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Impacts of bioenergy crop production and climate change on sediment management strategy at the watershed scale

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ABSTRACT

The objective of this study was to evaluate the potential impacts of both sediment management strategies and climate changes on sediment yield. The soil and water assessment tool (SWAT) model was applied to evaluate the changes in hydrologic components and sediment yield as well as the performance of sediment management strategies including bioenergy crop production in the Bogue Phalia River watershed in northwestern Mississippi. The SWAT model was calibrated and validated using streamflow and sediment yield data obtained from the U.S. Geological Survey gauge stations. To analyze the effectiveness of sediment management strategies under various scenarios, the calibrated SWAT model was applied with various sediment management strategies as well as climate change scenarios generated by using the LARS-WG stochastic weather generator. The results of this study indicate that although the implementation of terraces and contour farming is the effective strategies to reduce sediment yield under current weather conditions, growing switchgrass is the most appropriate strategy under the projected future periods. This study will help to develop the optimal sediment management strategy under various conditions in the study area, which can also be utilized in other similar watersheds in the country and abroad.

Keywords: Sediment; Best Management Practices; Climate change; Bioenergy; Soil and Water Assessment Tool (SWAT); LARS-WG

1. Introduction

Soil erosion from agricultural fields is a worldwide environmental concern. Since sediment eroded from agricultural fields contained nutrient contaminants and chemicals like pesticides, soil erosion has caused the water quality degradation at the downstream and impaired drainage networks [1,2]. For this reason, sediment has been recognized as one of the major nonpoint sources that affects water quality.

Agricultural conservation practices, often called best management practices (BMPs), such as conservation tillage, terrace, and contour farming have been extensively implemented as effective measures to reduce soil loss from cultivated lands and minimize degradation in water quality within agricultural watersheds [3,4]. Another promising strategy to help significantly reduce surface runoff and sediment in the agricultural areas is to grow the bioenergy crop such as switchgrass (*Panicum virgatum*) in selected locations within watersheds [5–7]. Switchgrass has a strong, deep, and extensive root system that can hold and prevent soil from erosion, leading to a decrease in sediment yield [6]. Nelson et al. [6] estimated that producing switchgrass instead of corn–soybean–wheat or sorghum–soybean–wheat rotation would reduce surface runoff by 55% and sediment loading by 99%. Love and Nejadhashemi [5] found that transitioning from row crops to perennial grass rotations of switchgrass,

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miscanthus, and native grasses would reduce sediment up to 87%. Zhou et al. [7] concluded that the land-use conversion from the entire current crop and pasture/hay lands to switchgrass production would reduce sediment loading by 77%.

Changes in climate caused by an increase in atmospheric carbon dioxide (CO_2) concentrations and air temperature have the potential to significantly alter precipitation, evapotranspiration, soil moisture, and streamflow in the watershed as well as growing season, resulting in changes in soil erosion and sediment yield [8,9]. Changes in the quality and quality of water discharge and sediment yield from the watershed with climate variability are likely to influence the efficiency of sediment management strategies like BMP. Previous studies [10–12] showed that BMP effectiveness varies with various future climate change scenarios and climate change may significantly affect BMP effectiveness. Therefore, it is necessary to consider climate change in selecting suitable agricultural conservation practices for reducing sediment yield and protecting water quality.

In order to help policymakers make decisions on sediment management in the watershed, it is important to estimate the effectiveness of sediment management strategies and to better understand how climate change will affect sediment yield from watershed and control strategies. However, understanding of the coupled impacts of future climate changes and sediment management strategies including bioenergy crop production on sediment yield is very limited, especially at the watershed scale. Therefore, the objective of this study was to assess the impacts of both sediment management strategies and climate changes on sediment yield at the watershed scale.

2. Material and methods

2.1. Study area

Bogue Phalia River watershed (BPRW), with an area of about 1,324 km^2, is located in northwest Mississippi USA (Fig. 1). The BPRW flows from north to south to its confluence with the Sunflower River, which ultimately discharges into the Mississippi River. The land use in the BPRW is predominately agricultural at more than 90% with soybean (55%), rice (21%), corn (11%), and cotton (4%). From 1991 to 2010, annual precipitation in the BPRW ranges from 943 to 1,814 mm.

The BPRW was listed on the Environmental Protection Agency Section 303(d) list of impaired waterbodies in Mississippi due to sediment, organic enrichment/low dissolved oxygen, and nutrients [13]. There, however, are no studies available in BPRW to estimate the effectiveness of sediment management strategies with climate change. Thus, the BPRW was selected for carrying out this study.

