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Strategic switchgrass (*Panicum virgatum*) production within row cropping systems: Regional-scale assessment of soil erosion loss and water runoff impacts

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Abstract

A strong need exists for tools to assess the efficacy of conservation practices across large regions supporting informed policy decisions that may lead to better soil and water conservation while optimizing agricultural production options. Perennial warm-season grasses (WSGs) such as switchgrass (*Panicum virgatum*), can be grown on marginally productive and/or environmentally sensitive lands to meet growing bioenergy demands while reducing water runoff and soil erosion compared to current row crop systems. Quantifying the soil and water conservation effects of WSG when strategically placed on the landscape would help support decisions favoring both economic and environmental benefits. We used the Daily Erosion Project (DEP) to simulate the effects of WSGs on hillslope water runoff and soil loss for 2008–2016 across eight major land resource areas (MLRA) in the Midwest United States. Four different scenarios (baseline or existing conditions and switchgrass grown on slopes $\geq 3\%$, $\geq 6\%$, and $\geq 10\%$) were modeled. Across all hillslope groups replacing row crops with switchgrass reduced yearly water runoff and soil loss by 3.2%–12.1% and 43.7%–95.5% compared with the baseline levels, respectively. Water and soil conservation efficiency (water runoff reductions or soil loss reductions associated with 1% increase in switchgrass coverage) increased with slope as $10\% > 6\% > 3\%$ for all MLRAs. Switchgrass replacement on slopes $\geq 10\%$ reduced average soil loss estimates as much as $22.6 \text{ Mg ha}^{-1} \text{ year}^{-1}$ for the most erosive MLRA (baseline soil erosion rate of $28.6 \text{ Mg ha}^{-1} \text{ year}^{-1}$) and resulted in all MLRA erosion estimates $\leq 6.0 \text{ Mg ha}^{-1} \text{ year}^{-1}$. For soil loss, an apparent interaction existed between slope group and total annual precipitation; as annual precipitation increased, the difference in soil loss between slope groups increased. Soil loss was more sensitive to these factors than was water runoff. Policy supporting a renewable energy industry while strategically improving soil and water resources seems globally advantageous.

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KEYWORDS

Daily Erosion Project, erosion, marginal land, perennial biomass crops, runoff, switchgrass, WEPP

1 | INTRODUCTION

A strong need exists for novel tools to assess the efficacy of conservation practices across large regions that support informed policy decisions. Informed policy may help lead to better soil and water conservation that concurrently optimize agricultural production options. Agricultural crop production faces many important environmental and economic challenges, one of the most serious is soil erosion. Land degradation caused by soil erosion has played and likely will continue playing a critical role in global food security (Amundson et al., 2015). Much of the world's most vulnerable land (Borrelli et al., 2017) is also associated with the most productive rainfed areas (Fischer, van Velthuisen, Shah, & Nachtergaele, 2002). Sustaining agriculture, the world's life support system, will depend on our ability to produce on these productive lands while sustaining these soil resources.

Most farm fields have neither uniform slopes nor uniform soil types, hence areas with high risk for soil and water loss are spatially distributed both within fields and across agricultural landscapes (Schumacher et al., 2005; Schumacher, Lindstrom, Schumacher, & Lemme, 1999). Extreme precipitation events, which are increasing in frequency due to climate change, further increase the spatial variability in runoff and soil erosion (Saunders, Findlay, Easley, & Spencer, 2012). Cropping systems that optimize both crop productivity and soil erosion control within spatially variable fields and across spatially variable landscapes are increasingly needed. Addressing these issues is complex. How science tools, policy, and economics interact to meet these needs was emphasized in the FAO Global Symposium on Soil Erosion in May 2019 dedicated to three themes: (a) use of data and assessment tools in soil erosion control; (b) policy in action to address soil erosion; and (c) the economics of soil erosion control and restoration of eroded land (Panagos, Borrelli, & Robinson, 2019).

Production of perennial biomass crops for use as biofuel feedstocks on environmentally vulnerable and/or unprofitable field areas (Acharya & Blanco-Canqui, 2018; Blanco-Canqui, 2010, 2016) has elements of each theme identified in Panagos et al. (2019). Strategically placed perennial biomass crops have the potential to enhance ecological services (Schulte et al., 2017), reduce soil erosion (Acharya, Blanco-Canqui, Mitchell, Cruse, & Laird, 2019; Cibir, Trybula, Chaubey, Brouder, & Volenec, 2016; Helmers et al., 2012), improve water quality (Zhou et al., 2014), improve soil properties (Blanco-Canqui, 2010), and improve overall farm profitability (Brandes et al., 2016). Furthermore, the disproportionate

benefit concept implies that relatively large ecological benefits can be obtained from integrating relatively small areas of perennial crops within row crop fields (Guo et al., 2018; Smith et al., 2013). This is based on the concept of diminishing marginal returns—the impact of initial inputs is high while impacts of additional inputs progressively decrease. The strategic placement of perennial biomass crops within fields and across agricultural landscapes is therefore hypothesized to disproportionately and favorably affect ecologically positive outcomes, while producing needed feedstock for an emerging biofuel industry and having a small or even favorable impact on the economic viability of farm operations.

Multiple field and plot studies illustrate the role of perennial vegetative filters in reducing sediment load in runoff water (Blanco-Canqui, Gantzer, Anderson, Alberts, & Thompson, 2004; Dillaha, Reneau, Mostaghimi, & Lee, 1988; Dillaha, Sherrard, Lee, Mostaghimi, & Shanholtz, 1989; Gharabaghi, Rudra, & Goel, 2006; Helmers et al., 2012; Pan et al., 2018; Robinson, Ghaffarzadeh, & Cruse, 1996). Perennial grasses are widely recognized for armoring soils against gully formation through the strategic placement of relatively small perennial grass waterways (Zaimis & Schultz, 2012). Also, the potential impact of row crop replacement with switchgrass on soil erosion rates at the field scale is well-established (Cooney et al., 2017). However, the regional-scale quantitative impact of perennial biomass crop replacement of row crops on soil conservation efficiency (SCE; change in soil loss/change in area planted to perennials) has not been determined and would be important in building informed policy related to soil resources and cropping systems. We anticipate that the law of diminishing returns is applicable for the efficiency of reducing soil loss through the strategic planting of perennials within row crop fields. The anticipated change in efficiency is further hypothesized to be mediated by slope gradient, slope length, and soil type differences.

