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Response of Surface Runoff and Sediment to the Conversion of a Marginal Grassland to a Switchgrass (*Panicum virgatum*) Bioenergy Feedstock System

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Abstract: The land systems between the humid and arid zones around the globe are critical to agricultural production and are characterized by a strong integration of the land use and water dynamics. In the southern Great Plains (SGP) of the United States, lakes and farm ponds are essential components in the land systems, and they provide unique habitats for wildlife, and critical water resources for irrigation and municipal water supplies. The conversion of the marginal grasslands to switchgrass (*Panicum virgatum*) biofuel feedstock for energy production has been proposed in the region. However, we have limited experimental data to assess the impact of this potential land-use change on the surface runoff, which is the primary water source for surface impoundments. Here, we report the results from a paired experimental watershed study that compared the runoff and sediment responses that were related to the conversion of prairie to a low-input biomass production system. The results show no significant change in the relationship between the event-based runoff and the precipitation. There was a substantial increase in the sediment yield (328%) during the conversion phase that was associated with the switchgrass establishment (i.e., the site preparation, herbicide application, and switchgrass planting). Once the switchgrass was established, the sediment yield was 21% lower than the nonconverted watershed. Our site-specific observations suggest that switchgrass biofuel production systems will have a minimum impact on the existing land and water systems. It may potentially serve as an environmentally friendly and economically viable alternative land use for slowing woody encroachment on marginal lands in the SGP.

Keywords: biofuel; experimental watershed; switchgrass; southern Great Plains



Citation: Zou, C.B.; Lambert, L.H.; Everett, J.; Will, R.E. Response of Surface Runoff and Sediment to the Conversion of a Marginal Grassland to a Switchgrass (*Panicum virgatum*) Bioenergy Feedstock System. *Land* **2022**, *11*, 540. <https://doi.org/10.3390/land11040540>

Academic Editors: Todd Fagin, Kate Zeigler and Bruce Hoagland

Received: 19 November 2021

Accepted: 19 March 2022

Published: 7 April 2022

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1. Introduction

Carbon assimilation and ecosystem water use are tightly linked in the transitional land system between the semiarid and subhumid regions. Changes in the land use and ecosystem productivity will likely alter the ecosystem water use and the land and water system dynamics [1,2]. Water resources for environmental and municipal use in transitional land systems, such as in the southern Great Plains (SGP) of the United States, and similar transitional land systems between humid and arid zones around the globe, are critical to agricultural production and are vulnerable to land-cover and land-use alterations. Research in China and West Africa has determined that the water resources in transitional land systems are scarce, uncertain, and are relatively more sensitive to land-cover and land-use changes, with negative and positive effects, depending on the location [3,4]. The water yield is primarily dependent on the land use and the land cover in the surrounding area, but there are also continental and global influences [5].

Historically, vast grasslands were the main cover of the transitional land systems between humid and arid zones. Although the annual average precipitation in these land

systems may also support woody plant growth, the woody plant cover was confined by drought, fire, grazing, brush control, and soil characteristics [6,7]. Overgrazing, active fire suppression and exclusion, and the extinction, or near extinction, of native grazers result in woody plant encroachment in many grasslands across the globe [8], which usually adversely affect livestock production, water availability, and wildlife habitats [9–11].

The SGP encompasses 72.8 million hectares (ha) of land area and three major agricultural states: Kansas, Oklahoma, and Texas. There are three ecoregions in the SGP, including the Central Great Plains, the High Plains, and the Southwestern Tablelands [12].

Mixed-grass and shortgrass prairie ecosystems dominate, and they provide habitat for wildlife and outdoor recreational activities [13]. Grasslands are vital to the region's cattle production and they provide ecosystem services to rural communities and to the broader society. According to the 2017 Census of Agriculture, the regional agricultural commodity sales exceeded USD 51 billion [14], with livestock accounting for more than 71% of the total.

In recent decades, much of the SGP region, especially in Texas and Oklahoma, has faced the challenge of woody plant encroachment into grasslands [6]. Converting grassland to switchgrass (*Panicum virgatum*) stands has the potential to ease woody plant encroachment for two reasons: (1) Switchgrass can be mowed annually after its establishment, which can suppress the growth of woody plants; and (2) Switchgrass can be used as a bioenergy feedstock, which may provide an incentive for landowners to adopt this practice. However, it is unclear how this land conversion will impact the water resources in the region.

Runoff is the quantity of water that is discharged into streams from the land surface (surface runoff) and subsurface (interflow), usually in direct response to storm events. The runoff that is generated from grasslands is an essential source of water for the streams, farm ponds, reservoirs, and municipalities in the SGP [15–18]. The SGP has relatively low topographic relief, with marginal and often variable rainfall. The annual precipitation decreases from east to west [18]. Active management that is focused on the quantity and quality of the surface runoff is critical in order to ensure an adequate supply during droughts and to prevent flooding during fluvial events [18–21]. Consequently, this region has the highest density of surface impoundments in the United States that are constructed to store and confine runoff [15,22]. This unique hydroscape provides a wide range of social and ecological benefits, which are vulnerable to land-use and vegetation changes within the upland watersheds.

