Drought Impacts on Ecosystem Functions of the U.S. National Forests and Grasslands:

Part I Evaluation of a Water and Carbon Balance Model

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Abstract: Understanding and quantitatively evaluating the regional impacts of climate change and variability (e.g., droughts) on forest ecosystem functions (i.e., water yield, evapotranspiration, and productivity) and services (e.g., fresh water supply and carbon sequestration) is of great importance for developing climate change adaptation strategies for National Forests and Grasslands (NFs) in the United States. However, few reliable continental-scale modeling tools are available to account for both water and carbon dynamics. The objective of this study was to test a monthly water and carbon balance model, the Water Supply Stress Index (WaSSI) model, for potential application in addressing the influences of drought on NFs ecosystem services across the conterminous United States (CONUS). The performance of the WaSSI model was comprehensively assessed with measured streamflow (Q) at 72 U.S. Geological Survey (USGS) gauging stations, and satellite-based estimates of watershed evapotranspiration (ET) and gross primary productivity (GPP) for 170 National Forest and Grassland (NFs). Across the 72 USGS watersheds, the WaSSI model generally captured the spatial variability of multi-year mean annual and monthly Q and annual ET as evaluated by Correlation Coefficient ($R=0.71-1.0$), Nash-Sutcliffe Efficiency ($NS=0.31-1.00$), and normalized Root Mean Squared Error ($0.06-0.48$). The modeled ET and GPP by WaSSI agreed well with the remote sensing-based estimates for multi-year annual and monthly means for all the NFs. However, there were systemic discrepancies in GPP between our simulations and the satellite-based estimates on a yearly and monthly scale, suggesting uncertainties in GPP estimates in all methods (i.e., remote sensing and modeling). Overall, our assessments suggested that the WaSSI model had the capability to reconstruct the long-term forest watershed water and carbon balances at a broad scale. This model evaluation study provides a foundation for model applications in understanding the impacts of climate change and variability (e.g., droughts) on NFs ecosystem service functions.

Keywords: Evapotranspiration; Gross Primary Productivity; National Forests and Grasslands; Water Yield, Modeling

1. Introduction

Forest water yield (Q), evapotranspiration (ET), gross primary productivity (GPP), and net primary productivity (NPP) are the critical ecosystem functions (Xiao et al., 2008, 2010; Jung et al., 2010; Sun et al., 2011a, 2011b) that sustain many ecosystem services, such as stable and high quality water supply, carbon sequestration, climate regulation, and biodiversity conservation. For example, over half of U.S. fresh water supply originates from forests and grasslands (Brown et al., 2008; Sun et al., 2015). It is estimated that forests and grasslands offset 10-40% of annual carbon emissions from burning fossil fuels each year of the U.S. (Ryan et al., 2010; McKinley et al., 2011; Xiao et al., 2011). However, with a changing climate, the tightly coupled water and carbon cycles are changing from the leaf to global scales (IPCC, 2014). Consequently, there are concerns about the diminishing potential for forest ecosystem services under a changing environment.

To meet the American publics' demand for stable and abundant water, timber supply, recreation, and other ecosystem goods and services, the U.S. National Forest and Grassland System (NF) was established over a century ago. Now the NF lands cover about 781,000 km² (193 million acres) or about 8.8% of the total land area of the U.S. The top priority of the USDA-Forest Service is to sustain ecosystem health, diversity, and productivity to meet the needs of present and future generations. However, ongoing climate variability and change and related environmental impacts have exerted serious threats to NFs stability and thus their ability to deliver ecosystem services (NCA, 2014). A comprehensive quantitative assessment of global change impacts, particularly for climate extremes (e.g., droughts), on the ecosystem services of NFs is urgently needed for land managers and policy makers to develop sound mitigation and adaptation strategies (Vose et al., 2012; NCA, 2014).

Over the last decade, numerous tools have been developed to quantify regional carbon fluxes and stocks including machine-learning techniques (Xiao et al., 2008, 2010, 2011; Jung et al., 2009; Zhang et al., 2011), remote sensing-based diagnostic models (Mu et al., 2007), process-based ecosystem models (Xiao et al., 2009; Tian et al., 2010), atmospheric inverse modeling (Deng et al., 2007) and inventory methods (Pacala et al., 2001). These approaches are typically not designed to simulate water and carbon fluxes using watersheds as the