Quantifying farm and regional-scale soil and water conservation associated with biofuel feedstock production has significant policy implications. To exemplify, in the United States, government subsidy support for farms requires limiting soil loss to tolerable levels, a term more often referred to as “cross compliance” (Natural Resources Conservation Service, 2017). Loss of subsidy support for commodity grain production due to excess soil loss could be economically devastating for farms, yet leaving large areas idle or unfarmed is also economically unpalatable; the potential for perennial biomass crop production in these areas to bolster income while favorably impacting soil conservation seems large, especially

if policy encouraged transitioning the vulnerable row cropped areas to biofuel feedstock production. Understanding where and how the strategic placement of perennials across different agricultural landscapes can maximize profitability by producing conventional crops and biofuel feedstocks while reducing soil erosion to acceptable levels would help meet global agronomic, biofuel, and ecological goals.

The Soil & Water Assessment Tool (SWAT model) has been used to estimate perennial biofuel crop impacts on soil loss and water dynamics for single watersheds (Feng et al., 2015; Gassman et al., 2017). These studies yielded evidence that the targeted use of perennial grasses can greatly reduce soil loss for the studied watersheds. Knowing whether these results are applicable for soil and water conservation at a regional scale that includes different physiographic areas and whether different topographies alter these relationships, adds another important dimension to understand the potential for the strategic placement of perennial biomass crops to help meet global soil and water conservation and long-term sustainability goals. This will require another level of dynamics not available in most currently used models.

Large-scale evaluation can be accomplished most efficiently through a modeling framework adapted to spatial land management options coupled with inputs impacting soil erosion and water runoff processes. The Daily Erosion Project (DEP; Gelder et al., 2017) offers current and archived spatial georeferencing of land, soil, and field cropping attributes accompanied by georeferenced precipitation files covering segments of the Central United States beginning in 2008. DEP estimates hillslope soil loss using the WEPP model and reports these estimates daily at the hydrologic unit code (HUC) 12 level (Seaber, Kapinos, & Knapp, 1987). DEP soil erosion estimates illustrate stark variations in soil loss between physiographic land regions and time periods. Comparing soil erosion and water runoff associated with traditional crop management to strategic placement of perennials offers a unique opportunity to evaluate large-scale land management practices using real-time spatial and temporal inputs. Furthermore, the geospecificity of data inputs allows testing impacts of strategic in-field management options in different physiographic regions, a critical step in prioritizing recommendations for future soil and water conservation efforts.

The overall goal of our research is to evaluate the use of the DEP and WEPP models as tools for regional-scale assessments of the efficacy of soil conservation policy options. The specific objectives of this study were to quantify, as a case study, the impact of the strategic conversion of row crops to switchgrass across eight different major land resource areas (MLRAs) in the Central United States for the 2008–2016 climate period on: (a) hillslope sheet and rill water erosion for different hillslope groups (baseline condition, slopes $\geq 3\%$, $\geq 6\%$, and $\geq 10\%$); (b) the efficiency of reducing soil and water loss as a function of switchgrass placement on different

hillslope gradients; and (c) the soil loss and water runoff interaction associated with switchgrass placement on different hillslope groups and precipitation amounts.

2 | MATERIALS AND METHODS

The modeled domain includes all or parts of eight MLRAs in the Midwest United States, an area that covers most of Iowa and portions of neighboring states (Figure 1). This area was selected because it fits within the modeled domain of the DEP and is dominated by row crop agriculture. This area is also a focal point for soil erosion and water runoff/water quality issues. MLRAs are geographically associated land resource units that are characterized by a specific combination of soils, topography, water, climate, vegetation, land use, and type of farming. Using defined spatial units with different topographies allows a deeper investigation and better understanding of where perennial grass treatments offer the greatest potential environmental benefits across this landscape and suggests potential use and impacts in other areas having similar characteristics outside the domain. A brief

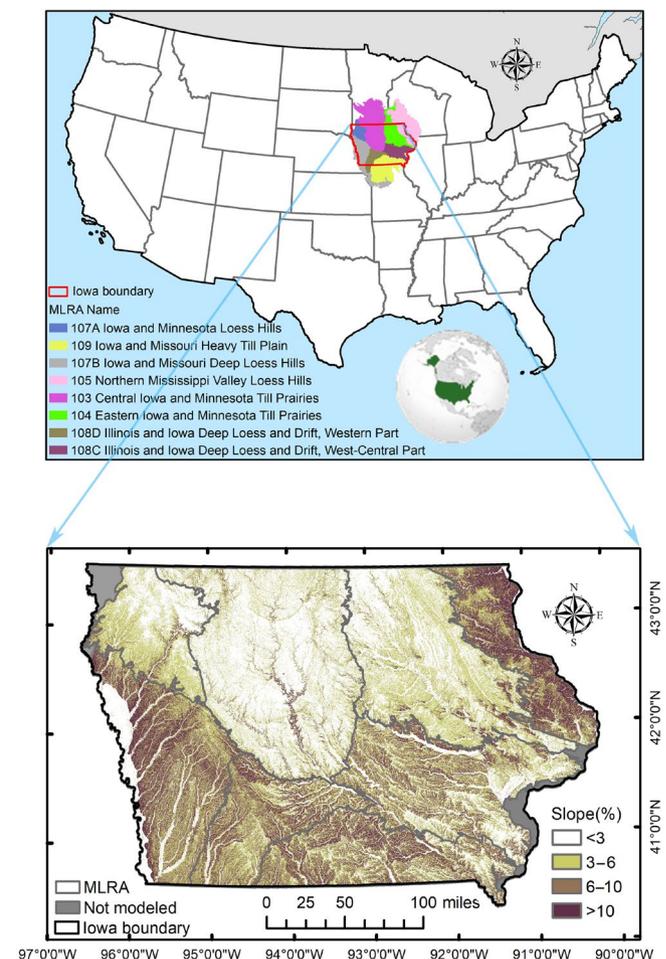


FIGURE 1 Locations of major land resource areas (MLRAs) modeled in this study and slope classifications within each MLRA

physiographic description of these eight MLRAs, obtained from U.S. Department of Agriculture (USDA) and Natural Resources Conservation Service (NRCS) (2006), is given in Table 1. Table 1 also includes information on the distribution of the different hillslope groups for each MLRA within the studied domain.

