Simulating the hydrologic response of a semiarid watershed to switchgrass cultivation

Justin C. Goldstein, Aondover Tarhule and David Brauer

ABSTRACT

The conversion of land from existing uses to biofuel cultivation is expected to increase given concerns about the sustainability of fossil fuel supplies. Nonetheless, research into the environmental impacts of biofuel crops, primarily the hydrological impacts of their cultivation, is in its infancy. To investigate such issues, the response of a 1,649 km^2 semiarid basin to the incremental substitution of the widely discussed biofuel candidate switchgrass (*Panicum virgatum* L.) for native land uses was modeled using the Soil and Water Assessment Tool (SWAT). Median discharges decreased by 5.6–20.6% during the spring and by 6.4–31.2% during the summer, depending on the quantity of acreage converted. These were driven by an increased spring and summer evapotranspiration of 3.4–32.0% and 1.5–18.9%, respectively, depending on the quantity of switchgrass biomass produced. The substitution of switchgrass also resulted in larger quantities of water stress days than in baseline scenarios. The authors encourage the exploration of alternative biofuel crops in semiarid areas to mitigate such negative impacts.

Key words | biofuels, great plains, land use change, semiarid regions, Soil and Water Assessment Tool, switchgrass

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INTRODUCTION

Land conversion from existing uses to biofuel crops cultivation is an important form of land use change in the 21st century. According to the Renewable Fuels Association (2012), annual US corn ethanol production increased nearly nine-fold from 6 billion to 52 billion liters between 2000 and 2010, while the number of ethanol plants quadrupled from 54 to 204. Driving this increase are a number of factors including increased oil prices, US demand for greater energy independence, increased awareness and interest in renewable energy sources and the policies and mandates of the United States Government. In his 2006 State of the Union address, US President George W. Bush proposed the Advanced Energy Initiative, which called for energy from biofuels to replace greater than 75% of imported oil from the Middle East by 2025 (Bush 2006). It also called for increased Federal investment in the production of ethanol from sources other than corn, including wood chips and switchgrass, with the goal of making these alternative forms of ethanol (called cellulosic ethanol) competitive with corn-based ethanol by 2012. That call resulted ultimately in the Energy Independence and Security Act (EISA) of 2007. The goals of the EISA are to increase energy security in the USA and to increase the production of clean fossil fuels, among others, including the mandated production of 61 billion liters of cellulosic-based gasoline additives by 2022 (One-hundred Tenth Congress of the United States of America 2007).

The Ecological Society of America defines biofuels as 'liquid fuels derived from biological materials' (e.g. Mitchell *et al.* 2010; Robertson *et al.* 2010). Common sources of biofuel crops include corn (*Zea mays* L.), switchgrass (*Panicum virgatum* L.), soybeans (*Glycine max* L.), sweetgum (*Liquidamber styraciflua* L.), rapeseed (*Brassica napus L. rape*), sugarcane (*Saccharum officinarum* L.), palm oil (*Elaeis guineensis*), and jatropha (*Jatropha curcus*). Resultant fuels include ethanol (the most

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common), methanol, propanol, butanol, methane, and biodiesel.

Native to the tallgrass prairies and a wide range of mesic environments in the eastern two-thirds of the United States, the warm season perennial switchgrass (Parrish & Fike 2005) has received much attention as a possible cellulosic biofuel source because of its perceived advantages over other biofuel crops. In their review paper, Simpson *et al.* (2008) concluded that, compared to corn, switchgrass facilitates improved nutrient retention and carbon sequestration in soils, it has the ability to grow on marginal soils and it needs replacement only once every 20 years. Also, it has been projected that switchgrass-based ethanol reduces the emission of greenhouse gases by 94% relative to those emitted by traditional gasoline (Schmer *et al.* 2008).

As with any other major land use modification, biofuel production is expected to have major (but not yet fully understood) impacts on regional hydrology. Acknowledging this point, the National Research Council (2008, p. vii) refers to the hydrology of biofuel production as an 'emerging field' of scientific inquiry. Similarly, Georgescu & Lobell (2010, p. 33) noted 'changes to local hydrology caused by large-scale perennial systems may be complex, and thus require careful evaluation'.

Two other factors related to climate change and sustainability also make such evaluation imperative. A number of authors (e.g. Sala *et al.* 2000; Vorosmarty *et al.* 2000; Foley *et al.* 2005; Turner II *et al.* 2007; Wagener *et al.* 2010) have noted that land use change dwarfs or is at least of comparable magnitude to the much more widely publicized topic of climate change, both as a driver and as an impact of future global environmental change.

With specific respect to water resources, Ren *et al.* (2012) and Jiang *et al.* (2012) found that both climate change and anthropogenic activities including reservoir construction and irrigation are responsible for changes in streamflow in China's Laohahae Basin during the late 20th and early 21st century, although the relative contribution of each varies by a decade.

In their study of the Shaumalun Basin in China, Yang *et al.* (2012) found a decline in annual runoff post-1998 far in excess of what could be attributed to changes in basin precipitation. The authors concluded that the unexplained difference was likely due to land use changes, including deforestation and urbanization.

Ma *et al.* (2009) investigated the impacts of climate and land use change in the Kejie watershed in China during 1965–2005. They found that the hydrologic effects of climate change were offset by land use changes and that, while seasonal changes in streamflow were mostly a function of precipitation, mean annual changes in streamflow were largely influenced by land use change. Overall, they found that surface hydrology was more impacted by land use change than climate.

Franczyk & Chang (2009) assessed the impacts of climate change and future urbanization on the hydrology of the Rock Creek Basin, Oregon, USA, through the 2040s. They found that climate change and urbanization combine to amplify the magnitudes of the volumes of mean annual runoff and evapotranspiration (eT) relative to those in the absence of one of those factors.

Du *et al.* (2012) found that the impacts of urbanization on mean annual runoff are a function of the magnitude of precipitation; in their investigation of the Qinhuai River watershed in China, they found that annual runoff in dry years increases more than in wet years given a 10-fold increase in the area of impervious surfaces. Additionally, Raymond *et al.* (2008) and Schilling *et al.* (2010) attributed the increased in discharges in the Mississippi River Basin to agricultural production, and explicitly discounted the role of climate.

With specific respect to regional hydrology, a number of studies have reported significant stream depletion due to groundwater mining associated with agricultural expansion (e.g. Reisner 1993; Glennon 2009; Kustu *et al.* 2010; McGuire 2011; Scanlon *et al.* 2012). These findings underscore a critical need to unbundle and quantify the relative contributions of specific land use changes, especially in semiarid areas such as the US Great Plains where the issue of the sustainability of scarce water supplies is of paramount importance (see below). This study is a contribution toward that goal.

With regard to the sustainability of biofuel hydrology, the myriad of factors comprising the hydrologic impacts of biofuel production may be grouped into three broad categories, namely: the water footprint (WF) defined as 'the total annual volume of fresh water used to produce goods and services for consumption' (see e.g. Gerbens-Leenes *et al.* (2009), pp. 10219); water quality (e.g. Nyakatawa *et al.* 2006; Simpson *et al.* 2008; Chamberlain *et al.* 2011; Sarkar *et al.* 2011); and impacts on the local or regional water balance. This paper focuses on the third category. Specifically, we investigate the impact of switchgrass production on local-scale changes in constituent components of the water balance, including runoff and eT.

A number of studies have investigated the impact of the planting of different biofuel crops on local water *balances* (e.g. Schilling *et al.* 2008; Thomas *et al.* 2009). These studies suggest that increased biofuel crop cultivation can significantly alter local water balances through altering local eT and discharge rates, although the results are mixed due to variations in crop management (i.e. till, no till, etc.), climate and topography. Generally, switchgrass and the biofuel-grass miscanthus (*Miscanthus* × *giganteus*) have been shown to increase soil moisture retention and to reduce the volumes of river discharge relative to other crops.

For example, Schilling *et al.* (2008) simulated the impact of various land use scenarios involving combinations of biofuel crops in the Raccoon watershed in Iowa, USA, on the water balance using the Soil Water and Assessment Tool (SWAT). They devised nine scenarios, ranging from an expansion of corn acreage to cover solely United States Department of Agriculture (USDA) lands to those in which switchgrass became the dominant biofuel crop and, finally, those in which cool season biofuel crops (i.e. fescue) dominated. They found that the conversion of grassland to corn decreases mean annual eT by 1% and increases mean annual runoff by nearly 8%, but the conversion of cropland to warm season biofuel crops (switchgrass) increases mean annual eT by 2.6% and decreases mean annual runoff by 17%.

