



## Drought impacts on ecosystem functions of the U.S. National Forests and Grasslands: Part II assessment results and management implications



Shanlei Sun<sup>a,b</sup>, Ge Sun<sup>c,\*</sup>, Peter Caldwell<sup>d</sup>, Steve McNulty<sup>c</sup>, Erika Cohen<sup>c</sup>, Jingfeng Xiao<sup>e</sup>, Yang Zhang<sup>b</sup>

<sup>a</sup> College of Hydrometeorology, Nanjing University of Information Science & Technology, Nanjing 210044, Jiangsu Province, China

<sup>b</sup> Department of Marine, Earth, and Atmospheric Sciences, North Carolina State University, Raleigh, NC 27606, USA

<sup>c</sup> Eastern Forest Environmental Threat Assessment Center, Southern Research Station, United States Department of Agriculture Forest Services, Raleigh, NC 27606, USA

<sup>d</sup> Coweeta Hydrologic Laboratory, Southern Research Station, USDA-FS, Otto, NC 28763, USA

<sup>e</sup> Earth Systems Research Center, Institute for the Study of Earth, Oceans, and Space, University of New Hampshire, Durham, NH 03824, USA

### ARTICLE INFO

#### Article history:

Available online 11 June 2015

#### Keywords:

Droughts

Ecosystem productivity

National Forests and Grasslands

Water yield

### ABSTRACT

The 781,000 km<sup>2</sup> (193 million acre) United States National Forests and Grasslands system (NF) provides important ecosystem services such as clean water supply, timber production, wildlife habitat, and recreation opportunities to the American public. Quantifying the historical impacts of climate change and drought on ecosystem functions at the national scale is essential to develop sound forest management and watershed restoration plans under a changing climate. This study applied the previously validated Water Supply and Stress Index model (WaSSI) to 170 NFs in the conterminous U.S. (CONUS) to examine how historical extreme droughts have affected forest water yield (Q) and gross primary productivity (GPP). For each NF, we focused on the five years with the lowest annual SPI3 (Standardized Precipitation Index on a 3-month time scale) during 1962–2012. The extent of extreme droughts as measured by the number of NFs and total area affected by droughts has increased during the last decade. Across all lands in CONUS, the most extreme drought during the past decade occurred in 2002, resulting in a mean reduction of Q by 32% and GPP by 20%. For the 170 individual NFs, on average, the top-five droughts represented a reduction in precipitation by 145 mm yr<sup>-1</sup> (or 22%), causing reductions in evapotranspiration by 29 mm yr<sup>-1</sup> (or 8%), Q by 110 mm yr<sup>-1</sup> (or 37%) and GPP by 65 gC m<sup>-2</sup> yr<sup>-1</sup> (or 9%). The responses of the forest hydrology and productivity to the top-five droughts varied spatially due to different land-surface characteristics (e.g., climatology and vegetation) and drought severity at each NF. This study provides a comprehensive benchmark assessment of likely drought impacts on the hydrology and productivity in NFs using consistent methods and datasets across the conterminous U.S. The study results are useful to the forestry decision makers for developing appropriate strategies to restore and protect ecosystem services in anticipating potential future droughts and climate change.

Published by Elsevier B.V.

### 1. Introduction

Forest and grassland ecosystems are increasingly valued for their ecological functions and services in the United States (Sedell et al., 2000; Jones et al., 2009) and around the world (Costanza et al., 1997; Nasi et al., 2002; Brauman et al., 2007). For example, U.S. forests and grasslands provide over half of U.S. fresh water supply (Brown et al., 2008; Sun et al., 2015a). Water draining from forests, natural or managed, has the best quality among all land uses (Binkley and Brown, 1993; Brown and Froemke, 2012). Forests and grasslands can offset 10–40% of

annual carbon emissions from burning fossil fuels each year (Ryan et al., 2010; McKinley et al., 2011; Xiao et al., 2011). The 781,000 km<sup>2</sup> (193 million acres) National Forest and Grassland system (NF) managed by the United States Department of Agriculture-Forest Service (USDA-FS) was established over a century ago to meet the American public demand for stable and abundant water, timber supply, recreation, and other ecosystem goods and services. Sustaining ecosystem health, diversity, and productivity to meet the needs of present and future generations is the top priority of USDA-FS. It is estimated that NFs alone provide 14% of the national water supply (Brown et al., 2008). However, the ongoing climate change and variability and related environmental impacts have exerted serious threats to NFs and have posed many unprecedented challenges to land managers to meet the missions of the forest management agencies

\* Corresponding author at: USDA Forest Service, 920 Main Campus Dr., Venture II, Suite 300, Raleigh, NC 27606, USA. Tel.: +1 9195159498; fax: +1 9192735154.

E-mail address: [gesun@fs.fed.us](mailto:gesun@fs.fed.us) (G. Sun).

(NCA, 2014). Increases in tree mortality, frequent and intensified wildfires, wide spread insect infestation and diseases are just a few of the symptoms of forest stress due to climate variability and change (Vose et al., 2012), reducing the benefits of forest ecosystem services.

Numerous empirical and modeling studies have clearly shown that climate extremes and associated with climate change are on the rise (Elsner et al., 2008; Min et al., 2011; Dai, 2013; IPCC, 2014; Trenberth et al., 2012). Among all the climate extremes, drought is one of the most common and costly disasters (e.g., World Meteorological Organization, 1992; American Meteorological Society, 1997). Studies on the ecological consequences of worldwide droughts on forest water supply and productivity have emerged in recent years (Vose and Swank, 1994; Easterling et al., 2007; Larsen, 2000; Allen et al., 2010; Zhao and Running, 2010; Schwalm et al., 2012; Chen et al., 2013; Zhou et al., 2014; Zscheischler et al., 2014). The most recent noticeable severe droughts occurred in 2002, 2003, 2011 and 2012 in the U.S. (<http://droughtmonitor.unl.edu/MapsAndData/DataTables.aspx>). In 2002, more than 50% of the conterminous U.S. (CONUS) experienced moderate to severe drought conditions with record or near-record precipitation deficits throughout the western U.S. (Cook et al., 2004). Four consecutive drought years (2001–2004) led to water supply deficits in reservoir storage below average by May 2004, and below 50% capacity in Arizona, New Mexico, Nevada, Utah, and Wyoming (USDA, 2004). In the Colorado River Basin, the electricity generating capacity was threatened in 2007 due to the longest drought in the past 100 years that left Lakes Mead and Powell at roughly 50% of their capacities (Strzepek et al., 2010). Increased drought intensity led to significant decreases in net primary productivity in many areas of the south-eastern U.S., with the largest decrease up to 40% during extreme droughts (Chen et al., 2013). Similarly, Xiao et al. (2009) showed that severe extended droughts in China during the twentieth century reduced carbon uptake in large parts of the drought-affected areas. Previous site-level studies (e.g., Noormets et al., 2010; Xie et al., 2013a) indicated many other environmental factors beyond precipitation, such as timing of droughts, groundwater availability, radiation, extreme air temperature, can complicate assessment of the impacts of drought on forest ecosystems. A small shift in drought frequency or severity could substantially reduce the magnitude of regional carbon sinks (Reichstein et al., 2013).

There are no indications that extreme drought frequencies will increase across the whole U.S. in the future (Easterling et al., 2007; IPCC, 2014). However, droughts are general regional, and spatial differences of drought prevalence are becoming more and more obvious (Andreadis and Lettenmaier, 2006), drought onset is occurring more quickly, and drought intensity is increasing (Webb et al., 2005; Karl et al., 2009; Gutzler and Robbins, 2011; Dai, 2013). Our knowledge about the impacts of historical droughts on forest water supply and productivity at large scales are incomplete due to the dynamic nature of droughts and complex mechanisms of ecohydrological response to droughts in forest ecosystems. A comprehensive quantitative assessment of drought impacts on the ecosystem services of NFs using a consistent modeling approach is needed but is not currently available (Vose et al., 2012; NCA, 2014).

This study was designed to evaluate the effects of historical droughts on the key forest ecosystem functions: water yield (Q), evapotranspiration (ET), and gross primary productivity (GPP) of NFs. These three variables represent the three most foundations of ecosystem services of clean water supply, climate moderation, and carbon sequestration. This study used the updated and validated version of the Water Supply and Stress Index (WaSSI) model that operates at the watershed scale (Sun et al., 2011a; Caldwell et al., 2012). The description of the WaSSI model and model

validations using historical water and carbon flux data were reported in a companion paper (Sun et al., 2015b). Specifically, the present study aims: (1) to examine historical drought patterns (e.g., intensity and extent) at each of the 170 NFs, and (2) to evaluate the impacts of historical droughts on Q, ET and GPP in the 170 NFs for the past five decades (1962–2012). Information from the historical analysis will be useful to understand the spatial patterns of drought impacts at the national scale, and to develop sound watershed management strategies for mitigating negative impacts of droughts and adapting to a changing environment for the NFs.

## 2. Methods

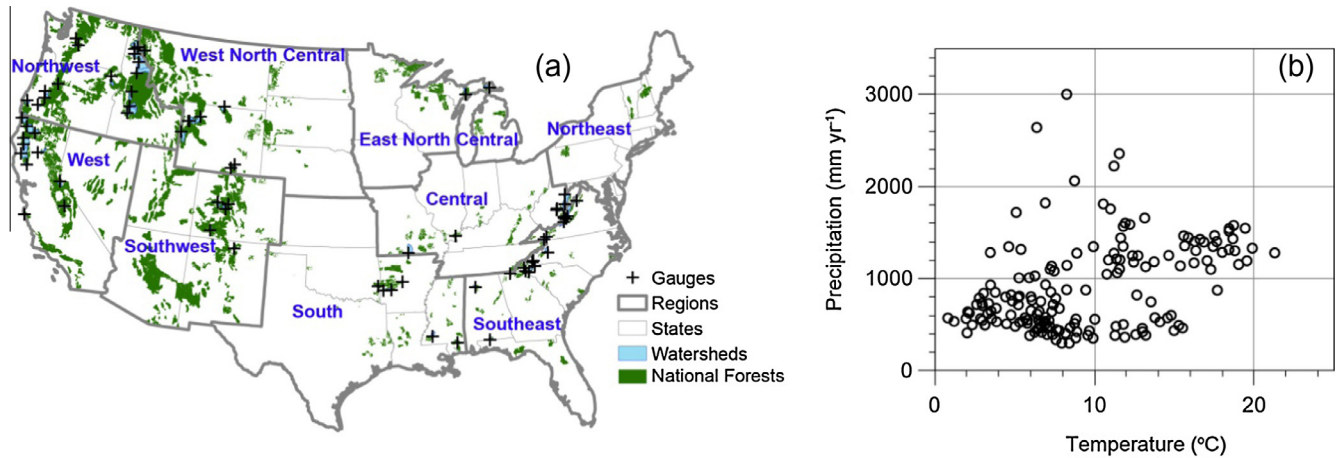
The water-centric ecosystem model, WaSSI, was parameterized to simulate monthly water and carbon balances for each of the approximately 88,000 Watershed Boundary Database (WBD) 12-digit Hydrologic Unit Code (HUC) watersheds for the past five decades (1961–2012). We hypothesized that ecosystem responses to droughts vary dramatically across the U.S. due to differences in climatic regimes and drought characteristics (e.g., intensity and extent). Spatial and temporal changes of droughts and their impacts on Q, ET, and GPP were examined. In particular, our analysis focused on the five extreme droughts, refereed as the top-5 droughts therein during the past five decades at each of the 170 NFs to provide a benchmark of the likely impacts of extreme droughts on Q, ET, and GPP.