Each MLRA was further subdivided into HUC watersheds allowing increased spatial resolution of estimates and reporting of results. Hydrologic Unit Coding of watersheds is a hierarchical US Geological Survey system for identifying watersheds. Larger watersheds have fewer digits (fewer

watersheds in a region) and smaller watersheds have more digits in their HUC digital code. This study used HUC 12 watersheds, which have a 12 digit identifier, and, while they vary in size, the average HUC 12 watershed in the modeled domain was approximately 10,000 ha.

2.1 | Daily Erosion Project

The DEP is a regional modeling system that estimates hillslope sheet and rill soil erosion and reports hillslope erosion averages

TABLE 1 Brief description of the eight major land resource areas (MLRAs), percent of Daily Erosion Project (DEP) catchments containing row crops for the baseline condition and percent of DEP catchments in row crops that are converted to switchgrass within each hillslope group scenario

| MLRA | Brief description on geology, physiography, climate (annual average rainfall, AAR; annual average temperature, AAT) and soil | Baseline row crop coverage (%) | Row cropped hills converted to switchgrass (%) | | |
|---|---|--------------------------------|--|-----|------|
| | | | Hillslope groups | | |
| | | | ≥3% | ≥6% | ≥10% |
| Central Iowa and Minnesota Till Prairies (103) | Level to gently rolling glaciated till plain with relief less than 3–6 m, some valleys are 50 m or more below the adjoining uplands; AAR: 585–890 mm; AAT: 6–10°C; Mollisols, and lesser Alfisols, Inceptisols | 93 | 57 | 29 | 14 |
| Iowa and Minnesota Loess Hills (107A) | Undulating to rolling glaciated plain with relief of 3–30 m, some valley floors are 25–60 m below the adjacent uplands, some upland flats and valley floors are 1–2 m; AAR: 660–790 mm; AAT: 7–9°C; Mollisols | 91 | 65 | 39 | 24 |
| Eastern Iowa and Minnesota Till Prairies (104) | Level to gently rolling glaciated plain with long slopes with relief of 3–6 m, Karst topography is common; AAR: 735–940 mm; AAT: 7–10°C; Mollisols and Alfisols | 89 | 63 | 36 | 22 |
| Iowa and Missouri Deep Loess Hills (107B) | Rolling to hilly with relief of 3–30 m, some valley floors are 25–90 m below the adjacent uplands, some upland flats and valley floors are 1–2 m; AAR: 660–1,040 mm; AAT: 8–13°C; Mollisols and lesser Alfisols, Entisols | 88 | 76 | 63 | 47 |
| Illinois and Iowa Deep Loess and Drift West-Central Part (108C) | Rolling to hilly with relief of 3–6 m, some valley floors are 25–60 m below the adjacent uplands, some upland flats and valley floors are 1–2 m; AAR: 840–965 mm; AAT: 8–11°C; Mollisols, and lesser Alfisols, Entiesols, Inceptisols | 75 | 73 | 55 | 38 |
| Illinois and Iowa Deep Loess and Drift Western Part (108D) | Rolling to hilly, with relief of 3–6 m, some valley floors are 25–60 m below the adjacent uplands, some upland flats and valley floors are 1–2 m; AAR: 840–940 mm; AAT: 9–11°C; Mollisols and Alfisols, lesser Entiesols | 58 | 81 | 67 | 49 |
| Northern Mississippi Valley Loess Hills (105) | Gently sloping to rolling summits with relief of 3–6 m, some valley walls along streams are 15–30 m, some are 75 m on the Mississippi River bluffs; AAR: 760–965 mm; AAT: 6–10°C; Alfisols and Entiesols, lesser Mollisols | 52 | 84 | 66 | 48 |
| Iowa and Missouri Heavy Till Plain (109) | Rolling hills with relief of 3–6 m, some valley floors are 25–50 m below the adjacent uplands, some upland flats and valley floors are 1–2 m. AAR: 865–1040 mm; AAT: 9–12°C; Mollisols and Alfisols | 41 | 75 | 60 | 45 |

at the HUC 12 watershed scale on a daily time step (Gelder et al., 2017). DEP has four principal components: (a) the Water Erosion Prediction Project (WEPP) model (Flanagan, Gilley, & Franti, 2007; Flanagan & Nearing, 1995); (b) soil, topography and land management input data files; (c) meteorological input data files; and (d) a stratified random hillslope sampling scheme that supports scaling of daily sheet and rill hillslope soil erosion estimates to the HUC 12 watershed scale. Unique to DEP are detailed remotely sensed and electronic database inputs required to run WEPP daily for each of approximately 200,000 randomly selected hillslopes across the modeled domain.

System inputs are georeferenced and form temporally specific data layers; this structure allows substitution of a scenario specific data layer for an existing, or baseline data layer input. For this study, the archived cropping practices data layer (baseline condition) for the time period 2008–2016 was replaced with specific data layers needed to address the scenarios identified in the objectives. That is, the existing, or baseline, cropping practices on slopes $\geq 3\%$, $\geq 6\%$ and $\geq 10\%$, were replaced with switchgrass production for subsequent model runs but otherwise using all other archived inputs for the 2008–2016 period.

2.1.1 | WEPP model

The WEPP model is a physically based distributed parameter soil erosion estimating system developed by the US Department of Agriculture since 1985 that has been extensively used to predict the impact of management on runoff and sediment yield. Hillslope sheet and rill erosion processes are estimated along topographically determined water flow paths. Details of the WEPP model can be found in Flanagan and Nearing (1995) and Flanagan et al. (2007). DEP enlisted the WEPP hillslope model due to its physically based processes, rigorous testing, and capacity to simulate event-based erosion using high temporal resolution rainfall input data (Gelder et al., 2017).