2.2. Model description and setup

In this study, the soil and water assessment tool (SWAT) model was applied to simulate the streamflow and sediment. The SWAT model is the physically-based and continuous daily time-step watershed model [14,15]. The major model components of the SWAT model include hydrology, soil erosion, nutrients, crop growth, and stream routing. In the SWAT model, the watershed is divided into multiple sub-watersheds with further subdivisions of several hydrological response units (HRUs) consisting of homogeneous soil type, land use, and slope classes. The model predicts

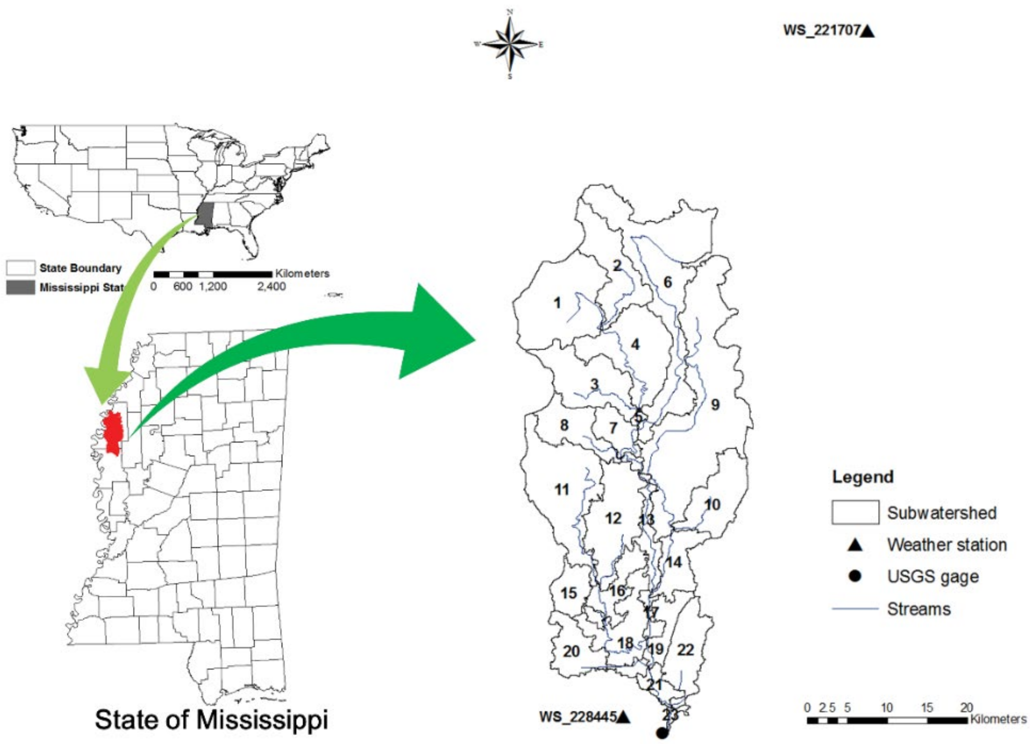

Fig. 1. Location map of the Bogue Phalia River watershed.

the hydrology at each HRU using the water balance equation. Erosion and sediment yield are estimated for each HRU with the modified universal soil loss equation [15,16]. The eroded sediments at HRUs level are routed along the channels to the outlet of the watershed. For channel sediments, the SWAT model simulates the two dominant sediment transport processes of degradation and deposition with a simplified version of the Bagnold stream power relationship. The crop growth is simulated by calculating leaf area development, light interception, and conversion to biomass. The model calculates the stresses occurring as a result of water, temperature, and nutrients. The potential evapotranspiration in this study was calculated using the Penman-Monteith method to simulate the impacts of changes in CO_2 concentration on plant stomatal conductance. A more detailed description of the SWAT model can be found in Neitsch et al. [15]. In this study, the ArcSWAT version of SWAT 2005 was applied.

The topography data were obtained using the digital elevation model with a 30 m resolution obtained from the United States Geological Survey [17], which resulted in 23 sub-watersheds for the BPRW. To characterize land use, the crop data layer from the United States Department of Agriculture National Agricultural Statistics Service [18] was used. The soil data derived from the Soil Survey Geographic (SSURGO) database [19] were used to characterize the soil properties in the study area. The climatic data including daily temperature, precipitation, relative humidity, solar radiation and wind speed were obtained from the National Climatic Data Center (NCDC) weather station [20]. The atmospheric CO_2 concentration was set to 363 ppm, based on a 30 y (1981–2010) CO_2 concentration dataset [21].

The SWAT model has a default land cover/plant growth database (crop.dat) including land cover/plant growth parameters. In this study, the nutrients for crop cultivation were applied by the automatic fertilization options in the SWAT model.

2.3. Model calibration and validation

The SWAT model was manually calibrated by adjusting major parameters related to streamflow and sediment. As shown in Table 1, a total of fourteen parameters including twelve streamflow parameters and two sediment parameters were selected and adjusted within the range based on the SWAT manual [15] and previous studies [8,22,23]. Those streamflow and sediment parameters were adjusted from the SWAT initial values to fit the model simulations with the observed streamflow and sediment data.

