall does not necessarily mean less intense droughts. Other factors such as time spans between precipitation events, air temperature, and land use pattern could also induce drought events (Ji and Peters 2003; Houghton 2004). Global warming is predicted to cause massive droughts in the next 100 years (IPCC 2007). Likely increases in future temperatures have raised concerns about drought frequency and intensity on terrestrial ecosystems in the U.S. (Houghton 2004).

To effectively characterize drought conditions, several indices have been introduced, such as Palmer Drought Severity Index (PDSI, Palmer 1965), Standard Precipitation Index (SPI, McKee et al. 1993), and Palmer Hydrologic Drought Index (PHDI, Karl and Knight 1985). SPI has been widely used to evaluate drought events worldwide (e.g., McKee et al. 1995; Wilhite et al. 2000; Ji and Peters 2003). It is an index based on the probability of precipitation for any time scale, which was first created to address some limitations of PDSI. Like PDSI, this index is negative for dry and positive for wet conditions. However, SPI is a probability index that considers only precipitation, while PDSI is a water balance index that considers water supply, demand, and loss (Dai 2010). In addition, SPI is relatively simple, spatially consistent, and temporally flexible, thus making this index more reliable for providing early warning of drought and its severity and well-suited for risk management (Guttman 1998; Ji and Peters 2003; Dai 2010).

Climate in most areas of the Southern United States (SUS) is generally warm and wet, with mild winters and high humidity, compared to the rest of the continental U.S. (Karl et al. 2009); however, due to increased water demand and climate variability, this water-rich region has experienced serious water stress (McNulty et al. 2007). Although climate (precipitation and air temperature) was not reported to change significantly in the SUS during 1895–2007 (Karl et al. 2009), drought events and their impacts have been frequently reported on regional scales, such as the drought events of 1954, 1963, and 2007. Precipitation patterns in the SUS exhibit a great spatial variability with a gradient that increases from west to east and huge inter-annual variability with alternate extreme high and low precipitation. In the future (present to 2100), many climate change scenarios suggest that more frequent and/or intense drought periods could be expected across the SUS, and potential ET is predicted to exceed summer precipitation (Karl et al. 2009; Seager et al. 2009). This region has been identified as the largest C sink among the six major bioclimatic regions in the U.S. (Schimel et al. 2000) and has the highest potential to be a significant C sink in the future due to large area of young pine forests and increasing planted forest area (Turner et al. 1995; Malmsheimer et al. 2008). Until 2007, over 22% of forests were pine plantations in the SUS, and most forests are less than 60 years old (Smith et al. 2009; Pan et al. 2011). These forests demand more water due to higher productivity, likely intensifying water stress in this region.

Carbon and water fluxes between the atmosphere and terrestrial ecosystems are interactively linked at various temporal and spatial scales (Jackson et al. 2005). Drought directly influences photosynthesis of individual plants and thus the ecosystem C cycle. Drought impacts on ecosystem functions such as mortality, gross primary production (GPP), NPP, and C storage have been reported worldwide (e.g., Hanson and Weltzin 2000; Ciais et al. 2005; Grainer et al. 2007; Zhao and Running 2010; Asner and Alencar 2010). While much attention has been paid to drought issues in the arid and semi-arid regions of the U.S. such as the Great Plains, the interior West, and the Southwest (Seager et al. 2009), much less paid to the traditional high-precipitation regions such as SUS. Several experimental studies have addressed drought impacts on plant productivity, mortality, and ecosystem C storage in the SUS (e.g., Elliott and Swank 1994; Olano and Palmer 2003; Klos et al. 2009). It is rather limited to specifically study drought effects on long-term ecosystem productivity and C storage at regional scales. To overcome this knowledge gap, we employed SPI and a process-based Dynamic Land Ecosystem Model (DLEM, Tian et al. 2010a) which fully couples C, N, and water cycles in terrestrial ecosystems to address the following objectives: 1) quantifying spatial and temporal patterns of drought intensity and duration in the SUS; and 2) exploring drought impacts on ecosystem NPP and C storage.

2 Methods and data

2.1 Study region

The SUS defined in this study includes 13 states covering about 215.6 million ha land area from the Mid-Atlantic coast west to Texas (Fig. 1). This represents ~24% of the land area, 60% of forest land, and 25% of agricultural land for the U.S. This region belongs to temperate climatic zone, becoming largely subtropical near the coast. The dominant land cover types are temperate evergreen needleleaf and deciduous broadleaf forests, among which planted forest area accounts for ~22% in 2007 and most are young- and even-aged forests and have a short rotation age (Pan et al. 2011).

2.2 Data source and description

2.2.1 Climate and other basic model input data

In this study, we used daily climate data (including precipitation, maximum, minimum and average air temperature, and dew point) at 8 km×8 km spatial resolution for the SUS from 1895 to 2007. The climate data generation methods have been described in detail by Zhang et al. (2010), Tian et al. (2010a, 2012), and Chen (2010). In addition, we generated a 30-year detrended (i.e., no obvious change trend) climate dataset from the daily climate of 1895–1924 for model spin-up run after equilibrium state. The climate change patterns in the SUS were described in the Electronic Supplementary Material S1.

The generation methods for other basic model input data including land use, atmospheric CO_2 concentration, nitrogen deposition, soil texture, and topography data have also been described in detail by Tian et al. (2010a, 2012) and Zhang et al. (2010).

