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Modeling the effects of land use change from cotton (*Gossypium hirsutum* L.) to perennial bioenergy grasses on watershed hydrology and water quality under changing climate

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ABSTRACT

Assessing the impacts of biofuel-induced land use change on hydrology, water quality and crop yield under the current and future climate scenarios enables selection of appropriate land uses and associated best management practices under the changing climate. In this study, the impacts of land use change from cotton (*Gossypium hirsutum* L.) to perennial grasses in the Double Mountain Fork Brazos watershed in the Texas High Plains were assessed using the Soil and Water Assessment Tool (SWAT). While switchgrass (*Panicum virgatum* L.) was assumed to replace cotton in irrigated areas, dryland cotton was replaced by *Miscanthus* × *giganteus* under the hypothetical land use change scenarios. Climate change impacts were assessed based on the Coupled Model Intercomparison Project Phase 5 (CMIP5) climate projections of 19 General Circulation Models (GCMs) under two Representative Concentration Pathway (RCP) emission scenarios of RCP4.5 and RCP8.5 during two 30-year periods of middle (2040–2069) and end (2070–2099) of the 21st century. Median irrigation water use of cotton was simulated to decrease by 41%–61% in the future when compared to historic (1994–2009) period based on projections by 19 GCMs. Under the future climate change scenarios, when compared to cotton, median annual irrigation water use by switchgrass reduced by 62%–89%. Simulated future median total nitrogen load decreased by 30%–40% under perennial grasses when compared to future cotton land use. The median irrigated switchgrass yield decreased by 16%–28%, but the median dryland *Miscanthus* yield increased by 32%–38% under the future climate change scenarios.

1. Introduction

Human population expansion and increased dependence on fossil fuels have considerably raised atmospheric concentrations of greenhouse gases (carbon dioxide-CO_2, methane-CH_4, nitrous oxide-N_2O, etc.), which trap heat and warm the earth system (USEPA, 2016). According to a series of emission scenarios of the Intergovernmental Panel on Climate Change (IPCC), CO_2 concentrations are expected to increase from their current level of about 330 parts per million (ppm) to between 530 and 800 ppm by the end of the 21st century (Van Vuuren et al., 2011). The IPCC emission scenarios also predicted increases in air temperatures and associated changes in the amount, intensity and duration of precipitation due to the increase of greenhouse gas concentrations in the atmosphere (IPCC, 2007). The effects of climate change on water resources and crop production are global concerns (Arnell, 1999; Ye and Grimm, 2013; Williams et al., 2015). Climate change is expected to affect both hydrology (actual evapotranspiration (ET), surface runoff, etc.) and water quality (sediment and nutrient discharge) at various spatial scales (Panagopoulos et al., 2014, 2015; Marshall and Randhir, 2008; Ye and Grimm, 2013; Zhang et al., 2005; Zhang et al., 2007; Zierl and Bugmann, 2005), and crop yield (Williams et al., 2015).

The effects of climate change vary across regions. Most General Circulation Models (GCMs) projected that the Southwest region of the United States, including the Texas High Plains (THP), would become hotter and drier than usual (IPCC, 2007), which could significantly reduce water resources availability in this region (Seager and Vecchi, 2010). Recently, Modala et al. (2017) also predicted an apparent increase in daily temperature by 1.9 °C to 3.2 °C and decrease in precipitation by 30–127 mm in the THP in the future (2041–2070). Using Modala et al. (2017) future climate data, Adhikari et al. (2016) simulated a 14%–29% increase in irrigated

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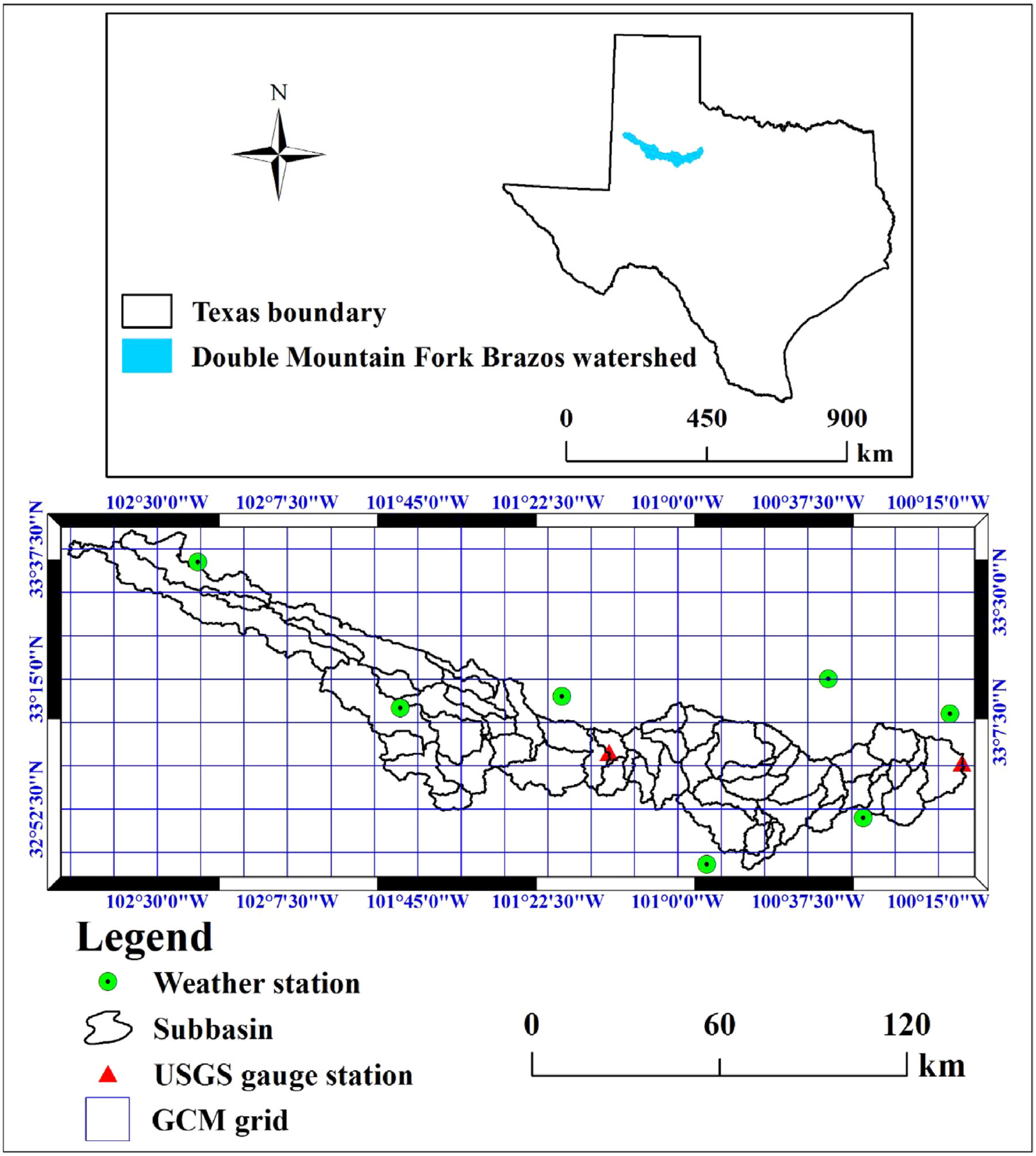