The streamflow data measure from USGS stream gauge station (USGS 07288650) within the BPRW were used to calibrate and validate the model for streamflow. To calculate daily sediment load, an exponential load-discharge relationship was established using the suspended sediment sample data measured from 2005 to 2010 at the USGS stream gauge station (USGS 07288650). A strong correlation (R^2 = 0.9407) between the observed sediment and discharge was observed as shown in Fig. 2. These sediment data derived from the load-discharge relationship were used to calibrate and validate the model for sediment.

The SWAT model performance in this study was evaluated using multi-criteria statistical measures of the coefficient of determination (R^2), Nash–Sutcliffe coefficient (NSE), the ratio of the root mean square error to standard deviation error (RSR), and percent bias (PBIAS). A detailed explanation of these statistical evaluation methods can be found in Moriasi et al. [24].

2.4. Climate change scenarios

For future climate scenarios, the Geophysical Fluid Dynamics Lab (GFDL) CM2.1 global coupled climate model [25] included in the Intergovernmental Panel on Climate Change (IPCC) Fourth assessment report [26] was implemented as a general circulation model (GCM). The resolution of the land and atmospheric components of the GFDL CM2.1 is 2.0° × 2.5° (longitude × latitude); the atmospheric

Table 1
Calibrated values of parameters used during the SWAT model calibration

Parameter	Description	Range	Calibrated value
CN2	SCS runoff curve number for moisture condition II	35–98	Increased by 4%
SOL_AWC	Available soil water capacity (m/m)		Decreased by 17%
ESCO	Soil evaporation compensation factor	0–1	0.418
ALPHA_BF	Baseflow alpha-factor (d)	0–1	0.428
GW_DELAY	Groundwater delay time (d)	0–500	124
GW_REVAP	Groundwater ‘revap’ coefficient	0.02–0.2	0.19
GWQMN	Threshold water depth in the shallow aquifer for return to reach to occur (mm)	0–5,000	2,038
REVAPMN	Threshold depth of water in the shallow aquifer for re-evaporation to occur (mm)	0–500	44
RCHRG_DP	Deep aquifer percolation fraction	0–1	0.07
CH_N2	Manning’s roughness coefficient in main channel routing	–0.01–0.3	0.03
CH_K2	Effective hydraulic conductivity in the main channel (mm/h)	–0.01–500	5.26
SURLAG	Surface runoff lag coefficient	1–24	2.2
SPCON	Linear re-entrainment parameter for channel sediment routing	0.0001–0.01	0.0018
SPEXP	Exponential re-entrainment parameter for channel sediment routing	1–1.5	1.25

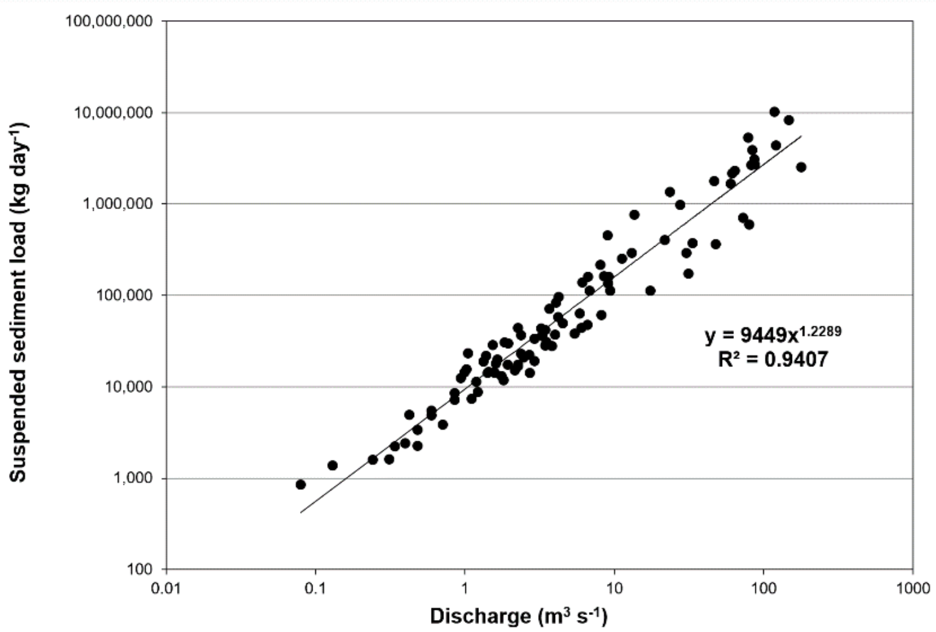

Fig. 2. The load-discharge relationship for suspended sediment at the stream gauge station (USGS 07288650).

model has 24 vertical levels [25]. Since the SWAT model needs daily time-series of weather as the main input data, the LARS-WG stochastic weather generator [27,28] was used to downscale the output of the GFDL CM2.1 in this study. The LARS-WG includes the statistical tests for statistical comparison of synthetic weather data produced by using the LARS-WG with parameters derived from observed data in the baseline period [29]. The χ^2 goodness-of-fit test was used to compare the probability distributions for the synthetic and observed data, whereas t and F tests were used to compare the means and standard deviations. The test values were considered to be significant at the 5% level [29].