Plowing native sod for agricultural production led to one of the worst environmental disasters in the history of the SGP, which is known as the “Dust Bowl” [23]. Soil erosion by wind and water decreased the relative productivity of the land for crops. The total cultivated land area declined throughout the Great Depression and into today. Without irrigation, many cultivated lands only supported marginal crop production, and, upon the cessation of cultivation, these lands would return to prairie vegetation naturally, or after reseeding for rangeland use. Over 84.1 million hectares are enrolled in the Conservation Reserve Program (CRP) to help protect marginal lands from further erosion [24]. Established in 1985, the CRP pays participants an annual land rental value to remove highly erodible land from agricultural production, such as row crops, to perennial land cover for 10 to 15 years. The CRP was amended in 2002 to allow for the biomass harvesting of the grassland enrolled in the program under certain restrictions. With the societal demand for renewable energy sources that is driven by the Energy Independence and Security Act of 2007, CRP lands are also considered to be a potential source of herbaceous-based feedstock for biofuel. The SGP region has adequate precipitation and sufficiently productive soils for producing switchgrass, which is a perennial grass that is native to the area, and which is a species that has been identified as suitable for bioenergy production by the U.S. Department of Energy [24–26], in large part because of its high productivity. Switchgrass produced ~50% more aboveground biomass than the adjacent prairie in northcentral Oklahoma [1]. Growing energy crops on the marginal land in the SGP could reduce the government payments to the CRP land while sustaining the environmental benefits from perennial vegetation cover on highly erodible land.

The U.S. Renewable Fuel Standard (RFS) program of 2006 mandated the production of 4.92 billion gallons of advanced biofuels by 2019. This mandate targeted the production of 36 billion gallons of biofuel by 2022. The United States Department of Agriculture Biomass Crop Assistance Program (BACP, 2008) also compensates bioenergy crop producers for the establishment and the logistics costs to meet these goals. The gap between the current production level and the goal of cellulosic biofuel remains wide because of the uncertainty and risk that is associated with the cellulosic biofuel industry [27–30]. However, cellulosic biomass, such as switchgrass, is still cost-competitive among the renewable energy sources. The current U.S. administration is likely to extend the biofuel mandate to a later time. A substantial increase in marginal lands that are dedicated to producing cellulosic energy crops for second-generation biofuel is needed to meet the Renewable Fuel Standard (RFS) mandate [31].

Land-use-systems changes, including the conversion of large amounts of marginal land from its current uses to switchgrass production, could have extensive environmental impacts in the SGP because of the close interactions and feedback processes between human decisions and ecological functionality [32,33]. The quantification of the environmental response to land-use change is needed to balance the trade-offs between meeting the feedstock demand for bioenergy production and maintaining the ecosystem functions [34]. An evaluation of the environmental performance of energy feedstock production in the SGP, especially of water resources, is critical for the sustainable production of biofuel feedstock. The existing research finds that the water quality benefits that are associated with planting switchgrass on marginal lands are overwhelmingly positive, especially in terms of reducing the soil erosion and nutrient efflux [35–38]. Planting switchgrass to serve as berms or hedges is a common practice that is used to slow overland flow and to trap sediments and nutrients on cropland edges or stream banks [39–42]. As a conservation tool, switchgrass can be planted on highly erodible areas and marginal croplands to reduce the soil erosion and nutrient efflux [43,44]. While established switchgrass is known to reduce soil erosion in cropland systems, the response of converting grassland to switchgrass on the water quality and quantity is not known. In addition, the land preparation for planting switchgrass can be a period when the runoff generation and sediment losses are quite different from those of a fully established switchgrass production system [45]. Herbicide application to assist in the planting of switchgrass by no-till drilling after the mechanical removal of juniper trees (*Juniperus virginiana*) resulted in pulsed increases in the runoff and soil erosion at the watershed scale [46]; however, the responses of the runoff and sediment that are related to herbicide application and switchgrass planting in prairie have not been thoroughly quantified at the watershed level.

Planting perennial grasses on marginal land could improve or enhance watershed health [47,48]. However, research on how the production of switchgrass will affect water use is mostly inconclusive and site-specific. For example, the conversion of land from row crop to switchgrass production may reduce the amount of water that is used [49], but the conversion from pastureland to switchgrass could increase the water loss and could potentially generate negative externalities on the water systems [50,51]. Evapotranspiration (ET) is the most significant component of the water balance. It accounts for nearly 90% of the total precipitation in the rangelands in the SGP [52,53]. The most advanced micrometeorological method for the direct observation of the exchange of the water flux between the ecosystem and the atmosphere (eddy covariance technique) reported a higher peak and greater accumulated ET in the growing season for switchgrass than prairie [54], which indicates a potential reduction in the runoff with the conversion to switchgrass. A simulation that incorporated the switchgrass growth parameters and fertilizer application into the Soil and Water Assessment Tool, which is a prevailing hydrology model that is used to simulate the impact of the land use, the land management practices, and climate change on the water quality and quantity, from the small-watershed scale to the river-basin scale, suggests that switchgrass production on existing grassland would substantially reduce the streamflow (27.7%) at the subwatershed scale [55]. However, an increase in the ET during

the growing season may not necessarily translate into a reduction in the total runoff since the runoff in this system occurs mainly before or after the growing season. There were no empirical subwatershed scale measurements available to validate the model estimation in the SGP.