Fig. 1. Locations of weather stations, USGS gauge stations and General Circulation Model (GCM) grids in the Double Mountain Fork Brazos watershed in the Texas High Plains.

seed cotton (*Gossypium hirsutum* L.) yield across the THP region under future (2041–2070) climate scenarios relative to the historic period (1971–2000), when atmospheric CO_2 concentration was assumed to vary from 493 ppm (in year 2041) to 635 ppm (2070). However, these simulated increases in cotton yield were possible only with increased irrigation water use in this already groundwater–depleted THP region. Therefore, projected changes in future climate may pose some serious challenges to efficient utilization of water resources and crop production in the semi-arid THP (Barnett et al., 2008; Gober and Kirkwood, 2010), and more studies that investigate climate change effects are needed in this predominantly cotton growing region.

The environmental policies and management strategies aimed at mitigation/adaptation of climate change effects need to be implemented at the watershed/regional scales. Therefore, watershed/regional scale climate change impact assessments are critical for devising and implementing relevant policies and strategies to mitigate negative impacts of climate change (Brekke et al., 2004; IPCC, 2001; Zhang et al., 2007). Some of the watershed-scale climate change mitigation policies and strategies are related to land use change, which has the potential to increase resiliency of the watershed to climate change (IPCC, 2001). Change in land use from conventional row crops, such as cotton, to perennial bioenergy crops could therefore play a significant role in mitigating the effects of climate change (Rose et al., 2012). The effects of biofuel-induced land use change on hydrology and water quality over the historic period were evaluated in several studies (Chen et al., 2016a, 2016b; Schilling et al., 2008; Srinivasan et al., 2010; Yasarer et al., 2016; Zhou et al., 2015; Zhuang et al., 2013; VanLoocke et al., 2010). However, such evaluations under future climate change scenarios are lacking, especially for the THP, which is one of the important agricultural regions of the United States.

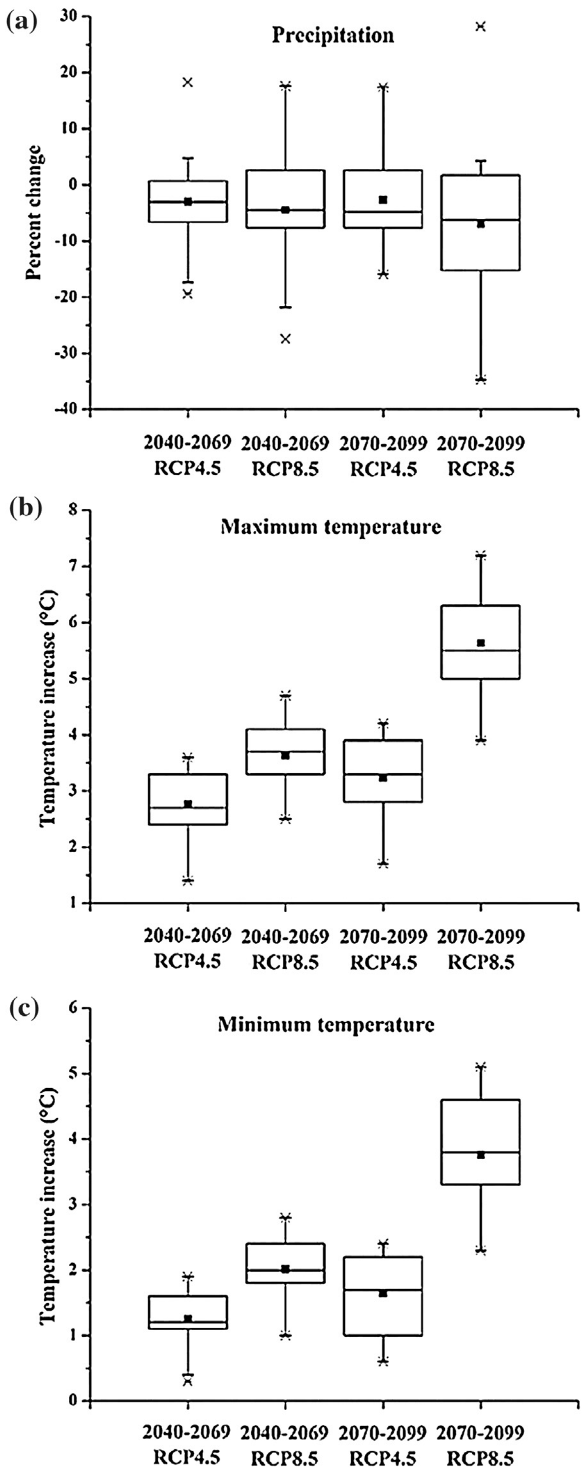

Fig. 2. Box plots showing changes in average annual (a) precipitation, (b) maximum air temperature, and (c) minimum air temperature based on 19 GCM projections under RCP4.5 and RCP8.5 scenarios during the 2040–2069 and 2070 to2099 time periods with reference to the historic period (1994–2009). The ends of whisker lines represent the minimum and maximum values of the parameter of interest among 19 GCMs. The box enclosed the middle 50% of the parameter of interest with the lower edge and upper edge indicating first quartile and third quartile values, respectively. The line inside the box represent median and the solid square indicate the mean of the parameter of interest among 19 GCMs.

A high variability exists in the future climate projections by different GCMs, and hence their effects on water balances, nutrient discharge and crop yield in the THP region also would vary considerably from one GCM to the other. In order to better capture these large uncertainties, projected climate data from 19 GCMs were used in this study. The Soil and Water Assessment Tool (SWAT) model (Arnold et al., 1998), which has been widely used for evaluating the climate change and land use change effects on water quantity and quality at the watershed scale (Ficklin et al., 2009; Jha et al., 2006; Wu et al., 2012), was used in this study.