2.1.2 | Soil, topography, and land management data

The soil data layer was obtained from the US Soil Survey Geographic Database, which includes gridded soil information at a 10 m resolution. Information on topography, soil types, and crop management for each hillslope was obtained from Landsat satellite imagery of land cover, light detection and ranging (LiDAR) surface elevations, the USDA NASS Cropland Data Layer, and the USDA Soil Survey Geographic database. Information on field boundaries and crop rotation practices was obtained from the Agricultural Conservation Planning Framework (Tomer et al., 2015).

Within the DEP model, each HUC 12 watershed is subdivided into smaller watersheds, or catchments. One randomly selected georeferenced hillslope within each catchment is selected for each daily WEPP soil erosion estimate and these estimates across all catchments within each HUC 12 watershed are averaged to obtain the reported HUC 12 soil erosion value. Elevations along each hillslope were estimated using LiDAR, yielding complex slope configurations for the WEPP model runs. Hillslope gradients were based on elevation and horizontal spatial difference from the top to the bottom of each hillslope. These hillslope gradients are the basis for identifying hillslope gradient frequencies within each MLRA, and for identifying the spatial placement of switchgrass for the modeled scenarios.

2.1.3 | Meteorological data

Meteorological data such as daily maximum and minimum temperature, daily solar radiation, daily average wind speed, daily average dew point temperature, and 2 min precipitation estimates are needed as inputs for the model. Estimates of meteorological parameters were obtained from the Iowa Environmental Mesonet and gridded to 0.25° by 0.25° spatial resolution. Precipitation data were obtained from the National Oceanic and Atmospheric Administration Multi-RADAR Multi-Sensor RADAR-Only “Q3” product that were gridded to 0.01° by 0.01° resolution. The 2 min temporal data on precipitation were processed to obtain 1 mm intensities for every 2 min time period across the temporal and spatial domains. Across the study domain, the 30 year annual average precipitation is 820 mm. For the modeled time period, the annual average precipitation across the domain was 963 mm with the lowest annual amount (2012) of 640 mm and the highest of 1,280 mm (2010). The area is well suited for warm season grass production and prior to European settlement was covered with mixed prairie vegetation.

2.2 | Scenario modeling

Cropping practices within the eight MLRAs were modified to meet the project objectives. Four different scenarios identified in this project's objectives were used to test the soil erosion impact of replacing the baseline land cover, dominated by row crops, with switchgrass on different hillslope groups. The amount of row crops in a specific area varied between MLRAs for the baseline condition (Table 1). Using archived soil, topography, climate, and land management data, we replaced existing or baseline cropping systems with switchgrass on slopes $\geq 3\%$, $\geq 6\%$ and $\geq 10\%$.

A custom WEPP plant file was created for switchgrass grown for biomass. The WEPP plant database was used to guide selection of reasonable plant parameter values. Procedures for the WEPP model plant growth calibration described by Flanagan, Frankenberger, Cochrane, Renschler, and Elliot (2013) were followed to create switchgrass plant inputs that approximated those observed in field experiments. Specifically, we selected a Biomass Energy Ratio (35 kg/MJ), the crop parameter for converting absorbed photosynthetic active radiation to biomass, that resulted in a WEPP model prediction of 12 t ha⁻¹ year⁻¹ of switchgrass biomass production, which has been obtained with fertilization in observed data. The maximum canopy height was increased to 1.8 m and the rooting depth was also increased to 1.5 m; these values are well within those observed in field studies of switchgrass production (Lemus et al., 2002). The maximum Leaf Area Index was also increased to 9.0 (Kiniry, Tischler, & Van Esbroeck, 1999). Annual late fall biomass harvest was modeled.

2.3 | Estimation of water and soil conservation efficiencies

Water conservation efficiency (WCE) and SCE were defined as reduction in runoff or soil loss per 1% change of switchgrass coverage; and were calculated in % using Equations (1) and (2) below, respectively:

$$\text{WCE} = 100\% \times \frac{(\text{Runoff}_{\text{baseline}} - \text{Runoff}_{\text{scenario}}) / \text{Runoff}_{\text{baseline}}}{\text{Switchgrass coverage}_{\text{scenario}}}, \quad (1)$$

where WCE is water conservation efficiency, %; Runoff_{baseline} is runoff from the baseline scenario, mm; Runoff_{scenario} is runoff from scenarios with hillslope groups ≥3%, ≥6%, ≥10%, respectively, mm; Switchgrass Coverage_{scenario} is the proportion of switchgrass area to total land area of each MLRA for scenarios with hillslope groups ≥3%, ≥6%, ≥10%, respectively, %, and is equal to “Row crop coverage (%) × Row cropped hills converted to Switchgrass (%)” (Table 1).

$$\text{SCE} = 100\% \times \frac{(\text{Soil loss}_{\text{baseline}} - \text{Soil loss}_{\text{scenario}}) / \text{Soil loss}_{\text{baseline}}}{\text{Switchgrass coverage}_{\text{scenario}}}, \quad (2)$$

where SCE is soil conservation efficiency, %; Soil loss_{baseline} is soil loss from the baseline scenario, Mg ha⁻¹ year⁻¹; Soil loss_{scenario} is soil loss from scenarios with hillslope groups ≥3%, ≥6%, ≥10%, respectively, Mg ha⁻¹ year⁻¹; Switchgrass coverage_{scenario} is proportion of switchgrass area to total land area of each MLRA for scenarios with hillslope groups ≥3%, ≥6%, ≥10%, respectively, %, and is equal to “Row crop coverage (%) × Row cropped hills converted to Switchgrass (%)” (Table 1).

2.4 | Statistical analysis

Linear regression analysis was used for characterizing the average reduction of water runoff and soil loss relative to baseline conditions with increasing switchgrass coverage. Linear and power regression analyses were used to investigate the relationship between water runoff and soil loss as a function of annual rainfall, respectively, for the four different scenarios across all MLRAs and through the 2008–2016 time period. Relationship differences between scenarios were compared by using the general linear model method. For power curve comparisons, logarithmic transformations were needed to convert nonlinear relationships to linear relationships. Relation significance and relationship differences between scenarios were conducted based on a 95% confidence level ($p < .05$) with SPSS 19.0 for windows (SPSS Inc.).