Economic opportunities are the main drivers for global land-use and land-cover change, and this is often at the cost of ecosystem services [56]. The growing interest in cellulosic biofuel and the national clean energy mandate could potentially convert a significant area of marginal land to switchgrass production in the water-scarce SGP region. This study aimed to advance our mechanistic understanding of the runoff and sediment responses to the conversion of a marginal grassland watershed to a switchgrass biomass production system in the SGP by using the paired experimental watershed approach. The objectives included: (1) Examining the change in the watershed hydrologic function by statistically testing the quantitative relationships of the event-based runoff and the sediment load from these two watersheds, and their interactions with the phases of the vegetation change (i.e., calibration, conversion, and switchgrass); (2) Improving the mechanistic understanding of the runoff generation potential by analyzing and comparing the monthly runoff coefficients between the paired watersheds; and (3) Comparing the accumulated runoff depth and the sediment yield to assess the water quality and quantity impacts during the switchgrass planting and after switchgrass establishment.

2. Materials and Methods

2.1. Study Site

The field study was conducted at the Oklahoma State University Range Research Station (OSU-RRS), which is a 2000 ha research facility that is located 15 km southwest of Stillwater, Oklahoma ($36^{\circ}3'46.73''$ N, $97^{\circ}11'3.33''$ W), and that is managed by the Oklahoma Agricultural Experiment Station. The two experimental watersheds were constructed on restored grassland in 2009. Both of the watersheds were cultivated for cotton in the 1930s, which resulted in severe soil erosion and led to subsequent terrace construction (Figure 1). When the cultivation ceased, the watersheds reverted to grassland (also called “prairie” to differentiate it from switchgrass). On the basis of the cover, the vegetation was composed of approximately 85% graminoid and 15% forb [1]. The watershed to the southwest was 2.28 ha, and the watershed to the northeast was 3.32 ha. The main soil types in this study area included the Stephenville–Darnell complex and Coyle loam, which accounted for 64 and 20%, respectively, for the watershed to the southwest, and for 67 and 14%, respectively, for the watershed to the northeast. Both soil types have loamy soils in the top 10 cm, which vary from fine sandy loam in the Stephenville–Darnell complex, to loam in the Coyle. The slopes of the watersheds were from 0 to 5%. The average soil depth was less than 1 m and was underlain by sandstone substrates. Both watersheds were well drained [52].

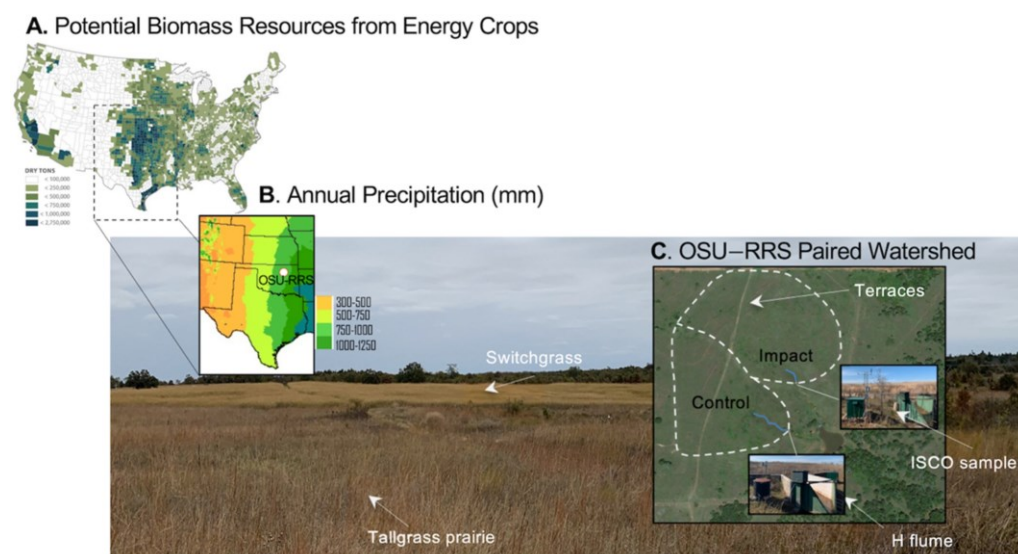


Figure 1. The southern Great Plains of the United States, which encompass Kansas, Oklahoma, and Texas: (A) The region that has the greatest potential biomass resources from energy crops in the United States adapted from the report by Union of Concerned Scientists [57]. A distinct precipitation gradient characterizes this region from over 1250 mm in the east to less than 500 mm in the west; (B) The study watersheds are located in the climate transition zone (750–1000 mm). Watershed boundaries were overlaid on a Google Earth image (2015) before the Impact Watershed was converted. Historic terraces are visible in the upper portion of both watersheds; (C) The watershed to the southwest was the Control Watershed, and the watershed to the northeast was the Impact Watershed, which was converted to a switchgrass production system in 2016. Runoff was gauged using USDA prefabricated H flumes and was subsampled for sediment analysis using the ISCO sampler (Model 3700C, Teledyne ISCO, Lincoln, NE, USA).