The overall goal of this study was to evaluate the impacts of land use change from cotton, a non-food crop, to the perennial bioenergy grasses of switchgrass (*Panicum virgatum* L.) and *Miscanthus* × *giganteus* on the water cycle and nitrogen load under the changing climate in the Double Mountain Fork Brazos watershed in the THP. Such kind of land use change mitigates competition between food versus fuel crop production. In addition, the USDA estimated that about 11.4% of the existing croplands and pastures in the southeastern US that includes the study watershed/region would be required for biofuel production in order to meet the 2022 national cellulosic biofuel target (USDA, 2010). Specific objectives of the study were to: (1) quantify the effects of future climate change on hydrologic fluxes, total nitrogen (TN) load and crop yield under the current cotton land use (baseline scenario) based on 19 GCM projections under two Representative Concentration Pathway (RCP) emission scenarios of RCP4.5 and RCP8.5 during two 30-year periods of middle (2040–2069) and end (2070–2099) of the 21st century and (2) assess the impacts of land use change from cotton to perennial grasses on water partitioning, TN load and biomass production potential under the four projected future climate change scenarios (2040–2069 RCP4.5, 2040–2069 RCP8.5, 2070–2099 RCP4.5 and 2070–2099 RCP8.5) compared to respective future cotton land use scenarios.

2. Materials and methods

2.1. Study watershed

The Double Mountain Fork Brazos watershed in the THP was selected for this study (Fig. 1). The average (1994–2009) annual precipitation in the watershed was about 517 mm, and the mean air temperature during the cotton growing season (May to October) was around 24 °C. The delineated watershed area is about 6000 km^2, and the topography of the watershed is mostly flat with the dominant slopes ranging from 0% to 5%. Major land uses in the watershed are cotton (30%), winter wheat (2%), range grass (21%) and range brush (31%). Major soil types are Acuff sandy clay loam (fine-loamy, mixed, superactive, thermic Aridic Paleustolls), Amarillo sandy loam (fine-loamy, mixed, superactive, thermic Aridic Paleustalfs) and Olton clay loam (fine, mixed, superactive, thermic Aridic Paleustolls) (Soil Survey Staff, 2010). The Ogallala Aquifer is the main source of irrigation water for this region, and the center pivot systems are commonly used to apply irrigation water.

2.2. SWAT model inputs and calibration

In this study, surface runoff was simulated using the Curve Number method (CN) (USDA, 1972) available in the SWAT model, and the potential evapotranspiration (PET) was simulated using the Penman-Monteith method (Penman, 1956; Monteith, 1965). The crop management practices in the model were scheduled by specific dates. More details about the SWAT model inputs and setup for the study watershed are available in Chen et al. (2016a, 2017). In this study, the SWAT model (Version 2012.10_2.16 released on 9/9/14) compatible with ArcGIS 10.2.2 platform was used. The