2.2.2 Standard precipitation index

SPI was used to characterize drought intensity and duration for the SUS and to compare the spatial difference in ecosystem function response to drought. SPI has been widely used to evaluate the
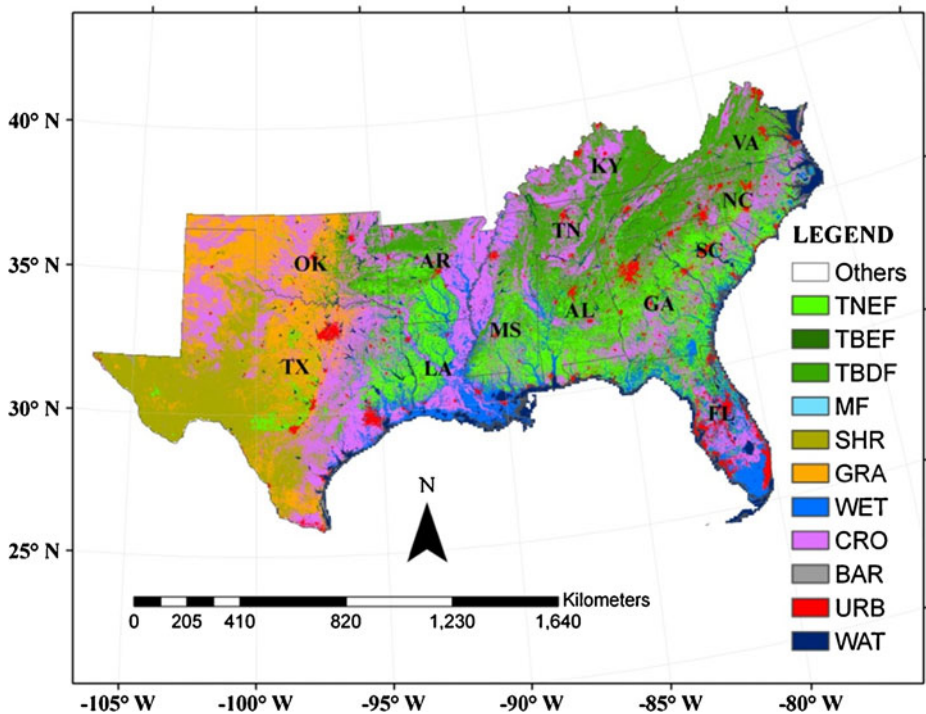
Fig. 1 Boundary and contemporary land cover map for the SUS. *TNF*: temperate needleleaf forest; *TBD*: temperate broadleaf deciduous forest; *MF*: mixed forest; *SHR*: temperate deciduous shrubland; *GRA*: grassland; *WET*: wetland; *CRO*: cropland; *BAR*: barren land; *URB*: urban and built-up land; *WAT*: water bodies (Source: MODIS 2005 land cover map, http://www.cec.org)

drought events worldwide. The monthly precipitation data collected from the PRISM (available online: http://prism.oregonstate.edu/) were used to calculate SPI. The same methods of McKee et al. (1993, 1995) were used to reconstruct historical SPI. 1-, 2-, 3-, 4-, 5-, 6-, 9-, 12- and 24- month SPI have ever been used to represent short-term, middle-term and long-term drought conditions and proved to be useful in monitoring drought conditions. In this study, 1-, 3-, 6-, and 12- month SPI were selected to represent monthly (short-term), seasonal, growing season, and annual drought conditions, respectively. Seven categories were defined by McKee et al. (1993, 1995): extremely wet (>2.0), very wet (1.5~1.99), moderately wet (1.0~1.49), near normal (−0.99~0.99), moderately dry (−1.49~−1.0), severely dry (−1.99~−1.5), and extremely dry (<−2.0). We redefined dry areas as SPI<−1.0 in this study (Wilhite et al. 2000; Ji and Peters 2003).

2.3 Model description

2.3.1 General description

DLEM model was used to simulate the influences of climate change and drought on GPP, NPP, and net C exchange (NCE; positive values indicate C sinks). DLEM is a highly-integrated process-based ecosystem model that couples C, N, P, and water cycles at a daily time step. DLEM is designed to simulate variations in biogeography, hydrological cycle, plant physiological processes, and soil biogeochemical cycle in terrestrial ecosystems driven by natural and anthropogenic forces such as climate, atmospheric CO_2 concentration, tropospheric ozone, land-use change, N

deposition, and land management and disturbance (e.g., N fertilization, site preparation, fire, harvest, and hurricane) on terrestrial C, water, and N cycles. This model was applied in China, Asia, U.S., and North America (e.g., Chen et al. 2006a,b; Ren et al. 2007, 2011a, b; Liu et al. 2008; Schwalm et al. 2010; Tian et al. 2008, 2010a, b, 2011a, b, 2012; Xu et al. 2010).

The modeling mechanisms for GPP and NPP have been described in detail by Tian et al. (2010a). We described the hydrological cycle submodel and the related algorithms for simulating drought impacts on NPP, GPP, and NCE in the Electronic Supplemental Material S2.

2.3.2 Model parameterization, initialization, and simulation experiments

Before running DLEM, it was parameterized against field measurement data for each major plant functional type (PFT) in the SUS. The sites and processes for DLEM parameterization have been described in detail by Tian et al. (2010a). DLEM was first run to an equilibrium state using 30-yr mean (1895–1924) climate data and other input data (i.e., land use, N deposition, and atmospheric CO_2 concentration) in 1895 to develop the simulation baseline for C, N, and water pools. Then a 90 year (30-yr climate data for 3 iterations) spin-up simulation was conducted using the detrended climate data to stabilize unusual fluctuations caused by simulation mode shifts from equilibrium to transient. Finally, a transient run will be conducted using the transient input data. Three simulation experiments were designed to achieve the objectives: climate change (CLM, changes in all climate factors including precipitation, air temperature and air humidity), precipitation change only (PREC, other factors kept constant while precipitation changes with time), and air temperature change only (TEMP). The interactive effect between precipitation and temperature was calculated as: CLM—PREC—TEMP.

2.3.3 Model evaluation and performance

DLEM's performance to simulate climate and drought impacts on C storage and NPP has been extensively evaluated against field observational data and regional inventory data in the SUS (Zhang et al. 2010; Tian et al. 2008, 2010a, 2012; Chen 2010), China (Tian et al. 2011a; Liu et al. 2008; Ren et al. 2011a), and North America (Tian et al. 2010b; Schwalm et al. 2010). In this study, we further evaluated DLEM's performance in simulating runoff/streamflow and NPP under climate change impacts (Electronic Supplementary Material S3).

2.4 Statistical analysis

The Spearman's correlation was utilized to evaluate temporal and spatial consistency between observed and simulated results. A simple linear regression method was used to retrieve the long-term trend of inter-annual variation in drought conditions and ecosystem functions. Significance test for correlation coefficients and linear regression models were conducted with F-test with the standard 0.05 level ($p < 0.05$) indicating statistical significance.