### 2.1. Study area

The research area in the 170 NFs covers about approximately 781,000 km<sup>2</sup> (193 million acres), or 8.8% of the CONUS land area. These NFs are located mostly in the Northwest and the Southwest regions (Fig. 1a). Climate, topography, and vegetation covers vary greatly among these 170 NFs (Fig. 1b) (Sun et al., 2015b).

### 2.2. The WaSSI model

For reconstructing a continuous and long-term hydrological (e.g., ET and Q) and ecosystem carbon balances (e.g., GPP), an integrated, process-based model, the WaSSI, was utilized in this study. It describes key ecohydrological processes at a broad scale (Sun et al., 2011a; Caldwell et al., 2012; Sun et al., 2015a), and simulates the full monthly water (ET, Q and soil moisture storage) and carbon balances (GPP, ecosystem respiration and net ecosystem productivity) for each land cover class at the 8-digit HUC or 12-digit HUC watershed scale across the CONUS. Three sub-models are integrated within the WaSSI model framework. The water balance sub-model computes ecosystem water use (i.e., ET), and Q from each watershed. As the core part within this sub-model, ET is described as a function of potential ET (PET), LAI, precipitation, and soil water availability for each land cover type in each HUC watershed with mixed land cover types. The water availability for each watershed land cover type is simulated using algorithms from the Sacramento Soil Moisture Accounting Model (SAC-SMA; Burnash, 1995). The carbon balance sub-model computes carbon dynamics (e.g., GPP and respiration) using linear relationships between ET and GPP derived from global eddy covariance flux measurements (Sun et al., 2011a, 2011b). The water supply and demand sub-model routes and accumulates Q through the river network according to topological relationships between adjacent watersheds, subtracts consumptive water use by humans from river flows, and compares water supply to water demand to compute the water supply stress index. The detailed description about this model can be found in the User Guide of WaSSI Ecosystem



**Fig. 1.** (a) Spatial distribution of the National Forest and Grassland System (NFs) over the CONUS and the 72 selected watersheds with streamflow gauges. The CONUS is divided into nine regions Northwest (NW), West (W), Southwest (SW), West North Central (WNC), East North Central (ENC), Central (C), South (S), Southeast (SE) and Northeast (NE). (b) Climate (multi-year mean annual precipitation and temperature) space of the NFs showing a large climatic gradient.

Services Model ([http://www.forestthreats.org/research/tools/WaSSI/WaSSIUserGuide\\_english\\_v1.1.pdf](http://www.forestthreats.org/research/tools/WaSSI/WaSSIUserGuide_english_v1.1.pdf)).

Previous versions of the WaSSI model has been tested and applied in a variety of geographical regions over the U.S. and other continents (Sun et al., 2008, 2011a; Lockaby et al., 2011; Caldwell et al., 2012; Averyt et al., 2013; Tavernia et al., 2013; Liu et al., 2013; Marion et al., 2014). In this study, we applied the latest WaSSI model that operated at a much higher spatial resolution than previous studies covering more than 88,000 12-digit HUC watersheds over the CONUS. Prior to this application study, we have validated the model with measured  $Q$  data monitored by USGS gauging stations and PRISM  $P$  minus USGS  $Q$  (referred as observed ET) for 72 watersheds, and satellite-based ET and GPP for 170 NFs over the CONUS. Overall, the assessments suggested that the latest WaSSI model had the capability to reconstruct the long-term water and carbon fluxes. The detailed model evaluation results are found in Sun et al. (2015b) as a companion paper to the present study.

### 2.3. Defining top-5 droughts

To define and identify extreme drought years, this study adopted the Standardized Precipitation Index (SPI), a drought index that has been widely used worldwide and was relevant to evaluate ecosystem services (Zhang et al., 2009; Zhao et al., 2011; Huang et al., 2014a, 2014b). This approach was designed to monitor droughts based on the long-term monthly precipitation data over a given period (McKee et al., 1993). After fitting a Gamma distribution and transforming precipitation to a normal distribution by an equal probability transformation, the SPI was estimated as precipitation anomaly divided by the standard deviation of the transformed data (Huang et al., 2014a, 2014b). The SPI tracks droughts at different time-scales, i.e., 1-, 3-, 6-, 12-, and 24-month, and is flexible with respect to the period chosen (Raziei et al., 2009). In our study, the SPI on a 3-month time scale were used (referred as SPI3 thereafter).

To reduce uncertainties from a single drought to represent drought characteristics for each NF, the five extreme drought years for each NF were used for impact analyses. We identified the top five droughts using a two-step procedure. First, the SPI3 time series for each NF was sorted in a descending order for the 1962–2012 time period. Second, the first five years with the least SPI3 were selected, referred to the top-5 droughts herein. The characteristics of top-5 droughts for each NF can be found in the Supplementary

data (S11). For consistency, precipitation, temperature, ET,  $Q$ , and GPP were evaluated over the same temporal period (1962–2012) as the SPI3 for impact analysis.

### 2.4. Impact analysis

We examined the impacts of droughts in NFs at two spatial levels: the entire NFs as whole and the individual NF sites. The anomalies of annual precipitation, temperature, ET,  $Q$ , and GPP were first examined using area weighted averages across the NFs for the 1962–2012 period. Then, the responses of ET,  $Q$ , and GPP to droughts were analyzed for each of the 170 sites. These identified drought years represented the worst cases in terms of potential hydrologic and ecosystem impacts. Impacts of the top-five droughts on ET,  $Q$  and GPP of each NF were presented as absolute and relative changes (%) from the 51-year means. In each NF, the absolute differences were expressed as the means under the top-5 droughts minus that of means over the period of 1962–2012, while the percent differences were calculated using the absolute difference divided by the 1962–2012 means. At the regional and the national scales, the absolute and percent differences were calculated using area-weighted method considering the size of the NFs.

## 3. Results

### 3.1. Variability of annual climate, $Q$ , ET, and GPP during 1962–2012 across NFs

The variability in the overall weighted means of annual  $P$ , Air Temperature,  $Q$ , ET, and GPP across all 170 NFs is presented as their anomalies over time (Fig. 2). For  $P$ , the most negative anomalies greater than  $80 \text{ mm yr}^{-1}$  were found during the 1980s and 2000s, while large anomalies of temperature occurred before 1986 (cooling) and after 2000 (warming). A clear warming trend was found during the 2000s (Fig. 2b). Similar to  $P$ , ET and  $Q$  also showed negative anomalies during the 1980s and 2000s (Fig. 2c and d). For GPP, consistent negative anomalies occurred prior to 1980, but large reductions ( $>30 \text{ gC m}^{-2} \text{ yr}^{-1}$ ) generally occurred during the 1980s and 2000s (Fig. 2e).

Interestingly, the overall precipitation reduction for all NFs did not always correspond to the anomaly rankings for ET,  $Q$  and GPP. Taking year 2002 as an example, relative to the 1962–2012 mean, precipitation was the second lowest ( $119 \text{ mm yr}^{-1}$  reduction), but

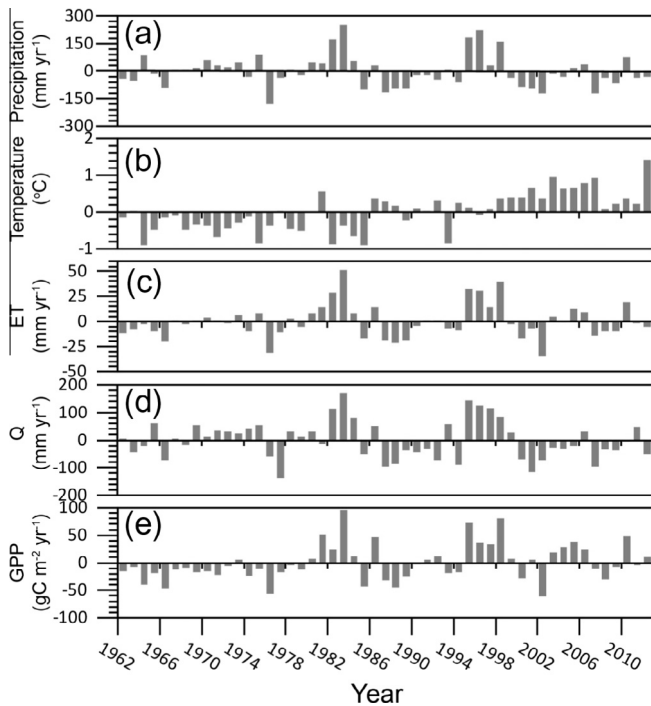


Fig. 2. Anomalies of mean annual mean precipitation, temperature,  $Q$ , and GPP across the 170 NFs during the period 1962–2012.

ET,  $Q$  and GPP decreased  $35 \text{ mm yr}^{-1}$  (the lowest),  $74 \text{ mm yr}^{-1}$  (the 2nd lowest) and  $61 \text{ gC m}^{-2} \text{ yr}^{-1}$  (the lowest), respectively. The year 2002 represented the highest annual precipitation reduction in the recent decade over all the NFs. As shown in Fig. 3 and 75% of the NFs (Fig. 1a), mostly in the central and western CONUS, showed negative anomalies for ET,  $Q$  and GPP in 2002. However, overall, the eastern CONUS did not have large decreases in  $P$ . Also, a large percentage of the NFs were located in the central and western CONUS, and any changes in the eastern regions might not affect the means of the NFs as a whole. Another reason might be related to antecedent soil moisture changes, which could impact the eco-hydrological processes by controlling soil water storage. Therefore, a decrease in annual  $P$  did not always coincide with the negative anomalies of ET,  $Q$  and GPP at the annual scale.