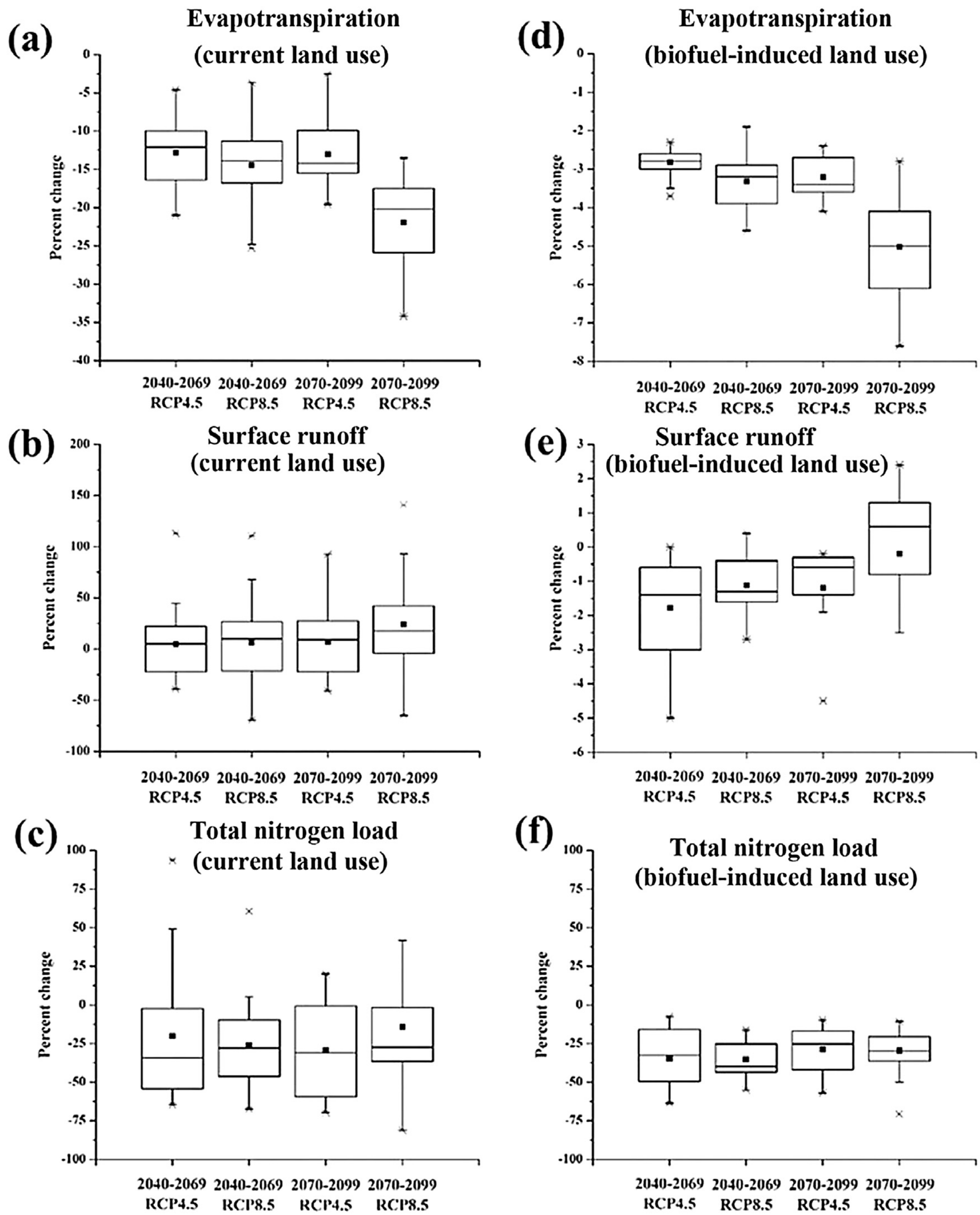

Fig. 3. Box plots showing average annual percent changes in actual evapotranspiration, surface runoff and total nitrogen load (for the entire watershed) based on 19 GCM projections under RCP4.5 and RCP8.5 scenarios during the 2040–2069 and 2070–2099 time periods compared to the base line cotton scenario over the historic period (1994–2009). The ends of whisker lines represent the minimum and maximum values of the parameter of interest among 19 GCMs. The box enclosed the middle 50% of the parameter of interest with the lower edge and upper edge indicating first quartile and third quartile values, respectively. The line inside the box represent median and the solid square indicate the mean of the parameter of interest among 19 GCMs.

Sequential Uncertainty Fitting version-2 (SUFI-2) procedure of SWAT Calibration and Uncertainty Procedures (SWAT-CUP 2012) (Abbaspour et al., 2007) was used for the model sensitivity analysis and calibration of hydrology and water quality related parameters.

The hydrologic and crop yield components of the SWAT model of the study watershed were initially calibrated as a part of our previous study (Chen et al., 2016a). In Chen et al. (2016a) SWAT model, default parameter values were used for range brush, which occupied about 41% of the watershed area. In this study, hydrology and crop yield calibration of the Chen et al. (2016a) SWAT model was further improved by simulating honey mesquite, which is predominant in the range brush land use of the study watershed, in all range brush Hydrologic Response Units (HRUs). The most commonly adopted heavy continuous grazing management practice was simulated in all range grass HRUs (Park et al., 2017). The calibrated values of Max leaf area index (BLAI) and Biomass/energy ratio (BIO_E) parameters in case of dryland cotton were slightly higher than irrigated cotton, mainly because of differences in cultivars and seed

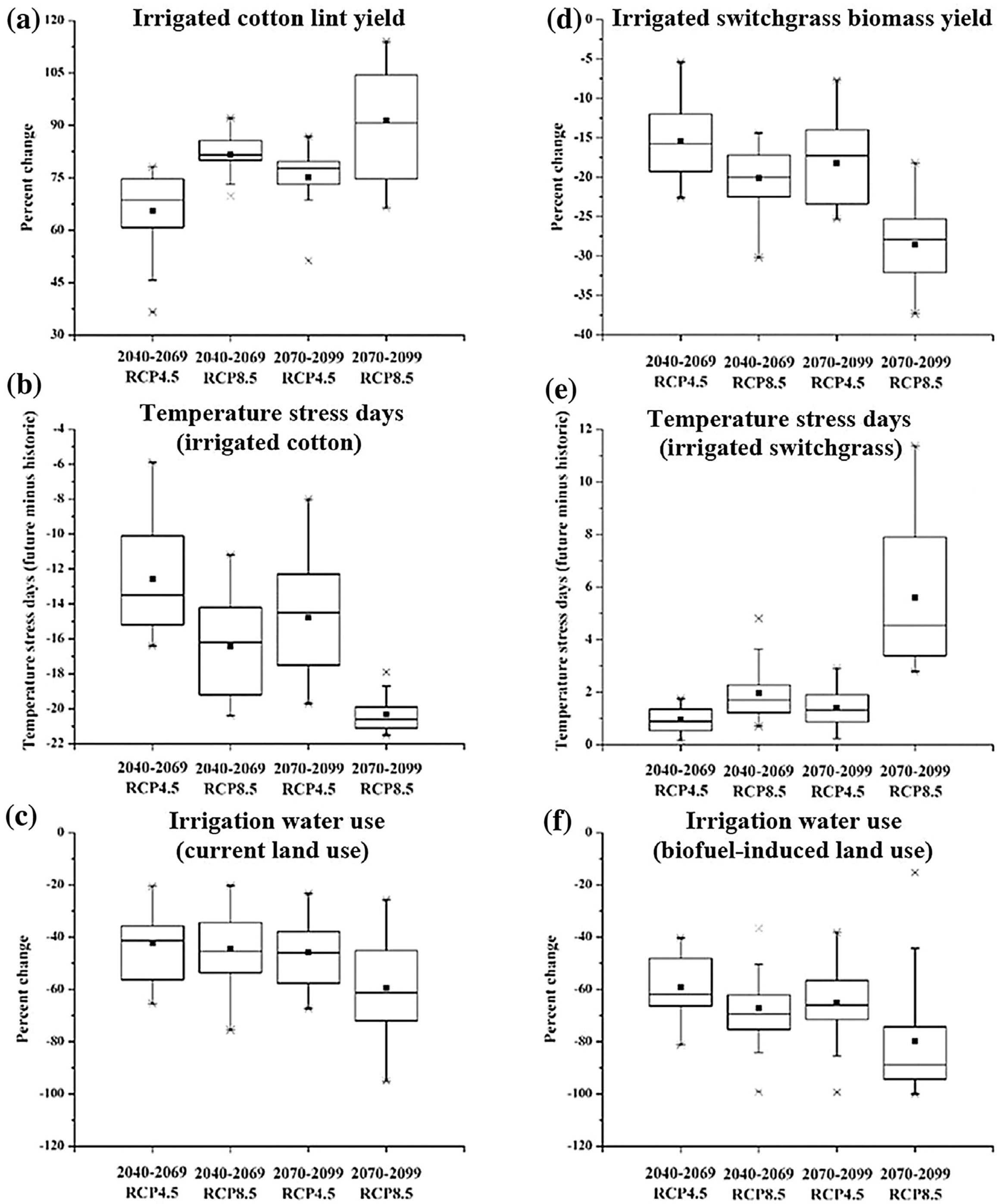

Fig. 4. Box plots showing changes in average annual irrigated crop yields, irrigation water use and number of temperature stress days based on 19 GCMs under RCP4.5 and RCP8.5 scenarios during the 2040–2069 and 2070–2099 time periods compared to the historic period (1994–2009). Irrigation water use under future switchgrass land use was compared to that under the baseline cotton scenario. The ends of whisker lines represent the minimum and maximum values of the parameter of interest among 19 GCMs. The box enclosed the middle 50% of the parameter of interest with the lower edge and upper edge indicating first quartile and third quartile values, respectively. The line inside the box represent median and the solid square indicate the mean of the parameter of interest among 19 GCMs.