3 Results and analysis

3.1 Drought conditions in the SUS during 1895–2007

SPI was used to characterize drought conditions in the SUS. From an annual perspective, there were only 6 dry years (1904, 1910, 1917, 1954, 1956, and 1963 for 12-month SPI<
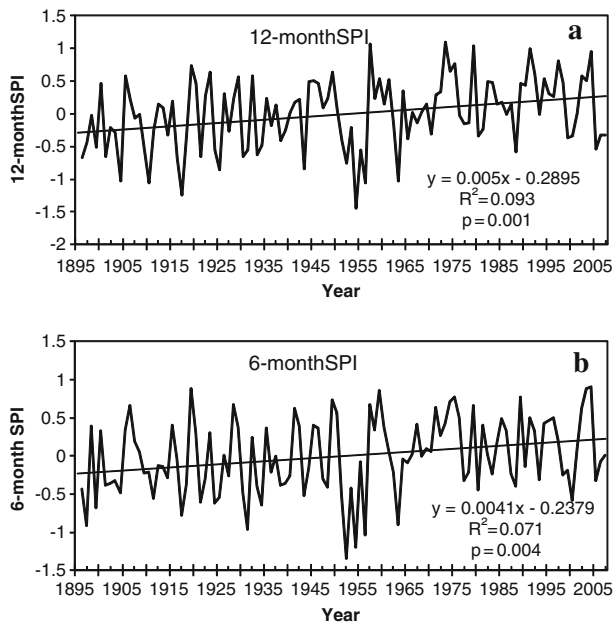
Fig. 2 Regional mean annual (**a**) and growing-season (May-October, **b**) SPI (based on 12- and 6- month SPI respectively) for the entire SUS. R^2 are less than 0.05, indicating no significant changing trends

−1.0) for the entire SUS (Fig. 2a). The 12-month SPI displayed a slight increasing trend (significant at $p<0.05$) during 1895–2007. Most years after the 1970s were normal or wet years, indicating a slight wetter trend for the entire SUS. For growing season (May–October), we found 3 very dry years (1952, 1954, and 1956) (Fig. 2b). A consistent dry period was found during 1951–1956. Both from annual and growing season perspectives, the drought conditions were alleviated from 1895 to 2007.

Drought area and duration (which conveys spatial drought information) were used to further represent drought conditions. Drought area slightly ($p=0.65$) decreased in the SUS (Fig. 3a). The highest percent of drought area was ~33% in 1954. This year was reported as the driest year during 1895–2007 (Seager et al. 2009). Other high drought area percent occurred in 1917 (27%), 1925 (30%), and 1963 (27%). Drought duration also showed a slight decreasing trend (not significant, Fig. 3b), indicating that drought periods from 1895 to 2007 had not extended. A consistent dry period was also found during 1951–1956 and the longest drought duration was ~4 months in 1954. It is notable that the longer drought durations occurred in the same years with the higher drought area. Combining the trends for drought area and drought duration, we concluded that drought intensity and frequency had not been significantly increased during 1895–2007. The annual and growing-season mean SPI (Fig. 2a, b) indicated a slight decreasing drought trend but drought area and duration did not reflect this pattern. Although there appears to be no long-term trends in drought, the area of the SUS experiencing excessive wetness appears to be increasing (particularly since the 1970s), which means flooding frequency could have increased during this study period. This pattern of climate change has also been reported for the continental U.S. by Karl et al. (1996) and Easterling et al. (2000).

The regional average SPI, drought area, and duration could not reflect the real drought conditions at spatial scales. We found a large spatial variation in the change trend of SPI
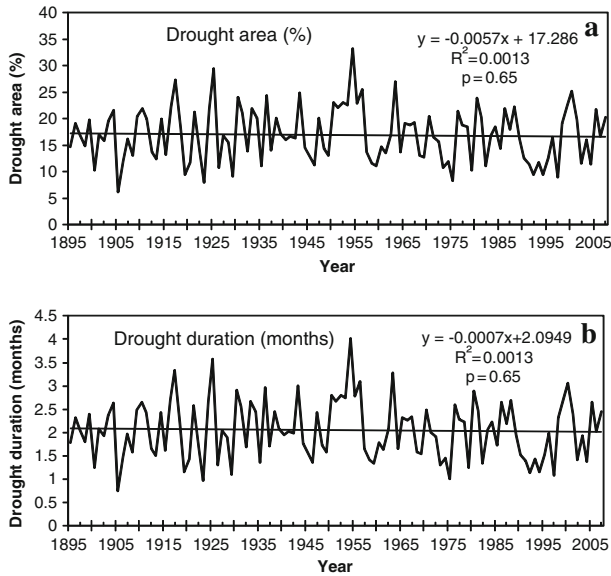
Fig. 3 Area percentage in the SUS experiencing drought (%, **a**) and mean drought duration (months, **b**) based on the 1-month SPI at or below the drought threshold value of −1.0
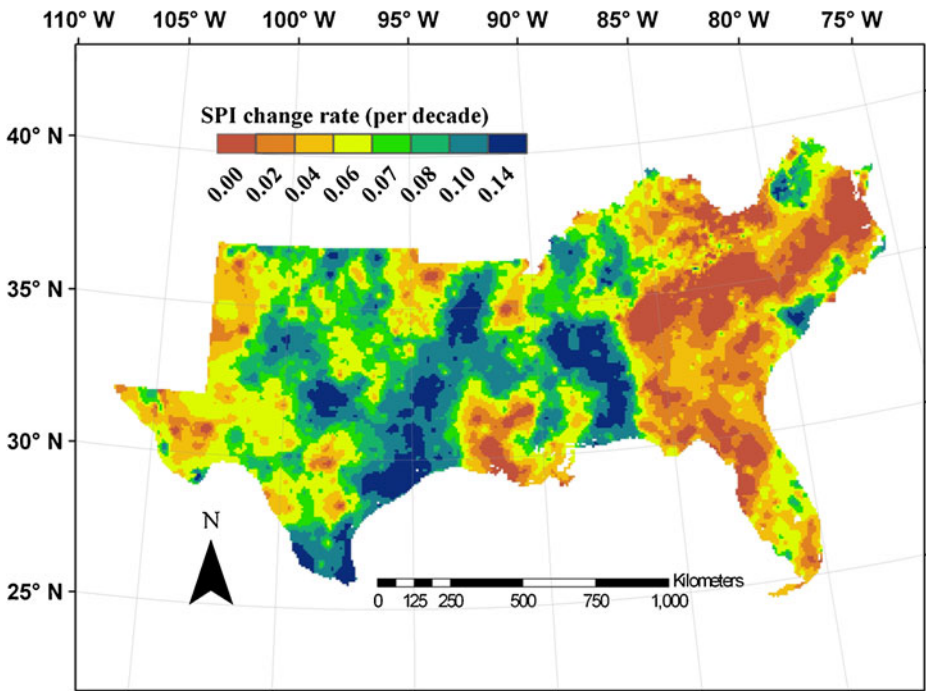