In general, annual  $P$  reduction resulted in a decrease in  $Q$ , but several NFs had a small increase in  $Q$  likely due to an increase in snow melting processes or/and seasonal shift in precipitation (Fig. 3c). The increase in GPP was likely because of an increase in temperature and ET even under a decreased precipitation in the cool and wet Pacific Northwest region where long-term water stress was not common. The responses of  $Q$  and GPP to precipitation reduction differed among the NFs for different reasons. Overall, precipitation reduction could occur at any place and anytime, and different response mechanisms existed over the NFs under various physical conditions. Therefore, it was necessary and useful to explore the responses of ET,  $Q$  and GPP to droughts at each NF with selected droughts years (e.g., the historic top-5 droughts) using a common and widely used drought index (e.g., SPI).

### 3.2. Changes in extreme droughts (top-5 droughts) occurrences over time across NFs

For exploring drought intensity changes over the whole NFs, annual mean SPI3 for the 1962–2012 period was summarized in Fig. 4a. The worst drought (SPI3 =  $-0.63$ ) was found in 2002,

followed by the 2nd (SPI3 =  $-0.51$ ) and the 3rd worst (SPI3 =  $-0.51$ ) in 1987 and 1966, respectively. On a decadal scale, the ranked mean SPI3 with an ascending order was  $-0.15$  in the 2000s,  $-0.05$  in the 1970s,  $-0.04$  in the 1960s,  $0.12$  in the 1970s, and  $0.17$  in the 1990s. The 2000s had the highest drought intensity with 8 occurrences. There was no significant trend in annual average SPI3 for the whole NFs during the 1962–2012 period. However, a significant decreasing trend ( $p < 0.05$ ) with SPI3 value of  $-0.01$  was detected during 1986–2012, which indicated that the drought intensity after 1986 had become stronger for the NFs as a whole. The linear trend of SPI3 for each NF was showed spatial differences in SPI3 (Fig. 5). A total of 10 NFs located in the SW, NW and SE regions had negative (i.e., increasing drought intensity) significant ( $p < 0.05$ ) trends while 12 NFs had a significant ( $p < 0.05$ ) positive trends (i.e., decreasing drought intensity).

On average, 17 NFs or 10% of the NFs were under extreme drought conditions (top-five drought) during the period 1962–2012. The number of NFs that suffered from extreme droughts fluctuated dramatically from year to year (Fig. 4b). The most widespread droughts occurred in 2002 (65 NFs or 38%), followed by the year of 2012 (51 NFs or 30%), 1987 (47 NFs or 28%), and 1963 and 2001 (41 NFs or 24%). On a decadal basis, 10%, 9%, 10%, 3% and 15% of the 170 NFs suffered from the top-five droughts in the period 1960s, 1970s, 1980s, 1990s and 2000s, respectively. The temporal fluctuations of the percent area under extreme droughts (Fig. 4c) were similar to those of the NFs number percentage, and the highest value of 54% was found in 2002 followed by 46% in 1987 and 44% in 1966. The discrepancies between the fluctuations of the NFs number and area percentage were likely caused by the spatial distribution of the NFs over the CONUS and the spatial and temporal patterns of the droughts. By decadal mean percent area under the top-five droughts, 16% was found in the 2000s, followed by other periods ranging from 3% to 11%. During the past five decades, the recent decade (i.e., the 2000s) saw the highest NFs number and the highest area suffering from the extreme droughts.

### 3.3. Impacts of the “top-5” droughts on 170 individual NFs

#### 3.3.1. Top-5 droughts at individual NFs site and by region

In general, when extreme droughts occurred, the humid regions in the east and west coasts showed the highest absolute reductions in  $P$  ( $>300 \text{ mm yr}^{-1}$ ). The highest relative reductions in  $P$  ( $>30\%$ ) were found in the arid regions (e.g., California) followed by the SW, S and WNC (Table 1; Fig. 6a and b). Extreme droughts were generally accompanied by warmer than average air temperatures, except in the regions of NW, C and NE. The absolute and relative reductions in  $P$  at an individual location varied greatly across the NFs (Fig. 6a and b). Spatially, temperatures increased during the top-5 droughts in most of the NFs, especially in the WNC and SW (Fig. 6c). However, contrary to our common perceptions, the NW, C and NE regions experienced cooler temperatures, ranging from  $-0.8$  to  $0 \text{ }^\circ\text{C}$  during extreme droughts, suggesting complex interactions and decoupling of precipitation and temperature. Also, the general warming trend of air temperature across the U.S. might also have complicated drought-temperature relations and patterns.

Therefore, quantifying the impacts of droughts on ecosystem functions should consider changes in both precipitation and temperature. The decrease in precipitation and increase in temperature found in the western CONUS indicated that drought severity in the region was relatively high historically. A warmer weather condition would exacerbate the drought effects. In contrast, a cooler temperature accompanying the reduction in precipitation in drought years could compensate for the decrease in water availability to some extent because a cooler climate could result in lower water loss through ET.

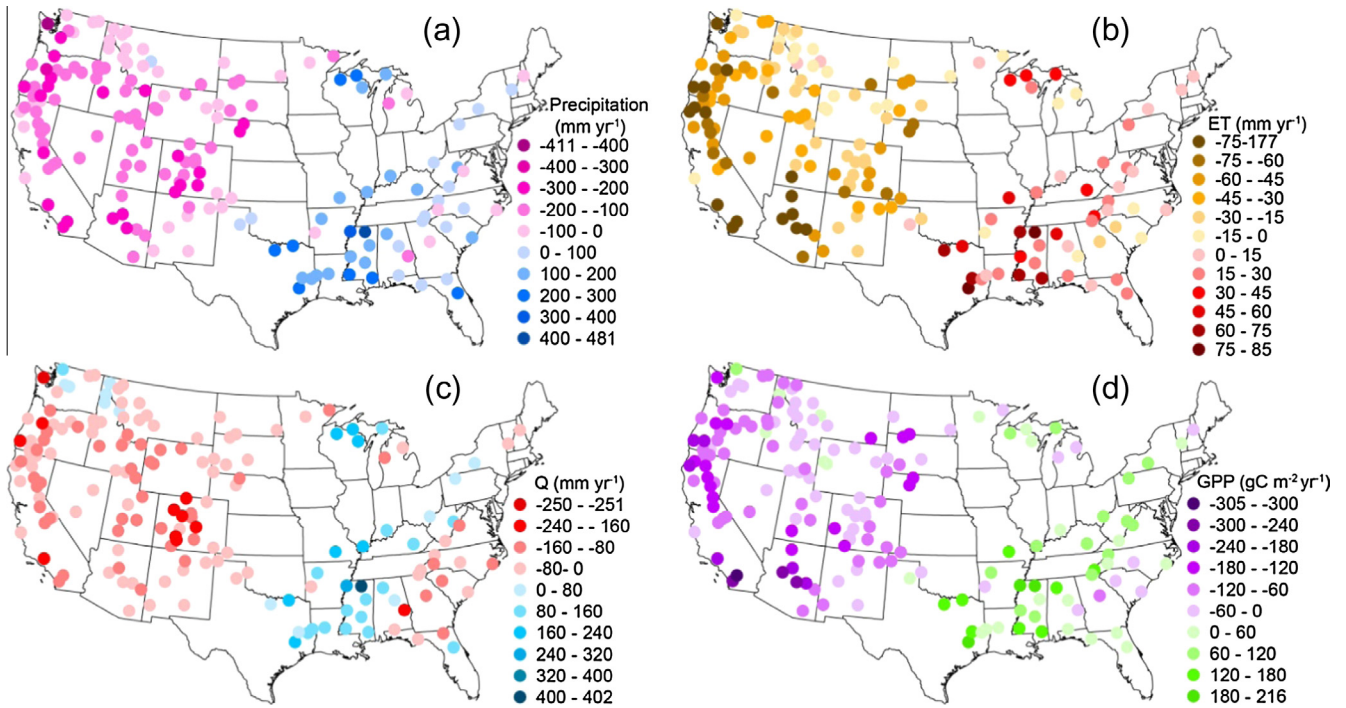


Fig. 3. Distribution of anomalies of annual precipitation (a), ET(b), Q (c) and GPP (d) in 2002.

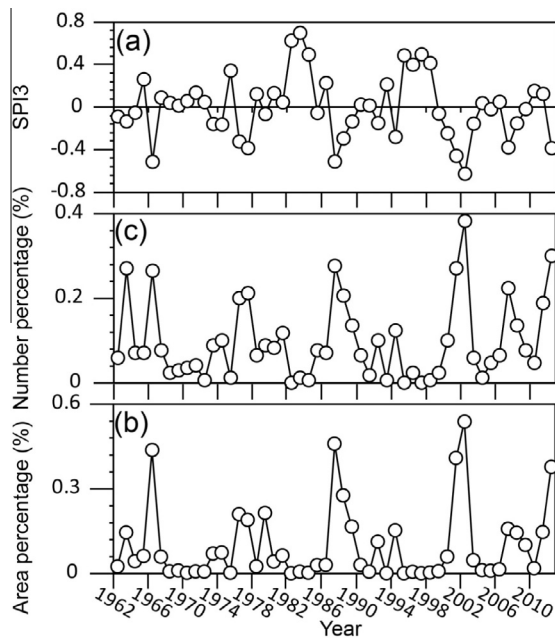


Fig. 4. Annual SPI3 averaged over all the NFs (a), and number (b) and area percentage (c) of NFs with the top-five droughts during the period 1962–2012. The number (area) percentage for each year was estimated by number (area) of NFs with the top-five drought divided by 170 (the sum area of the 170 NFs).

3.3.2. Impacts of extreme droughts on ET and Q at each of the NFs and by region

When extreme droughts occurred, on average across the 170 NFs, ET and Q rates decreased by 29 mm yr<sup>-1</sup> (or 8%) and 110 mm yr<sup>-1</sup> (or 37%), respectively. There were large variations in both the absolute and percent differences among the NFs due to the spatial variability of climatic regimes and land-surface characteristics as well as local climate change (Table 1 and Fig. 7). For

ET, the highest absolute decreases (>75 mm yr<sup>-1</sup>) were found mostly in the west coasts and SE (Fig. 7a), while the highest percent reduction occurred in the arid California and the south of the SW (>15%; Fig. 7b). The NFs on the west coast had the highest reduction in Q (>320 mm yr<sup>-1</sup>) followed by the SE (160–400 mm yr<sup>-1</sup>; Fig. 7c). The S, SW, WNC and C regions had the highest percent changes in Q (>45%), particularly in the east part of the WNC (>60%) (Fig. 7d). The SE exhibited the 2nd highest percent decreases in Q (30–75%). Annual ET declined in all the NFs despite some of them having temperature decreased, suggesting that P had a major control on ET during droughts.

