HYDROLOGICAL PROCESSES
Hydrol. Process. (2015)
Published online in Wiley Online Library
(wileyonlinelibrary.com) DOI: 10.1002/hyp.10469

Modelling the potential role of forest thinning in maintaining water supplies under a changing climate across the conterminous United States

Ge Sun,[1]* Peter V. Caldwell[2] and Steven G. McNulty[1]

[1] *Eastern Forest Environment Threat Assessment Center, Southern Research Station, USDA Forest Service, Raleigh, NC, 27606, USA*
[2] *Coweeta Hydrologic Laboratory, Southern Research Station, USDA Forest Service, Otto, NC, USA*

Abstract:

The goal of this study was to test the sensitivity of water yield to forest thinning and other forest management/disturbances and climate across the conterminous United States (CONUS). Leaf area index (LAI) was selected as a key parameter linking changes in forest ecosystem structure and functions. We used the Water Supply Stress Index model to examine water yield response under 18 scenarios that combine hypothetical LAI changes (+10%, ±20%, −50%, and −80%), uniform increases in temperature (+1 °C and +2 °C) and precipitation change (±10%), and four climate change scenarios projected by general circulation models (GCMs) for the year 2050. Approximately 2100 large basins produced approximately 2003 billion cubic metres of water annually from 2002 to 2007. Forest lands covered 23% of the land surface area, but contributed 43% of the total water yield for the CONUS. As a whole, water yield increased by 3%, 8%, and 13% when LAI was reduced 20%, 50%, and 80%, respectively, while water yield decreased by 3% when LAI increased by 20%. Temperature increases of 2 °C alone could decrease water yield by 11%. A reduction of precipitation by 10% and 20% could result in a decrease of water yield by 20% and 39%, respectively. The direction and magnitude of water yield response to the combinations of LAI (+10%), climate warming (+1 °C), and precipitation change (±10%) were dominated by the change in precipitation. Climate change projected by the four GCMs (CSIROMK2 B2, CSIROMK3.5 A1B, HADCM3 B2, and MIROC32 A1B) resulted in a large change in water yield (+18% to −64%) by 2045–2055 when compared with the baseline. A 50% reduction in forest LAI under the four GCMs scenarios could greatly mitigate or exacerbate future climate change impacts on water yield in forest-dominated watersheds with high precipitation. This study provides the first quantitative estimate of the effects of forest thinning options on water yield under future climate across the CONUS. Effective forest water management for climate mitigation should focus on those watersheds identified. Published 2015. This article is a U.S. Government work and is in the public domain in the USA.

KEY WORDS forest thinning; climate change; water yield

Received 7 June 2014; Accepted 24 February 2015

INTRODUCTION

Water supply is one of the important ecosystem services of forests (Brown *et al*., 2008; Sun *et al*., 2011a) that are under increasing threats from global climate change (Vose *et al*., 2012a; Sun *et al*., 2013). Evidence about the impacts of climate change on forests is widespread in the United States (McNulty *et al*., 2013a; Joyce *et al*., 2014) and elsewhere in the world (IPCC, 2014). Direct and indirect negative consequences of climate change include water yield decline and flooding, water quality degradation, changes in the distribution of tree species, increases in fire frequency and severity, and insect and disease outbreaks (Vose *et al*., 2012a; Amatya *et al*., 2015). Novel watershed management practices are needed to mitigate the negative impacts of climate change and variability and adapt to a new environment (Vose and Klepzig, 2014). Forest thinning has been increasingly adopted as one of the management options to reduce wildfire fuel loads and high-severity fire risk (Stephens *et al*., 2009), reduce tree competition for water and nutrient resources (McLaughlin *et al*., 2013), and improve overall forest health and wildlife habitat (Demaynadier and Hunter, 1996). In addition, watershed managers have become increasingly concerned about changes in water yield. Water yield, also known as runoff or streamflow, represents the long-term differences between precipitation and evapotranspiration (ET) in a watershed. Forest thinning, among other 'water saving' methods, has been recommended as a potential strategy to increase water availability for both ecosystems and humans, and thus

*Correspondence to: Ge Sun, Eastern Forest Environment Threat Assessment Center, Southern Research Station, USDA Forest Service, Raleigh, NC 27606, USA.
E-mail: gesun@fs.fed.us
Contract/grant sponsor: Joint Fire Science Program (JFSP) Project # 14-1-06-18 and USDA Forest Service.

increase the resilience of watersheds to climate change and variability (Grant *et al*., 2013). Quantifying the spatial variability of watershed hydrologic response to thinning is needed to prioritize forest management for climate change mitigation and adaptation.

We know much about how watershed hydrology responds to forest cover change and climatic variability at a small watershed scale (Amatya *et al*., 2011; Sun *et al*., 2011a, b; Vose *et al*., 2012a, b). Worldwide, small watershed vegetation manipulation experiments over the past century confirm that water yield can be significantly influenced by forest management including thinning (Andréassian, 2004; Brown *et al*., 2005). However, there is a large uncertainty regarding the magnitude of watershed response in part due to the large variability of watershed climate, vegetation cover, and the magnitude of disturbances (Edwards and Troendle, 2012). In addition, it is unclear how changes in water yield observed in small experimental watersheds manifest itself at the large basin scale. Similarly, forest hydrologic response to future climate varies across forest types (i.e. coniferous *vs* deciduous forests) and climatic regimes (arid *vs* humid climate) (Lu *et al*., 2013; Creed *et al*., 2014). Therefore, it is difficult to disentangle and quantify the influences of climate, ecosystem feedbacks, and other compounded environmental (i.e. CO_2) (Warren *et al*., 2011; Tian *et al*., 2012) and human factors (Sun *et al*., 2008) on watershed hydrological change.

Global studies on forest ecohydrological processes have shown that forest productivity and water use or ET are strongly controlled by ecosystem biomass or leaf area index (LAI) (Gholz *et al*., 1990; Gholz and Clark, 2002; Sun *et al*., 2011a,b) in addition to many other biophysical factors such as age, species, and climate. Simply put, the higher the leaf and basal area of a forest, the more water it uses. Over 60% of the variability in monthly ecosystem-level ET can be explained by LAI (Sun *et al*., 2011a). Thus, as forest thinning or mortality reduces leaf area, total tree transpiration, canopy interception, and consequently total water loss (ET) at the stand level will also be reduced resulting in an increased water yield.

A reduction in water use by trees and canopy interception due to biomass removal results in an increase in water yield for groundwater recharge and streamflow generation. For example, a 20–30% increase in water yield after thinning mountain ash (*Eucalyptus regnans*) was reported in Australia (Lane and Mackay, 2001; Hawthorne, 2011). Studies on the Appalachians in the eastern USA suggest that first-year water yield increases due to forest management are proportional to the basal area removed and solar energy available (Douglass, 1983). Although there is evidence that some tree species may increase transpiration after thinning because of increased light and soil water/nutrient availability (Hernandez-Santana *et al*., 2012; Boggs *et al*., 2014 this issue), watershed scale studies suggest that thinning generally reduces ecosystem ET, alters snow pack patterns, and increases total water yield at least for the short term (Edwards and Troendle, 2012). The long term effects of thinning on water yield depend on the transpiration characteristics (i.e. leaf area and stomatal conductance) of the regrowth after the treatment (Hawthorne, 2011). Grace *et al.* (2006a,b) found that thinning a 15-year old loblolly pine plantation on the North Carolina coastal plain (basal area = $39\,m^2\,ha^{-1}$) by removing one third of the basal area reduced ET by about 5% and doubled water yield, indicating a strong vegetation control on ET and watershed runoff in dry years. A 7-year study in the Ouachita Mountains of Arkansas concluded that water yield from a pine forest increased by an average of 23% from thinning and 67% from clear cutting, mostly during the growing season (Edwards and Troendle, 2012). However, removing 32% of the basal area in a watershed in at Dickey Brook, MA (under a colder climate) resulted in no changes in the average peak discharges for 3 years (Bent, 1994) but an increase in baseflow, direct runoff, and total streamflow, groundwater recharge for six dormant seasons and six growing seasons (May–September) during 1968–1973 (Bent, 2001). McLaughlin *et al*. (2013) developed an empirical model that related pine forest ET/precipitation ratio to LAI and stand basal area and examined the cumulative effects of thinning and understory removal on water yield. This study concluded that maintaining a lower basal area could gain up to 64% more water yield through a full 25-year stand rotation on the southeastern US coastal plain compared with the current high-density plantations.