smallest modeling unit. In addition, the short temporal span of remote sensing data of land cover and biophysical parameters needed for model application (e.g. 10 years) will limit our ability to explore historical drought impacts on water and carbon cycles. Considering the limitations of these methods, Sun et al. (2011b) developed a water-centric monthly scale model (WaSSI) that operates at 2103 Watershed Boundary Database (WBD) 8-digit Hydrologic Unit Code (HUC) watersheds across the conterminous U.S. (CONUS). Algorithms were derived on the basis of empirical water and carbon flux measurements from the FLUXNET network. The WaSSI model has been used to quantitatively assess the combined or separate effects of climate change, land cover change, and population dynamics on past and future water supply stress and ecosystem productivity over the CONUS, and can be easily implemented because few input climatic variables are needed and no model calibration is necessary. The model has been applied in Mexico, China and some African countries (Sun et al., 2008, 2011b; Lockaby et al., 2011; Caldwell et al., 2012; Averyt et al., 2013; Tavernia, et al., 2013; Liu et al., 2013; Marion, et al., 2014, McNulty et al., 2015).

Recently, the WaSSI model was upgraded to a higher spatial resolution of 12-digit HUC (88,000 watersheds) compared to the previous 8-digit HUC (2103 watersheds) across the CONUS. The overall goal of this study was to validate the improved version of the WaSSI, and to then use the model to examine impacts of long-term climate variability on Q, ET and GPP, under droughts in selected NFs. The specific objectives of the study were: (1) to evaluate model performance by comparing WaSSI estimates to the measured Q at 72 U.S. Geological Survey (USGS) gauges within the 170 NFs (1990-2009); (2) to evaluate model performance by comparing simulated ET (2000-2012) and GPP (2001-2012) against satellite-based estimates for 170 NFs; and (3) to reconstruct a long-term Q, ET and GPP time-series (1960-2012) of the 170 NFs over the CONUS.

This paper reports multi-year comprehensive model validation results. Model application to study the drought impacts on NFs is found in a follow-up paper in this issue (Sun et al., 2015).

2. Methods

2.1. Study area

The research area for this modeling study was the NFs over the CONUS, mainly including 150 National Forest and 20 National Grasslands. The NFs (see supplementary materials S1) cover about approximately 781,000 km² (930 million acres), or 9% of the CONUS land area. More than 70% NFs are located in the Northwest and the Southwest regions (Fig. 1a). Climate, topography, and vegetation cover vary dramatically among these 170 NFs. For example, mean annual precipitation varies from 300 mm yr⁻¹ at the *Crooked River National Grassland* (the Oregon State) to 3000 mm yr⁻¹ at the *Olympic National Forest* in the state of Washington (Fig. 1b). Eighty-five (50%) of the NFs had a multi-year mean annual precipitation below 1000 mm yr⁻¹ and a multi-year mean temperature lower than 10°C. Forty-six (27%) of the NFs had mean annual precipitation and temperature ranging from 1000 to 2000 mm yr⁻¹ and from 10 to 20 °C, respectively. Grasslands were found in the West and Southwest region with mean precipitation below 600 mm yr⁻¹.

2.2. The WaSSI model

The WaSSI model was originally designed and applied to the southeastern U.S. at the USGS 8-digit HUC watershed scale to model water supply and demand on an annual time-step (Sun et al., 2008) and later it was improved to simulate both water and carbon balances at a monthly scale for the CONUS (Sun et al., 2011b; Caldwell et al., 2012). An internet version of model and user guide is available (<http://www.forestthreats.org/research/tools/WaSSI>). The WaSSI model has been updated to operate at a monthly, 12-digit HUC scale. WaSSI is an integrated, process-based model that describes key ecohydrological processes at a broad scale (Sun et al., 2011; Caldwell et al., 2012; Sun et al., 2015). It can predict water and carbon balances, such as ET, soil water storage, Q, GPP and NEE for each of eight land cover types within a given watershed, and then aggregates these fluxes to the whole basin using area-weighted averaging. Three sub-models are integrated within the WaSSI model framework. The water balance sub-model computes ecosystem water use (i.e., ET), and Q generated from each watershed. Herein, Q is the amount of water yield ‘produced’ in each watershed assuming that the water balances within each watershed are in isolation without any flow contribution from upstream watersheds. The carbon balance sub-model simulates monthly carbon gains (GPP) and losses

(i.e., ecosystem respiration) in each watershed as functions of ET and GPP, respectively (Sun et al., 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. In this study, we focused on the model performance in predicting Q, ET and GPP, thus only detailed information about the sub-models of water and carbon balances is described below. For a complete description of the WaSSI model, the readers can refer to the WaSSI User's Guide (http://www.forestthreats.org/research/tools/WaSSI/WaSSIUserGuide_english_v1.1.pdf).