3 | RESULTS

The eight MLRAs differ in both physiography and land use. The three MLRAs with the least baseline row crop (MLRA 108D, 105, and 109) had 45% or more of their randomly selected DEP catchments with hillslope gradients greater than 10% (Table 1). However, the Iowa and Missouri Deep Loess Hills MLRA (107B), which had the greatest soil erosion and water runoff potential, had relatively high row crop coverage (88%) even though much (>47%) of MLRA 107B has slope gradients greater than 10%. At the opposite end of the slope spectrum, the Central Iowa and Minnesota Till Prairies (MLRA 103) had flatter topography (only 14% of MLRA 103 has slope gradients ≥10%) and were almost entirely of row crop agriculture (93%).

3.1 | Water runoff

Water runoff estimates for each MLRA were reduced by replacing row crops with switchgrass on sloping land for all hillslope scenarios (Table 2; Figure 2). Runoff estimates for the hillslope scenarios ranged from 87.9% to 96.8% of the runoff estimated for the baseline condition, indicating a relatively low impact of strategic switchgrass placement on water runoff. The low effect on runoff was even observed with more than 80% switchgrass replacement of row cropped hillslopes (MLRAs 108D and 105 for switchgrass on slopes ≥3%; see Tables 1 and 2).

The greatest row crop replacement water runoff impact occurred for Iowa and Missouri Deep Loess Hills (MLRA 107B; Table 2), which had 88% row crop coverage for the baseline condition, and 76%, 63%, and 47% of hillslopes converted to switchgrass for the ≥3%, ≥6%, and ≥10% scenarios,

TABLE 2 Runoff (mm/year) averaged over 2008 to 2016 for each major land resource area (MLRA) and different hillslope group scenarios. Numbers in parentheses identify runoff (%) relative to the baseline condition

| MLRA | Baseline | Hillslope groups | | |
|--|----------|--|------------------|-------------------|
| | mm/year | $\geq 3\%$ slope mm/year (% compared to baseline) | $\geq 6\%$ slope | $\geq 10\%$ slope |
| Central Iowa and Minnesota Till Prairies (103) | 108.83 | 99.32 (91.3) | 100.27 (92.1) | 101.01 (92.8) |
| Iowa and Minnesota Loess Hills (107A) | 120.38 | 110.49 (91.8) | 111.63 (92.7) | 112.49 (93.4) |
| Eastern Iowa and Minnesota Till Prairies (104) | 130.15 | 123.68 (95.0) | 123.57 (94.9) | 123.68 (95.0) |
| Iowa and Missouri Deep Loess Hills (107B) | 153.91 | 135.27 (87.9) | 136.28 (88.5) | 137.87 (89.6) |
| Illinois and Iowa Deep Loess and Drift, West-Central Part (108C) | 150.31 | 141.72 (94.3) | 141.26 (94.0) | 141.20 (93.9) |
| Illinois and Iowa Deep Loess and Drift, Western Part (108D) | 157.48 | 144.25 (91.6) | 144.99 (92.1) | 146.53 (93.0) |
| Northern Mississippi Valley Loess Hills (105) | 136.95 | 132.03 (96.4) | 131.79 (96.2) | 132.37 (96.7) |
| Iowa and Missouri Heavy Till Plain (109) | 165.92 | 160.62 (96.8) | 160.47 (96.7) | 159.87 (96.4) |

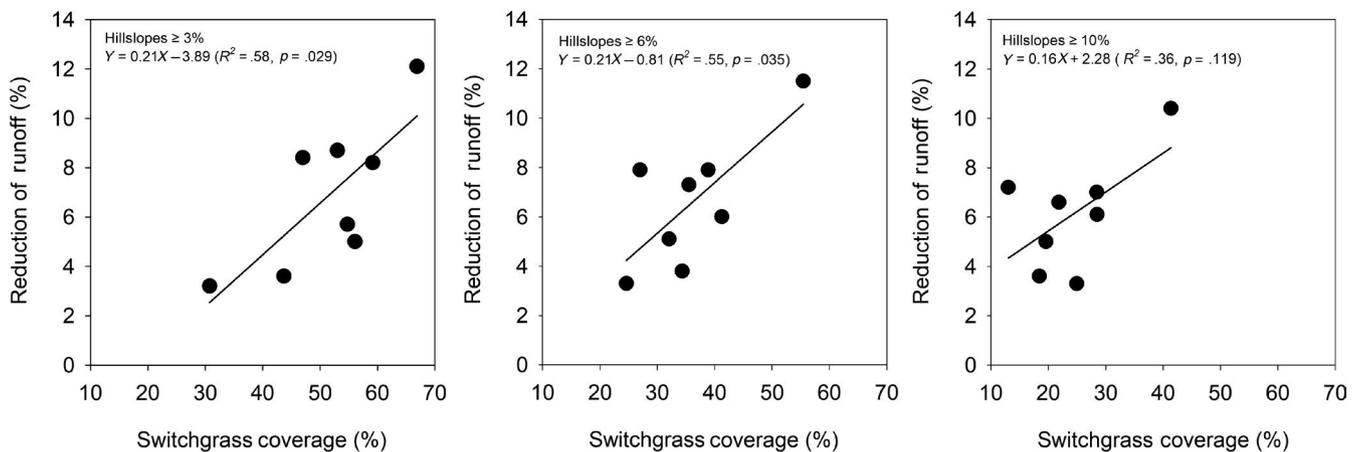


FIGURE 2 Effects of switchgrass coverage on reduction of runoff relative to baseline for the three hillslope groups averaged for each of the eight major land resource areas over the 2008–2016 time period

respectively. While less water runoff was estimated with increasing switchgrass coverage for each hillslope scenario across all MLRAs (Figure 2), this relationship was significant only for the $\geq 3\%$ and $\geq 6\%$ scenarios. However, the $\geq 10\%$ scenario had the greatest WCE value for each MLRA (Table 3).