On the other hand, Thomas *et al.* (2009) suggested that planting corn on an annual basis increases eT. In an investigation using SWAT in a watershed in Eastern Kansas, United States, Nelson *et al.* (2006) modeled the percent reduction in surface runoff when the planting of switchgrass replaced the planting of traditional crop rotations, including corn-soybean, corn-soybean-wheat, grain sorghum-soybean, and grain sorghum-soybean-wheat. They found that the planting of switchgrass reduced surface runoff by 55% over a 24-year period relative to baseline. Graham *et al.* (1996) modeled the hydrologic impact of replacing plots of soybeans, wheat and cotton with switchgrass in the vicinities of the cities of Nashville and Memphis (Tennessee, USA) using the Environmental Policy Integrated Climate (EPIC) model. They found that replacing such crops with switchgrass would result in lower runoff, erosion, eT and phosphorus loss. Specifically, replacing soybeans with switchgrass reduced eT by 20–60% and phosphorus by 80–95%. Additionally, replacing corn with switchgrass reduced eT by up to 10–50% and phosphorus loss by 80–95%. Finally, replacing wheat with switchgrass reduced eT by 15–40% and phosphorus loss by approximately 90%.

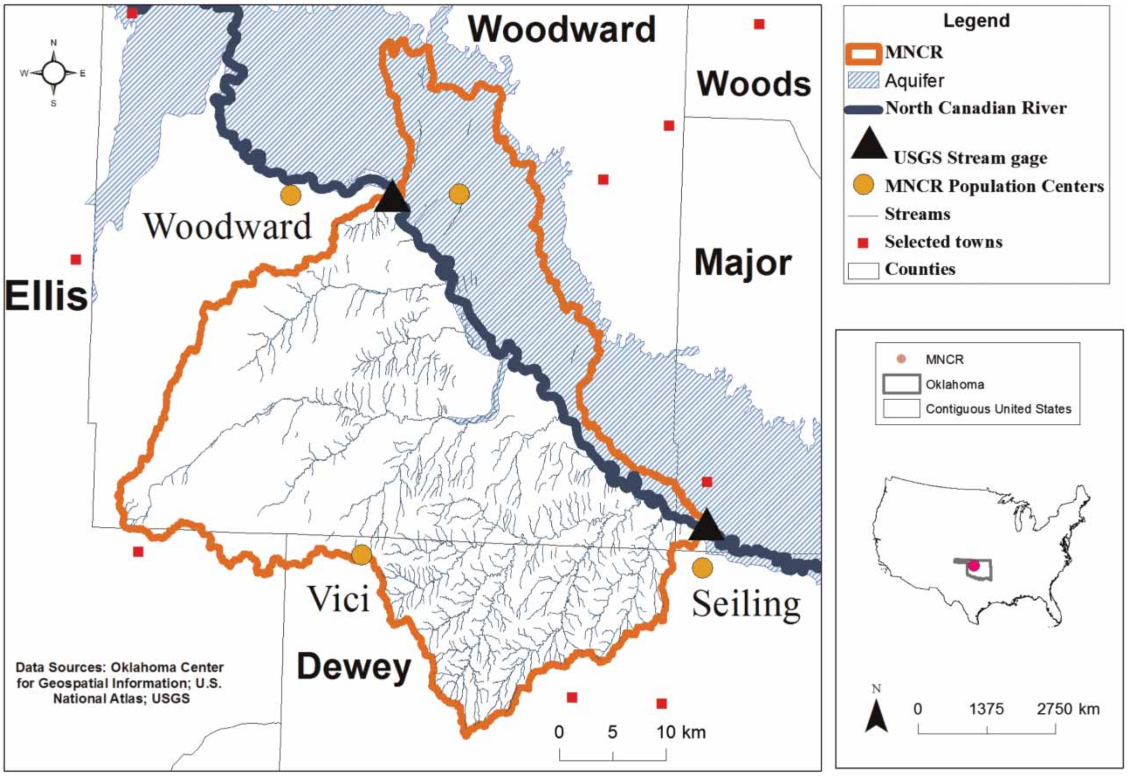
Vanlocke *et al.* (2010) investigated the hypothetical impact on regional water balance of planting increasing proportions (i.e. 10% of area, 25, 50, 75, and 100%) of miscanthus in the Upper Midwest of the USA. By simulating the different land cover configurations using the Integrated Biosphere Simulator – Agricultural Version, the authors found that the planting of miscanthus significantly increased eT and decreased discharge relative to its predecessor land cover type. In yet another experimental study, McIsaac *et al.* (2010) found that late-season soil moisture under switchgrass plots exceeded that of miscanthus and maize-soybean because of the higher transpiration levels of miscanthus and maize-soybean relative to switchgrass (due to higher leaf-area indices and biomass) throughout much of the growing season. Estimated eT from miscanthus exceeded that of switchgrass by 140 mm and that of maize-soybean by 104 mm.

In addition to differences in management practices, impacts of biofuel cultivation have been shown to be region specific as a result of differences in climatic conditions (e.g. Garoma *et al.* 2012). For example, soybeans and cotton require more water than corn when planted in the Pacific and Mountain regions of the USA, but the opposite is true in the semiarid Great Plains (National Research Council 2008). These differences, and sometimes contradictory results, point to a need for more studies investigating the impacts of biofuel production generally in different regions and bioclimatic environments. This study contributes to that goal.

STUDY AREA

The study area is part of the Middle North Canadian River (MNCR) watershed located in Western Oklahoma, USA. It covers approximately 1,649 km^2 within the US Geological Survey (USGS) Hydrologic Unit Code 11100301 (Figure 1). The headwaters of the basin are located at 36°26′12″ N, 99°16′41″ W and the watershed outlet is situated at 36°11′00″ N, 98°55′15″ W. Because of its predominantly agricultural character, the MNCR could be considered representative of other basins in the semiarid US Great Plains. Largely rural, the largest settlements in the MNCR are Mooreland (population 1190), Seiling (population 860), and Vici (population 699). Elevation varies from 762 m at the headwaters to 512 m at its outlet, a distance of approximately 53 km. For the period 1980–2010, average annual precipitation was 666 mm with precipitation peaking during May and June (PRISM Climate Group 2012). Average daily temperatures range from 1 °C during January to 27 °C during July and August. Like other portions of the Great Plains, the study area is drought prone and suffers from water shortages associated with evaporative losses (Zume & Tarhule 2006, 2011).

The MNCR overlies two geological provinces: the Western Sand-Dune Belts and the Western Sandstone Hills (Goins & Anderson 2006). The sand dune belts, which were blown from Quaternary alluvium and terrace deposits, are found on the north side of the North Canadian River and are oriented southeast. These deposits create the Alluvium and Terrace aquifer of the Beaver/North Canadian River (BNCR A&T), which originates upstream of the MNCR and ends at Lake Eufaula, 290 km downstream from the MNCR. This aquifer serves as an important water source for irrigation and public water supplies in this region. The Quaternary deposits vary in thickness; the alluvium deposits average 10 m in thickness while the high terrace deposits average 21 m in thickness. The terrace and alluvium deposits are the main water-bearing portions of the aquifer, and it is believed that these deposits are hydraulically continuous and comprise a single aquifer system. These deposits contain poorly sorted sand and minor portions of gravel, silt and clay



Data Sources: Oklahoma Center for Geospatial Information; U.S. National Atlas; USGS

Figure 1 | Location of the Middle North Canadian River Basin (MNCR), located within the US state of Oklahoma.

(Davis & Christenson 1981). It is believed that the base of the aquifer coincides with the relatively impermeable Permian Red Beds Formation (Zume & Tarhule 2008).

The depth to bedrock at the BNCR A&T varies spatially up to a maximum of 100 m, although it does outcrop at a few locations outside of the MNCR. Hydraulic conductivity values vary over the range 18–24 m d^{-1} (Davis & Christenson 1981; Adams *et al.* 1997), with specific yield around 0.28 (Zume & Tarhule 2008) and transmissivity values within the range 0–749 $m^2 d^{-1}$ (Davis & Christenson 1981). Recharge is 1.39×10^{-4} m d^{-1} (Zume & Tarhule 2008), or approximately 7% of mean annual precipitation.