3.3.3. Impacts of extreme droughts on GPP at each of the NFs and by region

All of the 170 NFs had reductions in annual GPP under the extreme droughts (Table 1; Fig. 8), with an averaged reduction of 65 gC m<sup>-2</sup> yr<sup>-1</sup> or 9%. Similar to P, Q and ET, GPP exhibited relatively large absolute (0–370 gC m<sup>-2</sup> yr<sup>-1</sup>) and relative (0–39%) changes. The highest reductions in GPP in absolute values

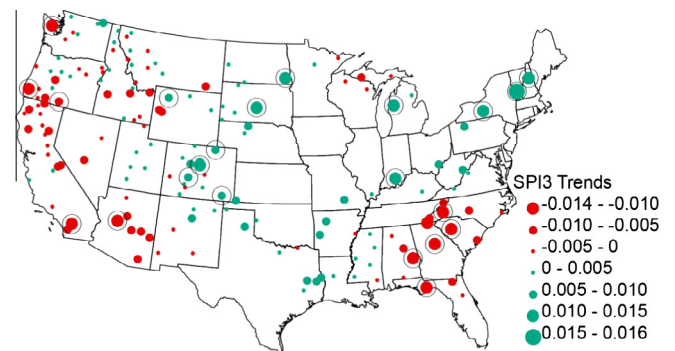
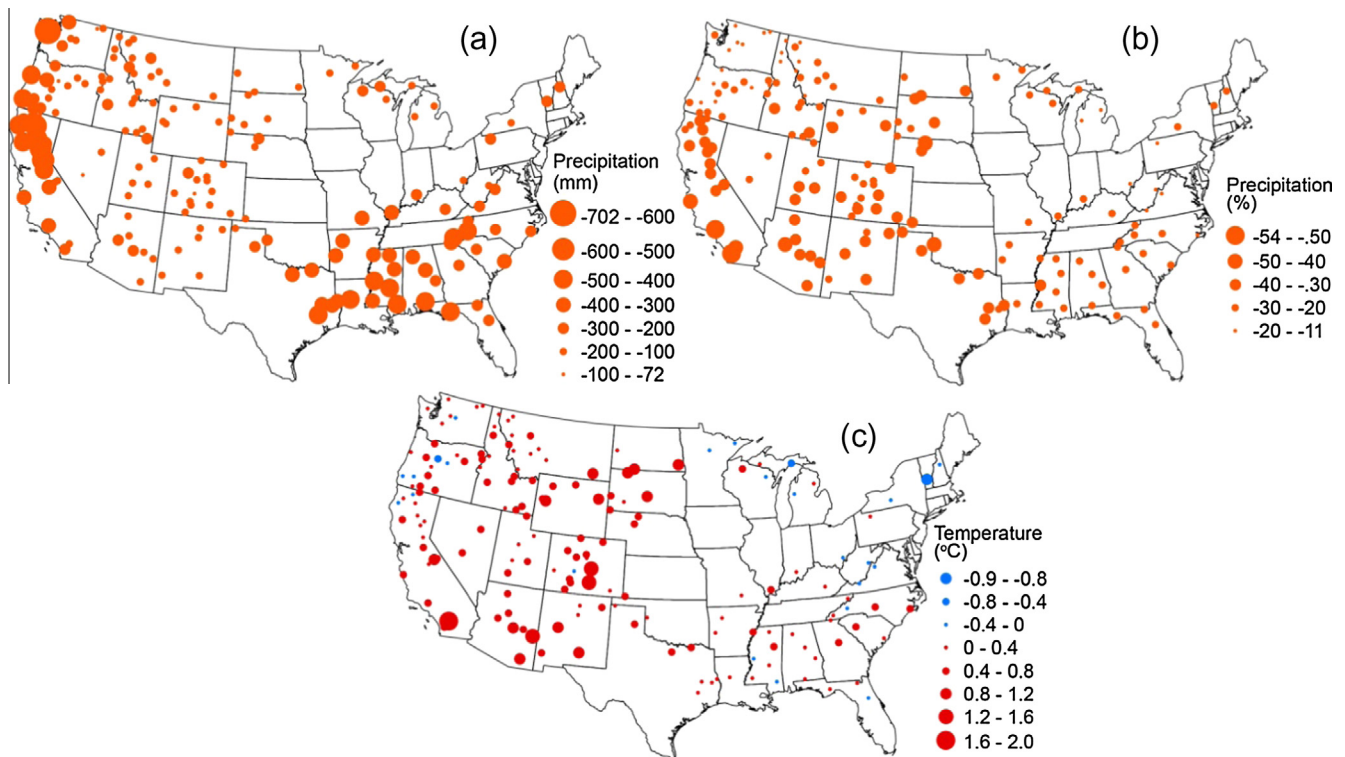


Fig. 5. The linear trends of SPI3 for the 170 NFs over the period 1962–2012. Negative values indicate drought intensity increases, and vice versa. The circles represent significant trends ( $p < 0.05$ ).

**Table 1**  
Averaged deviations of mean annual precipitation, temperature, ET, Q and GPP under the top-five droughts from the period of 1962–2012 for the National Forests and Grasslands Systems (NFs) by nine regions as presented in Fig. 1a.

Regions	Precipitation (mm yr <sup>-1</sup> ) (%)	Temperature (°C)	ET (mm yr <sup>-1</sup> ) (%)	Q (mm yr <sup>-1</sup> ) (%)	GPP (gC m <sup>-2</sup> yr <sup>-1</sup> ) (%)
NW	-179 (-16)	0.35	-36 (-7)	-181 (-29)	-75 (-7)
W	-109 (-27)	0.24	-28 (-15)	-86 (-41)	-54 (-14)
SW	-157 (-29)	0.54	-40 (-11)	-86 (-52)	-62 (-9)
WNC	-115 (-20)	0.24	-20 (-7)	-91 (-34)	-19 (-4)
ENC	-134 (-22)	-0.02	-18 (-5)	-102 (-42)	-45 (-5)
C	-80 (-22)	0.02	-15 (-7)	-56 (-37)	-45 (-7)
S	-191 (-29)	0.13	-51 (-12)	-123 (-51)	-131 (-12)
SE	-105 (-24)	0.01	-24 (-9)	-83 (-45)	-67 (-9)
NE	-232 (-21)	-0.27	-30 (-6)	-182 (-31)	-89 (-7)
All NFs	-145 (-22)	0.14	-29 (-8)	-110 (-37)	-65 (-9)



**Fig. 6.** Deviations of mean annual precipitation (a and b) and temperature (c) for the top-five droughts from the means over the period 1962–2012. Negative values (a and b) indicate drier, or cooler (c) conditions.

were found in the west coast and SE regions ( $>180 \text{ gC m}^{-2} \text{ yr}^{-1}$ ; Fig. 8a). For relative changes in GPP (Fig. 8b), the highest decreases ( $>15\%$ ) were generally found in the west coasts, C and the southern part of the SW. The spatial distributions of absolute and relative reductions in GPP mirrored drought severity (i.e.,  $P$  reduction).

## 4. Discussion

### 4.1. Uncertainty and limitations of assessment method and results

Forest ecohydrological processes under droughts are likely to change dramatically, but the changes are difficult to model mathematically at the large scale. For example, reduced precipitation lowers soil moisture (Lake, 2003) and affects vegetation growth by controlling stomata and structure (e.g., LAI) (Ji and Peters, 2003; McDowell et al., 2008; Jain et al., 2010). Reichstein et al. (2013) also found that droughts led to plant stomatal closure, decreasing leaf transpiration and evaporative cooling, and thus carbon uptake. Additionally, Reichstein et al. (2013) and Anderegg

et al. (2012) suggested that droughts, especially the most severe, usually led to a higher vapor pressure gradient between leaves and the atmosphere, causing a stress on the hydraulic system of plants. Consequently, high tension in the xylem can trigger embolism and partial failure of hydraulic transport in the stem, and even potentially caused the vegetation mortality that significantly influences water yield and carbon sink capability (Cook et al., 2007; Allen et al., 2010; Guardiola-Claramonte et al., 2011; Adams et al., 2012). The WaSSI model used a simplified algorithm to simulate the interactions between vegetation structure (e.g., LAI),  $Q$ , ET and GPP. The dynamic responses of vegetation to droughts, such as stomatal closure and LAI reduction, were not considered, thus may result in modeling uncertainties during prolonged droughts periods. Additionally, the WaSSI model needs improvement to include the effects of vapor pressure deficit (VPD) and  $\text{CO}_2$  concentration on plant hydraulic systems to truly reflect the effects of climate change on forest functions (Shi et al., 2010).

It is well known that natural disturbance factors (e.g., hurricane, wildfire, pest and pathogen outbreak) and their interactions with droughts also can strongly influence ecosystem structure and

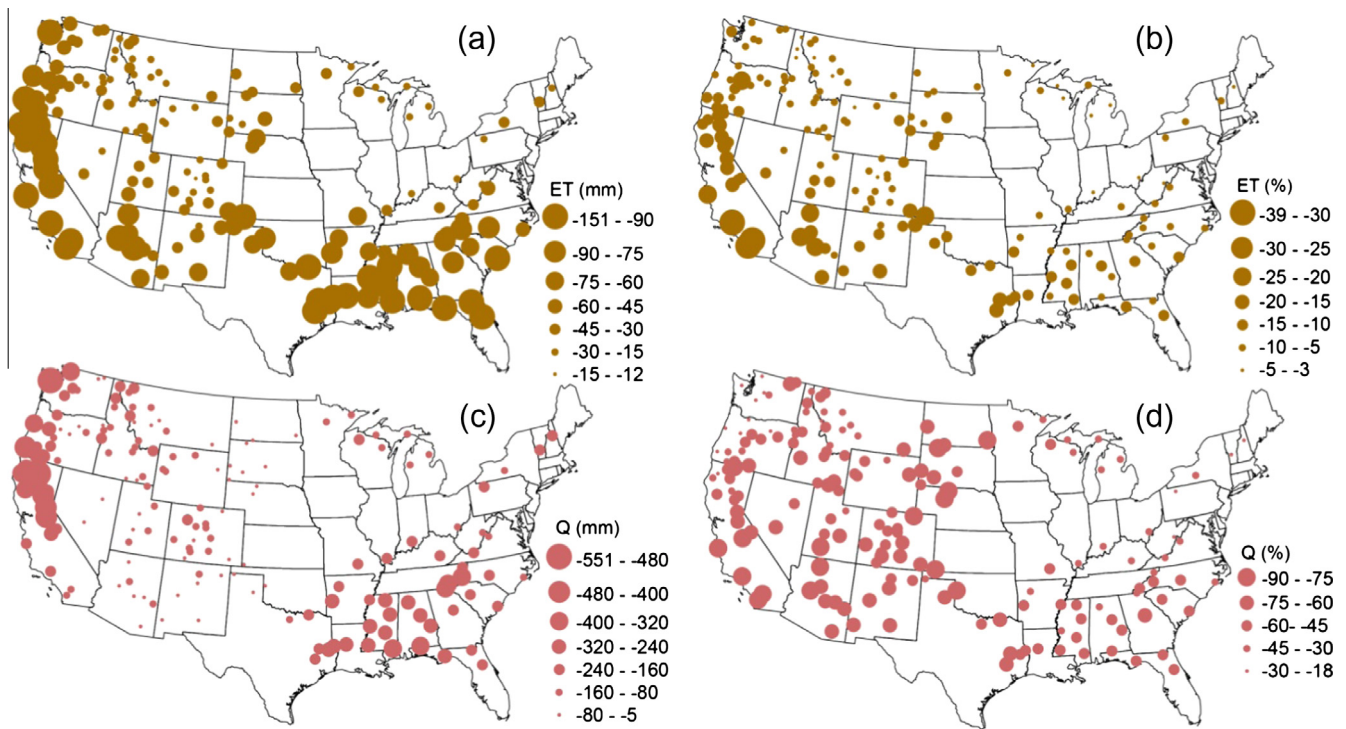


Fig. 7. Differences in mean annual ET (a and b) and Q (c and d) between the top-five droughts and the period 1962–2012.