Water yield response to climate change is highly dependent on changes in precipitation and potential evapotranspiration (PET) in addition to the associated changes in forest structure and composition (McNulty *et al*., 2013a; Sun *et al*., 2013). For example, long-term streamflow data in the USA suggest that mean annual streamflow has increased over the past century largely because of increased precipitation (Karl and Knight, 1998; Lins and Slack, 1999). Additionally, an increase in air temperature can be directly translated to an increase in PET (Lu *et al*., 2009; Dai *et al*., 2010) and decrease in streamflow (Krakauer and Fung, 2008). However, the magnitude and direction of the effects of climate change on actual ET and water yield can be influenced by other factors such as increasing carbon dioxide (CO_2) concentration and forest growth. The effects of CO_2 on watershed level ET and runoff are not well understood and are difficult to quantify due to multiple complex ecohydrologic interactions (Cech *et al*., 2003; Gedney *et al*., 2006; Warren *et al*., 2011), such as increasing plant growing season length and leaf area, and drought stress under a warming climate.

The goal of this modelling study was to determine the possible bounds of water yield response to prescribed forest thinning practices as represented by the reductions in LAI, potential climate change, and interactions between thinning and climate at the large basin scale [8-digit hydrologic unit code (HUC)] across the CONUS. The well validated Water Supply Stress Index (WaSSI) model (Sun *et al*., 2011b; Caldwell *et al*., 2012, Caldwell1 *et al*., 2015) was applied in this study. We hypothesized that the effects of forest thinning on water yield would vary spatially because of the spatial climatic variability under current and future climate conditions and associated forest leaf area dynamics over time and space. Specific objectives of this study were the following: 1) to examine the sensitivity of water yield to change in LAI for 2100 watersheds across a large physiographic and climatic gradient, 2) to examine the sensitivity of water yield to climate changes under a series of scenarios that were either fixed climate perturbations or projected by the general circulation models (GCMs) around the year 2050 (2045–2055), and 3) to explore how vegetation management (e.g. forest thinning) may mitigate (i.e. lessen) reductions in water yield due to changes in climate by reducing forest water use.

METHODS

We applied a watershed-scale monthly water balance model, WaSSI, (Sun *et al*., 2001a; Caldwell *et al*., 2012) to address our hypothesis and answer the proposed questions. Modelling schemes were developed to cover a range of potential temperature and precipitation change and forest management (i.e. thinning) options. Prescribed thinning scenarios were represented by the reductions in LAI at multiple hypothetical management levels. First, we used historical climate to test the sensitivity of watershed water yield to climate perturbations and LAI change simulating forest thinning or growth. Then, four future climate change scenarios projected by the four combinations of GCMs and future greenhouse gas emission storylines were examined to understand the water yield response under projected climate change. Finally, we examined how a 50% forest thinning practice would affect water yield under climate changes projected by the four GCMs and emission storyline climate scenarios around the year 2050.

The WaSSI model

In this study, we used a previously developed integrated ecosystem service assessment tool, WaSSI, that has been used to quantify the compounded impacts of climate change, land use change, and population growth on water supply stress and carbon sequestration across the conterminous United States (CONUS) (Sun *et al*., 2011a; Caldwell, *et al*., 2012). WaSSI has been used in climate change assessments (Lockaby *et al*., 2011; Marion, *et al*., 2013; Sun *et al*., 2013; Tavernia *et al*., 2013), has been used for examining the nexus of water and energy at the national scale (Averyt, *et al*., 2013), and has been applied internationally in Mexico, China (Liu *et al*., 2013), and Rwanda (McNulty *et al*., 2015), Tanzania, and Zambia. A brief introduction of the model's functionality and algorithms is provided in the succeeding paragraphs, and the details on model development and validation are found in the works of Sun *et al*. (2011a) and Caldwell *et al*. (2012).

Water Supply Stress Index simulates the full monthly water (ET, water yield, and soil moisture storage) and carbon balances for each of the 10 land cover classes at the 8-digit United States Geological Survey HUC scale (i.e. approximately 2100 watersheds with a median size of 3210 km^2). The HUC watershed is defined in a national standard, four-level hierarchical system of hydrologic units in the USA, ranging from 18 Water Resource Regions (WRR) in the CONUS at the first level to approximately 2100 Cataloging Units, or HUC watersheds, at the fourth level (Seaber *et al*., 1987) (Figure 1).

Mathematical algorithms describing carbon and water cycles in WaSSI reflect our accumulated ecohydrological knowledge derived from the global eddy flux monitoring community and station-based small watershed experiments across the USA. The core of WaSSI is an ecosystem ET model that calculates monthly ET as a function of PET, LAI, and soil water availability for each land cover type within HUC with mixed land uses (Sun *et al*., 2011a, b). The model used a conceptual snow model (McCabe and Wolock, 1999; McCabe and Markstrom, 2007) to partition precipitation in each watershed into rainfall and snowfall based on the mean watershed elevation and monthly air temperature, to estimate snow melt rates, and to compute mean monthly snow water equivalent over each watershed. Infiltration, surface runoff, soil moisture, and baseflow processes by land cover type are computed using algorithms of the Sacramento soil moisture accounting model (Burnash *et al*., 1973; Burnash, 1995). The 11 soil parameters used in the soil water routing model were derived from State Soil Geographic (Natural Resources Conservation Service, 2012). All water balance components were computed independently for each land cover class within each watershed and aggregated to estimate the totals for the watershed.

Generally speaking, an uncalibrated model is believed to be more robust than a calibrated, watershed-specific model to assess the impact of novel climate or land cover change outside of the conditions for which the model is developed because climate is not stationary. The uncalibrated (i.e. default model parameters are not adjusted to fit observed flow for each watershed) WaSSI