2.2.1. Water balance sub-model

The WaSSI model operates at a watershed scale assuming uniform climate across the watershed but with mixed land covers. The model first partitions monthly precipitation into rainfall and snowfall by watershed. A conceptual snow model (McCabe and Wolock, 1999; McCabe and Markstrom, 2007) is employed for partitioning monthly precipitation based on the mean watershed elevation and the monthly air temperature, estimating snow melt rates, and calculating mean monthly snow water equivalent (SWE). Snow accumulation is simulated and reported as one key output variable. Critical parameters for the snow partitioning and melting models are derived by model calibration for each USGS Water Resource Region (WRR) by comparing predicted regional monthly mean SWE to remotely sensed SWE from the Snow Data Assimilation System (National Operational Hydrologic Remote Sensing Center, 2004). Infiltration, surface runoff, soil moisture, and baseflow processes for each land cover type are simulated by the Sacramento Soil Moisture Accounting Model (SAC-SMA; Burnash, 1995). The SAC-SMA model has been used successfully by the National Oceanic and Atmospheric Administration (NOAA) National Weather Service (NWS) for river flood forecasting for decades; and State Soil Geographic Data Base (STATSGO; Natural Resources Conservation Service, 2012) derived SAC-SMA soil input parameters to drive the model has been developed, tested, and made available for the CONUS (Koren et al., 2003, 2005; Anderson et al., 2006).

Monthly water loss as ET for each land cover type in each watershed was first approximated as function of potential ET, leaf area index (LAI), and precipitation (Sun et al.,

2011a; 2011b). The empirical regression model is the core of the water balance sub-model and was derived from ecosystem-level ET measurements by eddy covariance or sapflow techniques across more than 240 research sites spanning a large climatic gradient (Sun et al., 2011a; 2011b). In addition to land cover diversity, management practices also vary widely across these sites. Since ET may be overestimated under extreme water-limited conditions, ET calculated by the regression model is further constrained. Within the WaSSI model, the two-soil-layer SAC-SMA algorithm is used to compare ET demand to soil water storage, and then limit ET if soil water is not sufficient to meet the demand. Soil moisture for ET is withdrawn sequentially from the upper soil layer tension water storage (i.e., soil water tension between field capacity and the wilting point), upper layer free water storage (i.e., soil water tension between saturation and field capacity), and from the lower layer tension water storage until the demand is met or until available soil water has been depleted.

2.2.2. Carbon balance sub-model

Previous studies have suggested that ecosystem ET and GPP are closely coupled at a monthly scale, and this simple linear relationship has been found in a number of forest ecosystems (Law et al., 2002; Xie et al., 2013). Sun et al. (2011b) developed a set of relationships between ET and GPP for 11 ecosystem types by synthesizing global eddy flux data (e.g., FLUXNET LaThuie dataset; <http://www.fluxdata.org>). These relationships allow for dynamic modeling of ET and GPP, and linking climate, water, and carbon balances at a broad scale. Although the model does not simulate the detailed processes of carbon cycling, it does account for the major control of carbon balances (i.e., soil moisture availability and energy availability - ET).

2.2.3. Model parameterization

To run the WaSSI model, the necessary inputs include monthly precipitation, monthly mean air temperature, monthly LAI by land cover, land cover composition within each watershed, and 11 SAC-SMA soil parameters. All the input data were re-scaled to the 12-digit HUC watershed scale from gridded data with different spatial resolutions. The historical climate dataset (4×4 km resolution) during 1961-2012 was derived from the Precipitation Elevation Regression on Independent Slopes Model (Daly et al., 1994; PRISM Climate Group,

213 2013). The land cover distribution was based on the 2006 National Land Cover Dataset
214 (30×30 m resolution; http://www.mrlc.gov/nlcd06_data.php) with 17 land cover classes (Fry
215 et al., 2011) aggregated into ten classes: crop, deciduous forest, evergreen forest, mixed forest,
216 grassland, shrubland, wetland, water, urban and barren. Monthly LAI data were derived from
217 the MODIS-MOD15A2 FPAR/LAI 8-day product (Myneni et al., 2002). Within each
218 watershed, the multi-year mean monthly LAI database for each land cover type was
219 individually constructed. The State Soil Geographic Data Base (STATSGO)-based
220 SAC-SMA soil parameter dataset (1×1 km resolution) was provided by the National Oceanic
221 and Atmospheric Administration-National Weather Service (NOAA-NWS) Hydrology
222 Laboratory, Office of Hydrologic Development.