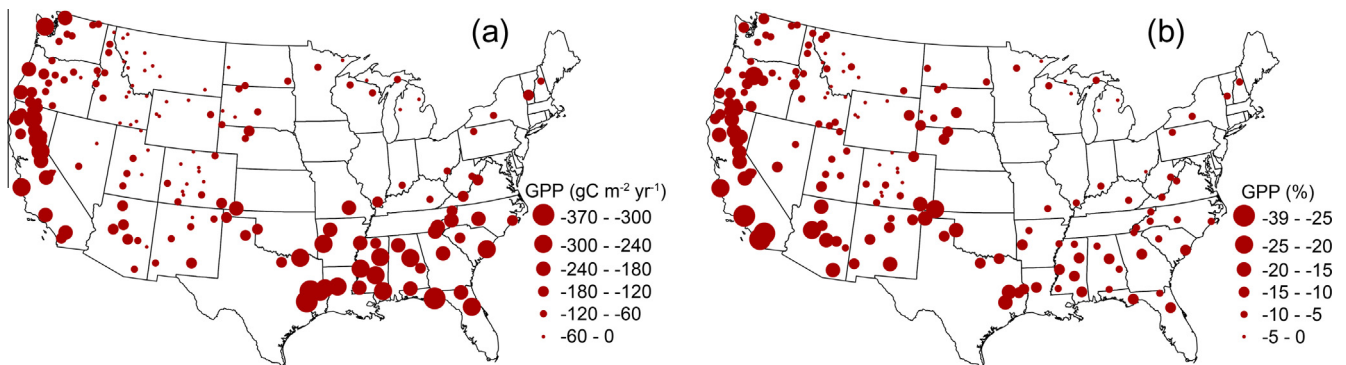


Fig. 8. Deviations of (a) absolute values and (b) relative values of GPP for the top-five drought years from the long-term (1962–2012) means.

functions (Hanson and Weltzin, 2000; Dale et al., 2001; Jayakaran et al., 2014). For wildfires, the direct effects on forest ecosystems include vegetation mortality and reducing soil infiltration capacity, consequently leading to a decrease in ecosystem productivity and increase in overland flow and water yield, and soil erosion (Inamdar et al., 2006). As an important disturbance regime, pests and pathogens also can predispose an individual plant species to disease or mortality under drought conditions (Schoeneweiss, 1981; Ayers and Lombarder, 2000). Previous studies (Overpeck et al., 1990; Hason and Weltzin, 2000; Taylor and Beatty, 2005; Westerling et al., 2006; Xiao and Zhuang, 2007; Marengo et al., 2008; DeRose and Long, 2012; Jactel et al., 2012) showed that droughts often lead to wildfires, pest and pathogen outbreaks.

Regional climate data scaled from station-based measurements at local weather stations remain uncertain for mountainous regions in western U.S. (Oyler et al., 2015). The PRISM climate data for both air temperature and precipitation used in the current drought impact analysis may not be accurate for forests located on high elevations in the western U.S. Cautions are needed to interpret WaSSI modeling results in this region, especially for small NFs sites.

Without considerations of these factors discussed above, simulation results may not be realistic in some cases. This study provides a complete picture of carbon and water sensitivity to climate variability although the cascading effects of extreme drought on other forest ecosystem processes have not fully considered. Future studies should use an integrated approach to model the interactions of all bio- and abio-environmental factors on forest ecosystem functions under droughts (Vose et al., 2012).

#### 4.2. Drought impacts on hydrology and ecosystem productivity

Our study found that droughts could reduce 5–500 mm yr<sup>-1</sup> or 18–90% of water yield in one particular NFs (Fig. 7). The large reduction in water yield was a direct consequence of the reduction in precipitation during droughts, but was compensated somewhat by the decrease in ET. Reduction in precipitation alone could reduce forest ET because of the reduction in canopy interception, soil evaporation, and tree transpiration. In this study, the associated increase in air temperature, thus the increase in potential ET, was obviously not able to overcome the ET reduction caused

by the large reduction in precipitation. The overall results were consistent with a model sensitivity analysis by Sun et al. (2015a,b) who found precipitation dominate the climatic (i.e., precipitation and temperature) effects on water yield. Short term, moderate droughts generally do not cause large decrease in ET due to the buffering capacity of forest soils and shallow groundwater (Sun et al., 2010; Xie et al., 2013b). However, soil moisture stress was common in extreme droughts that greatly reduced in ET such the cases in this study.

We found that forest GPP was also reduced substantially (0–39%) in NFs under extreme drought conditions (Fig. 8b). Our results were consistent with previous studies (Cook et al., 2004; Ciais et al., 2005; Hussain et al., 2011; Chen et al., 2013; Wagle et al., 2014; Zscheischler et al., 2014; Xiao et al., 2009, 2010, 2014). For example, using eddy covariance data and simulations by a carbon flux model, Ciais et al. (2005) estimated a 30% reduction of GPP in the extreme drought year of 2003 when compared to 1998–2002 over Europe. Similarly, Noormets et al. (2008) measured two-year carbon fluxes for a 50-year-old mixed oak woodland in northern Ohio, U.S. and found that the stand accumulated 40% less carbon during a drought year than a normal year. There were large differences among different regions in drought severity and GPP responses to droughts during the past 51 years. In a global study, Schwalm et al. (2010) also showed a dramatic regional variations in carbon flux response to droughts with the largest response found in the Midwest of the U.S., the prairie provinces of Canada, and Eurasia (eastward from France to Siberia, and eastern China). In this study we selected the worst drought cases (i.e., the top 10% percentile), and therefore our impact estimates for each individual NFs represented the likely upper bound of drought impacts for the U.S. forests.

#### 4.3. Implications to forest management for water supply, timber production, and carbon sequestration

Our analysis and numerous other studies around the world (Feyen and Dankers, 2009; Lu et al., 2013) suggested that droughts could induce dramatic reduction in water availability to ecosystems and humans. Our results showed that, at each individual NF, the historical extreme droughts could result in up to 54% reduction in  $P$  leading to decreases in  $Q$  and GPP by up to 90% and 39%, respectively. Although extreme droughts do not occur every year, understanding their magnitudes is important for land management to reduce risk of water shortages and decline in forest health. Over the U.S., in 1999, about 60 million Americans (20% of the nation's population in 3400 towns and cities) depended on water that originates in national forest watershed (Sedell et al., 2000). Therefore, episodic droughts will likely increase significant stress on the water supply through decreasing watershed water yield. Also, droughts can bring consequences to the economic sectors such as fisheries (Magoulick and Kobza, 2003; Dolbeth et al., 2008; Gillson et al., 2009) and navigation (Theiling et al., 1996; Roberts, 2001) by lowering water levels and degrading water quality (e.g., high water temperature and nutrient concentrations).

The decline in ecosystem productivity (GPP) during droughts will be reflected in the timber production, the timber price, and ultimately economic benefits from timberlands (Sohngen and Mendelsohn, 1998; Irland et al., 2001; Alig et al., 2004). Drought stress, as a ubiquitous phenomenon, has always shaped forest structure and species composition (Hanson and Weltzin, 2000). Such changes are likely to affect carbon stock and forests capacity to sequester atmospheric  $\text{CO}_2$  (Noormets et al., 2008, 2010; Xiao et al., 2014). Indeed, a recent study has already indicated that the southern forests ability to accumulate carbon is declining due to land use transition and forest aging (Coulston et al., 2015). Periodic droughts are likely to aggravate the problems.

Maintaining forest health is critical for the U.S. Forest Service, and the populations and economic sectors that depend on the forest ecosystem services (Grant et al., 2013). Management strategies to mitigate increasing water shortages for forest under the exacerbating climate change has become an issue among the forest managers and scientific communities (Gray et al., 2002; Spiecker, 2003; Castro et al., 2011; Choat et al., 2012; Grant et al., 2013; Williams et al., 2013). For example, to optimize forest productivity, Gray et al. (2002) suggested that creating openings and gaps was an alternative operation to enhance water availability for forests under the water-limited context. Considering the differences in capability of vegetation drought tolerance, Spiecker (2003) suggested that moving toward mixed species forests with a large percentage of broad-leaf species and high levels of genetic diversity may be a good choice for reducing drought risk in temperate European forests. An alternative method to increase water availability for maintaining forest health is reducing soil evaporation losses through ground mulching with tree branches (Castro et al., 2011) and fertilization (Dodson et al., 2010). Strategies to reduce forest vulnerability to water stress will need to be tailored to specific management objectives and landscapes (Grant et al., 2013). In the current study, we have comprehensively assessed adverse impacts of historical extreme droughts on  $Q$ , ET, and GPP for each of the 170 NFs and the CONUS. The study results provided the much needed information for identifying priority NFs (e.g., southern and Pacific NW U.S.) for forest management under extreme droughts. Achieving a 'win-win' for both protecting and enhancing forest health and satisfying human needs for water, timber and other services require a balanced approach in active forest management. This is especially true in regions that are vulnerable to droughts induced by climate change.

## 5. Conclusions

The number of NFs under extreme drought conditions in the 2000s was the highest during the past 51 years. Extreme climate significantly influenced the water balance and ecosystem processes. Droughts altered water balances by altering the hydrometeorological patterns and forest productivity. Climate change-induced droughts could result in substantial but variable consequences across the NFs due to differences in land-surface characteristics and drought severity.