Daily precipitation, and minimum and maximum temperatures, and daily solar radiation measured at weather stations within the study area were used for input data in the LARS-WG. The observed data from 1981 to 2010 were used to characterize the current climate. Thirty years of synthetic daily weather data were generated by the LARS-WG with parameters derived from the historical observations in the baseline period (1981–2010). Potential future climate scenarios were predicted for two time periods under the Special Report on Emissions Scenarios A1B: mid-21st century (2046–2065) with 541 ppm of CO_2 concentration and late-21st century (2080–2099) with 674 ppm. The A1B scenario describes a rapidly changing world with economic growth, population increase that then declines by 2100, and balance between supply sources and technological advancements to reduce the predominant reliance upon fossil fuel energy [26]. Relative humidity and wind speed were generated by the WXGEN weather generator [30] in the SWAT model.

2.5. Bioenergy crop production

In this study, it was assumed that all agricultural cropland for soybean, corn, rice, and cotton were converted to switchgrass in order to evaluate the impact of bioenergy crop production. To simulate cultivating switchgrass, the crop parameters for Alamo switchgrass in the SWAT model [15] were used for switchgrass. The planting and harvesting dates were assumed to be May 1 and November 1, respectively [8]. The automatic fertilization option within the SWAT model was applied for fertilizer application.

2.6. BMP representation in the SWAT model

In this study, terraces and contour farming practices were applied as BMPs. These practices were assumed to be implemented on agricultural lands including soybean, rice, corn, and cotton. Terraces are broad earthen embankments constructed across the slope to intercept runoff water and control erosion [4,31]. Implementation of contour farming practices in a field may lead to the decrease in surface runoff volume by impounding water in small depressions as well as the decrease in sheet and rill erosion by reducing erosive power of surface runoff and preventing or minimizing the development of rills [3]. To represent and simulate terracing and contour farming in the SWAT model, the values of the Soil Conservation Service (SCS) curve number (CN2) and the USLE support practice factor (USLE_P) was adjusted [32]. The values of CN2 were reduced by 3 and 5 from the calibrated values for contour farming and terracing, respectively [3,4]. The values of USLE_P were also modified depending on the slope of the HRU [4].

3. Results and discussion

3.1. Model calibration and validation

Daily streamflow and sediment yield simulations from SWAT were aggregated into monthly streamflow and sediment load for calibration and validation. In this study, the model performance during the calibration and validation periods was evaluated according to the criteria suggested by Moriasi et al. [24]. The model performance for streamflow during the calibration period (1996–2003) was determined to be very good with NSE (0.76), RSR (0.49), and PBIAS (–2.5%) as shown in Figs. 3 and 4. For the sediment yield, the model showed good performance (NSE = 0.66, RSR = 0.58, PBIAS = 16.2%). During the validation period (2004–2010), the model performance for stream flow was very good with NSE (0.78) and RSR (0.49) and good with PBIAS (–10.9%), while the performance for sediment yield was satisfactory with NSE (0.65) and RSR (0.60) and very good with PBIAS (11.1%). The statistical evaluation results and graphical comparisons showed that the simulated results for both streamflow and sediment agreed with observed values during both calibration and validation periods (Figs. 3 and 4).

3.2. Weather condition in the future periods

The data observed and simulated in the baseline period (1981–2010) were compared using the statistical tests in the LARS-WG model. The results showed no