rates adopted for dryland and irrigated crops in the THP region. The improved SWAT model was then calibrated for water quality predictions using the observed daily TN concentration data (39 samples) at the watershed outlet, which were converted into continuous daily TN load data using the USGS regression model, Load Estimator (LOADEST) (Runkel et al., 2004). A detailed description of the LOADEST model can be found in Jha et al. (2007). The estimated continuous daily TN load data was distributed from 1995 to 2000. The data from 1995 to 1997 and 1998 to 2000 was used for the model calibration and validation, respectively. A five-year warm up period from 1990 to 1994 was adopted for the TN load simulation (Daggupati et al., 2015). The calibrated values of major hydrologic and nutrient related parameters are shown in Table S1. The SWAT model performance in prediction of TN load was evaluated monthly using three statistical measures: the Nash-Sutcliffe efficiency (*NSE*) (Nash and Sutcliffe, 1970), square of Pearson's product–moment correlation coefficient (R^2) (Legates and McCabe, 1999) and percent bias (*PBIAS*).

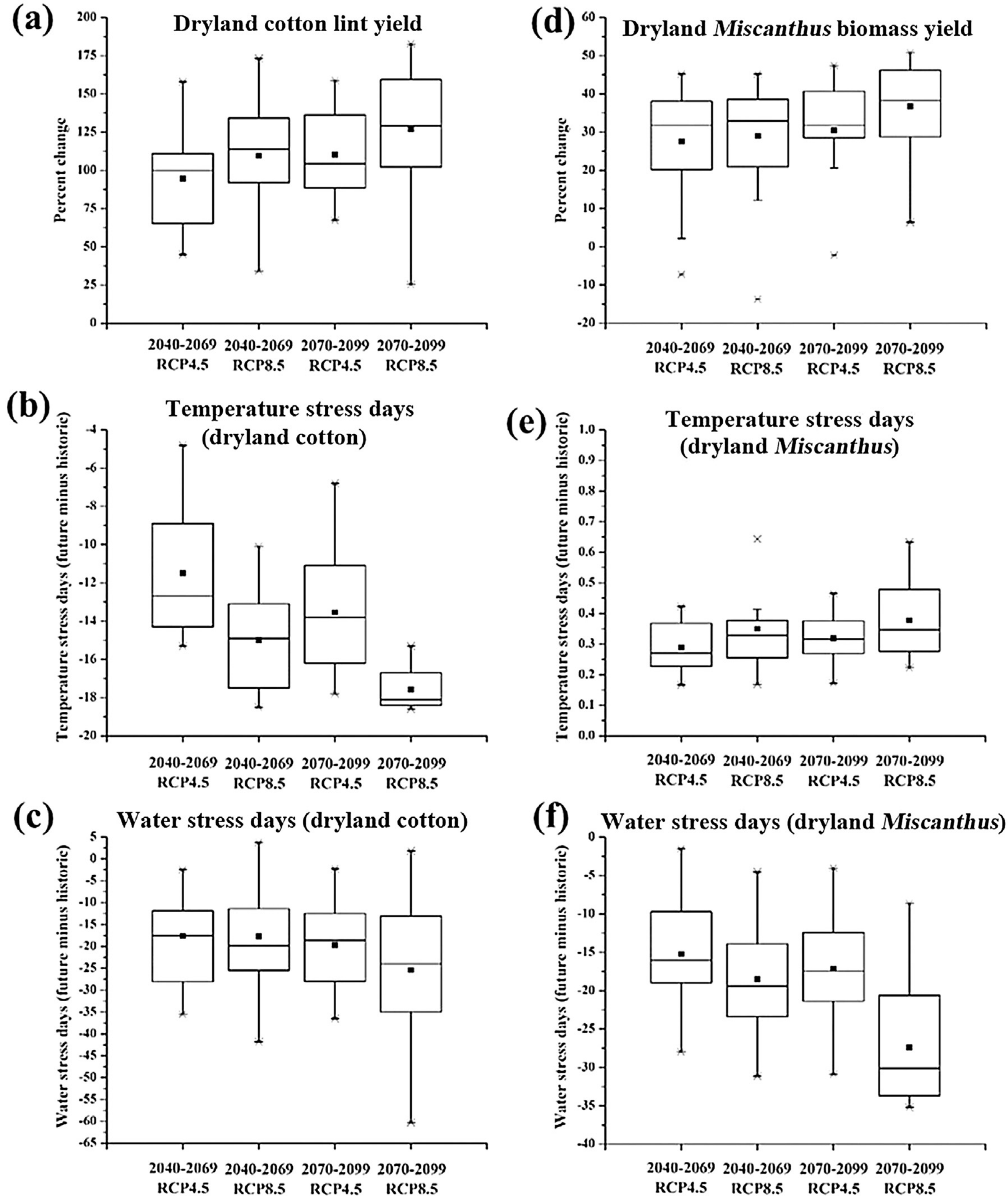

Fig. 5. Box plots showing changes in average annual dryland crop yields, and number of temperature and water stress days based on 19 GCM projections under RCP4.5 and RCP8.5 scenarios during the 2040–2069 and 2070–2099 time periods compared to the historic period (1994 2009). The ends of whisker lines represent the minimum and maximum values of the parameter of interest among 19 GCMs. The box enclosed the middle 50% of the parameter of interest with the lower edge and upper edge indicating first quartile and third quartile values, respectively. The line inside the box represent median and the solid square indicate the mean of the parameter of interest among 19 GCMs.

2.3. Scenario development and analysis

2.3.1. The GCM climate projections

Bias-Corrected Statistically Downscaled (BCSD) daily future climate data projected by 19 GCMs were obtained from the Downscaled Coupled Model Intercomparison Project Phase 5 (CMIP5) Climate and Hydrology Projections (http://gdo-dcp.ucllnl.org/), and used in the future climate change simulations. Future climate data were obtained for a total of 168 GCM grids that span over the study watershed, and input to the SWAT model for future climate change simulations (Fig. 1). The GCMs considered in this study are listed in Table 1. The GCM projections of daily precipitation, maximum temperature and minimum temperature were available for the period from 1950 to 2099. The spatial resolution of the GCM projections is 0.125° (~12.5 km × 12.5 km). An R code was used to convert the downloaded future climate data of the study watershed into the format required by the SWAT model.