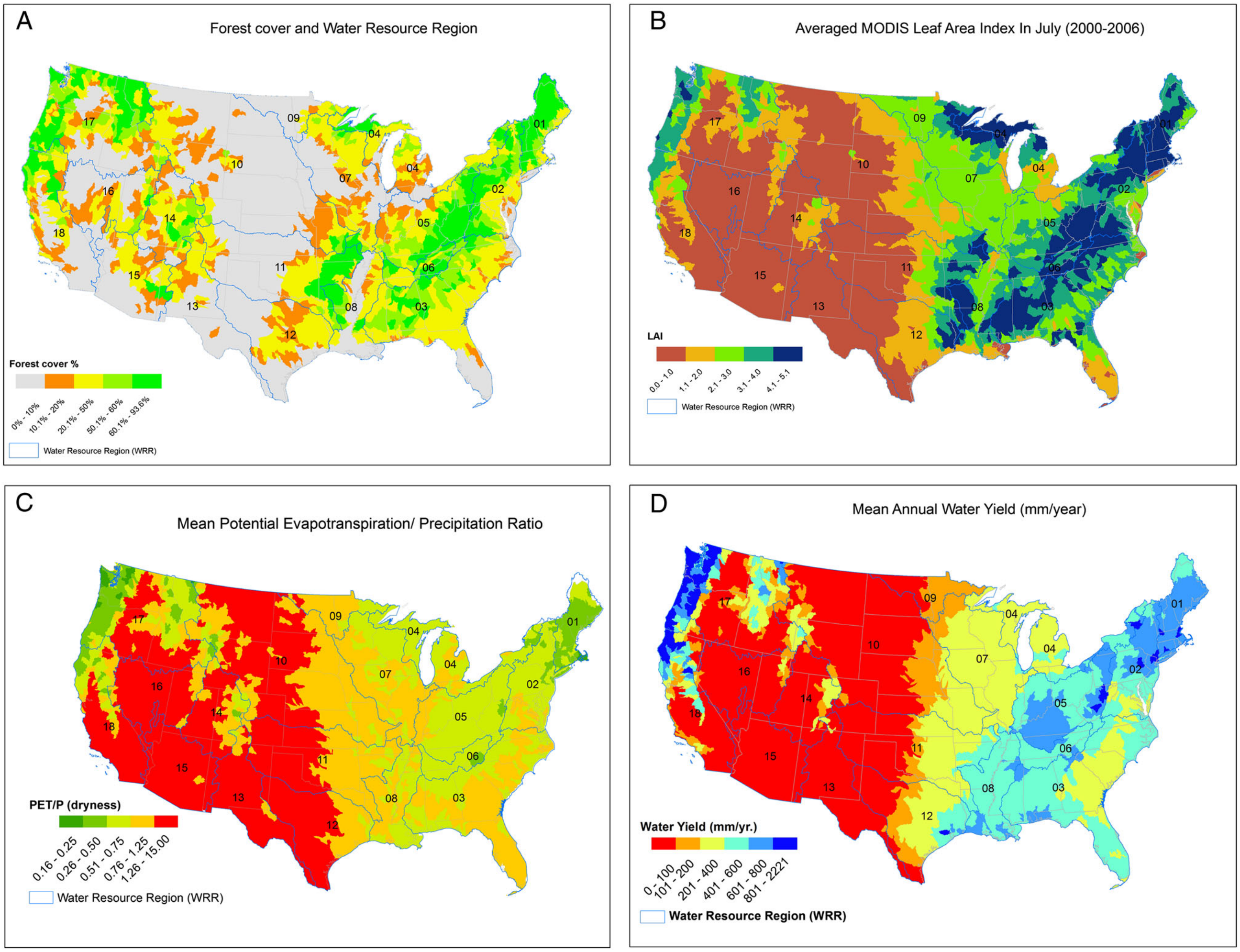

Figure 1. An illustration of inputs and outputs for the hydrologic model, Water Supply Stress Index. (a) Percentage of forests within each of the 2100 United States Geological Survey (USGS) hydrologic unit code-8 watersheds with mixed land covers; (b) mean leaf area index for the month of July (i.e. peak growing season) with values weighted across all 10 land cover types with each watershed; (c) modelled mean annual potential evapotranspiration estimated by Hamon's method/precipitation ratio or dryness index; and (d) modelling mean annual water yield (2002–2007). Also shown are the 18 USGS WRR. The 18 WRR include New England (01), Mid-Atlantic (02), South Atlantic-Gulf (03), Great Lakes (04), Ohio (05), Tennessee (06), Upper Mississippi (07), Lower Mississippi (08), Souris-Red-Rainy (09), Missouri (10), Arkansas-White-Red (11), Texas-Gulf (12), Rio Grande (13), Upper Colorado (14), Lower Colorado (15), Great Basin (16), Pacific Northwest (17), and California (18)

model has been extensively validated with both measured streamflow from gauged watersheds and regional remote sensing ET data across the USA (Sun *et al*., 2011b; Caldwell *et al*., 2012; Caldwell *et al*., 2015). We have achieved an acceptable level of confidence in model performance at the monthly temporal scale. A recent multiple model comparison study in the southeastern USA suggested that WaSSI generally had comparable performance to other more physically based model such as Soil Water Assessment Tool (SWAT) and Precipitation Runoff Modeling System (PRMS) that required more input parameters and were calibrated (Caldwell1 *et al*., 2015). WaSSI is sensitive to both land cover and climate variability, and thus was well suited to investigate the relative impact of multiple elements of global change on river flows (Caldwell *et al*., 2012; Averyt *et al*., 2013).

Simulation scenarios

Leaf area index, a key parameter of forest ecosystem structure, has a major control on the biological water demand (ET) and thus water yield in forested watersheds (Sun *et al*., 2011a, b). Our study used change in LAI as a proxy to the magnitude of forest disturbances or restoration activities such as forest thinning, wildfires, logging, or watershed restoration. For example, forest thinning as a forest management practice generally reduces LAI while reforestation increases LAI. Climate warming can also result in an increase in the length of the tree growing season, primary productivity, and LAI values (Xie *et al*., 2013).

A total of 18 simulation scenarios were developed to test the sensitivity of water yield response to a large spectrum of changes in LAI, air temperature, precipitation, and their combinations (Table I). The first baseline scenario (S1) represents the historic climate. The next four scenarios (S2–S5) were designed to test the sensitivity of water yield to LAI change from an increase of 20% (S2) to a decrease 80% (S5). Climate sensitivity scenarios were represented by S6–S8. The combined effects of uniform climate change and LAI increase were simulated using S9–S10. A uniform change in air temperature, precipitation, or LAI was applied to the baseline for each month across all the 2100 watersheds.

Four combinations of GCMs and future greenhouse gas emission storylines (CSIROMK2 B2, CSIROMK3.5 A1B, HADCM3 B2, and MIROC32 A1B) were used to evaluate potential impacts of 'real' climate change on water yield. We chose these GCMs because they give a wide range of future climate projections and they have been used in a series of climate change assessments in

Table I. Simulated water yield responses in relative to historic climate under 18 simulation scenarios by the Water Supply Stress Index model

Scenario (S)	Description	Climate and management representation	Modelled water yield response in relative to baseline (%) (weighted average across 2100 hydrologic unit code-8 watersheds)
S1: Baseline	Historic climate (2002–2007), 2001 land cover, and mean LAI	Background conditions	Baseline
S2: LAI*1.2	LAI increased 20%	Increase of biomass	−3%
S3: LAI*0.8	LAI decreased 20%	20% thinning (light thinning)	3%
S4: LAI*0.5	LAI decreased 50%	50% thinning (moderate thinning)	7.9%
S5: LAI*0.2	LAI decreased 80%	Severe thinning and/or insect and disease outbreak causing tree mortality	13%
S6: T + 2 °C	Monthly air temperature increased 2 °C	Moderate climate warming	−11%
S7: P*0.8	Monthly precipitation reduced 20%	Severe drought	−38%
S8: P*0.9	Monthly precipitation reduced 10%	Moderate drought	−20%
S9: P*0.9 + T + 1.0 °C + LAI*1.1	Combination of S8, increase T by 1 °C and LAI increased 10%	Moderate drought, climate warming, and increase of biomass	−26%
S10: P*1.1 + T + 1.0 °C + LAI*1.1	Similar to S9, but P increased 10%	Moderate wetting, climate warming, and increase of biomass	12%
S11: Climate change CSIROMK2 B2	Downscaled GCMs: World Climate Research Programme CMIP3 dataset	Similar P and warmer (14% higher PET) in 2050 compared with baseline (2002–2007)	−10%
S12: Climate change CSIROMK3.5 A1B	Downscaled GCMs: World Climate Research Programme CMIP3 dataset	Wetter (5% higher in P) and warmer (11% higher PET)	7%
S13: Climate change HadCM3B2	Downscaled GCMs: World Climate Research Programme CMIP3 dataset	Drier (−7% of P) and warmer (15% higher PET)	−21%
S14: Climate change MIROC3.2A1B	Downscaled GCMs: World Climate Research Programme CMIP3 dataset	Drier (−8% P) and hotter (19% higher PET	−25%
S15: LAI*0.5 + climate change CSIROMK2 B2	LAI decrease 50% + S11	50% thinning + warmer climate in 2050	−5%
S16: LAI*0.5 + climate change CSIROMK3.5 A1B	LAI decrease 50% + S12	50% thinning + wetter and warmer climate in 2050	12%
S17: LAI*0.5 + climate change HadCM3B2	LAI decrease 50% + S13	50% thinning + drier and warmer climate in 2050	−16%
S18: LAI*0.5 + climate change MIROC3.2A1B	LAI decrease 50% + S14	50% thinning + drier and hotter climate in 2050	−20%

LAI, leaf area index; GCM, general circulation model; PET, potential evapotranspiration southern USA (McNulty *et al*., 2013b; Wear and Greis, 2013; Vose and Klepzig, 2014). We set the 2002–2007 as the baseline for this impact assessment. This was a period in which land cover was most current (2006) and also overlaps WaSSI validation using remote sensing-based ET estimates and measured streamflow in our previous studies (Sun *et al*., 2011a; Caldwell *et al*., 2012).