223 2.3. Model evaluation

224 To evaluate the WaSSI model performance in simulating the water balance and carbon
225 cycles in NFs, the simulated Q, ET and GPP were compared against the streamflow measured
226 at 72 USGS gauges and MODIS remote sensing products for ET (2000-2012) and GPP
227 (2001-2012), respectively. The annual watershed-scale ET (1961-2009) estimated by the
228 watershed balances, P minus Q, for 72 gaged watersheds was also used to evaluate WaSSI
229 performance in simulating long-term ET, a major control on Q. The watershed water balance
230 method assumed that the change in soil water storage was negligible over a long term (Brown
231 et al., 2008; Sun et al., 2011b).

232 The observed monthly streamflow data between 1990 and 2009 were acquired from the
233 USGS reference stations that have not been subject to human disturbances
234 (<http://waterdata.usgs.gov/nwis/rt>). For model validation purposes, we used the following
235 three criteria to identify the USGS gauged watersheds that are most comparable to the
236 12-digit HUC watersheds within the NFs. First, several 12-digit HUC watersheds could be
237 integrated to match the corresponding USGS gauged watersheds to reduce the watershed
238 boundary mismatch errors. Second, the selected gauged watersheds must overlap more than
239 50% with the NFs. Third, the selected gauged watersheds should not receive flow from any
240 upstream watersheds. The resulting USGS streamflow data were then directly comparable to
241 the predicted Q by WaSSI. All 72 USGS gauged watersheds met these three criteria and were
242 selected for model validation.

Satellite-derived ET and carbon flux (e.g., GPP) products were available for regional model validation purposes (Cleugh et al., 2007; Mu et al., 2007; Fisher et al., 2008; Zhang et al., 2010). This is one type of the widely used ET datasets developed by Mu et al. (2007) based on reanalysis of surface meteorological data from NASA's Global Modeling and Assimilation Office with MODIS land cover, albedo, LAI and the Fraction of Absorbed Photosynthetically Active Radiation (FPAR) inputs. The MODIS ET algorithms for regional and global ET mapping and monitoring have been evaluated with AmeriFlux flux datasets. The new MODIS ET product (2000-2012) (1×1 km grid resolution) (Mu et al., 2010) was used in the present study. We also used gridded GPP data from the EC-MOD products (Xiao et al., 2008, 2010, 2011, 2014) that were derived from eddy covariance flux observations and MODIS data streams for the period 2001-2012. A data-driven approach (Xiao et al., 2014) was used to upscale carbon fluxes from eddy covariance flux sites to the continental-scale and to produce the EC-MOD flux estimates with 1×1 km spatial resolution and 8-day time step for the period 2001-2012 (Xiao et al., 2010, 2011, 2014). The MODIS ET and EC-MOD GPP datasets provided the independent estimates of ET and ecosystem productivity for evaluating the WaSSI model predictions. For comparison purposes, these gridded satellite-derived datasets were aggregated from 8-day to monthly sums, and then were rescaled to the NFs scale by spatial weighted averaging. Similarly, the simulated monthly datasets for each NFs was developed by weighing the area fractions of the 12-digit HUC within each NFs.

The model performance in simulating Q, ET and GPP was evaluated using scatterplots and difference maps (observed minus predicted), root-mean-square-error (*RMSE*), mean relative error (*MRE*), correlation coefficient (*R*), and slopes of the linear regression models. We validated the model against various reference products of multi-year mean Q, ET and GPP, and annual Q. As an additional criterion for Q evaluation, the Nash-Sutcliffe Efficiency statistic (*E_{NS}*; Nash and Sutcliffe, 1970) was also selected, and this statistic is expressed as:

$$E_{NS} = 1 - \frac{\sum_{i=1}^n (V_{o,i} - V_{s,i})^2}{\sum_{i=1}^n (V_{o,i} - V_o)^2} \quad (4)$$

where *n* is the number of observations during the evaluation period; *V_{O,i}* and *V_{S,i}* are the

observed and simulated values at each point i , respectively; and V_o is the arithmetic mean of observations. An E_{NS} value of 1.0 represents a perfect model fit.