3.2 | Soil loss

Soil loss estimates were much more sensitive to switchgrass replacement scenarios than were runoff estimates. Soil loss estimates were no more than 56.3% of that for the baseline condition across all MLRAs and hillslope scenarios (Table 4). Switchgrass replacement had the greatest impact on the MLRAs (107B, 108C, 108D, and 105) that were most vulnerable to erosion. These four vulnerable MLRAs had average baseline soil loss estimates exceeding what is considered tolerable ($11.2 \text{ Mg ha}^{-1} \text{ year}^{-1}$)

by the USDA for soils in this region. For these vulnerable MLRAs, switchgrass replacement on hillslopes with slope gradients $\geq 10\%$ lowered soil loss estimates to less than 33.3% of the baseline and well below the tolerable soil loss rate (Table 4). Across these vulnerable MLRAs, the average soil erosion rate was 28.6% of baseline when slope gradients $\geq 10\%$ were treated, even though less than 50% of the row crop hillslopes were converted to switchgrass across these MLRAs (Table 1). Replacement of row crops with switchgrass in the less vulnerable MLRAs (103, 107A, 104, and 109) reduced average soil erosion losses to a lesser extent than observed for the more vulnerable MLRAs. Average soil loss for the least vulnerable MLRAs was 47.5% of the baseline when row crops were converted to switchgrass on 26.3% of the hillslopes for the $\geq 10\%$ scenario (Table 1). For the least vulnerable MLRAs, the estimated average soil erosion loss of the baseline condition was already below the tolerable soil loss rate.

| MLRA | WCE (%) | | | SCE (%) | | |
|--|------------------|------|------|------------------|------|------|
| | Hillslope groups | | | Hillslope groups | | |
| | ≥3% | ≥6% | ≥10% | ≥3% | ≥6% | ≥10% |
| Central Iowa and Minnesota Till Prairies (103) | 0.17 | 0.29 | 0.55 | 1.42 | 2.14 | 3.47 |
| Iowa and Minnesota Loess Hills (107A) | 0.14 | 0.20 | 0.30 | 1.51 | 2.00 | 2.54 |
| Eastern Iowa and Minnesota Till Prairies (104) | 0.09 | 0.16 | 0.25 | 1.47 | 2.00 | 2.51 |
| Iowa and Missouri Deep Loess Hills (107B) | 0.18 | 0.21 | 0.25 | 1.43 | 1.64 | 1.91 |
| Illinois and Iowa Deep Loess and Drift, West-Central Part (108C) | 0.10 | 0.15 | 0.21 | 1.65 | 1.99 | 2.33 |
| Illinois and Iowa Deep Loess and Drift, Western Part (108D) | 0.18 | 0.20 | 0.24 | 1.97 | 2.22 | 2.45 |
| Northern Mississippi Valley Loess Hills (105) | 0.08 | 0.11 | 0.13 | 2.14 | 2.52 | 2.90 |
| Iowa and Missouri Heavy Till Plain (109) | 0.11 | 0.14 | 0.20 | 2.79 | 3.08 | 3.40 |

TABLE 3 Water and soil conservation efficiencies associated with converting row crop to switchgrass for different hillslope group scenarios for each major land resource area (MLRA) over 2008–2016

Abbreviations: SCE, soil conservation efficiency; WCE, water conservation efficiency.

TABLE 4 Soil loss ($\text{Mg ha}^{-1} \text{ year}^{-1}$) averaged over 2008–2016 for each MLRA and different hillslope group scenarios. Numbers in parentheses identify soil loss (%) relative to the baseline condition

| MLRA | Baseline ($\text{Mg ha}^{-1} \text{ year}^{-1}$) | Hillslope groups | | |
|--|---|--|------------|------------|
| | | ≥3% | ≥6% | ≥10% |
| | | $\text{Mg ha}^{-1} \text{ year}^{-1}$ (% compared to baseline) | | |
| Central Iowa and Minnesota Till Prairies (103) | 3.2 | 0.8 (25.0) | 1.4 (43.8) | 1.8 (56.3) |
| Iowa and Minnesota Loess Hills (107A) | 10.4 | 1.1 (10.6) | 3.0 (28.8) | 4.6 (44.2) |
| Eastern Iowa and Minnesota Till Prairies (104) | 6.0 | 1.0 (16.7) | 2.2 (36.7) | 3.1 (51.7) |
| Iowa and Missouri Deep Loess Hills (107B) | 28.6 | 1.3 (4.5) | 2.6 (9.1) | 6.0 (21.0) |
| Illinois and Iowa Deep Loess and Drift, West-Central Part (108C) | 12.3 | 1.2 (9.8) | 2.2 (17.9) | 4.1 (33.3) |
| Illinois and Iowa Deep Loess and Drift, Western Part (108D) | 18.8 | 1.4 (7.4) | 2.6 (13.8) | 5.7 (30.3) |
| Northern Mississippi Valley Loess Hills (105) | 15.5 | 1.0 (6.5) | 2.2 (14.2) | 4.6 (29.7) |
| Iowa and Missouri Heavy Till Plain (109) | 10.6 | 1.5 (14.2) | 2.6 (24.5) | 4.0 (37.7) |

Replacing row crops with switchgrass on all slopes $\geq 6\%$ further reduced predicted soil loss relative to the $\geq 10\%$ scenario. For the $\geq 6\%$ scenario, average soil loss ($2.4 \text{ Mg ha}^{-1} \text{ year}^{-1}$) across all MLRAs was only 29.1% of the average baseline rate (Table 4). The $\geq 6\%$ scenario required switchgrass replacement on an average of 52% of the row crop hillslopes across all MLRAs. Placing switchgrass on slopes $\geq 3\%$ yielded very low estimated soil loss rates ($<1.5 \text{ Mg ha}^{-1} \text{ year}^{-1}$) for all MLRAs, but resulted in only limited reduction in average soil loss rates relative to the $\geq 6\%$ hillslope scenario ($2.4 \text{ Mg ha}^{-1} \text{ year}^{-1}$).