2.2. Treatment Design

The paired watershed approach was developed to detect the watershed-level responses that were associated with the land-use or vegetation change [58–60]. This approach involves at least one pair of watersheds, both of which are similar in size, topography, soils, and vegetation cover, and are near to each other or are under the same climatic conditions. The quantitative relationships of the runoff and the sediment loads from these two watersheds are initially established when the vegetation cover is relatively unchanged (i.e., during the calibration phase). After the calibration phase, one of the watersheds is treated as the Impact Watershed, while the other remains untreated as the Control Watershed. In this study, the watershed to the southwest was selected as the Control Watershed, and the watershed to the northeast was chosen as the Impact Watershed.

The Impact Watershed was treated with the herbicide, glyphosate, in 2016, in order to kill all the vegetation. The lowland “Alamo” switchgrass cultivar was seeded at a rate of 7.8 kg ha^{-1} , and at a depth of 0.64 cm, by using a Truax no-till drill machine in April 2017 (Table 1). No fertilizer was applied during the study period. The aboveground biomass of the Impact Watershed was cut at ~10 cm in height annually after the first frost and was removed. Both watersheds were fenced in order to prevent cattle grazing and trampling. The treatment period was further divided into a conversion phase and switchgrass-biomass-production phase in order to separate the effect of the temporal change that was associated with the site preparation from the more permanent change in the vegetation cover. The conversion phase lasted for 16 months, from the herbicide spraying and the switchgrass planting, until the switchgrass was fully established. The switchgrass phase covered two water years, from 1 October 2017 to 30 September 2019.

Table 1. Timeline of treatments for the Impact Watershed from water years 2015 through 2019. The three major phases were: calibration; conversion (disturbance and establishment); and switchgrass (established switchgrass).

Phase	Time	Impact Watershed
Calibration	October 2014–April 2016	Pretreatment
Conversion	May 2016–March 2017	Herbicide spray
	April 2017	Plant switchgrass
	May 2017–September 2017	Establishing switchgrass
Switchgrass	October 2017–September 2019	Established switchgrass

2.3. Precipitation and Runoff

The precipitation was measured by using a tipping bucket rain gauge (TB3, Hydrological Service America, Lake Worth, FL, USA) that was installed between the control and the Impact Watersheds' outlets. Each experimental watershed was gauged by using a 0.9 m prefabricated USDA H-flume (Figure 1B). The stage level in the flume was measured at 5 min intervals by using an optical shaft encoder with a minimum stage reading and resolution of 3.0 mm (50386SE-105, HydroLynx, West Sacramento, CA, USA). The stage-level readings were converted to discharge values by using the known stage–discharge relationship for the given H-flume. The discharge was converted to the runoff depth by using the watershed areas. The annual runoff, the treatment period, and the event-based values were generated by summing the 5 min data for the period of interest.

2.4. Event-Based Sediment Load

Each H flume was also equipped with an ISCO sampler (Model 3700C, Teledyne ISCO, Lincoln, NE, USA) to collect the runoff samples in order to analyze the total suspended solids. The runoff samples were collected by using an intake strainer at the bottom of a 16 cm polyvinyl chloride (PVC) trough. The samples were collected on the basis of a flow-weighted and time-weighted sampling strategy in order to trigger the runoff sample collection [46]. The total suspended solids were analyzed in the lab according to ASTM Standard: D3977-97 (ASTM, 2000) [61]. The samples were dried at 105 °C by using a VWR Horizontal Air Flow Oven for a minimum of 72 h.

2.5. Data Analysis and Statistics

We determined the treatment impacts by testing whether the linear relationship of the event-based runoff depths and the sediment loads between the Control Watershed and the Impact Watershed significantly changed among the calibration, conversion, and switchgrass production system phases. Specifically, we tested the significance of the changes in the slope and the intercept between the appropriate sets of regression lines among the phases by using “Proc Mixed” in SAS 9.4, and by using an analysis of covariance (ANCOVA) approach, where the phase was the class variable [62]. When the slopes were significantly different, we conducted pairwise comparisons among the three phases to determine the differences among them. In order to improve our mechanistic understanding of the runoff generation potential, we calculated the runoff coefficients, which are defined as the proportion of rainfall that becomes runoff, at both events and monthly time steps, and we compared them between the paired watersheds. The accumulated runoff depth and the sediment yield associated with the land-use conversion were calculated. Data were presented for two different water years in the switchgrass phase in order to illustrate the responses to the annual precipitation variability.

3. Results

3.1. Precipitation and Its Variability

Between 2014 and 2018, the precipitation ranged between 695 and 1014 mm y^{−1}, and it averaged 819 mm y^{−1}, which is lower than the long-term average of 939 mm y^{−1}

for the nearby Marena weather station from 1981 to 2010 [63]. The 2019 water year was exceptionally wet, with 1469 mm, which increased the precipitation average during the study period to 928 mm y^{-1} , which is similar to the long-term average. Additional details on the intra-annual precipitation are provided by Zhong et al. (2020).

3.2. Impact of Land-Use Change on Watershed Behavior

Before the herbicide application, the Impact and Control Watersheds were hydrologically similar. Where each precipitation event that generated runoff was a data point, there was a robust and linear relationship between the two watersheds for the runoff (Impact = $0.02 + 1.08 * \text{Control}$, $R^2 = 0.97$) and the sediment load (Impact = $-0.06 + 1.07 * \text{Control}$, $R^2 = 0.62$) (Figure 2). For the runoff, the slopes and intercepts of the relationship between the Impact and Control Watersheds during the conversion and switchgrass phases were not statistically different when compared to the relationship during the calibration phase ($p = 0.28$ for test among slopes; $p = 0.07$ for test among intercepts). The equations were as follows: Impact = $0.98 + 1.17 * \text{Control}$, $R^2 = 0.87$; and Impact = $0.49 + 1.18 * \text{Control}$, $R^2 = 0.99$, for the conversion and switchgrass phases, respectively (Figure 2).