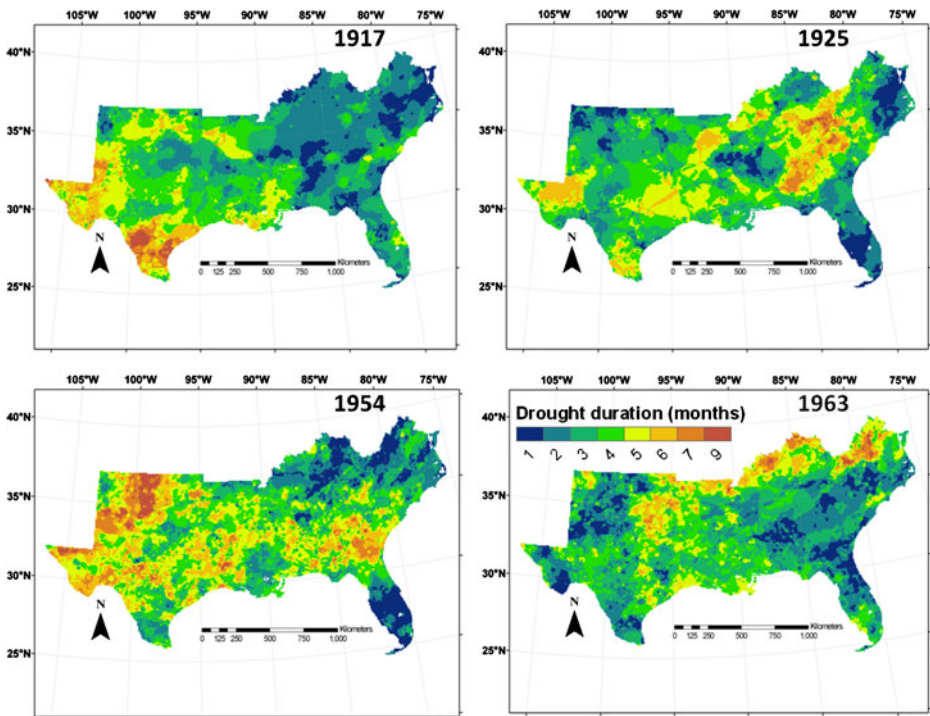**Fig. 4** Spatial variations in changing trends of 12-month SPI during 1895–2007 (per decade)

Fig. 5 Spatial distribution of drought duration (months) as calculated based on 1-month SPI in the 4 driest years (1917, 1925, 1954, and 1963)

during 1895–2007 (Fig. 4). SPI displayed an increasing tendency in most areas of the SUS, but decreased in some areas in the east, suggesting that most areas became wetter while some areas in the east became drier. The wetter trend occurred in the traditionally dry region (e.g., Texas), while drier trend occurred in the traditionally wet region (e.g., South and North Carolina). We selected the 4 driest years (1917, 1925, 1954, and 1963) to further illustrate spatial drought distribution patterns (Fig. 5). The longest drought duration occurred in different locations during these drought events.

3.2 Drought effects on NPP

Total NPP for the entire SUS did not exhibit a significant ($p < 0.05$) change trend but varied significantly among years during 1895–2007 with changes in climate, precipitation only, and temperature only (Fig. 6). NPP ranged from 0.84 Pg C in 1925 to 1.31 Pg C in 1957 as influenced by climate change, while it ranged from 0.89 Pg C in 1917 (one of the driest years) to 1.32 Pg C in 1919 (one of the wettest years) as influenced by precipitation change. The highest NPP were found during the wettest years, while the lowest NPP were observed during the driest years. 12-month SPI showed a slight increasing trend; however, mean NPP in recent years (after 1970) was not significantly different from that in the entire period. Although change in air temperature has a larger influence on the magnitude of NPP for some years, the
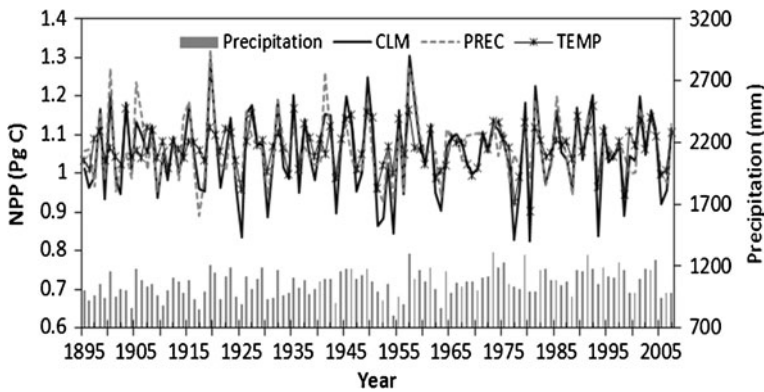
Fig. 6 Inter-annual variations in NPP under changing climate (CLM), precipitation only (PREC) and temperature only (TEMP) experiments

inter-annual variation was primarily controlled by precipitation pattern (Fig. 6). During the dry years, the effects of temperature and precipitation changes additively lowered NPP, significantly reducing NPP in very dry years. By selecting the 10 driest and wettest years during 1895–2007 (based on drought duration and area data), we found that annual total NPP in the extreme dry year (0.98 Pg C) was significantly ($p<0.05$) lower than those in both normal (1.07 Pg C) and extreme wet (1.15 Pg C) years (Table 1).

Although there was no significant change trend for NPP in the entire SUS, large spatial variation was observed (Fig. 7). NPP displayed a decreasing trend in most areas of the eastern and south-central SUS, while an increasing trend occurred in the west. The largest NPP change was ~110 g C m^{-2} during the study period, accounting for ~20% of the annual mean NPP in the SUS. Most vegetation in the west are grassland, cropland or shrubland, thus vegetation NPP in the west was relatively lower than that of the east; however, the accumulated increases in NPP in the west have offset the decreases in the east, resulting in no significant changes in NPP for the entire SUS. For four historical driest years (1917, 1925, 1954, and 1963), we found that NPP could be reduced by up to 40% in some areas, while it could also increase over 40% in the wet areas during these years (Fig. 8), which could offset most of NPP reductions induced by drought. It is notable that the most serious drought events and thus the largest reductions in NPP generally occurred either in the west or the east during reported drought events such as 2007.