In this study, GCM climate projections from two RCP emission scenarios of RCP4.5 (moderate) and RCP8.5 (severe) were used. Future climate change projections from these 19 GCMs were

Table 1
List of the 19 General Circulation Models (GCMs) considered in this study.

Model Name	Modeling group (or center)	Institute ID	Grid Spacing*
access1-0	Commonwealth Scientific and Industrial Research Organization (CSIRO) and Bureau of Meteorology (BoM), Australia	CSIRO-BoM	1.250° × 1.875°
bcc-csm1-1	Beijing Climate Center, China Meteorological Administration	BCC	2.7906° × 2.8125°
canesm2	Canadian Centre for Climate Modelling and Analysis	CCCMA	0.9424° × 1.25°
ccsm4	National Center for Atmospheric Research	NCAR	0.9424° × 1.25°
cesm1-bgc	National Center for Atmospheric Research	NCAR	1.4008° × 1.40625°
cnrm-cm5	Centre National de Recherches Météorologiques – Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique	CNRM-CERFACS	1.8653° × 1.875°
csiro-mk3-6-0	Commonwealth Scientific and Industrial Research Organization in collaboration with Queensland Climate Change Centre of Excellence	CSIRO-QCCCE	2.7906° × 2.8125°
gfdl-esm2g	NOAA/Geophysical Fluid Dynamics Laboratory	NOAA GFDL	2.0225° × 2°
gfdl-esm2m	NOAA/Geophysical Fluid Dynamics Laboratory	NOAA GFDL	2.0225° × 2.5°
inmcm4	Institute of Numerical Mathematics	INM	1.5° × 2°
ipsl-cm5a-lr	Institut Pierre Simon Laplace	IPSL	1.8947° × 3.75°
ipsl-cm5a-mr	Institut Pierre Simon Laplace	IPSL	1.2676° × 2.5°
miroc5	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	MIROC	2.7906° × 2.8125°
miroc-esm	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	MIROC	2.7906° × 2.8125°
miroc-esm-chem	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	MIROC	1.4008° × 1.40625°
mpi-esm-lr	Max Planck Institute for Meteorology (Max-Planck-Institut für Meteorologie)	MPI-M	1.8653° × 1.875°
mpi-esm-mr	Max Planck Institute for Meteorology (Max-Planck-Institut für Meteorologie)	MPI-M	1.8653° × 1.875°
mri-cgcm3	Meteorological Research Institute	MRI	1.12148° × 1.125°
noresm1-m	Norwegian Climate Centre	NCC	1.8947° × 2.5°

* Atmospheric grid spacing is the latitude-by-longitude spacing of computational grid.

Table 2
Scenarios considered in the climate change analysis.

Time period	Land use	RCP*	Assumed average CO_2 concentration (ppm)
Baseline (1994–2009)	Cotton	–	330
2040–2069	Cotton	RCP4.5	500
2040–2069	Cotton	RCP8.5	570
2040–2069	Perennial grasses	RCP4.5	500
2040–2069	Perennial grasses	RCP8.5	570
2070–2099	Cotton	RCP4.5	530
2070–2099	Cotton	RCP8.5	800
2070–2099	Perennial grasses	RCP4.5	530
2070–2099	Perennial grasses	RCP8.5	800

* RCP, Representative Concentration Pathway.

obtained for two 30-year periods: 2040–2069 (middle of the 21st century) and 2070–2099 (end of the 21st century). The four future climate change scenarios simulated in this study are hereafter denoted as 2040–2069 RCP4.5, 2040–2069 RCP8.5, 2070–2099 RCP4.5 and 2070–2099 RCP8.5. In the SWAT model, atmospheric CO_2 concentration can only be input as a single value and the model does not allow inputting variable (increasing) concentrations over a long-term (e.g. 30-year) simulation period. This is a limitation for future climate scenario analysis with the SWAT model and hence we adopted/estimated representative CO_2 concentrations for historic/future climate scenarios. For the baseline scenario with current land use in the watershed, an average atmospheric CO_2 concentration of 330 ppm was assumed (Wu et al., 2012). Average CO_2 concentrations for 2040–2069 RCP4.5, 2040–2069 RCP8.5, 2070–2099 RCP4.5 and 2070–2099 RCP8.5 scenarios were estimated as 500, 570, 530 and 800 ppm, respectively (Table 2) according to Van Vuuren et al. (2011).

2.3.2. Biofuel-induced land use change scenarios under changing climate

For the land use change scenario analysis, two promising perennial bioenergy crops, switchgrass and *Miscanthus* (Chen et al., 2016a, 2016b; Kiniry et al., 2008; Kiniry et al., 2012; Kiniry et al., 2013; Wang et al., 2014) were selected to replace cotton under both historic and future climate scenarios. Specifically, irrigated cotton was replaced by irrigated switchgrass and dryland cotton was replaced by dryland *Miscanthus* in view of their large biomass production potential and high water use efficiency under different irrigation management practices based on Chen et al. (2016a) study for this study watershed. The management practices implemented for switchgrass and *Miscanthus* simulations are summarized in Table 3.

The simulated annual results for cotton and perennial grass land uses based on each GCM-projected future climate data were averaged for the middle and the end of the 21st century scenarios and compared with the average (1994–2009) annual historic results for cotton land use. Box plots showing the percent changes in simulated variables/parameters/indices under the four future climate change scenarios (2040–2069 RCP4.5, 2040–2069 RCP8.5, 2070–2099 RCP4.5 and 2070–2099 RCP8.5) in comparison to the historic scenario were prepared based on the simulation driven by 19 GCMs. Temperature and water stress days were estimated for each scenario and used to assess the effects of climate change on crop yield/biomass. A day was considered as a temperature/water

Table 3
Simulated management practices for irrigated switchgrass and dryland *Miscanthus* in the SWAT model.

No.	Management operations	Input data
Irrigated switchgrass		
1	Fertilizer application parameters (May 1)	
	Fertilizer type	Urea
	Fertilizer application rate	270 (kg ha^{-1}) (Yimam et al., 2014)
2	Planting (Planting on May 15 in 1990)	Default
3	Irrigation (automatic irrigation) (Start date: May 15; End date: November 15)	
	Water stress identifier	Plant Water Demand
	Water stress threshold that triggers irrigation	0.9
4	Harvest only without kill (Harvest on November 15)	Default
Dryland *Miscanthus*		
1	Fertilizer application parameters (May 1)	
	Fertilizer type	Urea
	Fertilizer application rate	214 (kg ha^{-1}) (Lewandowski and Schmidt, 2006; Danalatos et al., 2007)
2	Planting (Planting on May 15 in 1990)	Default
3	Harvest only without kill (Harvest on November 15)	Default

stress day, if the average air temperature/soil water on that day was different from the specified optimum temperature/soil water (Neitsch et al., 2011).