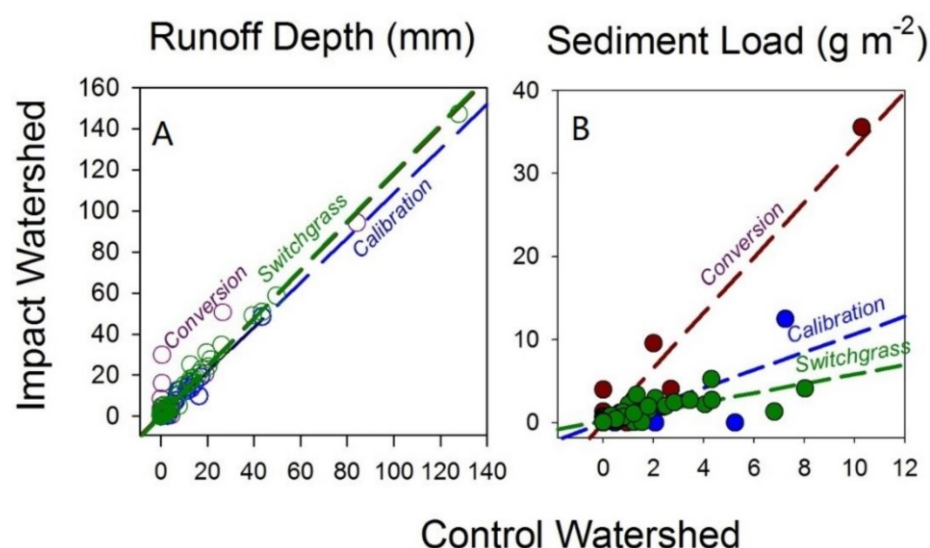


Figure 2. Relationships of event-based runoff and (A) sediment load (B) between the Control and Impact Watersheds during the calibration, conversion, and switchgrass phases.

In contrast, the sediment yield increased in the Impact Watershed during the conversion phase, and then decreased to levels below the calibration phase during the switchgrass phase. The slope between the Impact and Control Watersheds was significantly greater during the conversion phase than during the calibration ($p < 0.0001$) and switchgrass ($p < 0.0001$) phases. The slope was lower during the switchgrass phase than during the calibration phase ($p < 0.0001$). The equations were as follows: Impact = $-0.01 + 3.32 * \text{Control}$, $R^2 = 0.95$; and Impact = $0.11 + 0.56 * \text{Control}$, $R^2 = 0.66$, for the conversion and switchgrass phases, respectively (Figure 2). Because the slopes differed for the sediment yield, the differences among the intercepts were not tested. The net effect was that, for a similar precipitation event, the sediment load increased by 332% during the conversion phase compared to the calibration phase, but it was only 56% in the switchgrass phase compared to the calibration phase.

3.3. Runoff Coefficient

During the calibration phase, the monthly runoff coefficients varied greatly primarily in response to the precipitation pattern, with high coefficients during the rainy seasons in the spring and fall. The average coefficients (mean \pm SE) were $5.87 \pm 2.58\%$ in the Control

Watershed, which are comparable to the $6.06 \pm 2.86\%$ in the Impact Watershed (Figure 3). During the calibration phase, the accumulated runoff coefficient (accumulated runoff over accumulated precipitation) was 11.93% in the Control Watershed, which is similar to 13.02% in the Impact Watershed. During the conversion phase, there was an apparent increase in the runoff coefficient for the Impact Watershed during the summer months immediately after the herbicide application, while nearly no runoff occurred from the Control Watershed (Figure 3). The average monthly runoff coefficient was $5.74 \pm 3.22\%$ in the Control Watershed, compared to $11.16 \pm 4.67\%$ in the Impact Watershed. The accumulated runoff coefficient was 11.89% in the Control Watershed, compared to 18.82% in the Impact Watershed. During the switchgrass phase, the average monthly runoff coefficients were $4.15 \pm 1.94\%$ in the Control Watershed, which is similar to the $4.43 \pm 3.05\%$ in the Impact Watershed in the 2018 water year, which was a year with below-average precipitation. The monthly runoff coefficients greatly increased to $22.82 \pm 3.56\%$ and $30.79 \pm 4.44\%$ in the Control and Impact Watersheds, respectively, in the 2019 water year, which was a year with exceptionally high precipitation.