3. Results

3.1 Model evaluation of water yield (Q) and ET as estimated by P minus Q for 72 USGS gauged watersheds

The comparisons between model simulated and observed mean annual Q for the 72 watersheds during 1990-2009 (Fig. 2a and Table 1) indicated that the WaSSI model performed well over the long term as judged by model statistics ($R=0.97$; mean slope=0.86; $RMSE=12$ mm yr⁻¹; $MRE=4\%$). Overall, the model could match annual Q well for most of the watersheds, but underestimated flow for a few watersheds with high flow rates. The multi-year mean annual modeled Q values were significantly correlated to measured Q, and all data samples were clustered around the 1:1 line, suggesting that this model could capture the spatial variability as well. Except for the peaks in May and June, simulated intra-annual fluctuations of Q matched the measured Q reasonably well when all data for the selected 72 USGS watersheds were pooled together (Fig. 3a). Monthly Q generally increased from January to May with a peak of 102 mm yr⁻¹ and 86 mm yr⁻¹ in May for the observed and simulated values, respectively. Monthly flows drastically decreased during the summer growing season and reached the lowest values in August (21 mm yr⁻¹) for the observed, and September (26 mm yr⁻¹) for the simulated. The fall season is the groundwater recharge period and streamflow increased as a result of decreased ET (Fig. 3b).

The simulated and the observed multi-year mean annual Q exhibited a similar spatial pattern across the selected 72 USGS watersheds (Fig. 4a). Q was the highest (>900 mm yr⁻¹) in watersheds of the west coastal region and the southern Appalachian Mountains, mainly due to both moderate ET rates and high precipitation. Most watersheds of the WNC, SW and ENC regions generated very little Q (<500 mm yr⁻¹) because of low precipitation and high evaporative demand. Multi-year mean differences in annual Q between the USGS observations and the WaSSI simulations showed a complex pattern (Fig. 4c). In the NW and NWC regions, and the Appalachian Mountains, the model overestimated Q for most watersheds, especially for the NW coast (discrepancy Q > 120 mm yr⁻¹). However, for most of

the 72 watersheds, the WaSSI model underestimated Q to different degrees (Fig.4c).

The spatial distributions of the slopes of the linear regression models, the normalized *RMSE*, *R* and *E_{NS}* provided a complete picture of model performance in modeling Q (Fig.5). Among the 72 watersheds, 44 and 66 watersheds had regression slopes higher than 0.80 and normalized *RMSE* values lower than 0.30, respectively, indicating that the WaSSI model simulated the magnitudes of annual Q well for most watersheds (Fig. 5a, 5b). Similarly, 55 watersheds had *R* values higher than 0.90, suggesting that WaSSI captured the inter-annual fluctuations of Q (Fig. 5c). Except for few watersheds on the west coast and the Great Plains, 50 watersheds had *E_{NS}* values ranging from 0.60 to 1 (Fig. 5d), implying that the model accurately predicted annual Q, especially for the humid SE region.

A comparison between simulated ET by WaSSI and estimated ET as the differences between precipitation and measured USGS streamflow provided more confidence in model annual streamflow (Fig. 2b). The simulated annual ET and estimated ET as P-Q were highly correlated ($R=0.86$) with a moderate *RMSE* of 106 mm yr⁻¹ and *MRE* of 16%. Although the modeled ET values matched well with estimated in the low ET range (<450 mm yr⁻¹), over estimations were obvious for seven watersheds (Fig. 2b).

3.2 Model evaluation by ET for 170 NFs

The scatterplot of the measured vs. the predicted multi-year mean annual ET (2000-2012) provided evidence for the model's capability to simulate ET (Fig. 2b). The predicted ET across the 170 NFs was significantly correlated to the satellite-based estimates with *R* of 0.92. Moreover, the observed and the simulated multi-year mean ET in most of the NFs were distributed around the 1:1 line with *RMSE* of 104 mm yr⁻¹ and *MRE* of 16% (Table 1). However, WaSSI both over- and under- predicted ET compared to satellite-based ET estimates (Fig. 2b). At the monthly scale, the WaSSI model matched the mean variations of monthly ET derived from satellite-based MODIS data. Generally, monthly ET peaked in July, and after that ET began to decline. During April-June and September, the WaSSI model

slightly underestimated monthly ET, and overestimated ET in the winter months (>7 mm month⁻¹).

The WaSSI model captured the spatial patterns of NFs ET generally well when compared to the satellite-based data (Fig. 4d, 4e). The SE region had the highest ET (>700 mm yr⁻¹), particularly for those near the coast (>900 mm yr⁻¹). For the west coast and the ENC and NE regions, most NFs had the moderate ET ranging from 500 mm yr⁻¹ to 700 mm yr⁻¹. The NFs in the SW, WNC regions and the east NW and W exhibited the lower ET (<500 mm yr⁻¹). Overall, the WaSSI model tended to underestimate ET in the eastern U.S. and overestimated ET in the western U.S., especially for some NFs of the northwestern and southwestern U.S. with modeling errors greater than 100 mm yr⁻¹.