Overall, this study provided the potential upper limit of likely impacts of droughts on watershed hydrology and productivity for each NF although the past may not represent the future. The consistent approach across the CONUS provided useful information for identifying watersheds that were severely influenced by historical droughts. The modeling results also provided a benchmark of forest water yield and ecosystem productivity. This type of information will be useful for prioritizing watershed restoration resource and for developing specific measures to mitigate the negative impacts of future extreme droughts to sustain the NFs ecosystem services.

## Acknowledgements

This study was funded by the National Science Foundation EaSM program (AGS-1049200) with a grant award to North Carolina State University, and the Eastern Forest Environment Threat Assessment Center (EFETAC), USDA Forest Service. J. Xiao was supported by NASA's Carbon Cycle Science Program (Grant # NNX14AJ18G) and Terrestrial Ecology Program (Grant # NNX12AK56G).

## Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.foreco.2015.04.002>.



## References

- Adams, H.D., Luce, C.H., Breshears, D.D., Allen, C.D., Weiler, M., Hale, V.C., Smith, A.M.S., Huxman, T.E., 2012. Ecohydrological consequences of drought- and infestation-triggered tree die-off: insights and hypotheses. *Ecohydrology* 5 (2), 145–159.
- Alig, R.J., Adams, D., Joyce, L., Sohngen, B., 2004. Climate change impacts and adaptation in forestry: responses by trees and markets. *Choices* 19 (3), 1–7.
- Allen, C.D., Macalady, A.K., Chenchouni, H., Bachelet, D., McDowell, N., Venetier, M., Kitzberger, T., Rigling, A., Breshears, D.D., Hogg, E.H., Gonzalez, P., Fensham, R., Zhang, Z., Castro, J., Demidova, N., Lim, J.H., Allard, G., Running, S.W., Semerci, A., Cobb, N., 2010. A global overview of drought and heat-induced tree mortality reveals emerging climate change risks for forests. *For. Ecol. Manage.* 259, 660–684.
- American Meteorological Society (AMS), 1997. Meteorological drought—policy statement. *Bull. Am. Meteorol. Soc.* 78, 847–849.
- Anderegg, W.R.L., Berry, J.A., Smith, D.D., Sperry, J.S., Anderegg, L.D.L., Field, C.B., 2012. The roles of hydraulic and carbon stress in a widespread climate-induced forest die-off. *Proc. Natl. Acad. Sci. USA* 109, 233–237.
- Andreadis, K.M., Lettenmaier, D.P., 2006. Trends in 20th century drought over the continental United States. *Geophys. Res. Lett.* 33 (L10403). <http://dx.doi.org/10.1029/2006GL025711>.
- Averyt, K., Meldrum, J., Caldwell, P.V., Sun, G., McNulty, S.G., Huber-Lee, A., Madden, N., 2013. Sectoral vulnerabilities to changing water resources in the conterminous U.S. *Environ. Res. Lett.* 8 (035046). <http://dx.doi.org/10.1088/1748-9326/8/3/035046>.
- Ayres, M.P., Lombardero, M.J., 2000. Assessing the consequences of climate change for forest herbivore and pathogens. *Sci. Total Environ.* 262, 263–286.
- Binkley, D., Brown, T., 1993. A synopsis of the impacts of forest practices on water quality in North America. *Water Resour. Bull.* 29, 729–740.
- Brauman, K.A., Daily, G.C., Duarte, T.K., Mooney, H.A., 2007. The nature and value of ecosystem services: an overview highlighting hydrologic services. *Annu. Rev. Environ. Resour.* 32, 67–98.
- Brown, T.C., Froemke, P., 2012. Nationwide assessment of nonpoint source threats to water quality. *Bioscience* 62 (2), 136–146.
- Brown, T.C., Hobbins, M.T., Ramirez, J.A., 2008. Spatial distribution of water supply in the coterminous United States. *J. Am. Water Resour. Assoc.* 6 (44), 1474–1487.
- Burnash, R.J.C., 1995. The NWS river forecast system – catchment modeling. In: Singh, V.P. (Ed.), *Computer Models of Watershed Hydrology*. Water Resources Publications, Littleton, Colorado, pp. 11–366.
- Caldwell, P.V., Sun, G., McNulty, S.G., Cohen, E.C., Myers, M.J.A., 2012. Impacts of impervious cover, water withdrawals, and climate change on river flows in the conterminous US. *Hydrol. Earth Syst. Sci.* 16, 2839–2857. <http://dx.doi.org/10.5194/hess-16-2839-2012>.
- Castro, J., Allen, C.D., Molina-Morales, M., Marañón-Jiménez, S., Sánchez-Miranda, Á., Zamora, R., 2011. Salvage logging versus the use of burnt wood as a nurse object to promote post-fire tree seedling establishment. *Restor. Ecol.* 19, 537–544.
- Chen, T., van der Werf, G.R., de Jeu, R.A.M., Wang, G., Dolman, A.J., 2013. A global analysis of the impact of drought on net primary productivity. *Hydrol. Earth Syst. Sci.* 17, 3885–3894.
- Choat, B., Jansen, S., Brodribb, T.J., Hervé Cochard, H., Delzon, S., Bhaskar, R., Bucci, S.J., Feild, T.S., Gleason, S.M., Hacke, U.G., Jacobsen, A.L., Lens, F., Maherali, H., Martínez-Vilalta, J., Mayr, S., Mencuccini, M., Mitchell, P.J., Nardini, A., Pittermann, J., Pratt, R.B., Sperry, J.S., Westoby, M., Wright, I.J., Zanne, A.E., 2012. Global convergence in the vulnerability of forests to drought. *Nature* 491, 752–755.
- Ciais, P.H., Reichstein, M., Viovy, N., Granier, A., Ogee, J., Allard, V., Aubinet, M., Buchmann, N., Bernhofer, C., Carrara, A., Chevallier, F., Noblet, N.D., Friend, A.D., Friedlingstein, P., Grunwald, T., Heinesch, B., Keronen, P., Knohl, A., Krinner, G., Loustau, D., Manca, G., Matteucci, G., Miglietta, F., Ourcival, J.M., Papale, D., Pilegaard, K., Rambal, S., Seufert, G., Soussana, J.F., Sanz, M.J., Schulze, E.D., Vesala, T., Valentini, R., 2005. Europe-wide reduction in primary productivity caused by the heat and drought in 2003. *Nature* 437, 529–533.
- Cook, E.R., Woodhouse, C.A., Eakin, C.M., Meko, D.M., Stahle, D.W., 2004. Long-term aridity changes in the Western United States. *Science* 306, 1015–1018.
- Cook, E.R., Seager, R., Cane, M.A., Stahle, D.W., 2007. North American drought: reconstructions, causes, and consequences. *Earth Sci. Rev.* 81, 93–134.
- Costanza, R., D'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R.V., Paruelo, J., Raskin, R.G., Sutton, P., van den Belt, M., 1997. The value of the world's ecosystem services and natural capital. *Nature* 387, 253–260.
- Coulston, J.W., Wear, D.N., Vose, J.M., 2015. Complex Forest Dynamics Indicate Potential for Slowing Carbon Accumulation in the Southeastern United States. *Scientific Reports* 16.
- Dai, A., 2013. Increasing drought under global warming in observations and models. *Nat. Clim. Change* 3, 52–58.
- Dale, V.H., Joyce, L.A., McNulty, S., Neilson, R.P., Ayres, M.P., Flannigan, M.D., Hanson, P.J., Irland, L.C., Lugo, A.E., Peterson, C.J., Simberloff, D., Swanson, F.J., Stocks, B.J., Wotton, M., 2001. Climate change and forest disturbances. *Bioscience* 51 (9), 723–734.
- DeRose, R.J., Long, J.N., 2012. Drought-driven disturbance history characterizes a southern Rocky Mountain subalpine forest. *Can. J. For. Res.* 42, 1649–1660.
- Dodson, E.K., Peterson, D.W., Harrod, R.J., 2010. Impacts of erosion wildfire in the Eastern Cascades, USA. *Int. J. Wildland Fire* 19, 490–499.
- Dolbeth, M., Martinho, F., Viegas, I., Cabral, H., Pardal, M.A., 2008. Estuarine production of resident and nursery fish species: conditioning by drought events? *Estuar. Coast. Shelf Sci.* 78, 51–60.
- Easterling, D.R., Wallis, T.W.R., Lawrimore, J.H., Heim, Jr RR., 2007. Effects of temperature and precipitation trends on US drought. *Geophys. Res. Lett.* 34, L20709. <http://dx.doi.org/10.1029/2007GL031541>.
- Elsner, J.B., Kossin, J.P., Jagger, T.H., 2008. The increasing intensity of the strongest tropical cyclones. *Nature* 455, 92–95.
- Feyen, L., Dankers, R., 2009. Impact of global warming on streamflow drought in Europe. *J. Geophys. Res.* 114 (D17116). <http://dx.doi.org/10.1029/2008JD011438>.
- Gillson, J., Scandol, J., Suthers, L., 2009. Estuarine gillnet fishery catch rates decline during drought in eastern Australia. *Fish. Res.* 99, 26–37.
- Grant, G.E., Tague, C.L., Allen, C.D., 2013. Watering the forest for the trees: an emerging priority for managing water in forest landscapes. *Front. Ecol. Environ.* 11 (6), 314–321. <http://dx.doi.org/10.1890/120209>.
- Gray, A.N., Spies, T.A., Easter, M.J., 2002. Microclimatic and soil moisture responses to gap formation in coastal Douglas-fir forests. *Can. J. For. Res.* 32, 332–343.
- Guardiola-Claramonte, M., Troch, P.A., Breshears, D.D., Huxman, T.E., Switanek, M.B., Durcik, M., Cobb, N.S., 2011. Decreased streamflow in semi-arid basins following drought-induced tree die-off: a counter-intuitive and indirect climate impact on hydrology. *J. Hydrol.* 406, 225–233.
- Gutzler, D.S., Robbins, T.O., 2011. Climate variability and projected change in the western United States: regional downscaling and drought statistics. *Clim. Dyn.* 37, 835–849. <http://dx.doi.org/10.1007/s00382-010-0838-7>.
- Hanson, P.J., Weltzin, J.F., 2000. Drought disturbance from climate change: response of United States forests. *Sci. Total Environ.* 262, 205–220.
- Huang, J., Sun, S.L., Xue, Y., Li, J.J., Zhang, J.C., 2014a. Spatial and temporal variability of precipitation and dryness/wetness during 1961–2008 in Sichuan province, west China. *Water Resour. Manage.* 28, 1655–1670.
- Huang, J., Xue, Y., Sun, S.L., Zhang, J.C., 2014b. Spatial and temporal variability of drought during 1960–2012 in Inner Mongolia, north China. *Quart. Int.* 355, 134–144.
- Hussain, M.Z., Grünwald, T., Tenhunen, J.D., Li, Y.L., Mirzae, H., Bernhofer, C., Otieno, D., Dinh, N.Q., Schmidt, M., Wartinger, M., Owen, K., 2011. Summer drought influence on CO<sub>2</sub> and water fluxes of extensively managed grassland in Germany. *Agric. Ecosyst. Environ.* 141, 67–76.
- Inamdar, S.P., O'Leary, N., Mitchell, M.J., Riley, J.T., 2006. The impact of storm events on solute exports from a glaciated forested watershed in western New York, USA. *Hydrol. Process.* 20 (16), 3423–3439.
- IPCC, 2014. *Climate Change 2013: The Physical Science Basis*. Cambridge University Press, 134p.
- Irland, L., Adams, D., Alig, R., Betz, C., Chen, C., Hutchins, M., McCarl, B., Skog, K., Sohngen, B., 2001. Assessing socioeconomic impacts of climate change on US forests, wood-product markets, and forest recreation. *Bioscience* 51 (9), 753–764.
- Jactel, H., Petit, J., Desprez-Loustau, M.-L., Delzon, S., Piou, D., Battisti, A., Koricheva, J., 2012. Drought effects on damage by forest insects and pathogens: a meta-analysis. *Glob. Change Biol.* 18 (1), 267–276.
- Jain, S.K., Keshri, R., Goswami, A., Sarkar, A., 2010. Application of meteorological and vegetation indices for evaluation of drought impact: a case study for Rajasthan, India. *Nat. Hazards* 54, 643–656.
- Jayakaran, A.D., Williams, T.M., Ssegane, H., Amatya, D.M., Song, B., Trettin, C.C., 2014. Hurricane impacts on a pair of coastal forested watersheds: implications of selective hurricane damage to forest structure and streamflow dynamics. *Hydrol. Earth Syst. Sci.* 18, 1151–1164.
- Ji, L., Peters, A.J., 2003. Assessing vegetation response to drought in the northern Great Plains using vegetation and drought indices. *Rem. Sens. Environ.* 87, 85–98.
- Jones, K.B., Slonecker, E.T., Nash, M.S., Neale, A.C., Wade, T.G., Hamann, S., 2009. Riparian habitat changes across the continental United States (1972–2003) and potential implications for sustaining ecosystem services. *Landscape Ecol.* 25 (8), 1261–1275.
- Karl, T.R., Melillo, J.M., Peterson, T.C. (Eds.), 2009. *Global Climate Change Impacts in the United States*. Cambridge University Press.
- Lake, P.S., 2003. Ecological effects of perturbation by drought in flowing waters. *Freshw. Biol.* 48, 1161–1172.
- Larsen, M.C., 2000. Analysis of 20th century rainfall and streamflow to characterize drought and water resources in Puerto Rico. *Phys. Geogr.* 21, 494–521. <http://dx.doi.org/10.1080/02723646.2000.10642723>.
- Liu, N., Sun, P., Liu, S., Sun, G., 2013. Coupling simulation of water-carbon processes for catchment: calibration and validation of the WaSSI-C model. *Chin. J. Plant Ecol.* 37 (6), 492–502 (in Chinese with English abstract).
- Lockaby, G., Nagy, C., Vose, J.M., Ford, C.R., Sun, G., McNulty, S.G., Caldwell, P.V., Cohen, E., Moore Myers, J.A., 2011. *Water and Forests, in Wear, D.N., Greis, J.G., (Eds.), The Southern Forest Futures Project: Technical Report, USDA Forest Service, Southern Research Station, Asheville, NC. General Technical Report, 2011.*
- Lu, N., Sun, G., Feng, X., Fu, B., 2013. Water yield responses to climate change and variability across the North-South Transect of Eastern China (NSTEC). *J. Hydrol.* 481, 96–105.
- Magoulick, D.D., Kobza, R.M., 2003. The role of refugia for fishes during drought: a review and synthesis. *Freshw. Biol.* 48, 1186–1198.