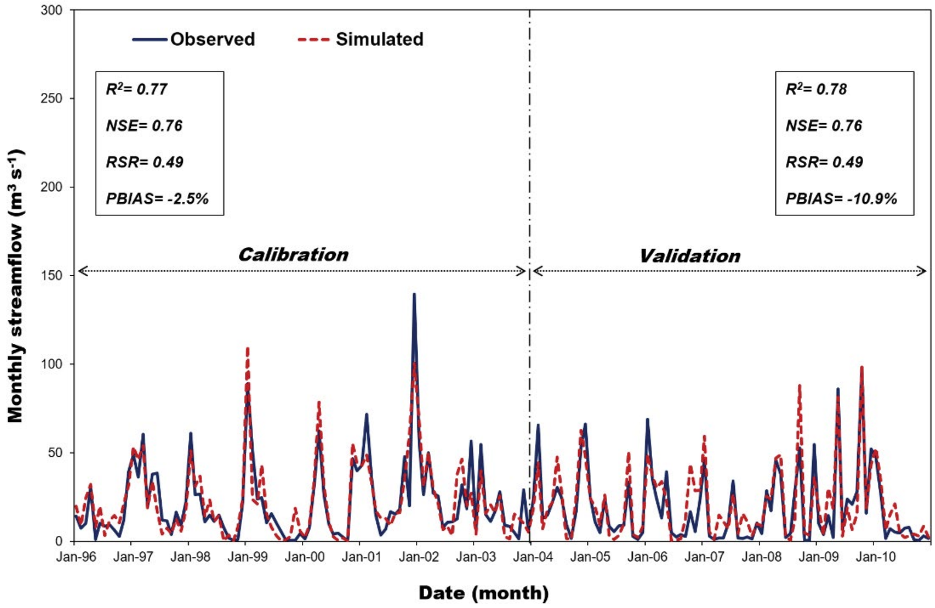

Fig. 3. Comparison of observed and simulated monthly streamflow for the calibration and validation periods at USGS gauge 07288650.

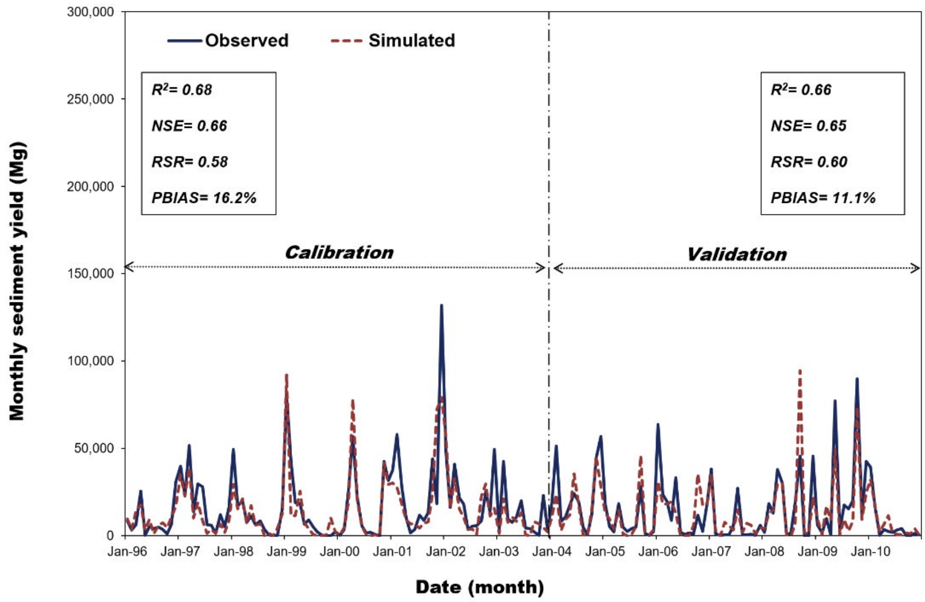

Fig. 4. Comparison of observed and simulated monthly sediment yield for the calibration and validation periods at USGS gauge 07288650.

significant difference between the observed and simulated data as *p*-values for all tests more than 0.05. These results indicate that the results derived from the LARS-WG model were acceptable to project climate change [29]. The average minimum and maximum temperatures in the future periods were projected to increase compared to the baseline period (Table 2). The annual precipitation tended to decrease by 12 mm in the mid-21st century (2046–2065) and 17 mm in the late-21st century (2080–2099). During May through July, the average monthly precipitation commonly decreased, whereas it increased from December to February (Fig. 5).

3.3. Impacts of climate change

As shown in Table 3, annual evapotranspiration (ET) in the future periods decreased due to an increase in CO_2 concentration, even with higher temperatures (Table 2). The increased atmospheric CO_2 concentrations resulted in a reduction of leaf conductance, leading to a decrease in ET [8,33]. The SWAT model used in this study does not simulate the impact of increased CO_2 concentration on leaf area index (LAI). Therefore, the results derived from this study are possible to overestimate ET reduction because the increase in LAI under increased CO_2 concentration can potentially offset the decrease in ET caused by the rising CO_2 concentration [8]. Despite annual precipitation decreased, the decreased ET led to an increase in surface runoff, resulting in an increase in sediment yield (Table 3). On a monthly basis, sediment yield shows a similar pattern to surface runoff (Fig. 6). Compared to baseline, the monthly sediment yield increased from August to April. Especially, the greatest changes in sediment yield and surface runoff were observed in December, January, and February due to increased precipitation in the future periods (Figs. 5 and 6). However, the monthly sediment yield from May through July decreased due to decreased precipitation (Figs. 5 and 6) although decreased ET alleviated the decrease in surface runoff.