The vegetation of the watershed is dominated by non-irrigated native range grasses and winter wheat, which is fertilized and irrigated. Grasses include buffalo grass, big and little bluestem, sideoats grama and blue grama. Winter wheat is planted during the middle of September and is harvested in the middle of June of the following summer. Most of the irrigation originates from the BNCR A&T.

Heavy groundwater pumping for irrigation since 1970 in portions of the North Canadian River watershed upstream of the MNCR has contributed to decreases in the medians of the peak annual streamflow values of about 40% in the MNCR (see Wahl & Tortorelli 1997). The two largest uses of BNCR A&T water are irrigation and municipal use (Tortorelli 2009). More groundwater is used from BNCR A&T for municipal use than in any other aquifer in Oklahoma, and 50–89% of the total withdrawals in the study area counties are BNCR A&T water. The MNCR lacks large impoundments although several small reservoirs exist.

MODEL DESCRIPTION AND METHODS

The response of the MNCR to the substitution of native land uses with switchgrass was investigated using SWAT, a physics-based semi-distributed hydrologic model (Arnold *et al.* 1998). Developed by the US Department of Agriculture in Temple, Texas, SWAT has been employed in over 600 published studies (Gassman *et al.* 2007; Douglas-Mankin *et al.* 2010), including many investigations of the impacts of crop substitution (e.g. Schilling *et al.* 2008; Baskaran *et al.* 2010; Ng *et al.* 2010). The model, along with associated documentation and related software, is available free of charge from the Texas A&M AgriLife Research Center (http://swatmodel.tamu.edu). It has been applied to a variety of water resource issues in a large range of locations and spatial scales from 0.004 to 491,665 km^2 (Gassman *et al.* 2007; Douglas-Mankin *et al.* 2010). SWAT divides a watershed into smaller user-defined sub-basins, and then into still smaller hydrologic research units (HRUs) which are areas of homogeneous land use, soil and slope based on user-provided information. The model operates on a water-balance principle on a daily time-step.

A key convenience of SWAT is that it is linked to various databases containing the data and information required for simulation, greatly simplifying model set-up and operation. The crop database contains alterable biophysical information (e.g. extinction coefficient, leaf area index) for 108 crops, including many biofuels, such as Alamo Switchgrass, corn, oil palm, sugarcane, grain sorghum and soybeans. The sources for the input data used in this investigation are listed in Table 1.

The MNCR was delineated in SWAT using a 30 m digital elevation model (DEM) and by the subsequent 'burning in' of the National Hydrography Dataset Plus dataset. Thirteen sub-basins were delineated. To reduce the quantity of HRUs to a manageable number without sacrificing model accuracy, a threshold of 3% land use, 10% soil and 0% slope for each sub-basin was used. In other words, land

Table 1 | Data sources for items used in investigation

Data for simulation	Source
Elevation: 30 m DEM	USGS
Groundwater: values for effective hydraulic conductivity	Zume & Tarhule (2008)
Land use: 56 m Crop Dataset Layer (CDL) 2006–2009	National Agriculture Statistics Service
Management: Planting, irrigation, and fertilization schedules	Agriculture extension agents
Soil: 1:15,000 scale Soil Survey Geographic (SSURGO) dataset	Natural Resources Conservation Service (NRCS)
Weather: Daily temperature and precipitation data	National Climatic Data Center

use types were retained if they covered greater than 3% of the sub-basin; otherwise they were incorporated into other HRUs. This led to the retention of 529 HRUs. The land use composition of the watershed post-threshold delineation is displayed in Table 2.

Driven primarily by the availability of streamflow data for calibration, SWAT was run for the period 1977–2009 with 1977–1979 as the initialization period, 1980–1994 as the calibration period and 1995–2009 as the simulation period. Following calibration, simulations of switchgrass replacement were conducted to quantify the response of the MNCR, specifically discharge (*Q*) and eT, to the cultivation of switchgrass during the spring and summer seasons which were the seasons with the best calibration results. The replacement scenarios are the following:

1. nowwht: replacement of winter wheat with non-fertilized Alamo switchgrass (12.3% of the MNCR).
2. nornge: replacement of range grasses with nonfertilized alamo switchgrass (74.5% of the MNCR).
3. noag: replacement of agricultural land uses (range grass and winter wheat) with non-fertilized alamo switchgrass (86.8% of the MNCR).
4. fert: similar to 'noag', except switchgrass is managed as follows: (a) fertilize April 15 (56 kg ha^{-1} N); (b) harvest May 15 (90% efficiency), July 15, November 1; and (c) fertilize (56 kg ha^{-1} N) May 17, July 17.

Switchgrass production was simulated using the default biophysical settings for Alamo switchgrass provided in the SWAT crop database with 1,187 heat units for growth and with increased rooting depth from 2 to 3 m (Baskaran *et al.* 2010).

Table 2 | Land use composition (%) of the MNCR post-land use threshold delineation

Land use	% of watershed
Native range grasses	74.59
Winter wheat	12.30
Low-density development	5.90
Evergreen forest	4.03
Shrubland	3.18

RESULTS

Calibration

The result of the calibration on total monthly discharge (in cubic meters per second or cms) at the watershed outlet is depicted in Figure 2(a). The simulated model reproduces the observed discharges reasonably well without evidence of systematic under- or overestimation. The Nash–Sutcliffe Efficiency (NSE, Nash & Sutcliffe 1970) estimate is 0.86, well above the 0.75 threshold generally regarded as indicative of a 'very good' simulation (Moriasi *et al.* 2007). The calculated percent bias (PBIAS; Gupta *et al.* 1999) estimate is 3.87% (values less than 10% are considered 'very good'). Finally, the calibration fit was evaluated using the root mean square error (RMSE) observations standard deviation ratio (RSR), a measure of the ratio of the normalized sum of squares to the standard deviation of the observed values (Singh *et al.* 2004). The RSR estimate is 0.38 (values below 0.5 are considered 'very good'; Moriasi *et al.* 2007). The simulation therefore performed satisfactorily on all three commonly used evaluation criteria.

Sensitivity analysis (van Griensven *et al.* 2006) was performed on 26 parameters, using observed data. The results showed that the curve number for soil moisture condition II ('average' moisture) was the most sensitive parameter, followed by maximum vegetation canopy storage and Manning's roughness coefficient (Table 3). A list of the curve numbers for the various land use classes in the calibration simulation is provided by Table 4. However, further fine tuning was deemed unnecessary given the low values of the sensitivity indices as well as the excellent calibration agreement already achieved.

Accordingly, the model was used to simulate total monthly discharge for the simulation period of 1995–2009 (Figure 2(b)). The results are likewise satisfactory with NSE of 0.80, PBIAS at 0.53 and RSR of 0.45.

Next, the model performance at seasonal timescale (i.e. winter: December, January, February; spring: March, April, May; summer: June, July, August, and fall: September, October, November) was evaluated for the calibration and simulation periods. The results are listed in Table 5. The statistics for winter during the calibration and

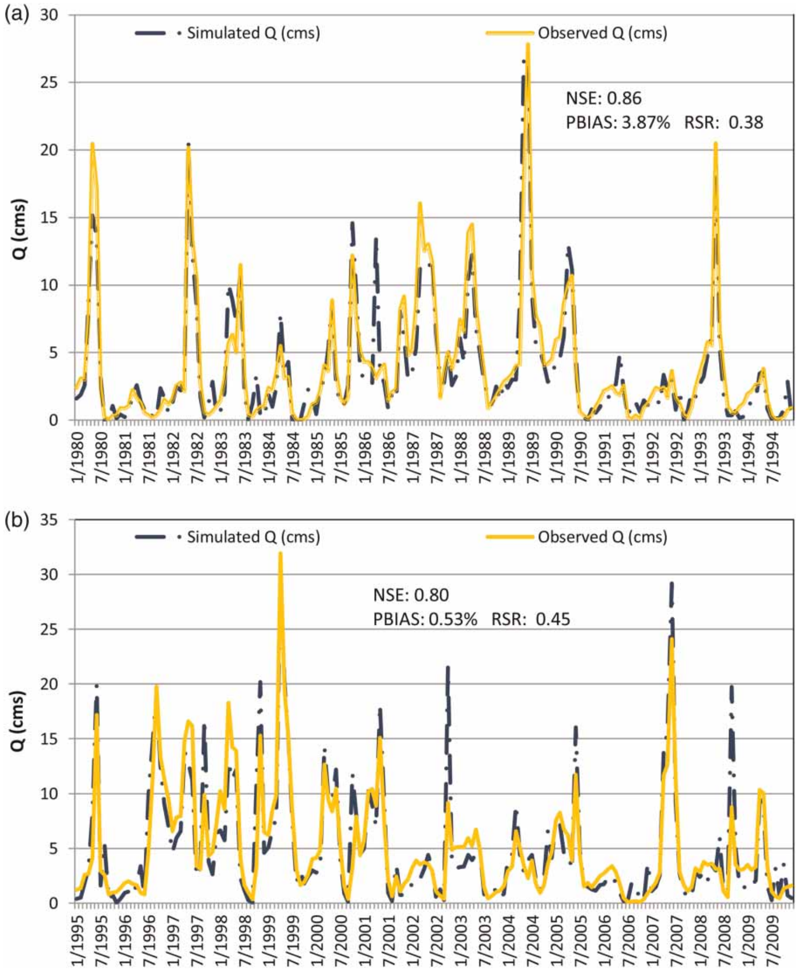


Figure 2 | Plot of simulated and observed monthly discharges at the watershed outlet during (a) the calibration period and (b) the simulation period.