The percent of row crop hillslopes converted to switchgrass was related to the average reduction in soil loss relative to the baseline condition, especially for the more steeply sloping areas (Figure 3). However, soil conservation efficiency was significantly ($p < .05$) correlated with increasing switchgrass coverage only for the $\geq 10\%$ scenario. Increasing switchgrass coverage for the $\geq 3\%$ scenario had little impact on predicted soil loss (Figure 3), which agreed with the soil conservation efficiency values (Table 3). Soil conservation efficiency of replacing row crops with switchgrass decreased with increasing switchgrass coverage in the following order: $\geq 10\%$, $\geq 6\%$, and $\geq 3\%$ scenarios.

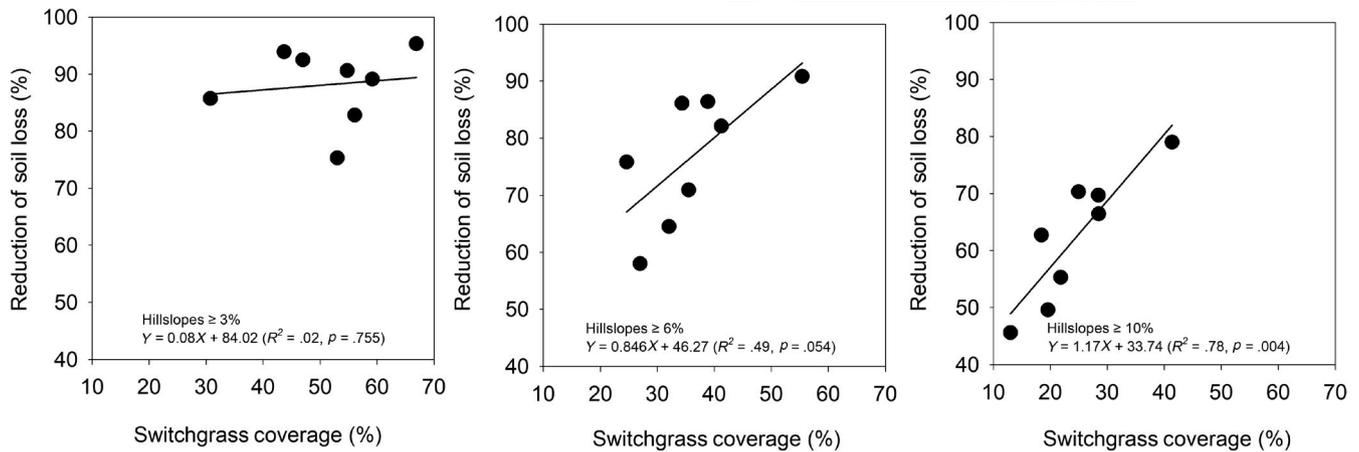
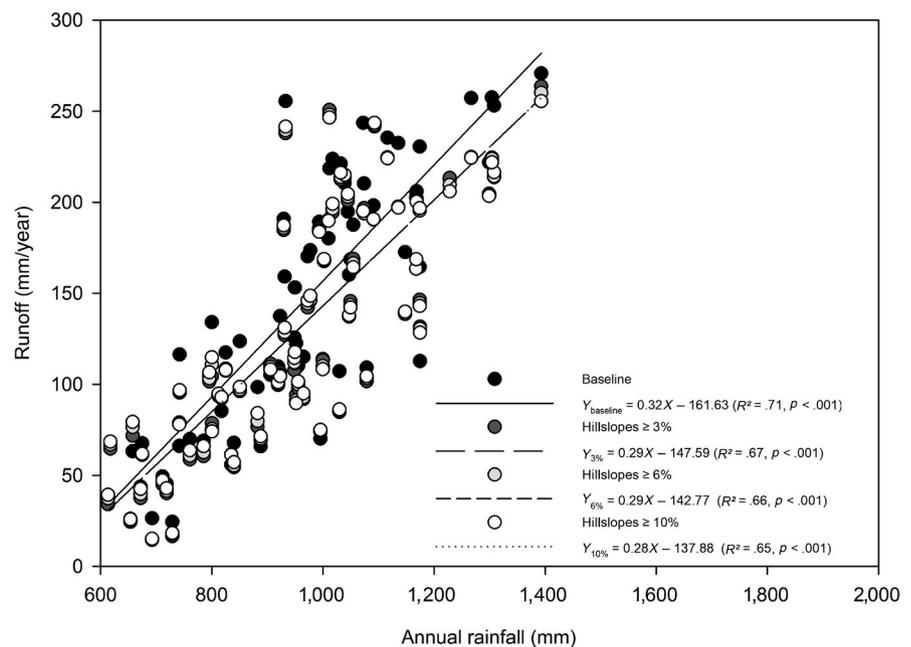


FIGURE 3 Effects of switchgrass coverage on reduction of soil loss relative to baseline for the three hillslope groups averaged for each of the eight major land resource areas over 2008–2016

FIGURE 4 Effects of the different hillslope scenarios on the relationship between average annual runoff and annual rainfall for each major land resource area and each year from 2008 to 2016 ($n = 72$)



3.3 | Relationship of annual rainfall and water runoff and erosion for different scenarios

The effects of annual rainfall on annual water runoff and average soil loss are shown in Figures 4 and 5, respectively, for all years, MLRAs, and scenarios. Replacing row crops with switchgrass did not significantly change the relationship between annual rainfall and water runoff compared to the baseline (Figure 4). Strong linear correlations exist between annual rainfall and water runoff ($p < .001$) for each scenario (Figure 4), but these relationships were statistically inseparable.

Replacing row crops with switchgrass on slopes should intuitively reduce soil loss; less intuitive are the relationships between soil loss and annual rainfall amount for the four different scenarios (Figure 5). In general, the impact of

switchgrass replacement on annual soil loss increased with annual rainfall; indeed significant relationships between annual rainfall and soil loss were observed for all four scenarios ($p < .05$).