3.4. Impacts of agricultural management strategy

When contour farming was applied in agricultural areas, annual ET was reduced and consequently annual

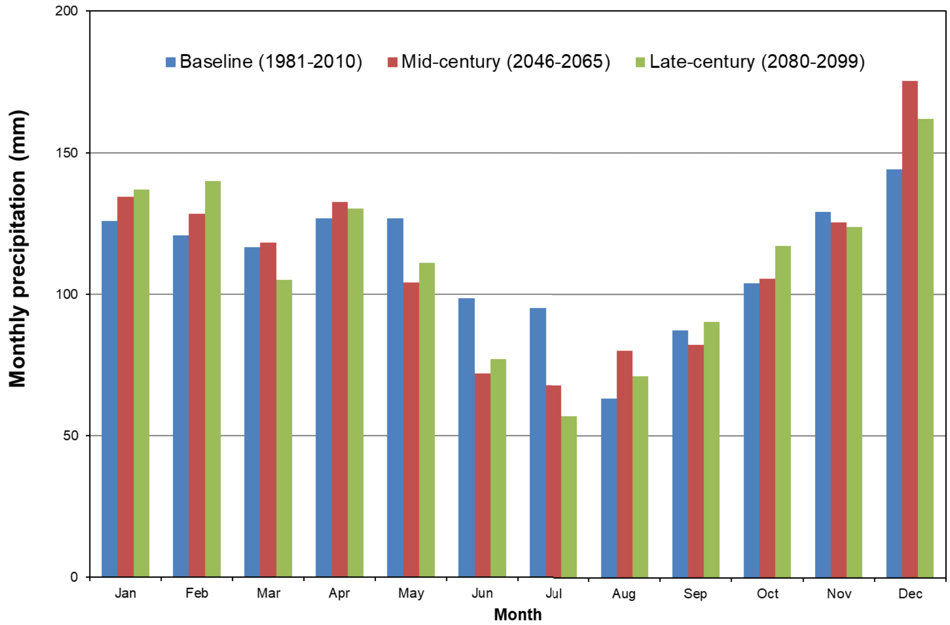

Fig. 5. Comparison of average monthly precipitation under baseline and various future scenarios.

Table 2
Average annual minimum and maximum temperatures, precipitation and CO_2 concentration in the BPRW under baseline and various future scenarios

Constituent	Baseline (1981–2010)	Mid-21st century (2046–2065)	Late-21st century (2080–2099)
Average minimum temperature (°C)	11.6	13.8	23.0
Average maximum temperature (°C)	23.0	25.3	26.2
Annual precipitation (mm)	1,339	1,327	1,322
CO_2 concentration (ppm)	363	541	674

Table 3
Annual water balance and sediment load yield under various sediment management strategies and climate scenarios

Climate scenario	Sediment management strategy	Precipitation (mm)	Evapotranspiration (mm)	Surface runoff (mm)	Sediment yield (Mg/ha)
Baseline (1981–2010)	Without management	1,339	790	512	11.79
	Contour farming	1,339	840	425	0.43
	Terrace	1,339	852	389	0.30
	Switchgrass	1,339	800	500	0.52
Mid-21st century (2046–2065)	Without management	1,327	761	537	16.92
	Contour farming	1,327	802	469	7.62
	Parallel terrace	1,327	819	430	2.19
	Switchgrass	1,327	770	527	1.09
Late-21st century (2080–2099)	Without management	1,322	753	541	16.45
	Contour farming	1,322	791	477	7.45
	Parallel terrace	1,322	806	438	1.80
	Switchgrass	1,322	762	530	1.03

surface runoff and sediment decreased (Table 3) since contour farming impounds the surface runoff and encourages infiltration as water ponds in the depressions [3]. Similar to terracing, the implementation of terraces to intercept runoff water and control erosion reduced surface runoff and sediment yield, whereas ET decreased (Table 3). Terraces may increase infiltration and thus plant available water, leading to an increase in ET [31]. When agricultural areas (95% of the total watershed area) were converted to grow switchgrass, annual ET increased, whereas surface runoff and sediment load decreased (Table 3). These results can be attributed to a higher LAI of switchgrass as well as a longer growing season than conventional crops, which may result in an increase in ET [7,8,34,35]. The higher LAI provides a greater area for interception of rainfall, which may reduce the effective rainfall energy of intercepted raindrops. Thus, the cover and management factor (USLE_C) was decreased, resulting in a reduction of sediment yield. Among all sediment management strategies, the highest sediment yield reduction (97.5%) was found in the implementation of terraces, while