simulation periods were problematic due to relatively low NSE values and unsatisfactorily high PBIAS values (>25%, which is the threshold for satisfactorily monthly values according to Moriasi *et al.* 2007). Subsequent analysis was therefore confined to the spring and summer seasons. Figures 3(a), (b) and 4(a), (b) depict plots of the simulated and observed spring and summer discharges during the calibration and simulation periods, respectively.

Spring and summer discharge

The changes in hydrology discussed below are driven solely by the impacts of land use change, as climatic parameters were not adjusted during the simulations. The results of four switchgrass substitution simulation scenarios for the spring and summer appear in Figure 5(a), (b). All four scenarios result in decreased discharges relative to baseline. Such decreases are consistent with the findings of Nelson *et al.* (2006) and Schilling *et al.* (2008), both of whom found decreased discharges when replacing pre-existing cropland with warm-season grasses. As may be expected, the magnitude of the decreased discharges is a function of the area converted to switchgrass, a finding which also echoes that of Schilling *et al.* (2008).

On the one hand, the magnitude of the reduction in median spring discharge for all scenarios is directly proportional to seasonal precipitation in Oklahoma Climate Division 2, in which the majority of the MNCR is situated (Figure 6(a)–(d)). All relationships are statistically significant

Table 3 | Sensitivity index rankings for the MNCR (10 most sensitive shown, in order of decreasing sensitivity)

Sensitivity ranking	Parameter	Description	Initial value	Range tested (max, min)	Sensitivity index
1	CN2	Curve number for soil condition II	Default	−10%, 10%[b]	0.199
2	Canmx	Maximum canopy storage (mm H_2O)	0	0, 10	0.112
3	Ch_N2	Manning's *n* value for the main channel	Varies within range tested	0.035, 0.11	0.0909
4	Alpha_bf	Baseflow recession factor (days)	0.75	0, 1	0.0816
5	Blai	Maximum potential leaf area index	Default	0, 1	0.0308
6	Surlag	Surface runoff lag coefficient (days)	Default	1, 24	0.0261
7	Sol_Z	Depth from soil surface to bottom of soil layer (mm)	Default	−4%, 4%[b]	0.0205
8	Esco	Soil evaporation compensation factor	0.7	0.65, 0.80	0.0166
9	Ch_K2[a]	Effective hydraulic conductivity in main channel alluvium (mm hr^{-1})	6.4–7	3, 20	0.0141
10	Sol_Awc	Available water capacity of the soil layer (mm)	Default	−4%, 4%[b]	0.0113

[a] Only applied to sub-basins with intermittent or ephemeral main channels. Values based on those reported by Zume & Tarhule (2008).
[b] Initial value multiplied by values in range.

Table 4 | CNs for crops in this investigation, by National Resources Conservation Service Hydrologic Soil Group (Soil Group A: lowest runoff potential; Soil Group D: highest runoff potential). *Source:* SWAT crop database

Crop	Soil Group A	Soil Group B	Soil Group C	Soil Group D
Winter wheat	62	73	81	84
Native range grasses	45	66	77	83
Shrubland	39	61	74	80
Low-density development	31	59	72	79
Alamo switchgrass[a]	31	59	72	79
Evergreen forest	25	55	70	77

[a] Not included in calibration simulation.

Table 5 | Effectiveness of calibration during the calibration and simulation periods. Thresholds for satisfactory calibration on the monthly timescale for NSE, PBIAS and RSR are 0.50, +/− 25% and 0.75, respectively (Moriasi *et al.* 2007).

Criterion	Winter	Spring	Summer	Fall
	Calibration period			
NSE	0.64	0.76	0.97	0.87
PBIAS (%)	29.34	−6.00	−9.90	−14.39
RSR	0.60	0.49	0.18	0.36
	Simulation period			
NSE	0.61	0.93	0.88	0.69
PBIAS (%)	25.17	6.75	−8.23	−29.63
RSR	0.62	0.27	0.35	0.56

($p < 0.05$). We hypothesize that higher rainfall results in greater switchgrass biomass accumulation, which then results in higher evaporative losses and therefore less water for discharge. Notice that the relationship is relatively weak for the 'nowwht' scenario. This may be explained by the fact that winter wheat relies more heavily on fertilizer applications, and less on precipitation, for growth. On the other hand, no statistically significant correlations exist between the magnitude of reduction in summer discharge and summer precipitation, implying that depletions in summer discharge are not a function of precipitation, explained below.

Spring and summer eT

The reductions in spring and summer discharge are driven by sizeable, statistically significant ($p < 0.05$) increases in eT (Figure 7(a), (b)). Median increases during the spring vary from 4.3 mm ('nowwht' scenario) to 46.0 mm ('fert' scenario) and from 2.2 mm ('nowwht' scenario) to 24.0 mm ('fert' scenario) during the summer. These increases appear not to be functions of land area converted, but of the quantity of switchgrass biomass produced (Figure 8). This is evident from the disparate eT values under the 'noag' and 'fert' scenarios, despite these scenarios converting an identical acreage of switchgrass.

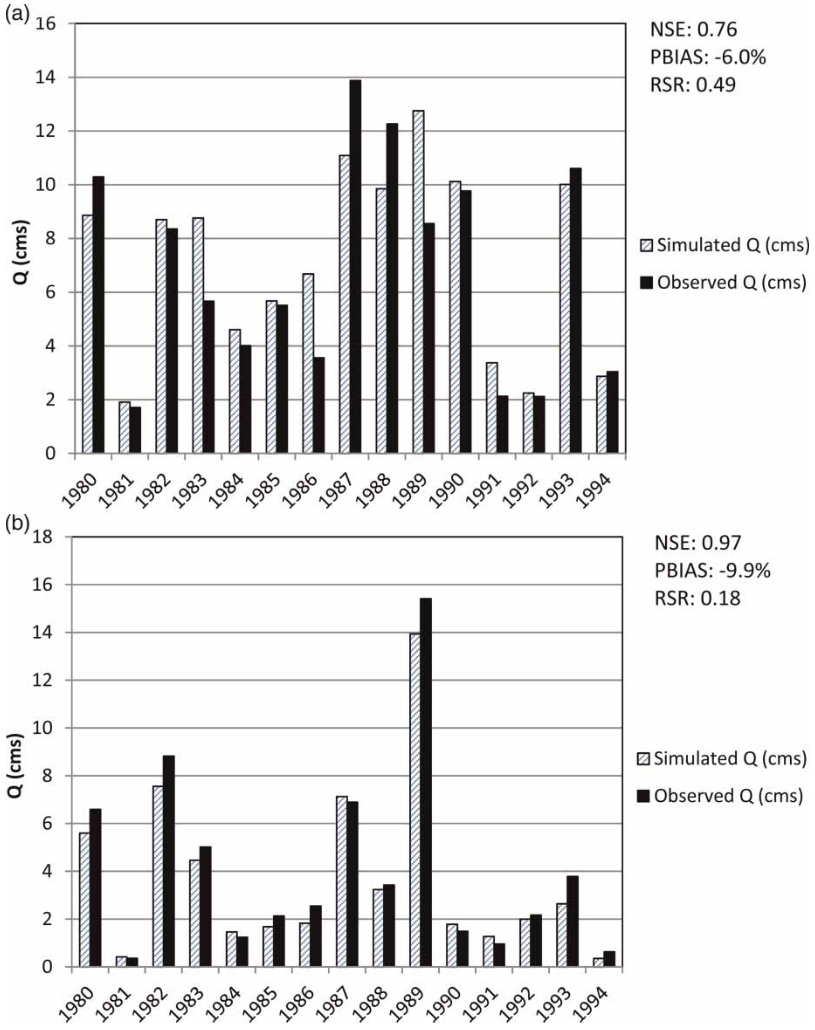


Figure 3 | Calibration of seasonal discharges at the watershed outlet for (a) spring and (b) summer.