3.3 Model evaluation by GPP for 170 NFs

The scatterplot of measured vs. predicted multi-year mean annual GPP indicated good model performance overall ($R=0.87$ and a slope near to 1.0). The *RMSE* (380 gC m⁻² yr⁻¹) and *MRE* (28%) values were moderate (Table 1). However, the simulated multi-year means for most NFs were above the 1:1 line, suggesting that there might be systemic discrepancies between the WaSSI modeled and the satellite-based GPP. The WaSSI modeled GPP had similar seasonal patterns as the satellite-based estimates. Both WaSSI-modeled and remote sensing-based estimates of monthly GPP peaked in July, 183 gC m⁻² yr⁻¹ and 167 gC m⁻² yr⁻¹, respectively. It suggests that systemic discrepancies existed in the multi-year mean monthly GPP (Fig. 3c). WaSSI overestimated monthly GPP for the whole of 170 NFs, especially for winter and spring months (>18 gC m⁻² month⁻¹) compared to the satellite-based estimates.

For spatial patterns of multi-year mean annual GPP, the WaSSI simulations were similar to the satellite-based estimates (Figs. 4g, 4h). The highest GPP (>1600 gC m⁻² yr⁻¹) was found in the SE region while the moderate GPP values (1000-1600 gC m⁻² yr⁻¹) were mainly located in the west coast and the ENC and NE regions. However, the western part of the CONUS, excluding the west coast, had relatively low GPP (< 800 gC m⁻² yr⁻¹). Despite the similar spatial patterns for GPP estimates by the two methods, some spatial differences were noted (Fig. 4i). The WaSSI model overestimated GPP in the S and SE regions and the east part of WNC (>300 gC m⁻² yr⁻¹) compared to MODIS-based GPP data. Nevertheless, the NFs in the California and the NE region with the negative GPP differences suggested that GPP was

underestimated by the WaSSI model.

4. Discussion

4.1. Outliers of ET and GPP predicted by WaSSI

Our multi-watershed and NFs-wide model evaluation suggested that the WaSSI model was effective for estimating annual watershed water and carbon balances. Our simulations generally agreed well with watershed observations and gridded MODIS ET (Mu et al., 2010) and EC-MOD GPP (Xiao et al., 2010, 2014) products. The large discrepancies between WaSSI simulations and the gridded ET and GPP products for a few NFs (with the italic characters in Fig. 2b, 2c) could be attributed to the fragmentation of NFs and the mis-match of watershed boundaries. These NFs had irregular boundaries and land cover compositions. The WaSSI model operated at the 12-digit HUC watershed level, but the presentation of simulated results for each NFs was computed through weighted averages using the area fraction of the 12-digit HUC watershed that fell within each NFs. Therefore, ET and GPP estimates for each NFs were influenced by the dominant land cover within each watershed, and therefore bias could occur, particularly for the smaller and more fragmented NFs. Mis-classification of land cover types was also possible by MODIS products, resulting in erroneous estimates of ET and GPP by either WaSSI or the remote sensing-based methods.

4.2. Uncertainties of modeled water balance

Similar to other hydrologic models, simulated Q and ET by the WaSSI model were subject to uncertainties due to the following factors: input data issues including potential errors in climate data, land cover, soil and LAI estimates from remote sensing as well as from the incomplete representation of the hydrological processes. A recent study suggests the PRISM data might have overestimated the magnitude of climatic warming in high elevation mountainous regions in western U.S. with complex terrains (Oyler *et al.*, 2015). An over estimating air temperature rise by the PRISM then may result in over estimating PET, ET, and underestimating Q. The present study assumed that the monthly LAI values in the historic period prior to 2000 were the same as the 2000-2012 period because MODIS LAI data only became available in 2000. This assumption might result in LAI errors for some NFs watersheds given that both climate and atmospheric CO₂ concentrations have changed

substantially during the past 50 years, altering forest ecosystem structure (LAI), tree species compositions, and ecosystem processes (i.e., ET processes) (Piao and Fang, 2003; Gedney et al., 2006). In addition, this study did not consider management activities such as logging, forest thinning, prescribed burning, and other natural disturbances (i.e., wildfire, insect and disease out breaks, hurricanes) in NFs. These disturbances have likely affected forest dynamics and ecosystem processes in some NFs over this time period (Vose et al., 2012; Masek et al., 2013).