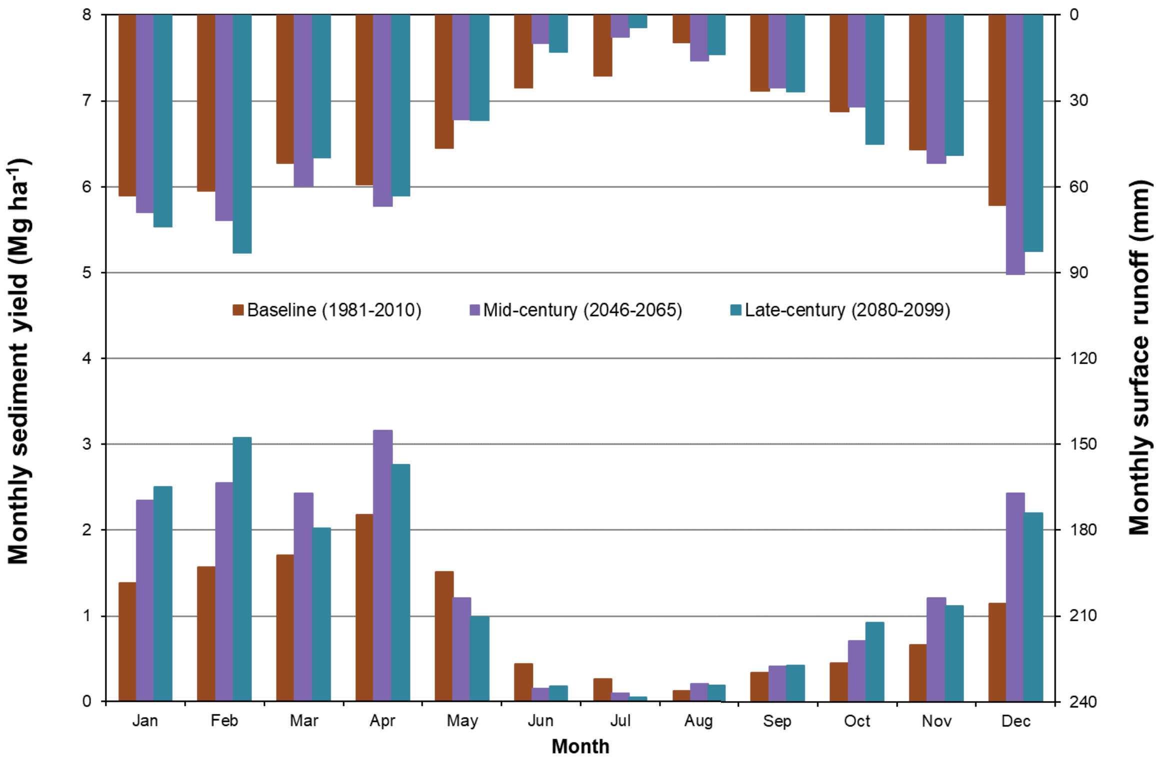

Fig. 6. Comparison of average monthly surface runoff and sediment yield under baseline and future climate scenarios.

the reduction rates by growing switchgrass and contour farming were 96.4% and 95.6%, respectively (Table 3).

3.5. Impacts of both sediment mitigation strategy and climate change

As agricultural areas were converted to switchgrass crop, average sediment reduction rates in the mid-21st century and late-21st century were 93.6% and 93.7%, respectively (Table 3), although it varied by sub-watersheds (Fig. 7). The reduction rates under two future climatic periods were similar to value (95.6%) when compared with the current climate condition (baseline) despite sediment yield under no management condition increased in the two future periods (Table 3 and Fig. 7). For terraces and contour farming, the large difference in reduction rate was found (Fig. 7). Compared to the baseline conditions, the sediment reduction rate decreased in the two future periods. The reduction rate decreased by 10% for terraces and 42% for contour farming. This large difference can be attributed to increased sediment yield and surface runoff because of increased precipitation from December to April