We examined water yield response from the entire watershed with mixed land cover types for the four GCMs 'real' projected climate scenarios. We compared mean water yield response under four GCMs for the year 2045–2055 to baseline (2002–2007) to determine the mean climate change effects (ΔQc). Then we quantified the forest management mitigation/exacerbation effects by comparing water yield response to LAI change under the climate change (ΔQl) to water yield response to GCMs alone. The management effect was calculated as (ΔQl/ΔQc). When climate change reduces flow, ΔQc becomes negative. Because ΔQl is always positive or an increase in flow under forest thinning, a negative ΔQl/ΔQc value indicates management mitigation and otherwise exacerbation of the hydrologic impacts of climate change. In other words, to mitigate the reduction in discharge (ΔQc) from climate change, thinning is effective because thinning increases discharge. Similarly, if ΔQc > 0 due to climate change, ΔQl/ΔQc values become positive. In this case, because thinning operations increase flow, forest management exacerbates floods caused by climate change.

Key databases

To run the WaSSI model across the 2100 8-digit HUC watersheds, spatially distributed input data for climate, land cover, soil, and watershed connectivity (i.e. upstream and downstream flow directions between adjacent watersheds) were needed. Details of database requirements and sources were found in the works of Sun *et al*. (2011a) and Caldwell *et al*. (2012). Briefly, climatic variables included monthly total precipitation and mean air temperature by year and watershed. Historical baseline climate data was derived from Parameter-elevation Regressions on Independent Slopes Model (4 km × 4 km resolution) (2002–2007) (Daly *et al*., 2008). Future projected climate variables from GCMs (three GCMs and two greenhouse gas emission storylines) for the period of 1981–2060 were acquired from Coulson *et al*. (2010a,b).

Land cover composition, the percentage of each of the 10 land cover types (i.e. crop, deciduous forest, evergreen forest, mixed forest, grassland, shrubland, wetland, water, urban, and barren) as well as the impervious cover fraction for each land cover type, was fixed using 2001 National Land Cover Database (NLCD) (http://www.mrlc.gov/nlcd06_data.php). We used the 2006 NLCD for the climate change scenario analysis. Monthly LAI for each land cover type was derived from the Moderate Resolution Imaging Spectroradiometer MOD15A2 FPAR/LAI 8-day composite (Zhao *et al*., 2005) for the years 2000 through 2006 (http: // modis.gsfc.nasa.gov/). An example of spatial distribution of forest cover (i.e. a composite of deciduous forest, evergreen forest, and mixed forest) and watershed level weighted mean LAI is presented in Figure 1 to demonstrate the large variability of both land cover and biomass. Like the land cover distribution, monthly mean LAI for each land cover was assumed to remain constant over time for climate change scenario analysis. All input data were rescaled from their native gridded or county resolution to the 8-digit HUC watershed scale for use in the WaSSI model.

RESULTS

We presented long-term means of water yield response as maps given that this study focuses on the sensitivity of water yield to climate and/or vegetation change (i.e. forest thinning) across the large climate and land cover gradients in the CONUS. Our analysis focused on

Table II. Modelled water yield by land cover type (2002–2007) across the conterminous United States

Land cover		Water yield (mm/year)	(billion m^3)	Water yield (%)	Land area (%)	Water yield(Brown *et al*., 2008) (mm/year.)	(billion m^3/yr.)	(%)
Croplands		298	699	35	30	225(agriculture)	461	26
Forest	Conifer	493	277	14	7	417(forests)	931	53
	Deciduous	471	339	17	9			
	Mixed Forests	420	244	12	7			
Grasslands		99	166	8	21	55(range land)	146	8
Shrubs		55	73	4	17	307(water and wetland)	137	8
Savanna		329	169	8	7			
Others		272	37	2	2	284 (others)	93	5
Total		255	2003	100	100	229	1768	100

forest-dominated watersheds to understand the water yield response to single factors, climate or LAI, or their combinations.

Water balances by watershed and land cover type for the baseline (2002–2007) period

Natural and plantation forests were mainly found in east of Mississippi River, the Pacific Northwest, the northern Great Lake states, and high-elevation mountain areas in the arid inland and Sierra Nevada in western USA (Figure 1A). Forest-dominated (>50% forest areas) regions or watersheds coincided with high precipitation (420–3267 mm/yr) but low dryness (PET/P) (<1.0) values where the mean water yield/precipitation ratios exceeded 0.30 (0.1–0.8). As a result, these forest watersheds provided disproportionately more water than watersheds dominated by other land covers (Table II). When evaluated on a per unit area, mean annual water yield from forests was estimated as 462 mm while croplands produced a mean water yield of 298 mm. Consequently, forests (23% of all land area) produced 860 billion cubic metres water/yr or 43% of the total water yield (2003 billion cubic metres per year) for the CONUS. In contrast, dry ecosystems, such as grassland and shrub lands, cover 38% of the land (Figure 2A) but produced only 12% of the water yield (Figure 2B). Cropland ranked second to forests in water yield production (699 billion cubic metres water per year, or 35% total yield for the CONUS) (Figure 2B).

The WRR 17 (Pacific Northwest), 03 (Southeast), and 05 (Central Appalachians in eastern USA) produced the highest water yield volume (308, 278, and 226 billion cubic metres, respectively) among the 18 WRR regions (Figure 1D) because of their favourable climate for water yield production and large land area. The overall spatial patterns of water yield (Figure 1D) followed closely to those of dryness index, PET/P (Figure 1C), LAI (Figure 1B), and percentage of forest cover (Figure 1A). Forests were found in relatively moist areas with low PET/P or dryness values.

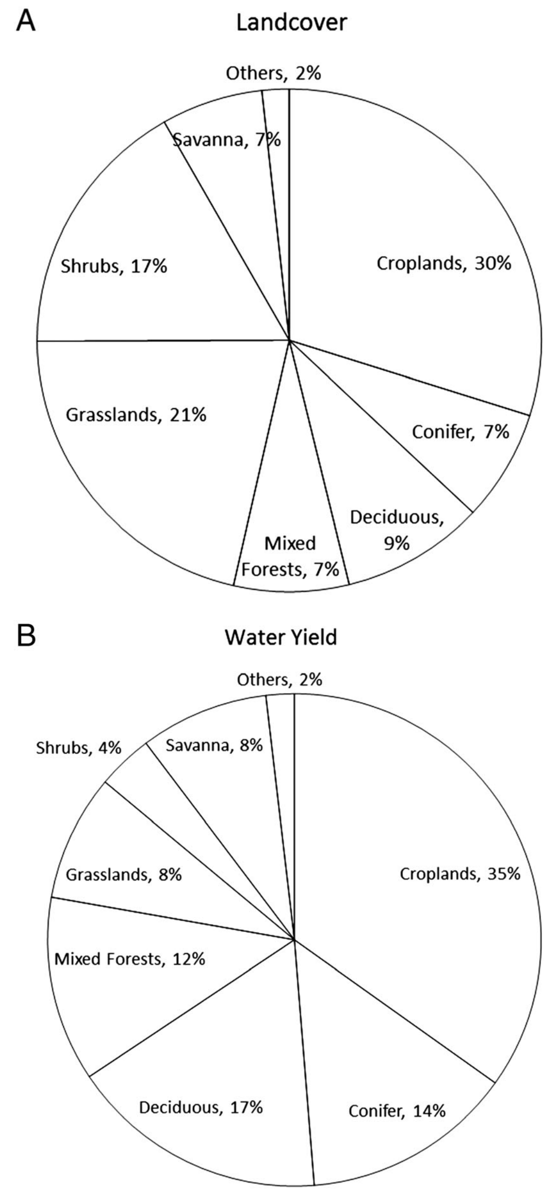

Figure 2. A comparison of (a) land cover composition of the lower 48 US states (2002); and (b) modelled contribution to water yield by land cover type, showing water yield production is dominated by forests (43%) and crop lands (35%)