4.3. Uncertainties of modeled ecosystem productivity

Despite the general agreement that North American ecosystems have a large capability for carbon sequestration, uncertainties exist in the size and distribution of ecosystem productivity by existing estimates by different methods (Goodale et al., 2002; Gurney et al., 2002; Deng et al., 2007; Xiao et al., 2011, 2014). Similarly, there were discrepancies between GPP estimated by the WaSSI model in this study and the estimates based on satellite data (Xiao et al., 2014). As shown in Fig. 2c, the simulated multi-year mean GPP by WaSSI were generally higher when compared against the satellite-based data, indicating that there were large uncertainties in estimating GPP by the two methods. Xiao et al. (2008, 2011, 2014) examine the effects of disturbance (e.g., hurricane, fire, pest and pathogen), stand age and nitrogen availability on ecosystem carbon dynamics and conclude that these disturbance factors are critical for accurately estimating regional GPP. Deng et al. (2013) and Chapin et al. (2011) stated that disturbance and stand age are closely related to forest structure and functions, which were known to impact terrestrial carbon budgets. Similarly, nitrogen availability was widely recognized as an important control of canopy photosynthesis and even the whole ecosystem carbon dynamics (LeBauer and Treseder, 2008). However, these factors were not accounted for by the WaSSI model due to lack of data over the CONUS. In addition, selection of the land cover product was likely another source of this uncertainty. Different land cover classes correspond to different parameters in the two models, so the landcover classification uncertainty directly introduces errors into flux simulations. Finally, the modeling unit of the WaSSI model is watershed while EC-MOD was run for 1-km grid cell, and thereby there is a large scale mismatch between these two datasets. The WaSSI model used a high resolution land cover product (i.e., 30×30 m NLCD), which may be more accurate

for land cover identification when compared to Xiao's (1×1 km) MODIS land cover map.

Numerous studies have found that the vegetation activity (e.g., plant photosynthesis and LAI) over the regional and global scales has increased remarkably (Tucker et al., 2001; Zhou et al., 2001; Piao and Fang, 2003; Wang et al., 2011). Therefore, not considering LAI dynamics over the time might lead some uncertainties into our GPP estimates. In our future work, we would like to parameterize the longer-term LAI (or normalized difference vegetation index; NDVI) series or to couple a dynamic module into the WaSSI model for representing vegetation dynamics. Generally, LUCC could offset or enhance ecosystem productivity depending on the type of land cover transformations (Meyer and Turner, 1994; Foley et al., 2005; Zhang et al., 2014).

In addition to these factors discussed above, climate data as a major driver to the hydrologic processes have a great influence on GPP estimates as well. Climate issues in PRISM for the mountainous regions identified by Oyler *et al.* (2015) might have resulted in over estimating ET then GPP in this study.

5. Conclusions

The latest version of the WaSSI model was validated with both decades-long hydrology (i.e., Q and MODIS-ET) and ecosystem productivity data (i.e., EC-MOD GPP) at a broad scale across the 170 NFs. The WaSSI model generally captured the spatial variability of multi-year means for annual Q, ET and GPP. The WaSSI model also performed well in matching annual and monthly water yield for most of the 72 USGS gauged watersheds. The WaSSI model generally led to higher GPP estimates than the remote sensing-based method, especially in the winter season. Overall, our assessments showed that the WaSSI model had the capability to reconstruct the long-term forest watershed water and carbon balances at a broad scale. This model evaluation study provides a foundation for future model applications in understanding the impacts of climate variability and change (e.g., extreme droughts) on NFs ecosystem service and function.

Acknowledgements: This study was funded by the National Science Foundation EaSM program (AGS-1049200) awarded 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).

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Fig.2 Comparisons of simulated multi-year mean annual Q, ET, and GPP by WaSSI against the observed Q and ET estimated as P minus USGS Q at 72 USGS gauges, and ET estimated by Mu et al. (2010) and GPP estimated from Xiao et al. (2014) based on remote sensing techniques for 170 National Forests and Grassland Systems, respectively. The symbols with empty circles with labels indicate NFs sites (see Supplementary I for NFs number and associated climate) with large simulation discrepancies. OL=Olympic National Forest (#140); MB=Mt. Baker National Forest (#143); DC=Deschutes National Forest (#123); SS=Siuslaw National Forest (#124); SK=Siskiyou National Forest (#83); and BV=Butte Valley National Grassland (#82).

Fig. 3 Intra-annual fluctuations of Q (1990-2009; a) across the 72 USGS watersheds, and ET (2000-2012; b) and GPP (2001-2012; c) over the 170 NFs of the CONUS. Gray line and black circle represented multi-year mean monthly values from the WaSSI model and the observations (or the satellite-based estimates), respectively. Differences by the simulated minus the measured (or the satellite-based estimates) were shown with the gray bars.