It is evident that summer eT is greatly limited by available moisture, as the increases in spring eT exceed those of the summer by a factor of 1.3–2.3 despite higher summer temperatures relative to spring (Figure 7(a), (b)). Higher water stress during the summer is evident in the higher ratio of summer eT to rainfall (0.632) relative to that during the spring (0.536). These results are consistent with those reported by Lakshmi *et al.* (2011) for an area situated just north of the MNCR. Additionally, the number of summer water stress days increases under all scenarios relative to baseline, resulting in an almost 300% increase under the 'fert' scenario in which the most switchgrass biomass is produced (Table 6). Under the 'fert' scenario, 48% of all summer days are water stressed. The increase in water stress days also explains the lack of a statistically significant relationship between precipitation and change in discharge (see above), as most of the MNCR's summer moisture supply is exhausted by the high evaporative demands. Additionally, the statistical relationship between the change in eT (mm) and the change in discharge (cms) during the simulation years is stronger during spring months than in summer, which indicates a lack of requisite moisture during the latter period (Table 7). Simply stated, the increase in summer eT associated with switchgrass production increases the quantity of summer water stress days in the MNCR.

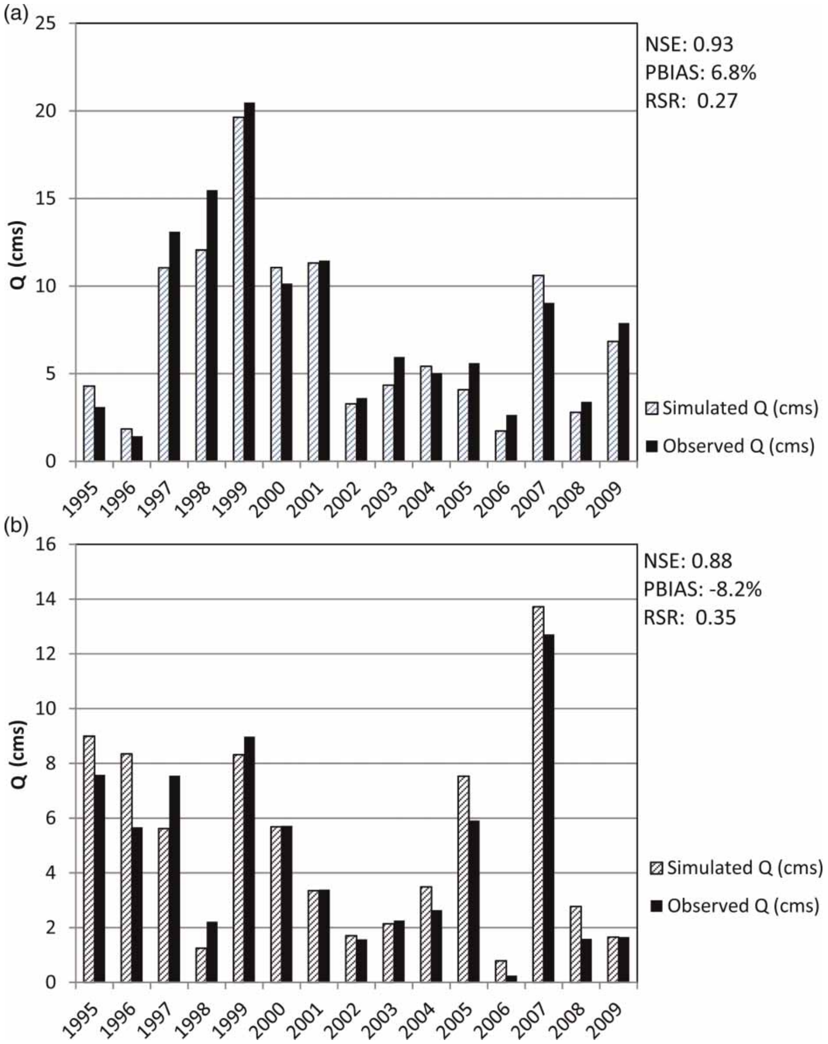


Figure 4 | Comparison of observed and predicted discharges at the watershed outlet for (a) spring and (b) summer during the simulation period.

Table 7 indicates that moderately strong, statistically significant ($p < 0.05$) relationships exist between changes in eT and changes in discharge during all seasons and scenarios except for 'nowwht'. We therefore conclude that changes in discharge in the MNCR are driven by eT except in this scenario, which may be driven by the application of spring fertilizer with the subsequent increase in the growth of winter wheat. Ignoring the 'nowwht' scenario, it is also noteworthy that the coefficient of determination for this relationship decreases with the volume of switchgrass production. This is further evidence of the occurrence of water stress mentioned above, as only so much moisture is available to be lost by eT.

CONCLUSIONS

The current interest in biofuel crops is likely to lead to major land use changes in some watersheds with major impacts on regional hydrology. However, due to the still-evolving nature of so-called biofuel hydrology, the dynamics and magnitudes of the possible hydrologic responses in different bioclimatic zones, as well as management practices, are not yet fully understood. Efforts toward achieving that understanding have tended to adopt a modeling approach because of the complexity and futuristic nature of the processes involved. Even though one of the largest experimental switchgrass plots is located in Guymon, Oklahoma, USA, in the