Table 1 Mean annual NPP and NCE under precipitation only experiment for the 10 driest, 10 wettest, and normal years based on drought area and drought duration data

Variables	Extreme dry	Extreme wet	Normal
NPP (Pg C yr^{-1})	0.98 (0.07) a*	1.15 (0.08) b	1.07 (0.07) c
NCE (Tg C yr^{-1})	−72.47 (60.55) a	81.45 (73.31) b	−2.64 (70.89) c

*Different letters within a row indicated significant difference at $p<0.05$. Values in the parenthesis are standard deviations
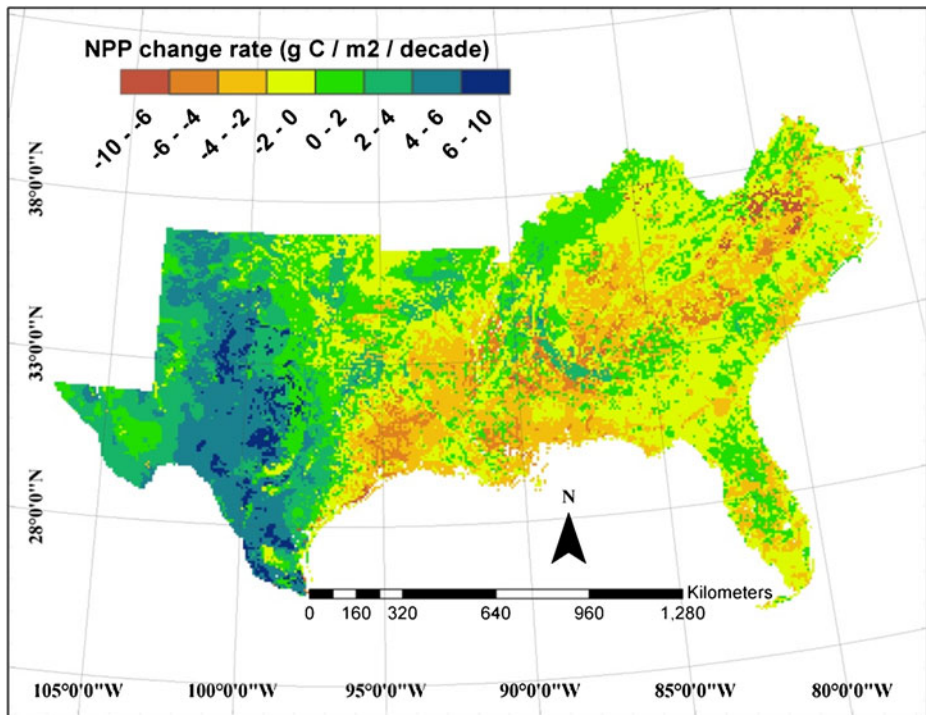
Fig. 7 Change trend (g C m^{-2} decade^{-1}) of ecosystem net primary productivity in the SUS during 1895–2007

3.3 Drought effects on C storage

Carbon fluxes varied significantly among years as influenced by changes in climate, precipitation only, and temperature only (Fig. 9a). NCE ranged from −0.16 Pg C in 1917 to 0.24 Pg C in 1919 under precipitation change only experiment. A continuous C source was found from 1951 to1956 (a period with continuous dry years). Changes in climate, precipitation, and air temperature have collectively resulted in about 0.37, 0.16, and 0.25 Pg C being released to the atmosphere during 1895–2007 (Fig. 9b). The interactions among precipitation and air temperature induced an emission of 0.04 Pg C, implying only a slight reduction in drought impact as influenced by temperature changes. Temperature change caused a larger C emission than precipitation change; however, the inter-annual variability of NCE was primarily controlled by the changing pattern of precipitation. Although many extreme drought events were reported during the recent half century (1951–2007), precipitation change in this period resulted in a negligible C source (0.002 Pg C), while it acted as a major C source (0.15 Pg C) during 1895–1950. SUS acted as a significantly large C source during the 10 driest years (72.47 Tg C yr^{-1}), whereas it was a C sink during the 10 wettest years (81.45 Tg C yr^{-1}, Table 1). Regional mean precipitation displayed an increasing trend; however, the SUS was still a C source, which was due to the large spatial difference in precipitation distribution.

Carbon fluxes as influenced by changing precipitation displayed a large spatial variation in the SUS. Most areas of the east and coastal region along the Gulf of Mexico were C sources, while most areas in the west were C sinks (Fig. 10a). The largest C sinks and sources were ~75 and 100 Gg (1 Gg=10^9 g) C on a grid cell scale (8×8 km^2), respectively.
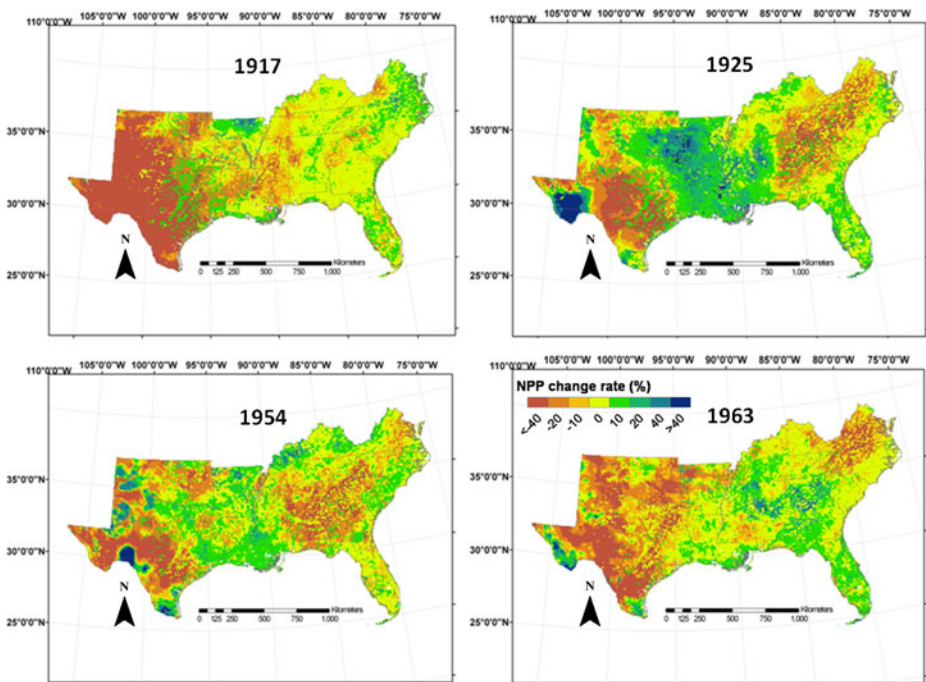
Fig. 8 Changes of NPP relative to the mean NPP during 1895–2007 in the 4 driest years (1917, 1925, 1954, and 1963)

The largest C sources were located in the southern Appalachian Mountains, where the major vegetation type is forest and has the highest biomass and soil C compared to other upland ecosystems (Tian et al. 2012). The largest C sinks were located in Texas, where major vegetation types are shrubland and grassland. The west is traditionally a semi-arid region with annual precipitation ranging from 200 to 800 mm. Precipitation is the major limiting factor for NPP and C storage. As compared to the climate change experiment (Fig. 10a), the spatial variability of C fluxes was controlled by precipitation change patterns.