Sensitivity of water yield to changes in leaf area index and climate

A change in forest LAI by 20% within each of 2100 watersheds resulted in a slight change in water yield by 3% across the CONUS scale (Table I). For forested areas only, the change in water production was much higher (7%). This is understandable because forest is only a portion of the watershed and any change in water yield due to LAI change for the forest portion should be reduced when the water yield response is expressed in per unit area for the entire watershed. Reduction in LAI by 50% could have a large impact on the total water yield for some watersheds (0–85 mm/year or 0–63%) and at the regional scale. At the CONUS level, the water yield response was 7.9% for all land uses and 18% for forest lands only. Spatially, there was large variability in both absolute and relative responses due to the spatial variability of land cover and climatic regime (Figures 3A and 3B). Regions dominated by forests and high precipitation (WRR 01–06, 17) were identified to have high absolute response (>40 mm/year in the Appalachians and the Pacific Northwest), while relatively dry regions (WRR 14, northern part of WRR 17) had highest relative increase of water yield (>25%). As expected, an

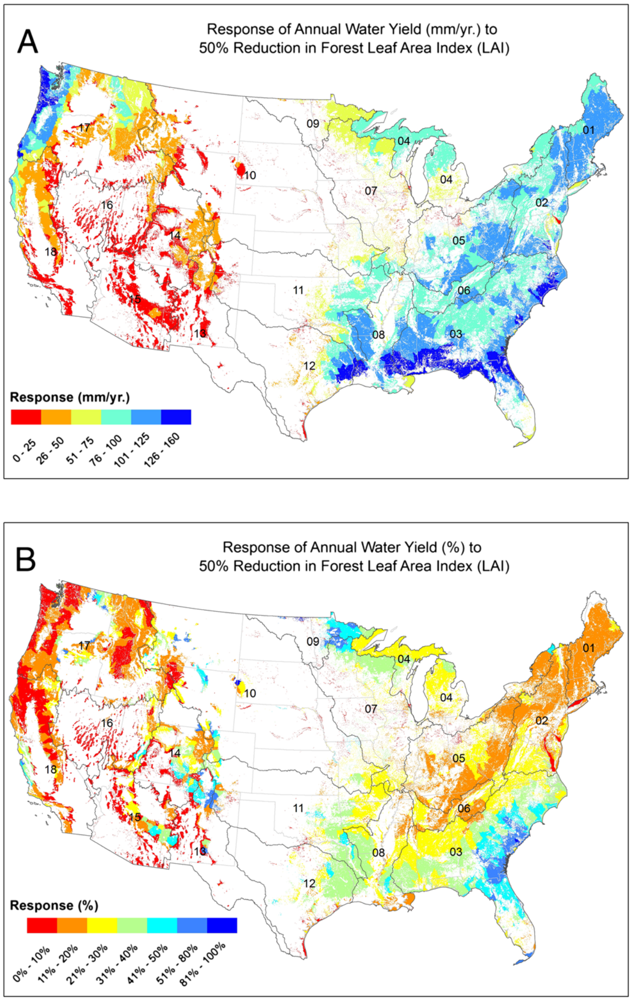

Figure 3. Spatial distribution of annual water yield response in forest lands to reduction of LAI in forests across the conterminous United States. (a) Absolute water yield response (mm/year); and (b) relative change (%). Simulation results at the United States Geological Survey hydrologic unit code-8 scale are presented at 1 km resolution using a mask for forest land cover

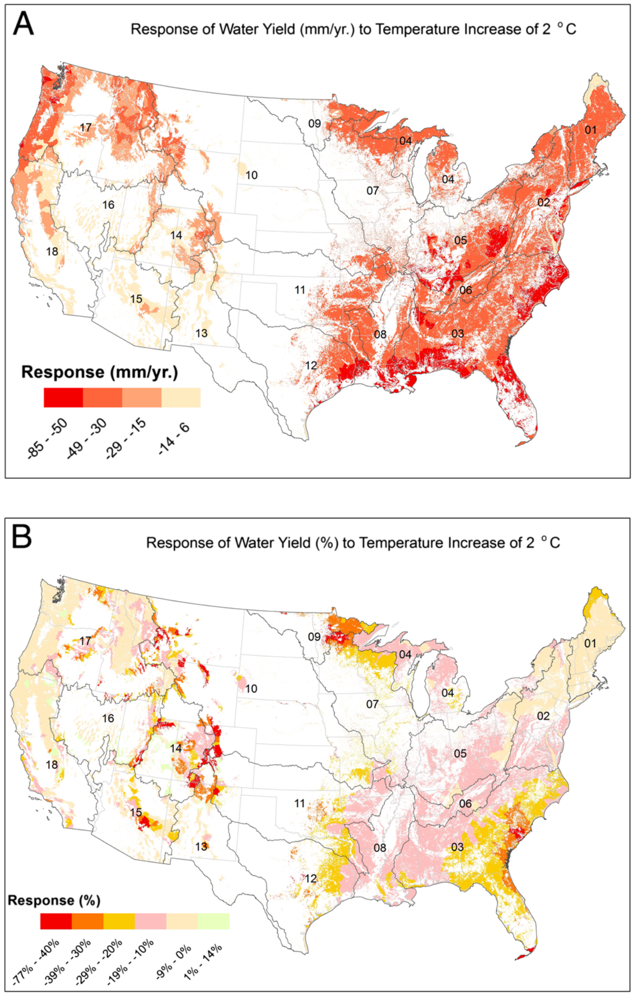

Figure 4. Spatial distribution of annual water yield response in forest lands due to an increase in mean air temperature of 2 °C in forest dominated watersheds across the conterminous United States. (a) Absolute water yield response (mm/year); and (b) relative change (%). Simulation results at the United States Geological Survey hydrologic unit code-8 scale are presented at 1 km resolution by a mask of forest land cover

80% LAI reduction scenario (S5) could result in a much larger increase, an average of 13% for all land uses and 30% for forests.

An increase in air temperature by 2 °C resulted in a mean reduction in water yield of 32 mm or 11% (Table I). Spatially, the wet areas in the east and west coasts had the highest reduction in absolute change, but the highest relative changes were found in the arid western regions and eastern coastal areas in South Carolina and Georgia (Figure 4A, 4B).

Water yield was highly sensitive to precipitation change for all four scenarios examined (S7-S10) (Table I). A decrease in precipitation of 10% across the USA would cause a decline in water yield by about 20% while a 20% reduction of precipitation would result in 39% reduction of water yield. Similar to response to air temperature, there was a large spatial variability in water yield response to changes in precipitation (Figure 5). Worth noting, the South Atlantic coastal region showed high sensitivity (relative change) to reduction of precipitation (i.e. droughts) (Figure 5B).