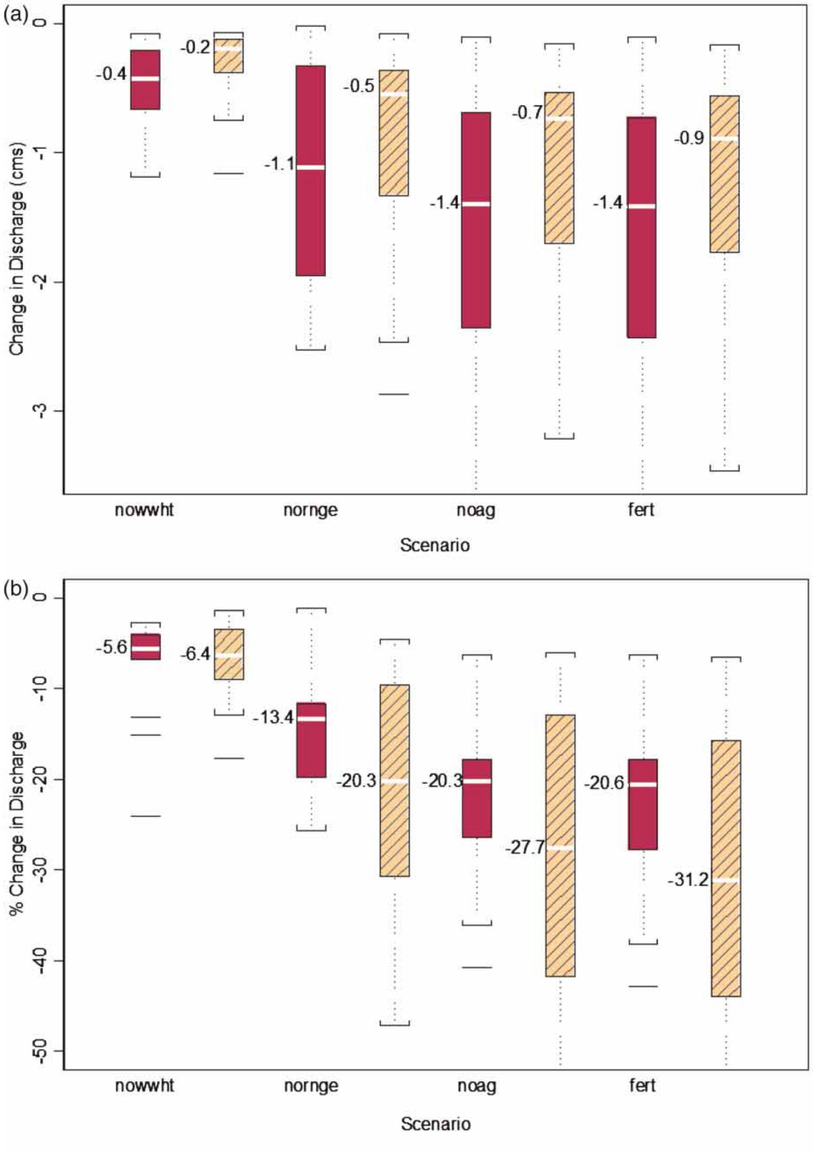


Figure 5 | Differences in (a) spring (solid) and summer (striped) discharge associated with switchgrass production and (b) the percent change in spring and summer discharge relative to baseline in all scenarios during the simulation period 1995–2009. The value of the median change is located to the left of each box. The proportion of the watershed converted in each scenario is shown as a percentage in brackets underneath the *x*-axis label. The boxplots are read as follows. The dots comprise the observations. The top and bottom of each box comprise the 75th and 25th percentiles, respectively, of the observations. The lengths of the boxes comprise the interquartile range (IQR), or the difference between the 75th and 25th percentiles. The white lines inside the boxes represent the median observations. The upper inner fence (downward-facing square bracket) categorizes 1.5 IQR above the 75th percentile observation, and the lower inner fence (upward-facing square bracket) categorizes 1.5 IQR beneath the 25th percentile observation. The upper outer and inner fences, represented by horizontal lines above and below the brackets, where applicable, identify 3 IQR above the 75th percentile observation and 3 IQR below the 25th percentile observation, respectively.

shortgrass prairies, few studies have investigated the hydrologic response to switchgrass cultivation in a semiarid environment. This study was carried out to help fill that gap and to contribute to the emerging literature on the possible environmental effects of biofuel production in various regions.

A SWAT model of the 1,649 km^2 MNCR watershed was developed. Model calibration resulted in excellent agreement between total simulated and observed discharges on three widely used model performance evaluation metrics (i.e. the NSE, PBIAS and RSR). At a seasonal scale, the evaluation yielded satisfactory simulations for the spring

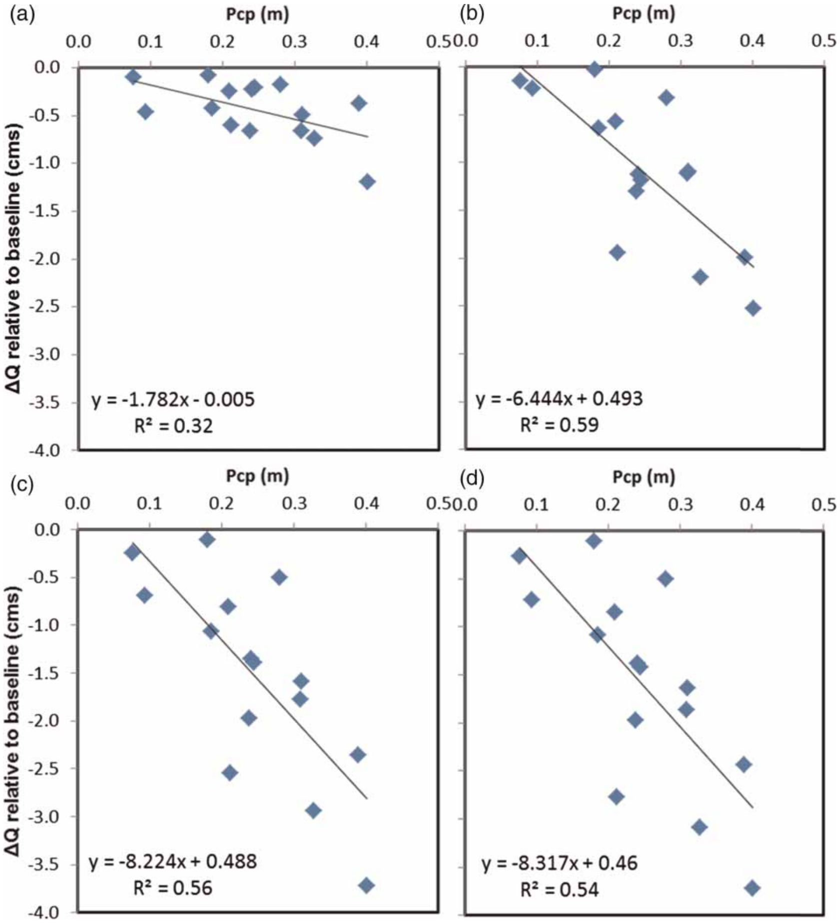


Figure 6 | Relationship between change in spring discharge relative to baseline and precipitation, 1995–2009 in the (a) nowwht, (b) nornge, (c) noag and (d) fert scenarios.

and summer seasons only. These seasons were therefore used to explore the hydrologic impacts of replacing various current land use types with switchgrass under different management practices. The major findings of the study are as follows.

1. Replacing any land use type with switchgrass reduces streamflow discharge. The decreases ranged from 6 to 21% (spring) and from 6 to 31% (summer). Overall, the reduction was greatest for the scenario in which native land uses were replaced by heavily managed switchgrass. The degree of the reduction is a function of the amount of area replaced.
2. Switchgrass substitution also leads to increased eT relative to base period for all scenarios investigated. The increases ranged from 3 to 32% (spring) and 2 to 19% (summer). The scenario involving heavily managed switchgrass produced the largest increase in eT. Since climactic inputs are identical in all scenarios, we hypothesize that increased eT is most likely the result of the quantity of switchgrass biomass generated.
3. The summer impacts of managed switchgrass scenario are the most acute in the MNCR. This approach is responsible for a 31% decrease in discharge and 19% increase in eT. Such impacts are significant in semiarid areas where evaporative losses are already high and discharges are relatively low (baseline discharges of 7.4 and 5.03 cms during the spring and summer, respectively, in the MNCR).

These results suggest that the hydrologic impacts of switchgrass cultivation may be non-trivial. The possible effects of such impacts on the sustainability of the water supplies in a groundwater-dependent region already facing

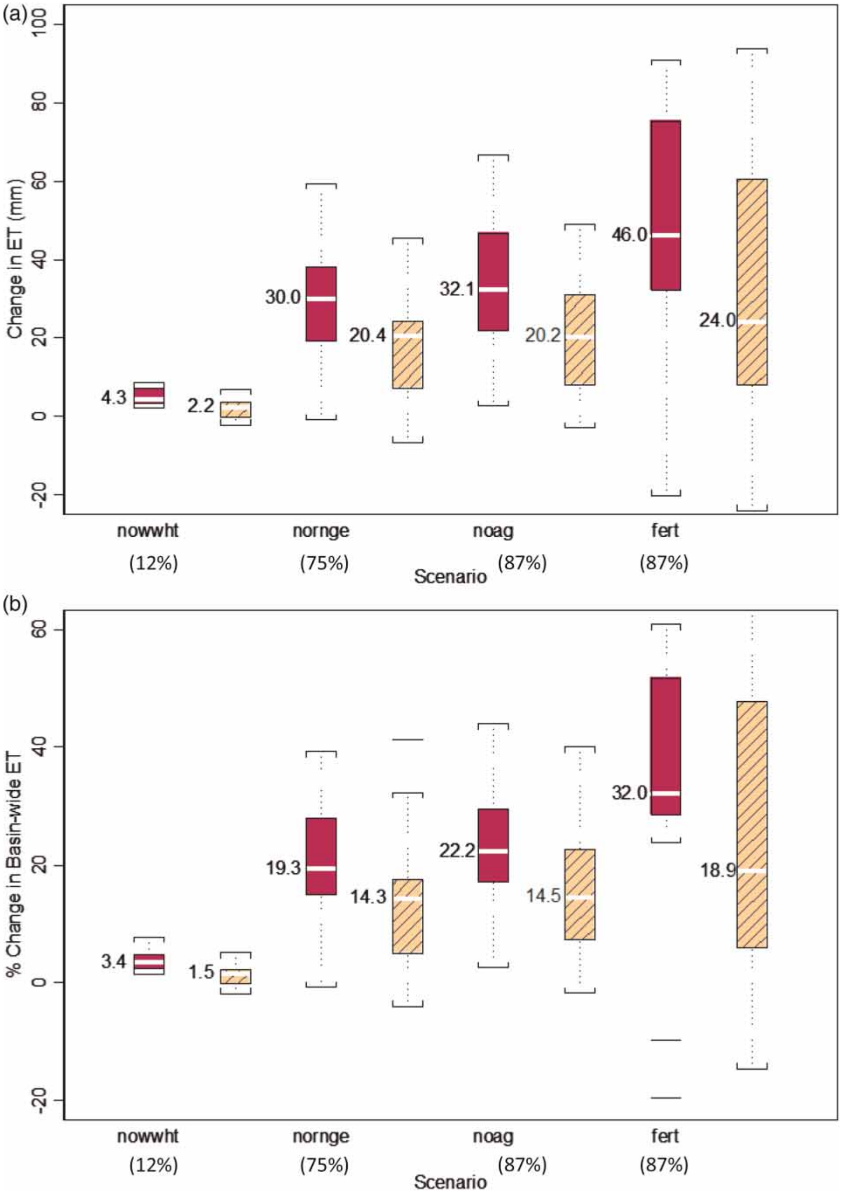


Figure 7 | Differences in basin-wide (a) spring (solid) and summer (striped) eT associated with switchgrass production and (b) the percent change in spring and summer eT relative to baseline in all scenarios during the simulation period, 1995–2009. The boxplots are read as for Figure 5.