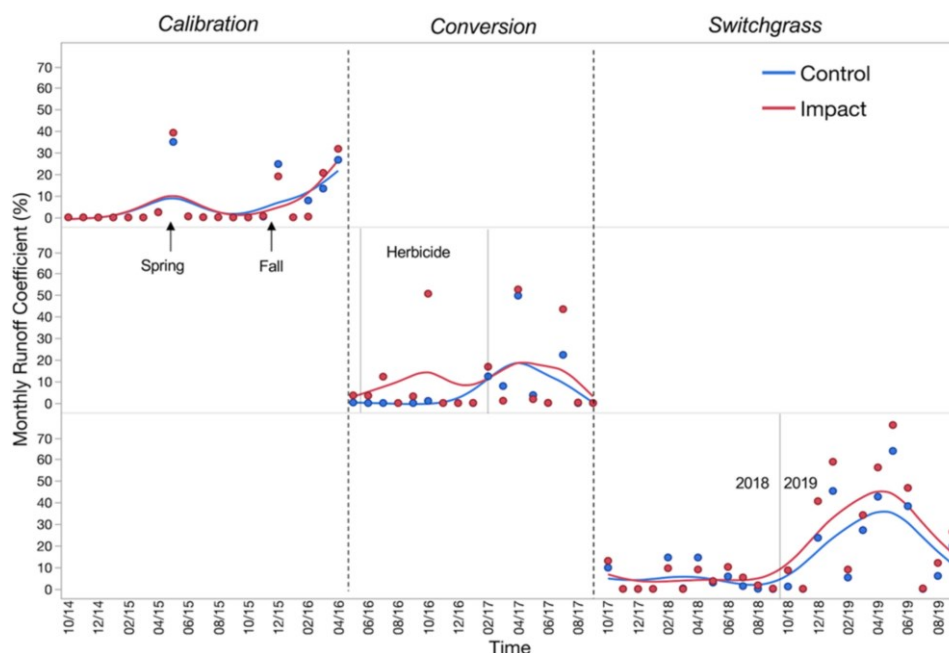


Figure 3. Comparison of monthly runoff coefficients between the Impact Watershed and the Control Watershed for each phase.

3.4. Accumulated Runoff and Sediment Responses

During the calibration period, the accumulated runoff and sediment yields were 173.4 mm and 25.3 g m^{-2} in the Control Watershed, respectively, which is comparable to the 189.3 mm and 23.7 g m^{-2} , respectively, from the Impact Watershed (Figure 4). During the conversion phase, the accumulated runoff and sediment yield were 162.9 mm and 18.4 g m^{-2} , respectively, from the Control Watershed, and were less than 257.8 mm and 60.6 g m^{-2} , respectively, from the Impact Watershed. The switchgrass phase encompassed two full water years: 2018 with slightly below-average precipitation (837.7 mm), and 2019 with extremely high precipitation (1509.8 mm , which is slightly higher than the 1469 mm for the 2019 calendar year). In 2018, the accumulated runoff and sediment yield were 47.7 mm and 5.6 g m^{-2} , respectively, from the Control Watershed, which is comparable to the 57.1 mm and 5.7 g m^{-2} , respectively, from the Impact Watershed. However, in 2019, the accumulated runoff and sediment yields were 503.2 mm and 48.0 g m^{-2} , respectively, from the Control Watershed, compared to 647.2 mm and 36.8 g m^{-2} , respectively, from the Impact Watershed. In summary, the sediment yield increased by 328% during the

conversion phase compared to the nonconverted watershed. Once the switchgrass was established, the sediment yield was 21% lower than the nonconverted watershed.

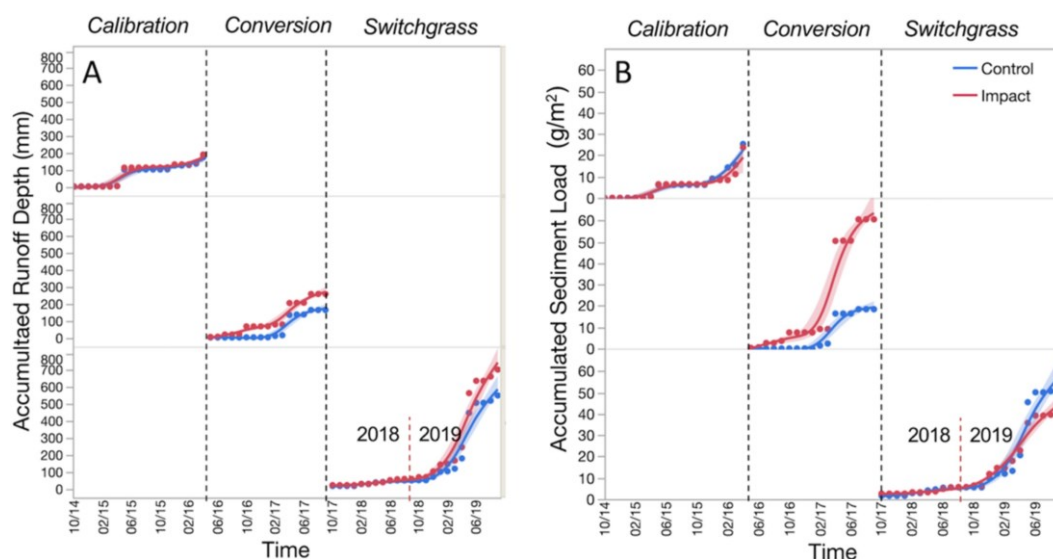


Figure 4. Comparison of accumulated runoff (A) and sediment load (B) between the Impact Watershed and the Control Watershed for each phase.