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713 Table 1. A summary of WaSSI model performance in simulating Q, ET across the 72 watersheds
714 (1990-2009), and ET and GPP across the 170 NFs (2000-2012)

Variables compared	Multi-year mean $\pm$ SD		Root Mean Square Error	Mean Relative Error
	Observed/Estimated	WaSSI Simulated		
USGS Q (mm yr ⁻¹)	716 $\pm$ 397	688 $\pm$ 342	12	4%
ET estimated as P minus USGS Q (mm yr ⁻¹)	595 $\pm$ 195	625 $\pm$ 181	106	13%
MODIS ET(mm yr ⁻¹)	516 $\pm$ 232	534 $\pm$ 196	104	16%
EC-MOD GPP (gC m ⁻² yr ⁻¹)	1012 $\pm$ 528	1254 $\pm$ 642	380	28%

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Fig.2 Comparisons of simulated multi-year mean annual Q, ET, and GPP by WaSSI against the observed Q and ET estimated as P minus USGS Q at 72 USGS gauges, and ET estimated by Mu et al. (2010) and GPP estimated from Xiao et al. (2014) based on remote sensing techniques for 170 National Forests and Grassland Systems, respectively. The symbols with empty circles with labels indicate NFs sites (see Supplementary I for NFs number and associated climate) with large simulation discrepancies. OL=Olympic National Forest (#140); MB=Mt. Baker National Forest (#143); DC=Deschutes National Forest (#123); SS=Siuslaw National Forest (#124); SK=Siskiyou National Forest (#83); and BV=Butte Valley National Grassland (#82).

Fig. 3 Intra-annual fluctuations of Q (1990-2009; a) across the 72 USGS watersheds, and ET (2000-2012; b) and GPP (2001-2012; c) over the 170 NFs of the CONUS. Gray line and black circle represented multi-year mean monthly values from the WaSSI model and the observations (or the satellite-based estimates), respectively. Differences by the simulated minus the measured (or the satellite-based estimates) were shown with the gray bars.

Fig.4 Spatial distributions of multi-year mean annual water and carbon fluxes with their differences (observations or satellite-based estimates minus model simulations).

Fig. 5 Spatial distributions of the validation criterion for annual Q (1990-2009) over the selected 72 USGS watersheds. (a) Slope presents the slope coefficient of the linear regression ($\text{Modeled } Q = a + b \times \text{Measured } Q$) equation derived from the least squares technique. (b) To compare $RMSE$ across different watersheds, it was normalized by dividing it with multi-year observed mean, referred as $RMSE/V_o$. (c) Correlation coefficient between modeled and simulated; and (d) Nash-Sutcliffe Efficiency coefficients (E_{NS}).

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 km² (193 million acre) United States National Forest and Grassland 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 from climate change.

Keywords: Droughts; Ecosystem productivity; National Forests and Grasslands, Water Yield

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., 2015). 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 km² (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 (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., 2014). 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., 2000b; Larsen et al., 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 et al., 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 et al., 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., [in review this issue](#)). 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 to 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 km² (193 million acres), or 8.8% of the CONUS land area. These NFs are located mostly in the Northwest and the Southwest regions (Figure 1a). Climate, topography, and vegetation covers vary greatly

among these 170 NFs (Fig.1b) (Sun et al., 2015 in review this issue).

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., 2015), 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 Services Model (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. ([in review](#)) 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 (SI1). 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 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 (Figs. 2c, 2d). 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 mm yr^{-1} reduction), but ET, Q and GPP decreased 35 mm yr^{-1} (the lowest), 74 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, 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 ecohydrological

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; Figs. 6a, 6b). 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 (Figs. 6a, 6b). 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°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.

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⁻¹ (or 8%) and 110 mm yr⁻¹ (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⁻¹) 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⁻¹) followed by the SE (160-400 mm yr⁻¹; 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⁻² yr⁻¹ or 9%. Similar to P, Q and ET, GPP exhibited relatively large absolute (0-370 gC m⁻² yr⁻¹) and relative (0-39%) changes. The highest reductions in GPP in absolute values were found in the west coast and SE regions (>180 gC m⁻² 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 CO₂ 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 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 Beaty, 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 year⁻¹ 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. (2015) 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 (Figure 8b). Our results were consistent with previous studies (Cook et al., 2004; Ciais et al., 2005; Hussain et al., 2011; Chen et al., 2012; 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., 2012) 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 3,400 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 et al., 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., 2004b). 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 CO₂ (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 broadleaf 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 draughts 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).

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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 ⁻¹) (%)	Temperature (°C)	ET (mm yr ⁻¹) (%)	Q (mm yr ⁻¹) (%)	GPP (gC m ⁻² yr ⁻¹) (%)
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)

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