- Marengo, J.A., Tomasella, J., Cardoso, M.F., Oyama, M.D., 2008. Hydro-climatic and ecological behaviour of the drought of Amazonia in 2005. *Philos. Trans. Roy. Soc. B* 363 (1498), 1773–1778.
- Marion, D.A., Sun, G., Caldwell, P.V., Miniati, C.F., Ouyang, Y., Amatya, D.M., Clinton, B.D., Conrads, P.A., Gull Laird, S., Dai, Z., Clingenpeel, J.A., Liu, Y., Roehl Jr., E.A., Moore Myers, J.A., Trettin, C., 2014. Managing forest water quantity and quality under climate change. In: Vose, J.M., Klepzig, K.D. (Eds.), *Climate Change Adaptation and Mitigation Management Options: A Guide for Natural Resource Managers in Southern Forest Ecosystems*. CRC Press, Boca Raton, FL, pp. 249–305.
- McDowell, N., Pockman, W.T., Allen, C.D., Breshears, D.D., Cobb, N., Kolb, T., Plaut, J., Sperry, J., West, A., Williams, D.G., Yepez, E.A., 2008. Mechanisms of plant survival and mortality during drought: why do some plants survive while others succumb to drought? *New Phytol.* 178, 719–739.
- McKee, T.B., Doesken, N.J., Kleist, J., 1993. The relationship of drought frequency and duration to time steps, preprints. In: 8th Conference on Applied Climatology. Anaheim, CA, 17–22 January 1993, pp. 179–184.
- McKinley, D.C., Ryan, M.G., Birdsey, R.A., Giardina, C.P., Harmon, M.E., Heath, L.S., Houghton, R.A., Jackson, R.B., Morrison, J.F., Murray, B.C., Pataki, D.E., Skog, K.E., 2011. A synthesis of current knowledge on forests and carbon storage in the United States. *Ecol. Appl.* 21 (6), 1902–1924.
- Min, S.-K., Zhang, X., Zwiers, F.W., Hegerl, G.C., 2011. Human contribution to more-intense precipitation extremes. *Nature* 470, 378–381.
- Nasi, R., Wunder, S., Campos, J.J., 2002. Forest Ecosystem Services: Can they Pay our Way out of Deforestation? A Discussion Paper Prepared for the GEF for the Forestry Roundtable Held in Conjunction with the UNFF II, 11 March 2002. New York.
- National Climate Assessment (NCA), 2014. Climate Change Impacts in the United States: The Third National Climate Assessment. U.S. Global Change Research Program. doi:<http://dx.doi.org/10.7930/J0231WJ2>.
- Noormets, A., McNulty, S.G., DeForest, J.L., Sun, G., Li, Q., Chen, J., 2008. Drought during canopy development has lasting effect on annual carbon balance in a deciduous temperate forest. *New Phytol.* 179 (3), 818–828. <http://dx.doi.org/10.1111/j.1469-8137.2008.02501.x>.
- Noormets, A., McNulty, S.G., Gavazzi, M.J., Sun, G., Domec, J.C., King, J., Chen, J., 2010. Response of carbon fluxes to drought in a coastal plain loblolly pine forest. *Glob. Change Biol.* 16, 272–287.
- Overpech, J.T., Rind, D., Goldberg, R., 1990. Climate-induced changes in forest disturbance and vegetation. *Nature* 343, 51–53.
- Oyler, J.W., Dobrowski, S.Z., Ballantyne, A.P., Klene, A.E., Running, S.W., 2015. Artificial amplification of warming trends across the mountains of the western United States. *Geophys. Res. Lett.* 42, 153–161.
- Raziei, T., Saghafian, B., Paulo, A.A., Pereira, L.S., Bordi, I., 2009. Spatial patterns and temporal variability of drought in western Iran. *Water Resour. Manage.* 23 (3), 439–455.
- Reichstein, M., Bahn, M., Ciais, P., Frank, D., Mahecha, M.D., Seneviratne, S., Zscheischler, J., Beer, C., Buchmann, N., Frank, D.C., Papale, D., Rammig, A., Smith, P., Thonicke, K., van der Velde, M., Vicca, S., Walz, A., Wattenbach, M., 2013. Climate extremes and the carbon cycle. *Nature* 500, 287–295.
- Roberts, T., 2001. Downstream Ecological Implications of China's Lancang Hydropower and Mekong Navigation Project. [ftp://ftp.gfz-potsdam.de/home/hydro/guentner/hohmann/Kummu\\_SedimentTrappingReservoirsMekong\\_Geomorphology2007.pdf](ftp://ftp.gfz-potsdam.de/home/hydro/guentner/hohmann/Kummu_SedimentTrappingReservoirsMekong_Geomorphology2007.pdf).
- Ryan, M.G., Harmon, M.E., Birdsey, R.A., Giardina, C.P., Heath, L.S., Houghton, R.A., Jackson, R.B., McKinley, D.C., Morrison, J.F., 2010. A synthesis of the science on forests and carbon for U.S. forests. *Issues Ecol.* 13, 1–16.
- Schoeneweiss, D.F., 1981. The role of environmental stress in diseases of woody plants. *Plant Dis.* 65, 308–314.
- Schwalm, C.R., Williams, C.A., Schaefer, K., Arneth, A., Bonal, D., Buchmann, N., Chen, J.Q., Law, B.E., Lindroth, A., Luyssaert, S., Reichstein, M., Richardson, A.D., 2010. Assimilation exceeds respiration sensitivity to drought: a FLUXNET synthesis. *Glob. Change Biol.* 16, 657–670.
- Schwalm, C.R., Williams, C.A., Schaefer, K., Baldocchi, D., Black, T.A., Goldstein, A.H., Law, B.E., Oechel, W.C., Paw, U.K.T., Scott, R.L., 2012. Reduction in carbon uptake during turn of the century drought in western North America. *Nat. Geosci.* 5, 551–556. <http://dx.doi.org/10.1038/ngeo1529>.
- Sedell, J., Sharpe, M., Dravieks-Apple, D., Copenhagen, M., Furniss, M., 2000. *Water and the Forest Service*. FS-660. U.S. Department of Agriculture, Forest Service, Washington, DC, p. 27.
- Shi, J.H., Zhou, S.Q., Yu, H., Sun, S.L., Jing, D.W., 2010. Stomatal conductance models of typical tree species in the Basin of Poyang Lake in summer and comparison of their influencing factors. *Res. Environ. Sci.* 23 (20), 33–40 (in Chinese with English Abstract).
- Sohngen, B., Mendelsohn, R., 1998. Valuing the impact of large-scale ecological change in a market: the effect of climate change on U.S. timber. *Am. Econ. Rev.* 88 (4), 686–710.
- Spiecker, H., 2003. Silvicultural management in maintaining biodiversity and resistance of forests in Europe—temperate zone. *J. Environ. Manage.* 67, 55–65.
- Strzepek, K., Yohe, G., Neumann, J., Boehler, B., 2010. Characterizing changes in drought risk for the United States from climate change. *Environ. Res. Lett.* 5 (044012). <http://dx.doi.org/10.1088/1748-9326/5/4/044012>.
- Sun, G., McNulty, S.G., Moore Myers, J.A., Cohen, E.C., 2008. Impacts of multiple stresses on water demand and supply across the southeastern United States. *J. Am. Water Resour. Assoc.* 44, 1441–1457. <http://dx.doi.org/10.1111/j.1752-1688.2008.00250.x>.
- Sun, G., Noormets, A., Gavazzi, M.J., McNulty, S.G., Chen, J., Domec, J.-C., King, J.S., Amatya, D.M., Skaggs, R.W., 2010. Energy and water balance of two contrasting Loblolly pine plantations on the lower coastal plain of North Carolina, USA. *Forest Ecol. Manage.* 259, 1299–1310.
- Sun, G., Caldwell, P., Noormets, A., Cohen, E., McNulty, S., Treasure, E., Domec, J.C., Mu, Q., Xiao, J., John, R., Chen, J., 2011a. Upscaling key ecosystem functions across the conterminous United States by a water-centric ecosystem model. *J. Geophys. Res.* 116, G00J05. <http://dx.doi.org/10.1029/2010JG001573>.
- Sun, G., Alstad, K., Chen, J., Chen, S., Ford, C.R., Lin, G., Liu, C., Lu, N., McNulty, S.G., Miao, H., Noormets, A., Vose, J.M., Wilske, B., Zeppel, M., Zhang, Y., Zhang, Z., 2011b. A general predictive model for estimating monthly ecosystem evapotranspiration. *Ecophysiology* 4 (2), 245–255. <http://dx.doi.org/10.1002/eco.194>.
- Sun, G., Caldwell, P.V., McNulty, S.G., 2015a. Modeling the potential role of forest thinning in maintaining water supplies under a changing climate across the Conterminous United States. *Hydro. Process.* <http://dx.doi.org/10.1002/hyp.10469>.
- Sun, S., Sun, G., Caldwell, P., McNulty, S.G., Cohen, E., Xiao, J., Zhang, Y., 2015b. Impacts of historic droughts on water yield and ecosystem productivity of the United States National Forests and Grasslands: model evaluation. *For. Ecol. Manage.*
- Tavernia, B.G., Nelson, M.D., Caldwell, P.V., Sun, G., 2013. Water stress projections for the northeastern and midwestern United States in 2060: anthropogenic and ecological consequences. *J. Am. Water Resour. Assoc.* 49 (4), 938–952. <http://dx.doi.org/10.1111/jawr.12075>.
- Taylor, A.H., Beaty, R.M., 2005. Climatic influences on fire regimes in the northern Sierra Nevada Mountains, Lake Tahoe Basin, Nevada, USA. *J. Biogeogr.* 32 (3), 425–438.
- Theiling, C.H., Maher, R.J., Sparks, R.E., 1996. Effects of variable annual hydrology on a river regulated for navigation: Pool 26, Upper Mississippi River System. *J. Freshwater Ecol.* 11 (1), 101–114. <http://dx.doi.org/10.1080/02705060.1996.9663498>.
- Trenberth, K.E., Dai, A., van der Schrier, G., Jones, P.D., Barichivich, J., Briffa, K.R., Sheffield, J., 2012. Global warming and changes in drought. *Nat. Clim. Change* 4, 17–22.
- United States Department of Agriculture (USDA), 2004. *Natural Resources Conservation Service, National Water and Climate Center. Reservoir Storage as of May 1, 2004*. <<http://www.wcc.nrcs.usda.gov/cgibin/resvgrp2.pl?area=west&year=2004&month=05>>.
- Vose, J.M., Swank, Wayne T., 1994. Effects of long-term drought on the hydrology and growth of a white pine plantation in the southern Appalachians. *For. Ecol. Manage.* 64, 25–39.
- Vose, J.M., Peterson, D., Patel-Weynand, T. (Eds.), 2012. *Effects of Climatic Variability and Change on Forest Ecosystems: A Comprehensive Science Synthesis for the US Forest Sector*. General Technical Report PNW-GTR-870. US Forest Service, Pacific Northwest Research Station, Portland, Oregon.
- Wagle, P., Xia, X., Torn, M.S., Cook, D.R., Matamala, R., Fischer, M., Ji, C., Don, J., Biradar, C., 2014. Sensitivity of vegetation indices and gross primary production of tallgrass prairie to severe drought. *Rem. Sens. Environ.* 152, 1–4.
- Webb, R.H., Hereford, R., McCabe, G.J., 2005. Climatic fluctuations, drought, and flow in the Colorado River Basin. In: *The state of the Colorado River ecosystem in Grand Canyon*, vol. 1282. U.S. Geological Survey Circular, 57–68 p.
- Westerling, A.L., Hidalgo, H.G., Cayan, D.R., Swetnam, T.W., 2006. Warming and earlier spring increase western U.S. forest wildfire activity. *Science* 313 (5789), 940–943.
- Williams, A.P., Allen, C.D., Macalady, A., Griffin, D., Connie, A., Woodhouse, C.A., Meko, D.M., Swetnam, T.W., Rauscher, S.A., Seager, R., Grissino-Mayer, H.D., Dean, J.S., Cook, E.R., Gangodagamage, C., Cai, M., McDowell, N.G., 2013. Temperature as a potent driver of regional forest drought stress and tree mortality. *Nat. Clim. Change* 3, 292–297.
- World Meteorological Organization (WMO), 1992. *International Meteorological Vocabulary*. second ed. WMO No. 182, WMO, 784 pp.
- Xiao, J.F., Zhuang, Q., 2007. Drought effects on large fire activity in Canadian and Alaskan forests. *Environ. Res. Lett.* 2 (044003). <http://dx.doi.org/10.1088/1748-9326/2/4/044003>.
- Xiao, J.F., Zhuang, Q., Liang, E., McGuire, A.D., Moody, A., Kicklighter, D.W., Melillo, J.M., 2009. Twentieth century droughts and their impacts on terrestrial carbon cycling in China. *Earth Int.* 13 (10), 1–31. <http://dx.doi.org/10.1175/2009EI275.1>.
- Xiao, J., Zhuang, Q., Law, B.E., Chen, J., Baldocchi, D.D., Cook, D.R., Oren, R., Richardson, A.D., Wharton, S., Ma, S., Martin, T.A., Verma, S.B., Suyker, A.E., Scott, R.L., Monson, R.K., Litvak, M., Hollinger, D.Y., Sun, G., Davis, K.G., Bolstad, P.V., Burns, S.P., Curtis, P.S., Drake, B.G., Falk, M., Fischer, M.L., Foster, D.R., Gu, L., Hadley, J.L., Katul, G.G., Matamala, R., McNulty, S., Meyers, T.P., 2010. A continuous measure of gross primary production for the conterminous United States derived from MODIS and AmeriFlux data. *Rem. Sens. Environ.* 114, 576–591.
- Xiao, J., Zhuang, Q., Law, B.E., Baldocchi, D.D., Chen, J., Richardson, A.D., Melillo, J.M., Davish, K.J., Hollinger, D.Y., Wharton, S., Oren, R., Noormets, R., Fischerm, M.L., Verman, S.B., Cook, D.R., Sun, G., McNulty, S., Wofsy, S.C., Bolstad, P.V., Burns, S.P., Curtis, P.S., Drake, B.G., Falk, M., Foster, D.R., Gu, L., Hadley, J.L., Katul, G.G., Litvak, M., Ma, S., Martin, T.A., Matamala, R., Meyers, T.P., Monson, R.K., 2011. Assessing net ecosystem carbon exchange of U.S. terrestrial ecosystems by integrating eddy covariance flux measurements and satellite observations. *Agric. For. Meteorol.* 151, 60–69.