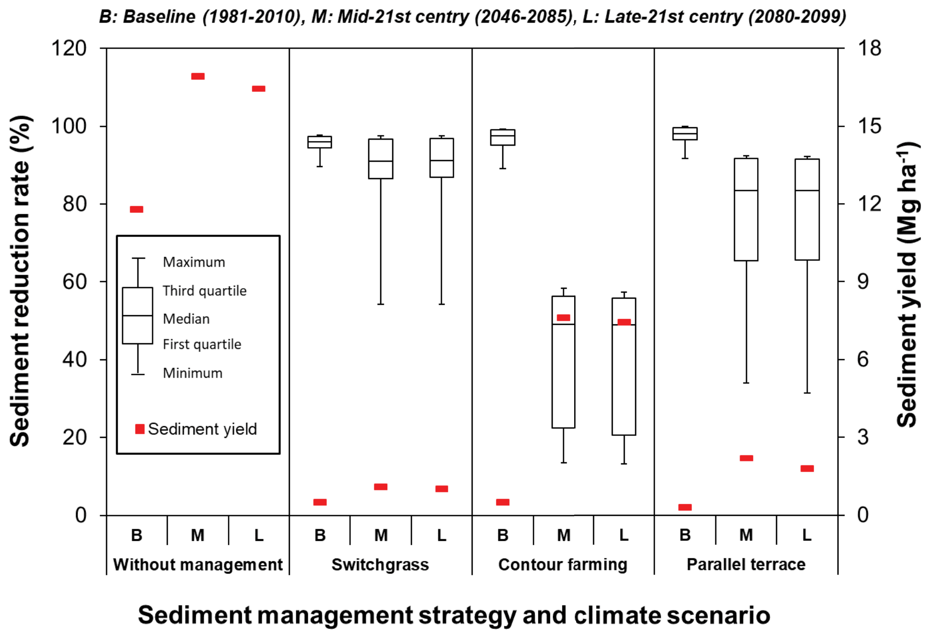

Fig. 7. Annual sediment yield and sediment reduction rate under various sediment management strategies and climate scenarios.

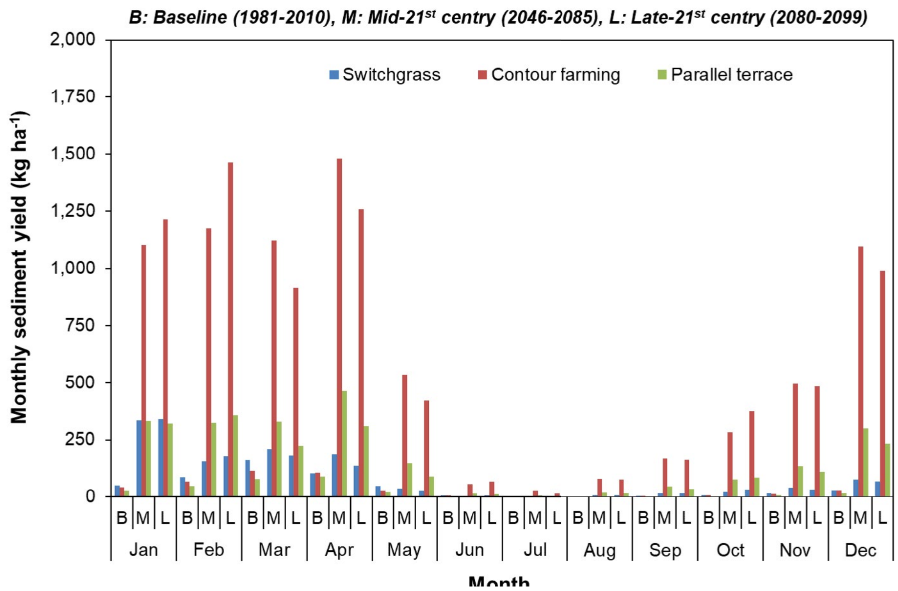

Fig. 8. Average monthly sediment yield under various sediment management strategies and climate scenarios.

(Fig. 6) when the crop residue and covered surface area were reduced due to the harvest of the crop. As shown in Fig. 8, the remarkable increase in sediment yield was found during December through April in two future periods.

The analysis of the coupled effects of future climate changes and sediment management strategies indicates that climate change affects the effectiveness of sediment management strategies and bioenergy crop production is the most effective strategy to reduce the sediment yield in the region where the increase in precipitation during the winter season or the non-growing season is projected in the future period.

4. Conclusions

In this study, the impacts of future climate changes and sediment management strategies on sediment yield were evaluated at the watershed scale using the SWAT model and LARS-WG stochastic weather generator. The changes in hydrologic components such as ET, surface runoff as well as sediment yield were analyzed based on the calibrated and validated SWAT model. The effectiveness of various sediment management strategies with future climate scenarios was also assessed.

The results from this study show that implementation of sediment management strategies including growing switchgrass with climate change may alter monthly and annual water balance and sediment yield as well as the sediment reduction rate. In addition, it was found that compared to terraces and contour farming, growing switchgrass can significantly reduce the sediment yield in the watershed where the increase in precipitation during the winter season or the non-growing season is projected in the future period, which has a positive environmental effect.

These results would help interested and involved watershed managers or policymakers to find the most effective sediment management strategy under various conditions including climate change in this watershed and/or in other similar watersheds.

This study, however, analyzed the environmental impact of sediment management strategies including growing switchgrass without evaluation of their economic feasibility. Since farmers will not grow bioenergy crops on their land unless they can ensure increased income from bioenergy crops, the economic feasibility as well as effectiveness should be evaluated when choosing effective strategies to reduce sediment. Thus, further research to evaluate both the environmental impact and economic feasibility is recommended.

Acknowledgments

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