3. Results and discussion

3.1. Evaluation of the SWAT model performance in predicting streamflow, cotton lint yield and total nitrogen load

The predicted monthly streamflow during the calibration (1994–2001) and validation (2002–2009) periods at two USGS gauges closely matched with the observed monthly streamflow (Figs. S1 and S2). The *NSE*, R^2 and *PBIAS* values for monthly simulations of streamflow at Gauge I were 0.86, 0.88 and 12.1%, respectively, during the model calibration period, and 0.59, 0.71 and 7.5%, respectively, during the model validation period (Fig. S1). At Gauge II, the *NSE*, R^2 and *PBIAS* for monthly streamflow predictions were 0.62, 0.66 and 14.2%, respectively, during the model calibration period, and 0.61, 0.75 and −12.8%, respectively, during the model validation period (Fig. S2). The model performance statistics for streamflow prediction were well above satisfactory range according to Moriasi et al. (2007) criteria. The average *PBIAS* in predicting irrigated cotton lint yield over the entire simulation period (1994–2009) was 3.2% (Fig. S3). In the case of dryland cotton, the average *PBIAS* in cotton lint yield prediction was 2.3%.

A graphical comparison of monthly simulated TN load with the LOADEST estimated data during the calibration (1995–1997) and validation (1998–2000) periods indicated that they matched fairly well (Fig. S4). The *NSE* for monthly TN load predictions was 0.75 and 0.71 for the calibration and validation periods, respectively (Table 4). The *PBIAS* in predicting TN load was within ±25% during the calibration (−17%) and validation (16.8%) periods. The model performance ratings (*NSE* and *PBIAS)* achieved in this study for monthly TN load predictions during the calibration and validation periods were considered good according to Moriasi et al. (2007) criteria.

3.2. The impacts of climate and land use changes on hydrology, water quality and crop yield

3.2.1. Projected changes in future climate of the Double Mountain Fork Brazos watershed

According to the future climate data projected by 19 GCMs, the median annual precipitation would decrease by about 5% under the four future climate change scenarios (2040–2069 RCP4.5, 2040–2069 RCP8.5 and 2070–2099 RCP4.5) when compared to the historic period (Fig. 2a). However, a slight increase in the precipitation during cotton growing period (May to October) was projected under the future climate change scenarios compared to the historic period. A high variation in annual precipitation was projected among different GCMs, especially under the 2070–2099 RCP8.5 scenario with the changes ranging from −35% to 28% when compared to the historic period (Fig. 2a). The median annual maximum air temperature increased by 2.8 °C, 3.8 °C, 3.5 °C and 5.8 °C under the 2040–2069 RCP4.5, 2040–2069 RCP8.5, 2070–2099 RCP4.5 and 2070–2099 RCP8.5 scenarios, respectively, relative to the historic period (Fig. 2b). The median annual minimum air temperature also increased by 1.3 °C, 2.1 °C, 1.7 °C and 3.7 °C under the 2040–2069 RCP4.5, 2040–2069 RCP8.5, 2070–2099 RCP4.5 and 2070–2099 RCP8.5 scenarios, respectively (Fig. 2c). The projected temperatures during the cotton growing period also showed similar increasing trends. The projected changes in precipitation, and maximum and minimum temperature for the study watershed over the mid-century were comparable to those projected by Modala et al. (2017) for the THP using the CMIP3 data. They predicted an increase in average daily minimum temperature by about 1.9 °C to 2.9 °C, increase in average daily maximum temperature by 2.0 °C to 3.2 °C, and decrease in precipitation by 30–127 mm in the future (2041–2070). The projected increase in temperature was the highest under the 2070–2099 RCP8.5 scenario, which had the highest projected CO_2 concentration (800 ppm) (Fig. 2b and c). The projected increase in CO_2 concentration in the future is expected to trap heat, and hence warm the earth system (USEPA, 2016).

3.2.2. Climate change effects on hydrology, water quality and crop yield under the current (cotton) land use

The simulated median annual actual ET under future cotton land use decreased by 12.1%, 13.9%, 14.2% and 20.2% under the 2040–2069 RCP4.5, 2040–2069 RCP8.5, 2070–2099 RCP4.5 and 2070–2099 RCP8.5 scenarios, respectively, relative to the historic period based on the 19 GCM projections (Fig. 3a). The increase in CO_2 concentration from 330 to 800 ppm under different future climate scenarios was the major reason for this reduction in the simulated future actual ET under cotton land use. The stomatal apertures close partially under the elevated CO_2 concentration (Wand et al., 1999; Medlyn et al., 2001), and hence inhibit transpiration. The reduction in the future median annual actual ET caused reductions in the annual irrigation water use by cotton. The median annual irrigation water use for future cotton land use reduced by about 41% (ranged from 21% to 65% among different GCM projections), 45% (range: 20% to 76%), 46% (range: 23% to 67%) and 61% (range: 26% to 95%) under the 2040–2069 RCP4.5, 2040–2069 RCP8.5, 2070–2099 RCP4.5 and 2070–2099 RCP8.5 scenarios, respectively, compared to the historic period (Fig. 4c). The decline in the future irrigation water use by cotton was much higher

Table 4
Model performance statistics during the model calibration and validation for monthly total nitrogen loads.

Statistic/Time scale	Calibration (1995–1997)	Validation (1998–2000)
Nash-Sutcliffe efficiency	0.75 (Very good*)	0.71 (Good)
R^2	0.81	0.86
PBIAS (%)	−17.0 (Very good)	16.8 (Very good)

Observed number of data used in the LOADEST estimation for total nitrogen loads was 39.
* General model performance ratings suggested by Moriasi et al. (2007) for monthly predictions of nitrogen.

under the 2070–2099 RCP8.5 scenario when compared to other three future scenarios.