Change in precipitation also had a large impact on water yield responses under two composite scenarios (S9 and S10). The scenario S9, which represents a decrease of precipitation by 10% + increase in air temperature of 1 °C + increase of LAI by 10% (Table I), resulted in a substantial reduction in water yield, 68 mm/year or 26.3% compared with baseline conditions. In contrast, the second combination scenario (S10), which represents an increase of precipitation by 10% + increase in air temperature of 1 °C + increase of LAI by 10%, caused water yield to increase by 35 mm/year or 12.2%, presumably as a result of increase in precipitation. The effects from each of the three factors

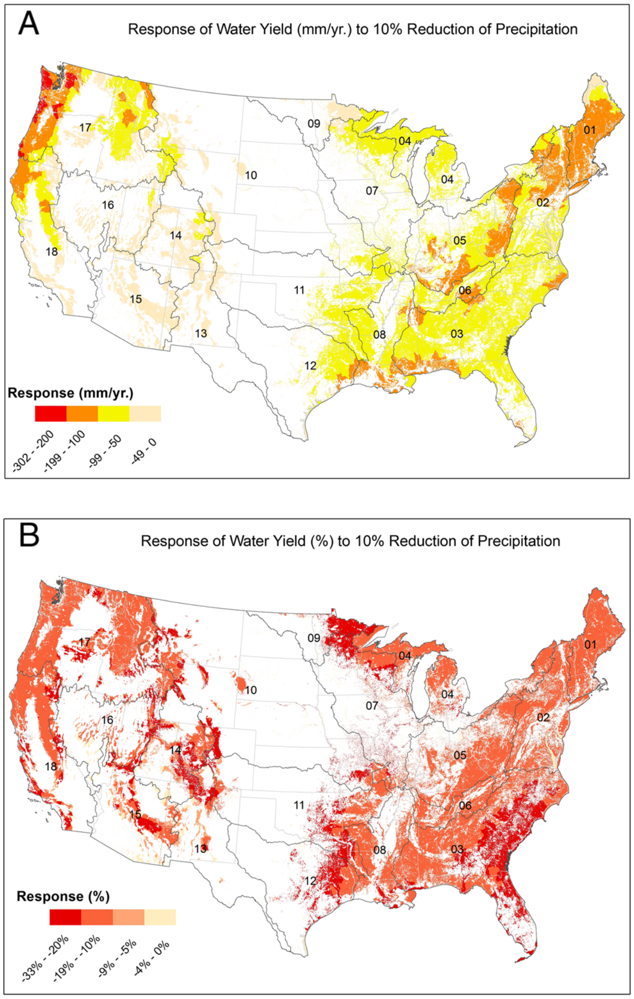

Figure 5. Spatial distribution of annual forest water yield response to an increase in precipitation across the conterminous United States. (a) Absolute water yield response (mm/year); and b) relative change (%). Simulation results at the United States Geological Survey hydrologic unit code-8 scale are presented at 1 km resolution by a mask of forest land cover

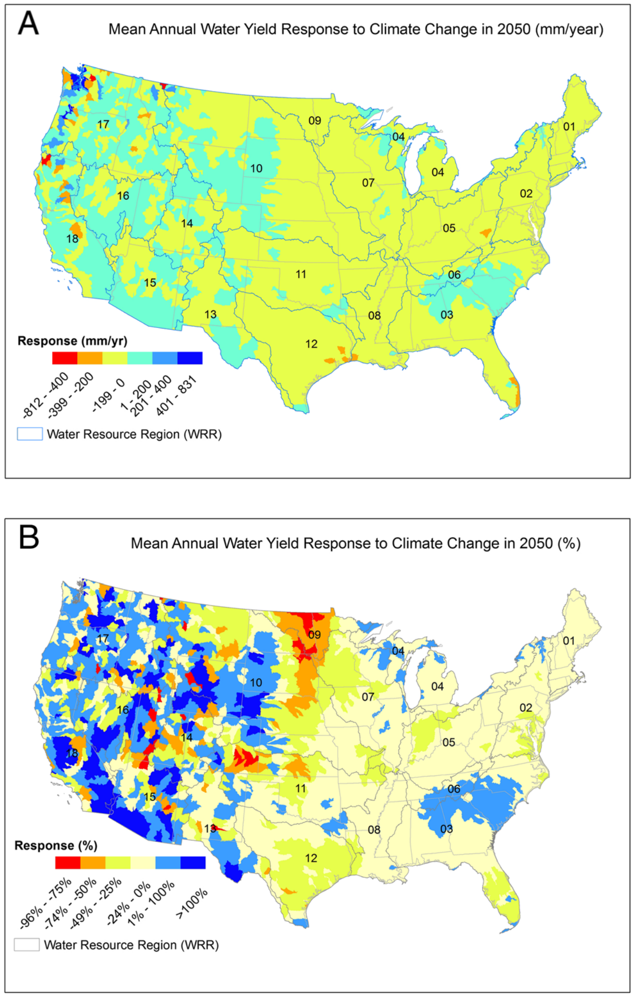

Figure 6. Averaged water yield responses to climate change across four different climate change scenarios (CSIROMK2 B2, CSIROMK3.5 A1B, HADCM3 B2, and MICROC3.2 A1B) that represent two greenhouse gas emission storylines in 2045–2055 (A1B, B2). (a) Absolute response (mm/year); and b) relative change (%) in comparison with the baseline (2002–2007)

appeared to be additive, but the combined impact on water yield was dominated by the reduction in precipitation.

Water yield response (ΔQc) to climate change in 2050 under four GCMs scenarios

By 2050 (2045–2055), the four climate change scenarios all projected elevated PET (11–18%), but with varying magnitude and direction of changes in precipitation ranging from an increase of 5% to a decrease of 8% on average across the USA (Table I). The combined changes in water availability and evaporative energy by 2050 resulted in complex and dramatically different hydrologic regimes from the baseline (Figure 6). Under the ‘Wetter and Warmer’ CSIROMK3.5A1B scenario (S12), water yield response showed a small increase (18.0 mm or 7%). In contrast, the other three warmer or drier scenarios resulted in large decreases in water yield, up to 64 mm or 25% (MICRO3.2A1B scenario) (Figure 6). Consequently, the mean water yield response across scenarios was a decrease of 34 mm or 12%.

When averaged across the four GCM climate scenarios, water yield in the mid-western and eastern regions (except coastal South Carolina) (WRR 1–12) was consistently projected to decrease by 2050 while the rest of the country showed a more complex pattern, especially the western regions (Figure 6). A large change in water yield in both absolute (Figure 6A) and relative (Figure 6B) terms was projected in the Piedmont, southern Appalachian area in the southeast (WRR 03, 06). A large relative change in the arid western USA was due to the low water yield in the baseline. Similar to our findings in the climate sensitivity analysis (S6–S10), future precipitation patterns dictated the water yield responses.

Water yield response (ΔQl) to 50% LAI reduction + climate change in 2050 under four GCMs scenarios

A 50% reduction in LAI under historic climate resulted in water yield increase of 14.7 mm/year (or 5.7%) when the 2006 land cover was used. Similarly, a 50% reduction in LAI resulted in an increase in water yield by 12.3–14.4 mm/year or 5–6% under the four future climate scenarios. Comparing with climate change only scenario (S11–S14), a 50% reduction in LAI in addition to climate change showed additive effects on water yield response. Compared with historic conditions, water yield response to LAI + climate change (S15, S16, S17, and S18) (Table I) was −12.5, 32.2, −42.1, and −51.5 mm, or −5%, 12%, −16%, and −20%, respectively. The mean interactive effects of LAI reduction and climate change could be estimated as the difference of LAI effect under future climate change minus that under historic climate. Using this scheme, we estimated the LAI*climate interactive effect to be −1.2 mm/year or −1.2/–14.7 mm = 8%.