- Xiao, J., Ollinger, S.V., Frolking, S., Hurr, G.C., Hollinger, D.Y., Davis, K.J., Pan, Y., Zhang, X., Deng, F., Chen, J., Baldocchi, D.D., Law, B.E., Arain, M.A., Desai, A.R., Richardson, A.D., Sun, G., Amiro, B., Margolis, H., Gu, L., Scott, R.L., Blanken, P.D., Suyker, A.E., 2014. Data-driven diagnostics of terrestrial carbon dynamics over North America. *Agric. For. Meteorol.* 197, 142–157.
- Xie, J., Chen, J.G., Sun, G., Chu, H., Noormets, A., Ouyang, Z., John, R., Wan, S., Guan, W., 2013a. Long-term variability and environmental control of the carbon cycle in an oak-dominated temperate forest. *For. Ecol. Manage.* 313, 319–328.
- Xie, J., Sun, G., Chu, H.S., Liu, J., McNulty, S.G., Noormets, A., John, Ouyang, R.Z., Zha, T., Li, H., Guan, W., Chen, J., 2013b. Long-term variability in the water budget and its controls in an oak-dominated temperate forest. *Hydrol. Process.* <http://dx.doi.org/10.1002/hyp.10079>.
- Zhang, Q., Xu, C.Y., Zhang, Z.X., 2009. Observed changes of drought/wetness episodes in the Pearl River basin, China, using the standardized precipitation index and aridity index. *Theor. Appl. Climatol.* 98, 89–99.
- Zhao, M., Running, S.W., 2010. Drought-induced reduction in global terrestrial net primary production from 2000 through 2009. *Science* 329, 940–943.
- Zhao, G.J., Mu, X.M., Hormann, G., Fohrer, N., Xiong, M., Su, B.D., Li, X.C., 2011. Spatial patterns and temporal variability of dryness/wetness in the Yangtze River Basin, China. *Quat. Int.* 282, 5–13.
- Zhou, L., Tian, Y., Myneni, R.B., Ciais, P., Saatchi, S., Liu, Y.Y., Piao, S., Chen, H., Vermote, E.F., Song, C., Hwang, T., 2014. Widespread decline of Congo rainforest greenness in the past decade. *Nature* 509, 86–90. <http://dx.doi.org/10.1038/nature13265>.
- Zscheischler, J., Mahecha, M.D., von Buttlar, J., Harmeling, S., Jung, M., Rammig, A., Randerson, J.T., Schölkopf, B., Seneviratne, S.I., Tomelleri, E., Zaehle, S., Reichstein, M., 2014. A few extreme events dominate global interannual variability in gross primary production. *Environ. Res. Lett.* 9, 035001. <http://dx.doi.org/10.1088/1748-9326/9/3/035001>.