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

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ABSTRACT

The 781,000 km^2 (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^{-1} (or 22%), causing reductions in evapotranspiration by 29 mm yr^{-1} (or 8%), *Q* by 110 mm yr^{-1} (or 37%) and GPP by 65 gC m^{-2} yr^{-1} (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.

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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^2 (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

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(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 southeastern 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 (Easrterling 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^2 (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