Spatially, a 50% reduction in forest LAI resulted in variable effects across the CONUS. For some watersheds dominated by forests in the eastern USA, LAI change could fully mitigate (or cancel) the effects of climate change (red area in Figure 7). In contrast, for some watersheds that are projected to get wetter in the southeastern USA and most of the western USA, the LAI reduction could greatly increase water yield and magnify the climate change effects (blue area in Figure 7).

DISCUSSION

Baseline water yield by land use

By integrating continental scale spatial databases of the recent climate (2002–2007), we offer an independent estimate of water yield by watershed and by land

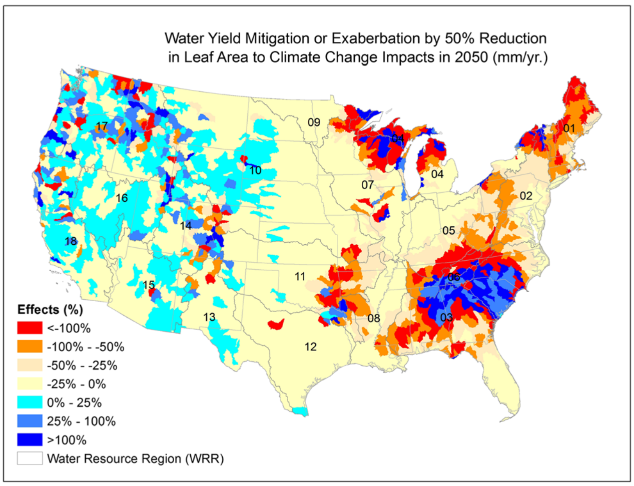

Figure 7. Simulated mean water yield mitigation (negative values in red) or aggravation (positive values in blue) in response to 50% reduction in forest leaf area under four climate change (2045–2055) scenarios in the conterminous United States

cover/use type across the lower 48 US states. Our estimate for total annual water yield, the sum of monthly simulations, for the entire CONUS landmass was 2003 billion cubic metres with 43% and 35% being contributed by forestland and cropland, respectively. Our water yield estimate was 13% higher than the reported 1768 billion cubic metres value by Brown *et al.* (2008) (Table II). However, our estimated water yield from forests (860 billion cubic metres) was 7% lower than reported by Brown *et al.* (2008).

The discrepancies between the two modelling studies could be caused by several factors. First, annual precipitation volume (6108 billon m^3) received in this study during 2002–2007 was 3% higher than reported in Brown *et al.* (2008) who used the mean climate for the time period of 1953–1994. An increase in precipitation could result in a two-fold increase in water yield as demonstrated in our sensitivity study (Table I, S7–S8). Across many regions of the USA, air temperature has increased significantly since the 1960s, and precipitation has showed an increasing (northeast and midwest) or decreasing trend (southeast) (Georgakakos *et al.*, 2014). Second, there were differences in land cover classification. Brown *et al.* (2008) used the 1992 land cover data that cited forest cover as 29%, which was higher than what this study used (23%). The 2001 land cover data used in this our study were assumed to be more current and accurate because the data were based on high spatial resolution remote sensing imageries. In general, under the same climate, forests have higher ET and thus less water yield than other land covers (Zhang *et al.*, 2001). Therefore, lower forest coverage in our cases could result in higher water yield at the CONUS level. Third, differences in model structure and ET algorithms might contribute the differences in both total water yield and contributions of each land cover. This study used a monthly scale model while Brown *et al.* (2008) applied a lumped annual ET model that did not account for vegetation dynamics (i.e. spatial and temporal changes in LAI) and ET differences among forest types and land covers (except forest). Uncertainty in parameterizing both models has been acknowledged by the two separate studies although both models were verified with measurement data from streamflow gauging stations.

Although there were some differences in the magnitude and spatial distribution of water yield estimated by the two modelling studies discussed previously, both studies showed that forests supply disproportionately more water than other ecosystems. Forests cover only one third of the land area of lower 48 states, but they provide 40–50% of the total water yield. The high water yield was mainly a result of the climatic environment where forests grow: comparatively higher precipitation and lower potential evaporation energy than other land covers. It should not be concluded that the higher percentage of water yield from forests as a whole was because that forests used less water than other ecosystems. In fact, worldwide watershed manipulation experiments (Brown *et al*., 2005) have confirmed that, when other factors (climate, topography, and soils) are equal, forests generally use more water, and thus have less water yield than rain-fed crops, grass or shrubs that have lower biomass, LAI, and shorter growing season than forests (Zhang *et al*., 2001; Andréassian, 2004; Jackson *et al*., 2005).

Water yield sensitivity to air temperature and precipitation

As expected, an increase in air temperature caused a decrease in water yield in most watersheds due to the increase in PET and actual ET. Our study used a temperature-based PET model (Hamon's method) without consideration of other meteorological variables such as radiation, thus the results might be biassed towards the influence of air temperature. However, our empirical ET model that was developed from eddy covariance data and Hamon's PET model likely minimizes the PET deficiency by including the seasonal LAI dynamics and precipitation (Sun *et al*., 2011b). Tree phenology reflects all biophysical controls on plant growth.

Spatially, water yield response (reduction) to a uniform 2 °C temperature increase varied from minor changes (dry regions) to −85 mm/year (wet regions). The relative change was as large as −77% in the 'water-rich' region such as the coastal South Carolina and northern Minnesota. These patterns are consistent with a theoretical analysis based on the Budyko's framework (Fu's model) (Ma *et al*., 2008). Ma *et al.* (2008) suggest that water yield sensitivity to potential ET is relatively high in extremely wet environments (PET/P < 0.5), and it decreases dramatically with the increase of watershed dryness when 0.0 < PET/P < 1.0.

The sensitivity analysis using multiple levels of likely future changes in air temperature (+2 °C) and precipitation change (±10%) showed that precipitation change dominated the future impacts of climate change on water yield for the scenarios in this study (moderate change in air temperature and precipitation). Our study showed that a 10% change in precipitation resulted in 20% change in water yield, a doubling effect. Changes in air temperature by +2 °C resulted in a reduction of water yield by 11%. Our study results were very similar to the findings from the work of Lu *et al*. (2013) who conducted climate sensitivity analysis for the south–north transect of eastern China (Longitude 108°–128° E, Latitude 18°–54° N). Lu *et al*. (2013) found an increase in 2 °C air temperature resulted in a 12% decrease in water yield while a reduction of 10% precipitation alone caused 18% decrease water yield and a 10% increase in precipitation resulted in 20% increase in water yield. McCabe and Wolock (2011) studied the separate effects of precipitation and temperature on runoff variability (1900–2008) using a monthly water balance model and historic climate data for the CONUS. Overall, water–year runoff has increased with increasing precipitation, and precipitation has accounted for almost all of the runoff variability. They concluded that temperature effects on runoff had been small for most locations even during periods when temperatures for most parts of the USA increased significantly.

Spatially, water yield responded rather differently to the fixed changes in precipitation and air temperature (Figures 4 and 5). In general, wetter regions (low PET/P) showed higher water yield response in absolute change (mm/yr) to both precipitation and air temperature. The relative change in percentage in water yield has a complex pattern reflecting the baseline water yield conditions. These patterns are consistent with a theoretical analysis by Ma *et al*. (2008) using the Budyko's framework (Fu's model). Ma *et al.* (2008) suggested that water yield sensitivity to precipitation was highest in extremely wet environments (PET/P < 0.5), and decreased dramatically with the increase of watershed dryness when 0.0<PET/P<2.0. They also indicated that water yield of forests was less sensitive to precipitation change than grasslands in dry conditions (PET/P > 1.0).

Future climate and water resources in the USA

Three out of four GCMs analysed in this study resulted in a significant and consistent decline (up to 25%) of water yield by 2050 for the CONUS as a whole. Under all four scenarios, our modelling results suggested that water yield would decrease in the traditionally 'water-rich' regions (southern and eastern states). Our projections are consistent with the recent report on climate change impacts on US water resources in the third US National Climate Assessment (Georgakakos *et al*., 2014). The national-level water sector assessment concludes that the mid-west and northeast regions have seen an increase in precipitation and streamflow, and that these trends are projected to continue or develop in northern states. In contrast, the southern states have observed a decrease in streamflow, and the trend was projected to continue.