4. Discussion

4.1. Impact of Land-Use Change on Watershed Behavior

The Control and Impact Watersheds were hydrologically similar during the calibration phase. The strong linear relationship for the event-based runoff depths and the sediment loads between the two watersheds during the calibration phase made it possible to detect the changes in the hydrological behavior after the conversion from prairie to a switchgrass production system. There was no change in the relationship between the Control and Impact Watersheds during the conversion phase for the runoff, but the large relative increase in the sediment indicated a greater sediment load per unit of runoff, which was due to the lack of vegetation cover [17,64,65]. The failure to find increased runoff from the Impact Watershed during the conversion phase could be related to the fact that most runoff generation occurs during the dormant season, when the ET is minimal, regardless of the vegetation cover.

After the switchgrass was established, the relative runoff among the watersheds did not differ from that of the calibration phase. Since the annual aboveground productivity of the Impact Watershed was substantially greater than the grassland Control Watershed during the switchgrass phase [1], this indicated that the switchgrass was more efficient in that it used less water to produce more growth. One result that was somewhat surprising was that the sediment load was significantly lower in the planted switchgrass system, which contrasts with our general understanding of the coproduction between the surface runoff and the sediment loads. We speculate that the generally higher leaf area and biomass in the switchgrass stand likely reduced the rainfall splash erosion but did not affect the runoff pattern, compared with the prairie. The reduced erosion that was related to the switchgrass was similar to other studies [35,38], and it points to the potential of using switchgrass to reduce the sediment and nutrient efflux.

Increased species diversity and the variation in the vegetation structure in rangelands should be expected to reduce the “leaking” of the soil and water resources (e.g., runoff and sedimentation) [66,67]. Our switchgrass production system lacked the level of species, structural, and phenological diversity that was observed in the prairie watershed. The mostly bare interstitial spaces between the switchgrass clumps remained for five years after the establishment of the switchgrass stands. This interstitial space was associated with the initial planting pattern and it likely contributed to the watershed connectivity

of the flow pathways, which could have increased the overland flow and the runoff. In contrast, the average biomass of the prairie was relatively lower than the switchgrass. Where bare soil did occur in the prairie, it was exposed directly to rainfall, which increased the sediment load per runoff. To improve our mechanistic understanding of the runoff and sediment responses to switchgrass, future studies should explore the dynamics of the interstitial space and contrast the species, structural, and phenology diversity, as well as the heterogeneity and the variability in the infiltration capacity, between a prairie and a switchgrass monoculture system.

4.2. Responses of Accumulated Runoff and Sediment Yield

The annual runoff depth from the rangelands in the SGP is primarily controlled by the annual precipitation, which ranges from 125 cm in the mesic grasslands in the east, to less than 25 cm in the mixed grasslands and deserts to the west [68]. Under the same annual precipitation, the land-use or vegetation type can significantly alter the annual runoff depth, with grasslands having greater runoff than woodlands [52]. During the protracted drought period in the SGP between 2011 and 2014, the average annual runoff depth that was measured from four juniper woodland watersheds was only 9.8 mm, which is much less than the 31.9 mm from the three adjacent grassland watersheds in northcentral Oklahoma [53], which suggests that the vegetation type is tightly coupled with the runoff potential, and that the transition from grassland to juniper woodland could significantly exacerbate the water shortage during periods of below-average precipitation in this climate transition zone. Herbaceous-based biofuel feedstock production systems, such as switchgrass, can be considered as an alternative land-use option that can potentially slow juniper encroachment and sustain the hydrological function of the landscape.

Switchgrass biofuel production is an herbaceous-based system. This study shows that the prairie conversion to switchgrass has little impact on the runoff. If anything, a slight increase in the annual runoff depths was observed upon the conversion to switchgrass. Even though the slopes between the Control and Impact Watersheds in the switchgrass phase were not significantly different from those of the calibration phase, the accumulated runoff increased by around 10%, which was associated with the switchgrass conversion and was primarily due to the differences during the wetter 2019 water year. Likewise, the relative runoff did not statistically differ among the calibration and conversion phases, but the runoff coefficients were somewhat greater during the period immediately after the herbicide application. This fits with what is expected on the basis of previous studies, where the vegetation was either killed or removed [46]. The lack of differences in the runoff among the phases is likely due to the temporal variation in the responses that are related to the plant phenology, the time since treatment, or the precipitation regime. Likely, there are finer-scale processes that lead to differences in the runoff. However, at the watershed scale, and at the time scale that we used, these differences were not significant.

The amount of sediment loss was very low for both the grassland watersheds. The herbicide application period tripled the sediment yield, but the total sediment yield during the conversion phase was only 60.6 g m^{-2} , which is a level of limited soil erosion concern. In contrast, the same site preparation and planting practice in an adjacent watershed that was undergoing conversion from juniper woodland to switchgrass during the same period produced a sediment yield of 1329.5 g m^{-2} [46]. These results suggest that herbicide application in a watershed with high initial grass cover results in a much smaller increase in the sediment yield than does a site with very low initial grass cover (after removing all juniper trees, the ground was mostly bare or covered with duff). During the switchgrass phase (two years), the annual sediment yield for the Control Watershed was only 5.6 g m^{-2} , which is similar to the Impact Watershed's 5.7 g m^{-2} in the 2018 water year, and the 48.0 g m^{-2} and 36.8 g m^{-2} for the Control and Impact Watersheds, respectively, in the 2019 water year. While the runoff from the switchgrass watershed tended to be greater than the grassland watershed, the sediment yield was less.