the effects of groundwater depletion deserve careful consideration. We recognize that any decision about land use modification on the scale analyzed here will likely involve a cost-benefit analysis that includes many more variables than just the regional hydrology. These results can be an important component of such a decision matrix. The study highlights the need for further simulations that include a larger variety of biofuel crops, an analysis of all seasons, as well as investigations into the possible confounding effects of the impact of climate change.

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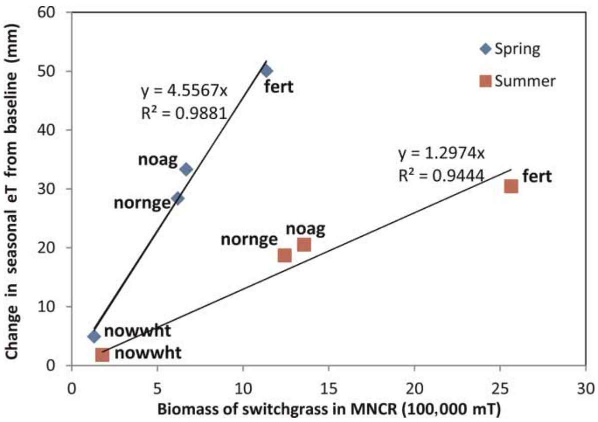

Figure 8 | Relationship between the change in seasonal eT in the four switchgrass scenarios relative to baseline, and the quantity of switchgrass biomass (in 100,000 metric tons) during the spring and summer.

Table 6 | Average quantity of spring and summer water stress days, by scenario, 1995–2009

Scenario	Spring	Summer
Baseline	5.74	11.02
Nowwht	5.57	13.23[a]
Nornge	7.32[a]	16.05[a]
Noag	7.15[a]	18.26[a]
Fert	13.03[a]	43.33[a]

[a] Quantities are statistically significant ($p < 0.05$) relative to baseline.

Table 7 | The strength of the relationship between changes in eT (mm) and discharge (cms) in each scenario by season, as measured by R^2 and p-values

Scenario	R^2	p-value
	Spring	
Nowwht	0.11	0.232
Nornge	0.81	5.2×10^{-6}
Noag	0.64	0.003
Fert	0.59	0.0008
	Summer	
Nowwht	0.01	0.77
Nornge	0.50	3.36×10^{-3}
Noag	0.47	0.0047
Fert	0.48	0.004

REFERENCES

Adams, G. P., Runkle, D. L. & Rea, A. 1997 Digital data sets that describe aquifer characteristics of the alluvial and terrace deposits along the Beaver-North Canadian River from the Panhandle to Canton Lake in Northwestern Oklahoma. Open-File Report 96–446. US Geological Survey, Oklahoma City, USA.

Arnold, J. G., Srinivasan, R., Muttiah, R. S. & Williams, J. R. 1998 Large area hydrologic modeling and assessment. Part 1: Model development. *Journal of American Water Resources Association* **34**, 73–89.

Baskaran, L., Jager, H. I., Schweizer, P. E. & Srinivasan, R. 2010 Progress towards evaluating the sustainability of switchgrass as a bioenergy crop using the SWAT model. *Transactions of the ASABE* **53**, 1547–1556.

Bush, G. W. 2006 *Address before a Joint Session of the Congress on the State of the Union*. Government Printing Office, Washington, DC, USA.

Chamberlain, J. F., Miller, S. A. & Frederick, J. R. 2011 Using DAYCENT to quantify on-farm GHG emissions and N dynamics of land use conversion to N-managed switchgrass in the Southern U.S. *Agriculture, Ecosystems and Environment* **141**, 332–341.

Davis, R. E. & Christenson, S. C. 1981 Geohydrology and numerical simulation of the alluvium and terrace aquifer along the Beaver-North Canadian River from the Panhandle to Canton Lake, Northwestern Oklahoma. Open-file Report 81–483. US Geological Survey, Oklahoma City, USA.

Douglas-Mankin, K. R., Srinivasan, R. & Arnold, J. G. 2010 Soil and water assessment tool (SWAT) model: current developments and applications. *Transactions of the ASABE* **53**, 1423–1431.

Du, J., Qian, L., Rui, H., Zuo, T., Zheng, D., Xu, Y. & Xu, C. Y. 2012 Assessing the effects of urbanization on annual runoff and flood events using an integrated hydrological modeling system for Qinhuai River basin, China. *Journal of Hydrology* **464**, 127–139.

Foley, J. A., DeFries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., Chapin, F. S., Coe, M. T., Daily, G. C., Gibbs, H. K., Helkowski, J. H., Holloway, T., Howard, E. A., Kucharik, C. J., Monfreda, C., Patz, J. A., Prentice, I. C., Ramankutty, N. & Snyder, P. K. 2005 Global consequences of land use. *Science* **309**, 570–574.

Franczyk, J. & Chang, H. 2009 The effects of climate change and urbanization on the runoff of the Rock Creek basin in the Portland metropolitan area, Oregon, USA. *Hydrological Processes* **23**, 805–815.

Garoma, T., Ben-Khaled, M. & Beyene, A. 2012 Comparative resource analyses for ethanol produced from corn and sugarcane in different climatic zones. *International Journal of Energy Research* **36**, 1065–1076.

Gassman, P. W., Reyes, M. R., Green, C. H. & Arnold, J. G. 2007 The soil and water assessment tool: historical development, applications, and future research directions. *Transactions of the ASABE* **50**, 1211–1250.

Georgescu, M. & Lobell, D. B. 2010 Perennial questions of hydrology and climate. *Science* **330**, 33.

Gerbens-Leenes, W., Hoekstra, A. Y. & van der Meer, T. H. 2009 The water footprint of Bioenergy. *Proceedings of the National Academy of Sciences of the United States of America*, 106, pp. 10219–10223.

Glennon, R. J. 2009 *Unquenchable: America's Water Crisis and What to Do About It*. Island Press, Washington, DC.

Goins, C. R. & Anderson, J. H. 2006 Geomorphic provinces. In: *Historical Atlas of Oklahoma*, 4th edition (C. R. Goins & D. Goble, eds). University of Oklahoma Press, Norman, OK, USA.

Graham, R. L., Downing, M. & Walsh, M. E. 1996 A framework to assess regional environmental impacts of dedicated energy crop production. *Environmental Management* **20**, 475–485.

Gupta, H. V., Sorooshian, S. & Yapo, P. O. 1999 Status of automatic calibration for hydrologic models: comparison with multilevel expert calibration. *Journal of Hydrologic Engineering* **4**, 135–143.

Jiang, S., Ren, L., Yong, B., Fu, C. & Yang, X. 2012 Analyzing the effects of climate variability and human activities on runoff from the Laohahe basin in northern China. *Hydrology Research* **43**, 3–13.

Kustu, M. D., Fan, Y. & Robock, A. 2010 Large-scale water cycle perturbation due to irrigation pumping in the US High Plains: a synthesis of observed streamflow changes. *Journal of Hydrology* **390**, 222–244.

Lakshmi, V., Hong, S., Small, E. E. & Chen, F. 2011 The influence of the land surface on hydrometeorology and ecology: new advances from modeling and satellite remote sensing. *Hydrology Research* **42**, 95–112.