3.4 Responses of different vegetation types to drought

Vegetation types differ in their responses to drought impacts due to differences in drought tolerance and environmental conditions. Precipitation change led to a C source of 198.47, 32.21, and 118.48 Tg C in forest, wetland (including herbaceous and woody wetland), and cropland ecosystems, respectively, while a C sink of 187.55 and 8.13 Tg C in shrubland and grassland ecosystems, respectively (Table 2). The grassland and shrubland are located in the western SUS, where drought intensity and duration were greatly decreased during 1895–2007 (Fig. 4). Forest and wetland are primarily located in the east or the coastal regions, where drought intensity and duration were found to increase. Although the interactive effects between temperature and precipitation were small for the SUS (0.04 Pg C), they could be very large for different vegetation types. Drought impacts on C sources for forest were enhanced by the interactive effects, while reduced for wetland and cropland. The interactions enhanced C sinks for shrubland, but not for grassland. Combining the drought effects from changing precipitation and interactive effect, the resultant total C sources for forest, wetland,
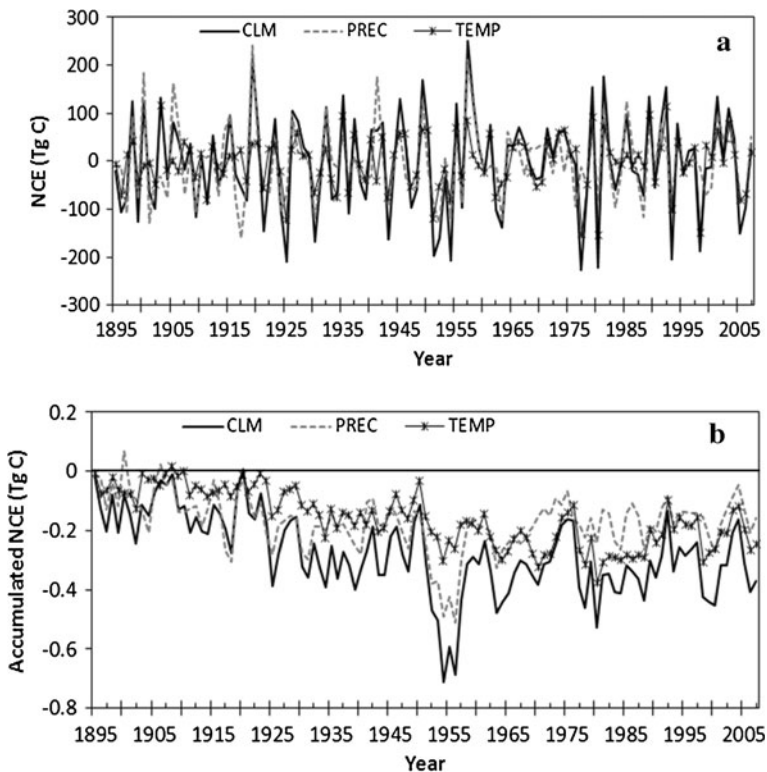
Fig. 9 Inter-annual variation (**a**) and accumulative (**b**) net carbon exchange (NCE) resulting from changes in climate (CLM), precipitation (PREC), and temperature (TEMP)

and cropland were 313.13, 23.10, and 15.38 Tg, respectively. These findings suggested that there were significantly different responses of various vegetation types to global change. Further studies are needed to specifically identify the mechanisms controlling these differences.

3.5 Relationships between SPI and C fluxes

Although drought has a significant impact on NPP and NCE distribution, it does not imply a significant linear relationship between them. Linear regressions were conducted to find out the relationships. The results indicated that the changes of 12-month SPI could explain about 38% ($R^2=\sim0.38$; $p<0.01$) of the changes in both NPP and NCE (Fig. 11). Other factors (such as soil physical and chemical properties, land cover types, solar radiation, etc.) and their interactions with precipitation explained the remaining changes. We found that growing-season SPI exhibited a higher influence on NPP and NCE ($R^2=0.51$; $p<0.01$), indicating greater impacts of growing-season drought events. SPI is an index based on only precipitation, the vegetation water demand and ecosystem water loss were not considered, resulting in less close relationship with NPP and NCE. This also implied that terrestrial vegetation in the SUS has a certain buffering capacity to respond to meteorological drought events.
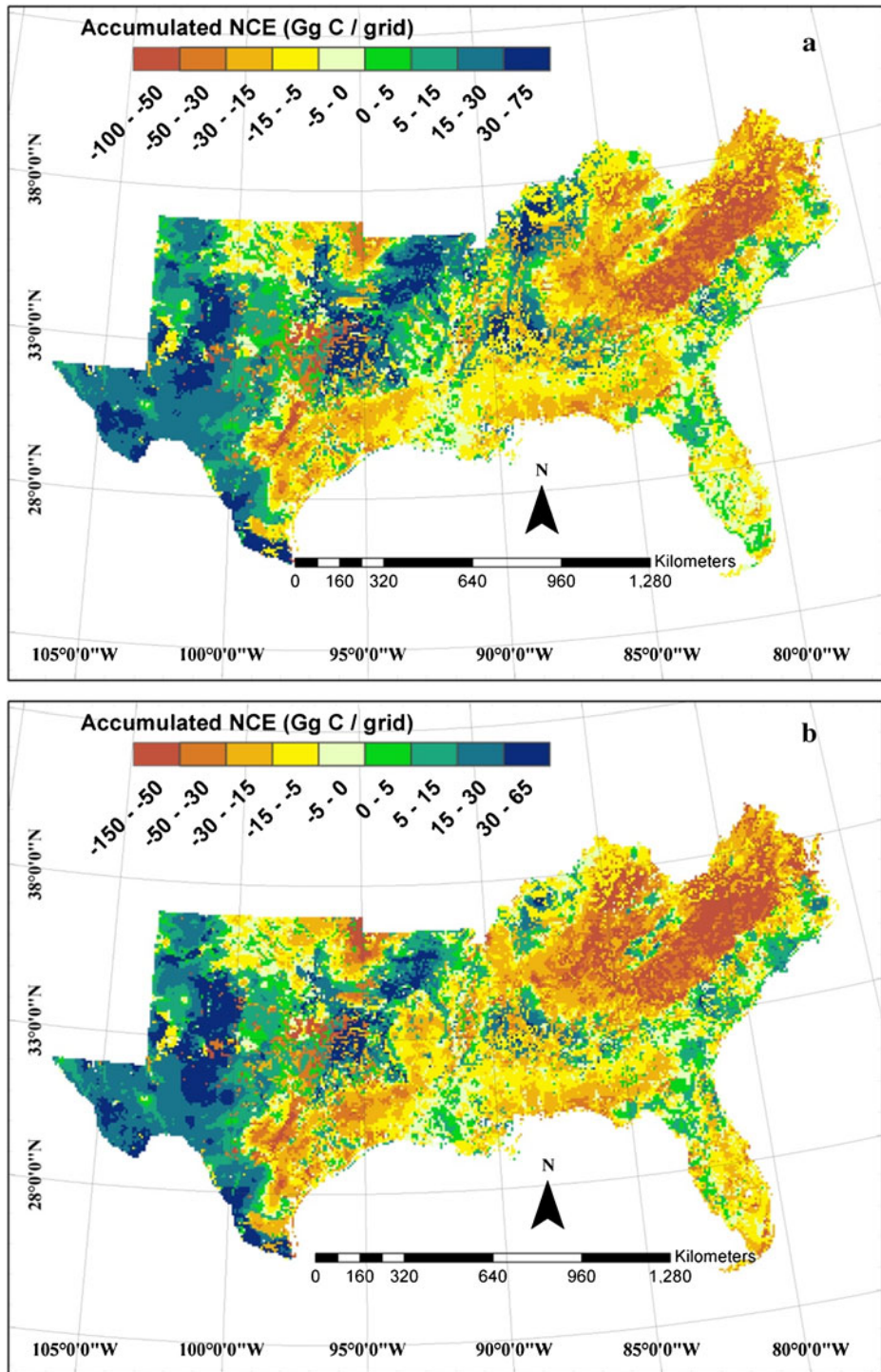
Fig. 10 Spatial distribution of cumulative NCE (Gg C grid^{-1}; 1 Gg=10^9 g; grid size: 8×8 km^2) during 1895–2007 as influenced by changes in precipitation (PREC, **a**) and climate (CLM, **b**) experiments