4.3. Climate and Land Management Impact

During the extreme drought year of 2011, which had only 524 mm of precipitation (before the current study), the annual runoff depths (coefficients) were 0.6 mm (0.1%) and 2.8 mm (0.5%), respectively, for the two watersheds that were used in this study [53]. Similar low precipitation and runoff in 2012 led to a major reduction in the quantity and quality of the water flowing into the ponds, streams, and reservoirs in the region. In contrast, this study shows that, during the extremely wet 2019 water year, the annual runoff depths (coefficients) were 503.2 mm (33.3%) and 647.2 mm (42.9%), respectively, for the Control and the Impact Watersheds. This level of runoff caused extended flooding in many parts of the SGP in the early summer of 2019. The annual variability of the runoff depths and the coefficients at this magnitude requires proactive watershed management practices that utilize the intensive network of the surface impoundment infrastructure in order to store and confine the storm runoff.

Both watersheds were fenced and were excluded from grazing and fire. In practice, this represents conditions that are similar to CRP lands, but that may be different from working rangelands under grazing and fire management. Both grazing and fire management will remove a substantial portion of the biomass from the watershed and could potentially reduce the water loss from transpiration. In addition, switchgrass productivity is very responsive to nitrogen fertilizer, and fertilizer application may increase the water loss because of the transpiration from the increasing biomass production and the evaporation due to the greater canopy interception. Consequently, the impact of converting a working grassland to a high-input switchgrass biomass production system may differ from the results that we present here.

For the same reason, the benefit of sediment reduction may be underestimated. Switchgrass production has been proposed for a wide range of precipitation and rangeland conditions. The grassland watersheds that were used in this study were well vegetated, had very little bare soil, and had small background sediment loading during the calibration phase. In contrast, the bare soil and background sediment loading may be greater in working rangelands, and particularly in regions of lower precipitation. The impact of similar land-use changes under these conditions needs further study. However, our site-specific observations, as well as previous studies [1,52,53,62], strongly suggest that switchgrass biofuel production systems might provide an environmentally friendly solution for restoring and utilizing degraded rangelands, and that they could potentially serve as an economically viable alternative land use for marginal lands.

5. Conclusions

Located in a transitional land system between humid and arid zones, the SGP region of the United States has a substantial amount of marginal grassland that can be used to produce bioenergy feedstock, such as switchgrass. This research aimed to understand the land and water system dynamics following the conversion of marginal grassland to bioenergy crop production.

A paired experimental study was conducted to quantify and assess the short-term and long-term impacts of converting marginal grassland for low-input switchgrass biomass production on the runoff and sediment yield in the SGP. The sediment loads increased following the herbicide application period, but the magnitude was much less than those from the cropping systems under the same precipitation. The conversion of mesic grassland to a switchgrass production system does not substantially change the hydrological function, but it does reduce the sediment yield at the experimental watershed scale.

Water is an indispensable component in land and water systems. The actions in any one particular component in the system can often affect one or several other components, and changes in the land use or cover type are often considered to be land management tools that can be used to improve or sustain water resources. Surface impoundments are essential components in the transitional land systems in the SGP, and they provide unique habitats for wildlife and critical water resources for irrigation and municipal water supplies.

Woody plant encroachment is a primary driver of the land-cover change in the rangelands. This change can significantly alter the land and water system dynamics, which could result in a substantial reduction in the runoff that is available for lakes, streams, and farm ponds. This research shows that the SGP region has excellent potential to produce biofuel feedstock without detrimentally affecting the water resources, and while minimizing the dual stresses of woody plant encroachment and climate change. The research has important implications for the growth of bioenergy crops in the SGP and in similar transitional land systems in other countries and regions. The conversion of marginal grasslands to dedicated energy feedstock production systems can help to meet the biorefinery demand at a low cost, without competing for the arable land or water resources that are used to produce food.

Author Contributions: Conceptualization, C.B.Z. and R.E.W.; methodology, C.B.Z. and R.E.W.; formal analysis, C.B.Z. and R.E.W.; investigation, C.B.Z. and R.E.W.; resources, C.B.Z. and R.E.W.; writing—original draft preparation, C.B.Z.; writing—review and editing, R.E.W., J.E. and L.H.L.; visualization, C.B.Z. and J.E.; supervision, C.B.Z. and R.E.W.; funding acquisition, C.B.Z., R.E.W. and L.H.L. All authors have read and agreed to the published version of the manuscript.

Funding: This work is supported by the AFRI, grant no. 2019-68012-29819/project accession no. 1019523, McIntire Stennis OKL03151 and OKL03152, the Oklahoma Center for the Advancement of Science and Technology (project number PS20-015), and the National Science Foundation under Grant No. OIA-1946093, and the USDA-NIFA multistate Hatch Project: W4190.

Acknowledgments: We would like to thank Chris Stansberry and Adam Gourley for their assistance in cutting the juniper. We thank Gopal Kakani and Jay Prater, Senior Agriculturist, for their assistance in planting the switchgrass. We thank Elaine Stebler and Ben Ferguson for aiding in the collection and processing of the runoff and the sediment samples.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of the data; in the writing of the manuscript; or in the decision to publish the results.

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