Ma, X., Xu, J. C., Luo, Y., Aggarwal, S. P. & Li, J. T. 2009 Response of hydrological processes to land-cover and climate changes in Kejie watershed, south-west China. *Hydrological Processes* **23**, 1179–1191.

McGuire, V. L. 2011 Water-level changes in the High Plains Aquifer, predevelopment to 2009, 2007–08, and 2008–09, and change in water in storage, predevelopment to 2009. US Geological Survey Scientific Investigations Report 2011–5089. US Geological Survey, Reston, USA.

McIsaac, G. F., David, M. B. & Mitchell, C. A. 2010 Miscanthus and switchgrass production in central Illinois: impacts on hydrology and inorganic nitrogen leaching. *Journal of Environmental Quality* **39**, 1790–1799.

Mitchell, R., Wallace, L., Wilhelm, W., Varvel, G. & Wienold, B. 2010 Grasslands, Rangelands, and Agricultural Systems. Biofuels and Sustainability Reports: Ecological Society of America, Washington, DC, USA.

Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D. & Veith, T. L. 2007 Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the ASABE* **50**, 885–900.

Nash, J. E. & Sutcliffe, J. V. 1970 River flow forecasting through conceptual models: Part 1 – a discussion of principles. *Journal of Hydrology* **10**, 282–290.

National Research Council 2008 *Water Implications of Biofuel Production in the United States*. National Academy Press, Washington, DC, USA.

Nelson, R. G., Ascough, J. C. & Langemeier, M. R. 2006 Environmental and economic analysis of switchgrass production for water quality improvement in Northeast Kansas. *Journal of Environmental Management* **79**, 336–347.

Ng, T. L., Eheart, J. W., Cai, X. & Miguez, F. 2010 Modeling miscanthus in the soil and water assessment tool. *Environmental Science & Technology* **44**, 7138–7144.

Nyakatawa, E. Z., Mays, D. A., Tolbert, V. R., Green, T. H. & Bingham, L. 2006 Runoff, sediment, nitrogen, and phosphorus losses from agricultural land converted to sweetgum and switchgrass bioenergy feedstock production in north Alabama. *Biomass & Bioenergy* **30**, 655–664.

One-hundred Tenth Congress of the United States of America 2007 *Energy Independence and Security Act*. Government Printing Office, Washington, DC, USA.

Parrish, D. J. & Fike, J. H. 2005 The biology and agronomy of switchgrass for biofuels. *Critical Reviews in Plant Science* **24**, 423–459.

PRISM Climate Group 2012 Oregon State University. Data available at: http://prism.oregonstate.edu (accessed January 2013).

Raymond, P. A., Oh, N.-H., Turner, R. E. & Broussard, W. 2008 Anthropogenically enhanced fluxes of water and carbon from the Mississippi River. *Nature* **451**, 449–452.

Reisner, M. 1993 *Cadillac Desert: The American West and its Disappearing Water*. Penguin Books, New York, USA.

Ren, L., Liu, X., Yuan, F., Xu, J. & Liu, W. 2012 Quantitative analysis of runoff reduction in the Laohahe basin. *Hydrology Research* **43**, 38–47.

Renewable Fuels Association 2012 Available from: http://www.ethanolrfa.org/ (accessed January 2013).

Robertson, G. P., Hamilton, S. K., Del Grosso, S. J. & Parton, W. J. 2010 Growing Plants for Fuel: Predicting Effects on Water, Soil, and the Atmosphere. Biofuels and Sustainability Reports: Ecological Society of America, Washington, DC, USA.

Sala, O. E., Chapin, F. S., Armesto, J. J., Berlow, E., Bloomfield, J., Dirzo, R., Huber-Sanwald, E., Huenneke, L. F., Jackson,

R. B., Kinzig, A., Leemans, R., Lodge, D. M., Mooney, H. A., Oesterheld, M., Poff, N. L., Sykes, M. T., Walker, B. H., Walker, M. & Wall, D. H. 2000 Global biodiversity scenarios for the year 2100. *Science* **287**, 1770–1774.

Sarkar, S., Miller, S. A., Frederick, J. R. & Chamberlain, J. F. 2011 Modeling nitrogen loss from switchgrass agricultural systems. *Biomass & Bioenergy* **35**, 4381–4389.

Scanlon, B. R., Faunt, C. C., Longuevergne, L., Reedy, R. C., Alley, W. M., McGuire, V. L. & McMahon, P. B. 2012 Groundwater depletion and sustainability of irrigation in the US High Plains and Central Valley. *Proceedings of the National Academy of Sciences of the United States of America* **109**, 9320–9325.

Schilling, K. E., Chan, K.-S., Liu, H. & Zhang, Y.-K. 2010 Quantifying the effect of land use land cover change on increasing discharge in the Upper Mississippi River. *Journal of Hydrology* **387**, 343–345.

Schilling, K. E., Jha, M. K., Zhang, Y. K., Gassman, P. W. & Wolter, C. F. 2008 Impact of land use and land cover change on the water balance of a large agricultural watershed: historical effects and future directions. *Water Resources Research* **44**, W00A09.

Schmer, M. R., Vogel, K. P., Mitchell, R. B. & Perrin, R. K. 2008 Net energy of cellulosic ethanol from switchgrass. *Proceedings of National Academy of Sciences of the United States of America* **105**, 464–469.

Simpson, T. W., Sharpley, A. N., Howarth, R. W., Paerl, H. W. & Mankin, K. R. 2008 The new gold rush: fueling ethanol production while protecting water quality. *Journal of Environmental Quality* **37**, 318–324.

Singh, J., Knapp, H. V. & Demissie, M. 2004 *Hydrologic Modeling of the Iroquois River Watershed Using HSPF and SWAT*. CR 2004–08. Illinois State Water Survey, Champaign, IL, USA.

Thomas, M. A., Engel, B. A. & Chaubey, I. 2009 Water quality impacts of corn production to meet biofuel demands. *Journal of Environmental Engineering (ASCE)* **135**, 1123–1135.

Tortorelli, R. L. 2009 Water Use in Oklahoma 1950–2005. Scientific Investigations Report 2009–5212. US Geological Survey, Reston, USA.

Turner, B. L. II, Lambin, E. F. & Reenberg, A. 2007 The emergence of land change science for global environmental change and sustainability. *Proceedings of the National Academy of Sciences of the United States of America* **104**, 20666–20671.

van Griensven, A., Meixner, T., Grunwald, S., Bishop, T., Diluzio, A. & Srinivasan, R. 2006 A global sensitivity analysis tool for the parameters of multi-variable catchment models. *Journal of Hydrology* **324**, 10–23.

Vanlocke, A., Bernacchi, C. J. & Twine, T. E. 2010 The impacts of Miscanthus × giganteus production on the midwest US hydrologic cycle. *Global Change Biology Bioenergy* **2**, 180–191.

Vorosmarty, C. J., Green, P., Salisbury, J. & Lammers, R. B. 2000 Global water resources: vulnerability from climate change and population growth. *Science* **289**, 284–288.

Wagener, T., Sivapalan, M., Troch, P. A., McGlynn, B. L., Harman, C. J., Gupta, H. V., Kumar, P., Rao, P. S. C., Basu, N. B. & Wilson, J. S. 2010 The future of hydrology: an evolving science for a changing world. *Water Resources Research* **46**, W05301.

Wahl, K. L. & Tortorelli, R. L. 1997 Changes in flow in the Beaver-North Canadian River basin upstream from Canton Lake, Western Oklahoma. Water-Resources Investigations Report 96–4304. US Geological Survey, Oklahoma City, USA.

Yang, X., Ren, L., Singh, V. P., Liu, X., Yuan, F., Jiang, S. & Yong, B. 2012 Impacts of land use and land cover changes on evapotranspiration and runoff at Shalamulun River watershed, China. *Hydrology Research* **43**, 23–37.

Zume, J. T. & Tarhule, A. 2006 Precipitation and streamflow variability in northwestern Oklahoma, 1894–2003. *Physical Geography* **27**, 1–17.

Zume, J. T. & Tarhule, A. 2008 Simulating the impacts of groundwater pumping on stream–aquifer dynamics in semiarid Northwestern Oklahoma, USA. *Hydrogeology Journal* **16**, 797–810.

Zume, J. T. & Tarhule, A. 2011 Modelling the response of an alluvial aquifer to anthropogenic and recharge stresses in the United States Southern Great Plains. *Journal of Earth System Science* **120**, 557–572.

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