Our study showed that the mean reduction in water yield in some regions such as the Mississippi Alluvial Valley was projected to reach a serious level (>200 mm/year or >25%) by 2050 that could cause severe hydrologic droughts. These conditions could seriously disrupt agricultural activities that depend on irrigation and stress drinking water supplies for large metropolitan areas (Sun *et al*., 2008). A shift of hydrologic regime to a drier condition could permanently alter wetland habitats (De Steven and Toner, 2004; Liu and Schwartz, 2010) and trigger forest wildfires and increase tree mortality in this heavily forested southeast (Vose *et al*., 2012a; Joyce *et al*., 2014). The complex pattern of projected water yield change in western USA indicated higher uncertainty in future climatic regime, especially at the basin level. Water resource managers and land planners are facing increasing new risks, vulnerabilities, and opportunities under climate change (Georgakakos *et al*., 2014).

Unfortunately, future changes in precipitation patterns are difficult to project due to the complexity of the atmospheric processes (e.g. hurricanes, El Nino, and La Nina events) under a warming environment (Li and Li, 2013). Our study indicated that it was important to reduce the uncertainty of precipitation projections to generate a realistic projection of water yield response at the regional scale.

Can forest management (thinning) mitigate water yield decline caused by climate change?

One of the key questions that this modelling study was to address whether traditional forest management practices such as thinning can mitigate water yield decline resulted from climate change at the watershed to regional scale. Previous empirical watershed studies (Edwards and Troendle, 2012) and simulation results from the present study and others (McLaughlin *et al*., 2013) indicated that a substantial increase (20–100%) of water yield, especially in the humid regions, can be achieved by reducing plant water use (ET) by reducing LAI of traditional plantation forests by 30–50%. Our study also suggests that forest thinning by 50% can substantially increase water yield and potentially mitigate the negative drought effects or aggravate flooding impacts from future climate change. The hydrologic effects of forest thinning are most pronounced in wet and densely forested regions. Therefore, watershed management options by altering forest structure and composition can play a role in mitigating hydrologic impacts from climate change in these areas and perhaps less so in areas with less dense forest stands.

Maintaining low density forest stands through thinning and understory control not only helps to produce more water from the soil for groundwater recharge and downstream users, and increase water availability for the remaining trees, but can also have additional benefits to improve wildlife habitats and forest resilience to disturbances (insect and disease and fires) (Grant *et al*., 2013; McNulty *et al*. 2014). However, maintaining low-density forests requires active management using prescribed fires and vegetation control techniques, and thus often is cost-prohibitive for a large area. Forest biomass removal through thinning reduces evaporative loss from forests, increases soil moisture content, decreases available soil water storage, and thus can result in higher stormflow during storm events. In addition, thinning can reduce total ecosystem productivity and reduce carbon sequestration (Caldwell *et al*., 2011) and cause concerns of water quality because of soil disturbances (e.g. road building). Forest managers have to balance the tradeoffs among water quantity, quality, carbon sequestration, costs, and other benefits and concerns.

Vose *et al.* (2012b) analysed long term of streamflow data with 20–30 years from nine experimental forests across the USA to understand processes that control the interactive effects of forest management and climate on water yield. Similar to our findings, they found that there was significant variability among the research watersheds regarding water yield response to climate change and management (e.g. forest cutting, species conversion, and recovery) due to difference in soil, forest structure and composition, and climate regimes. Managed forests interacted with climate differently than the unmanaged reference forests, so that forest management may exacerbate or mitigate the effects of future climate change. For example, conversion of native deciduous forests to pine could reduce flooding impacts because of the much higher ET rates of pine stands that have a much higher leaf area and canopy interception storage. Conversely, converting to white pine (*Pinus strobus*) plantations from deciduous forests could exacerbate the drought impacts on water yield. The different responses appeared to relate to the ET processes that were controlled by biophysical processes (e.g. leaf area dynamics) and watershed sensitivity to climate as discussed in our studies.

Our modelling study also indicated that a reduction in LAI could mitigate or magnify the effect of the future climate change on water yield depending on the direction of future climate change. A reduction in LAI could mitigate the effect of climate change on water yield where precipitation is projected to decrease or magnify the effect of climate change on water yield where precipitation is projected to increase. When climate change resulted in a decrease in water yield from a decrease in precipitation and/or increase in PET, the reduction in LAI mitigated the effect of climate change on water yield. On the other hand, when climate change resulted in an increase in water yield from an increase in precipitation, the reduction in LAI magnified the effect of climate change. Therefore, our multi-scenario study extended the generally empirical results in the work of Vose *et al.* (2012b) to the CONUS and provided a quantitative evaluation at the watershed level.

However, we acknowledge that hypothetical scenarios and results derived from this modelling study must be interpreted with caution. Not all of the modelled management scenarios can be implemented at one particular forest setting in practice because of the diversity of forest ecosystems and management objectives. For example, a forest thinning practice prescribed for managing southern pine forest plantations may not be practical for the Pacific Northwest temperate rain forests. Similarly, wildfires may cause more damage (thus a larger reduction in LAI) to forests in the arid regions than to those in the humid southeastern USA resulting lower reduction in LAI. Future studies should evaluate watershed-specific or region-specific scenarios to examine how forest management practices may help to mitigate negative impacts of climate change at large scales.

CONCLUSIONS

Using a validated water balance model, this study provided a consistent, independent account of water supply by land cover types across 2100 watersheds in the USA. Forests provide disproportionately more water than other land covers because of the relatively favourable climate including high rainfall and low PET/P in forest-dominated regions. Therefore, conservation and management efforts are critical to protecting these forest lands, which are the main sources of clean water for many metropolitan areas and aquatic ecosystems.

Simulations from this study and empirical data show that water yield responses to forest management and climate change vary tremendously in the CONUS. Thus, evaluating the impacts of forest management (e.g. thinning) and climate change at a large scale requires spatially distributed models. The WaSSI model captured key hydrologic processes (e.g. ET and soil water routing) and proved to be a powerful tool to examine the spatial and temporal patterns of water yield response to environmental changes using commonly available data.

Future changes in water yield across the USA were difficult to project because of the uncertainty in the future climate for particularly the amount of precipitation. However, there was evidence that the traditionally water-rich regions of the southern USA are getting drier and the trends will continue during the next 50 years. Future studies are needed to evaluate how the water yield decline impacts ecosystem structure (i.e. leaf area change and tree species shift) and functions (water and energy balances) and the feedbacks to ET under a CO_2 enriched climate (Vose *et al*., 2012a, b).

Our study has indicated that forested watersheds in wet regions were most responsive to forest thinning in terms of total water yield gain. However, other moderately wet areas (mesic) with lower water yield could see large relative changes of streamflow such as the South Atlantic coastal plain. Forest thinning designed to reduce fuel loads and risks of severe wild fires in the dry regions has the added benefit of reducing tree water stress under climate change while augmenting watershed water yield. Mitigating climate change impacts on forest water supply, and adapting to climate change requires innovative forest watershed management approaches. Watershed restoration should focus on high priority areas identified by this study to achieve cost-effective results. Future studies need to evaluate the tradeoffs between forest thinning and other climate change mitigation and adaptation management options among all ecosystem services (e.g. clean water supply, carbon sequestration, and biodiversity).

ACKNOWLEDGEMENTS

The authors thank two anonymous reviewers for their insight that helped improve the early version of this paper. Funding is provided by the Eastern Forest Environmental Threat Assessment Center, Southern Research Station, and USDA Forest Service. Erika Mack and Jennifer Moore Myers provided technical support.

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