Interestingly, the median annual surface runoff under cotton land use increased slightly under the four climate change scenarios although the simulated future actual ET and irrigation water use decreased. However, a large uncertainty existed. For example, under the 2040–2069 RCP4.5 scenario, 11 GCM projections simulated an increase in the surface runoff within a range of 4% to 113% relative to the historic period, while 8 GCMs projected a decrease in the surface runoff by about 1% to 39%. The large uncertainty in the simulated future surface runoff also emphasized that there was a high variation in the precipitation intensity projected by GCMs. Overall, the simulated future change in surface runoff under cotton land use ranged from −39% to 113%, −69% to 111%, −41% to 92% and −65% to 141% under the 2040–2069 RCP4.5, 2040–2069 RCP8.5, 2070–2099 RCP4.5 and 2070–2099 RCP8.5 scenarios, respectively, relative to the historic period (Fig. 3b). The simulated median annual TN loads under cotton land use reduced by about 34%, 28%, 31% and 27% under the four climate change scenarios compared to the historic period. Like surface runoff, a large variation in TN load was simulated among different GCMs (Fig. 3c).

The simulated future cotton lint yields increased under both irrigated (Fig. 4a) and dryland (Fig. 5a) conditions based on all 19 GCM projections under the four climate change scenarios. The median irrigated cotton lint yield increased by 69%, 82%, 78% and 91% under the 2040–2069 RCP4.5, 2040–2069 RCP8.5, 2070–2099 RCP4.5 and 2070–2099 RCP8.5 scenarios, respectively, relative to the historic period (Fig. 4a). Corresponding increases in dryland cotton lint yields under the four climate change scenarios were 100%, 114%, 104% and 129% (Fig. 5a). The increase in projected future irrigated cotton lint yield was primarily because of the reduction in temperature stress days during May to October (cotton growing period) (Fig. 4b). However, in case of dryland conditions, both temperature and water stress days reduced during the cotton growing period (Fig. 5b and c), which resulted in a much higher percent increase in the dryland cotton lint yield as compared to the increases in irrigated cotton lint yield (Figs. 4 a and 5 a). The optimal temperature for cotton growth is about 27 °C to 28 °C (Reddy et al., 2000). The projected increase in average air temperature by about 3 °C to 5 °C during the cotton growing period would provide better conditions for cotton growth compared to the average air temperature of 24 °C during the historic period. The projected increase in cotton lint yield would lead to an increase in plant nitrogen uptake, which could eventually result in the reduction in TN load through surface runoff.

3.2.3. Combined effects of land use and climate changes on hydrology, water quality and crop yield

The simulated median annual actual ET under the future perennial grass land use scenarios of 2040–2069 RCP4.5, 2040–2069 RCP8.5, 2070–2099 RCP4.5 and 2070–2099 RCP8.5 was smaller than that under respective future cotton land use scenarios according to the 19 GCM projections (Fig. 3d). In addition, the simulated future median irrigation water use of switchgrass was less by 62%, 69%, 66% and 89% than that of cotton under the 2040–2069 RCP4.5, 2040–2069 RCP8.5, 2070–2099 RCP4.5 and 2070–2099 RCP8.5 scenarios, respectively (Fig. 4f). The decrease in the irrigation water use under the future perennial grass land uses relative to the future cotton land use was simulated in case of all GCM projections.

The simulated future changes in median annual surface runoff under four climate change scenarios were negligible under the perennial grass land uses compared to those under the future cotton land use scenarios (please note the differences in Y-axis scales) (Fig. 3e). However, the simulated future median annual TN load under the perennial grasses reduced by about 33%, 40%, 25% and 30% under the 2040–2069 RCP4.5, 2040–2069 RCP8.5, 2070–2099 RCP4.5 and 2070–2099 RCP8.5 scenarios, respectively relative to those under the future cotton land use scenarios (Fig. 3f). Sarkar and Miller (2014) also reported that the SWAT-simulated long-term (15 years) nitrogen losses under the switchgrass land use were approximately 73% lower than those under the cotton land use in the Black Creek watershed in South Carolina. In contrast to surface runoff, large variations in the simulated future TN load were noticed between the future perennial grass and cotton scenarios. The perennial grasses uptake much higher amounts of nitrogen from the soil compared to cotton (Chen et al., 2017) and hence lesser quantities of nitrogen are available for the loss via surface runoff.

A decline in the irrigated switchgrass biomass yield, and an increase in the dryland *Miscanthus* biomass yield were simulated under the GCM projections of the four climate change scenarios when compared to respective land use scenarios under the historic period (Figs. 4 d and 5 d). The primary reason for the decline of irrigated switchgrass biomass yield based on the 19 GCM projections under the four climate change scenarios in this study was the global warming effect (Fig. 4e). The irrigated switchgrass underwent larger number of temperature stress days during its major growing period (June to September) due to the increase in air temperature under the four climate change scenarios than the historic period (Fig. 4e). The increase in dryland *Miscanthus* biomass yield was due to the decrease in water stress days during its major growing period (June to September) under the four climate change scenarios (Fig. 5f). In addition, *Miscanthus* can adapt to wider crop growth temperatures (optimal: 25 °C; minimum: 8 °C) compared to switchgrass (optimal: 25 °C; minimum: 12 °C), which resulted in a lower number of temperature stress days in case of *Miscanthus* when compared to switchgrass under climate change scenarios (Figs. 4 e and 5 e).

4. Conclusions

The SWAT model was used to investigate the effects of changes in land use from cotton to perennial bioenergy grasses on water balance parameters and nitrogen load under changing climate based on 19 GCM projections under four climate change scenarios in the Double Mountain Fork Brazos watershed of the THP. The potential land use change from irrigated cotton to irrigated switchgrass in the future was projected to enhance water conservation due to reduction in actual ET losses and hence groundwater use for irrigation under future climate scenarios. In addition, biofuel-induced land use change from cotton to perennial grasses was found to improve water quality by reducing the TN load at the watershed outlet by about 33%, 40%, 25% and 30% under the 2040–2069 RCP4.5, 2040–2069 RCP8.5, 2070–2099 RCP4.5 and 2070–2099 RCP8.5 scenarios, respectively, when compared to respective future cotton land use scenarios. A considerable increase in median biomass yields by 32%–38% was predicted under the dryland *Miscanthus* land use under the four climate change scenarios. The results from this study indicated that the irrigated switchgrass land use would be more suitable for the study watershed under the current climatic conditions when compared to the irrigated cotton land use. However, under future climate scenarios, irrigated switchgrass yields were projected to reduce by 16%–28% when compared to historic yields. Under dryland conditions, *Miscanthus* land use was found to be more appropriate under the future climate situations. The elevated CO_2 concentrations and reduced water stress days were the major factors for the increase in *Miscanthus* biomass yield. While the occurrence of future climatic conditions remains uncertain, this study provided an overview of the impacts of climate change and land use change on water balances, water quality and crop production.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agwat.2017.07.011.

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