Table 2 Accumulated changes in NCE (Tg C) for different vegetation types as influenced by drought and climate change during 1895–2007

Experiment	Upland forest	Shrubland	Grassland	Wetland	Cropland
CLM	−414.47	201.91	3.84	−34.80	−125.24
PREC	−198.47	187.55	8.13	−32.21	−118.48
TEMP	−101.35	−20.16	−2.7	−11.70	−109.85
Interactive effect[a]	−114.66	34.52	−1.58	9.11	103.10
Drought effect[®]	−313.13	222.07	6.55	−23.10	−15.38

[a] Interactive effect was calculated as CLM-PREC-TEMP, indicating the interactive impacts of changes in temperature and precipitation on carbon storage;

[®] Drought effect was calculated as PREC+interactive effect, indicating drought effects from both precipitation and temperature changes

4 Discussion

4.1 Drought conditions in the SUS

Although the SUS does not experience multiple years of extreme droughts, short periods (one to several years) do occur when precipitation reductions induce serious stresses on water supply, and thus drought events and their adverse impacts have often been reported and recorded. However, we found no obvious increases in drought duration and intensity during 1895–2007 based on the SPI. In contrast, we found a slight (not significant)

Fig. 11 Relationships between SPI and NPP (**a**) & NCE (**b**). Linear regression model for NPP vs. SPI: $Y = 1.05 + 0.12X$, $R^2 = 0.38$, $p < 0.01$; regression model for NCE vs. SPI: $Y = -3.05 + 117.69X$, $R^2 = 0.38$, $p < 0.01$
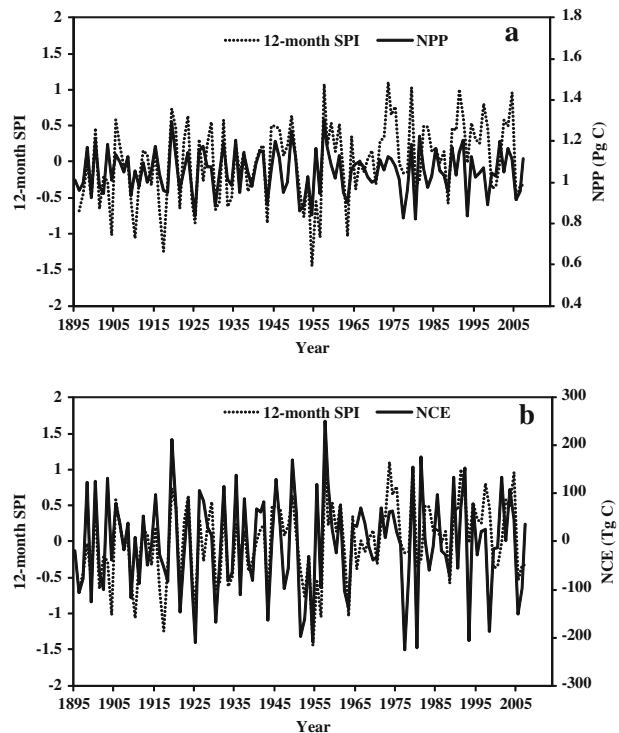
decreasing trend in drought intensity. Although reports from IPCC (IPCC 2007) and the U.S. Climate Report (Karl et al. 2009) indicated that it is likely that drought intensity, frequency, and duration will increase in the future for the SUS, we did not find this trend in the historical data. The IPCC (2007) and U.S. Climate Report predicted a rapid increase in air temperature, which would result in a higher ET thereby reducing available water. However, we found no obvious increase in air temperature for the entire SUS during 1895–2007.

Although drought intensity and duration due to global climate change were not found to increase in the SUS, drought impacts may be intensified by increased water demands for human usage and land use changes from natural vegetation to irrigated cropland (McNulty et al. 2007). We found that irrigated and fertilized croplands have a higher ET and runoff compared to those unmanaged croplands and many natural ecosystems, resulting in less water storage in terrestrial ecosystems. In addition, fast-growing population, industrialization, and urbanization caused by population migration and economic growth could significantly increase water demands. For example, almost a quarter of total water use in Georgia is for public use (http://ga.water.usgs.gov/projects/projectwateruse.html). Thus, significant increases in water demands coupling with a decrease in precipitation in 2007 caused a serious water shortage and a drought emergency for Georgia (http://www.georgia.gov). It is important to note that precipitation in 2007 was not extremely low (slightly lower than the long-term mean) in Georgia. Further studies are needed to explore how human activities have influenced drought intensity and duration in the SUS.

4.2 Relationships between drought and ecosystem function

Drought has been reported to significantly reduce NPP and C storage worldwide (e.g., Hanson and Weltzin 2000; Ciais et al. 2005; Klos et al. 2009; Zhao and Running 2010; Asner and Alencar 2010). Due to the difficulties in characterizing and monitoring drought at larger scales, the assessment of drought effects on NPP and C storage generally relies on modeling. Although a significant trend in drought intensity and frequency was not found during 1895–2007, the great inter-annual variation in precipitation could result in a large decrease in NPP and C storage due to the lag-effect from previous years and interactions among precipitation and other factors. Our simulation results indicated that drought could decrease NPP up to 40%, resulting in a significant reduction in C storage in the SUS. Through collection of observational data, Klos et al. (2009) found that the mean annual growth rate of pines decreased significantly with increasing drought intensity, while it only decreased slightly for oaks and mesophytes in the SUS. Further, growth rate could be reduced by ~20% for pines during extreme drought years. Our simulation results also indicated a reduction in NPP of 10–30% for pine forests in the southeastern SUS (e.g., extreme drought in 1954, Fig. 8) and 10–20% for broadleaf forests (e.g., extreme droughts in 1925 and 1963) in the northeast. The DLEM-estimated NPP was also comparable to MODIS-derived NPP (Zhao and Running 2010) during 2000–2007 (Fig. 12). The generally similar inter-annual variations in NPP for both estimates could indirectly reflect the consistency of drought impacts on NPP in the SUS.

Results from this study indicated that the SUS acted as a large C source in extreme dry years and a small C source in normal years, while a C sink in extreme wet years. This suggested that water is still one of the most important limiting factors to C storage capacity in the SUS despite this region having relatively wet climate. The SUS is characterized as a random and occasional drought region (Hanson and Weltzin 2000; Karl et al. 2009); however, the cumulative drought impacts on C storage could be very

Fig. 12 Comparison between DLEM-estimated and MODIS-derived NPP (Data source: Zhao and Running 2010) for the SUS during 2000–2007
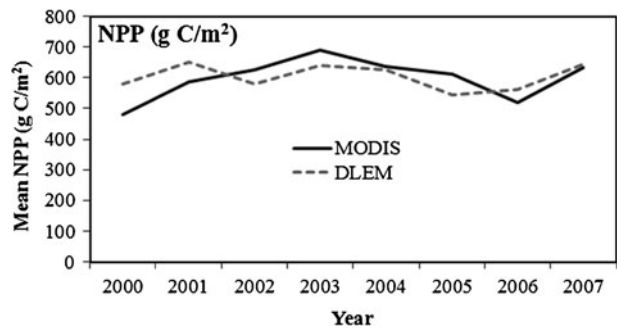
large. We found that drought could induce a C emission as high as 0.1 Pg C in some regions of the northeast during 1895–2007 (Fig. 10). It is notable that about half of terrestrial ecosystems in the east were C sources under the impacts of changing precipitation, while most parts of the west were C sinks. The east is traditionally a water-rich region (McNulty et al. 2007; Sun et al. 2008). Most vegetation types in this region have adapted to high precipitation and soil moisture conditions. The increased drought intensity and alternating high and low precipitation patterns could disrupt ecosystem stability, thus causing large C emissions. In contrast, the west is traditionally a low-precipitation region with shrubland and grassland being the major vegetation types. These vegetation types have adapted to dry conditions, increase in precipitation caused a significant increase in plant growth and large C sinks in this region.

4.3 Interactions between drought and other factors

Drought could interact with other factors (e.g., atmospheric CO_2 concentration, air temperature, land cover, and N deposition) to augment or attenuate its impacts on plant productivity and C storage (Norby et al. 1999; Olano and Palmer 2003; Hanson and Weltzin 2000; Houghton 2004; Luo et al. 2008). Results from this study suggested that the interactive effects between air temperature and precipitation could result in a minor C emission of 0.04 Pg in the SUS during 1895–2007; however, the interactive effects varied greatly over space and could be very large for some areas (Fig. 10a, b). Carbon emission induced by drought was amplified in most areas of the northeast, while C storage was enhanced in the west. This implied that global warming could impose a significant influence on drought intensity for some areas in the SUS. Based on four models and seven sites, Luo et al. (2008) also found that interactive effects between temperature and precipitation could amplify the single-factor effect. It is also notable that the interactive effects on C storage were different for various vegetation types. Drought impacts on C emissions in forest were enhanced by the interactive effects, but reduced for wetlands. However, this interaction enhanced C sinks in shrubland and reduced in grassland and cropland. Further studies are needed to explore the underlying mechanisms controlling the interactive impacts among drought, global warming, and other environmental factors.

4.4 Uncertainties and implications

In this study, forest management practices such as harvest and thinning were not considered. Forest regrowth after harvest could greatly influence the responses of forest to drought conditions. Reports have shown that over 80% are young or mid-rotation forest (<40 years old) in the SUS (Pan et al. 2011; Smith et al. 2009). These forests have higher productivity,

thereby demanding more water and possibly resulting in water shortage (Jackson et al. 2005; McNulty et al. 2007; Sun et al. 2008). Therefore, our results might somewhat underestimate drought impacts on NPP and C storage. We found that drought effects could be enhanced by changes in air temperature; however, other factors such as land use, N deposition, and atmospheric CO_2 concentration were not considered to change with time in this study, which could also result in some uncertainties.

Although climate in the SUS exhibited no significant change trend during 1895–2007, many climate models have predicted a rapid increase in air temperature for the entire SUS and a decrease in precipitation for some areas in this region (Field et al. 2007; Karl et al. 2009). Our study found that drought impacts could be augmented by increasing temperature. Therefore, the future climate change pattern may likely cause more serious drought conditions and affect larger regions in the SUS. In addition, the increasing water use by industry and irrigated cropland could greatly decrease regional water availability in the SUS (McNulty et al. 2007; Field et al. 2007; Tian et al. 2010a), which resulted in water shortage even in relatively wet years (e.g., 2007). Thus, to mitigate drought impacts and maintain terrestrial ecosystem sustainability in the eastern SUS, it is necessary to reduce water use by industry and irrigated cropland.

5 Conclusions

Based on SPI, we characterized drought intensity and duration in the SUS during 1895–2007. No significant changes in drought intensity and duration were found for this time period. However, we found that the areas in the SUS experiencing extreme high rainfall events appeared to be increasing, which might imply an increased flooding frequency. NPP was greatly reduced during dry years and could be more than 40% in some areas. NPP decreased in large areas of the eastern SUS, while increasing in most areas of the west. Changes in precipitation pattern resulted in a C emission and displayed great spatial variability. Changes in precipitation induced C sinks in most areas of the western SUS and C sources in most areas of the east. Drought impacts on NPP and C storage could be enhanced by changes in other environmental factors such as air temperature and land use change. Therefore, future studies on drought impacts should consider the interactive effects of drought events and other factors.

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