Estimated soil erosion losses were most sensitive to annual rainfall for the baseline scenario and progressively became less sensitive to rainfall amounts as more area was converted to switchgrass (Figure 5). Before converting row crops to switchgrass, that is, the baseline scenario, annual rainfall used as an independent variable explained only 26% of the soil loss ($p < .05$); however, after converting some row crop areas to switchgrass, the coefficient of determination (R^2) increased by .11–.32 (Figure 5). Thus the interaction between the scenarios and annual rainfall indicates that the impact of switchgrass replacement on soil loss increased as annual rainfall increased, a result that should be expected.

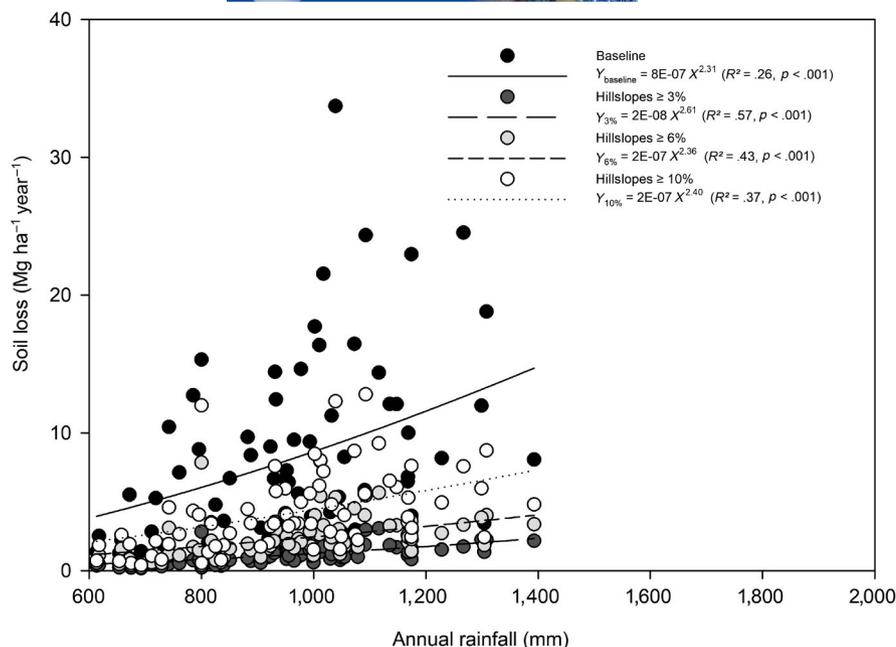


FIGURE 5 Effects of the different hillslope scenarios on the relationship between average annual soil loss and annual rainfall for each major land resource area and each year from 2008 to 2016 ($n = 72$)

4 | DISCUSSION

4.1 | Switchgrass replacement effects on soil and water losses

Daily Erosion Project, a unique geospatial and temporally dynamic modeling framework, illustrates its capacity to generate large-scale soil erosion and water runoff data. In this case, the results could inform policy realistically leading to increased biofuel feedstock production and concurrently better soil and water conservation. DEP estimated substantial differences in baseline soil loss estimates between MLRAs for 2008–2016 (Table 4). Indeed, some MLRAs have much higher estimated average soil loss rates than do other MLRAs, indicating spatial variation in the distribution of soils vulnerable to elevated soil loss. Areas of elevated erosion are considered marginal for row crop production because of the high risk of soil damage and offsite environmental impacts without the use of aggressive conservation measures.

This regional-scale assessment quantifies the disproportionate soil and water conservation benefit associated with preferentially planting less erosive crops such as switchgrass on the most erosion-sensitive areas. Indeed, disproportionately favorable environmental benefits are associated with producing switchgrass on the most steeply sloping areas as indicated by the direct relationship between soil conservation efficiency and slope gradient. Increasing environmental benefits associated with row crop replacement on steeper slopes gives a strategic basis for optimizing environmental outcomes while minimizing reductions in row crop production. This scenario also could be economically advantageous if markets are developed for perennials such as the use of switchgrass as feedstock for biofuel production (Mitchell,

Vogel, & Uden, 2012). To exemplify a region-specific potential policy/economic implication, four of the eight MLRAs in this study had baseline area-wide average soil losses in excess of the USDA's tolerable soil loss rate; one of these MLRAs (107B) had annual erosion rates more than twice the tolerable soil loss rate. By replacing row crops with switchgrass only on slopes with gradients $\geq 10\%$, predicted average soil loss was reduced for all MLRAs to approximately one-half, or considerably less than one-half, of the tolerable soil loss value. For the most vulnerable MLRA (107B), which had 47% of hillslopes with slope gradients $\geq 10\%$, soil loss estimates were reduced from 28.6 to 6.0 $\text{Mg ha}^{-1} \text{ year}^{-1}$. In complementary studies based on SWAT simulations, Feng et al. (2015) and Gassman et al. (2017) estimated that converting marginal lands under row crops to switchgrass in the St. Joseph River Watershed and the Boone River Watershed in the Midwest US could reduce soil erosion by 27%–98% and over 70%, respectively. The potential impact of strategic row crop replacement with switchgrass or similar perennials on soil erosion rates over large topographically diverse areas such as MLRAs in this study is important when considering efficient ways of meeting global soil and water conservation goals.

In this study, the greatest impact and the only significant erosion reduction scenario was switchgrass replacement of row crops on slopes $\geq 10\%$. Faster flowing water on steeper slopes supports elevated detachment of soil particles and transport of sediment leading to relatively high soil erosion rates. Switchgrass offers greater surface coverage than row crops for much of the year reducing soil detachment caused by raindrop impact on all slopes. Additionally, switchgrass's impact on sediment transport capacity increases for faster flowing water carrying heavier sediment loads, hence differences

in soil erosion rates between row crops and switchgrass increase as slopes become steeper. Higher frequency of interaction between suspended soil particles and switchgrass stems compared to row crop stems increases onsite sediment deposition and reduces offsite soil loss rates (Dabney, Meyer, Harmon, Alonso, & Foster, 1995).

Soil water infiltration rates are typically favored by perennials compared to annual row crops (Acharya & Blanco-Canqui, 2018; Blanco-Canqui et al., 2004). While perennials favor higher infiltration rates, the impact on water runoff seems to be relatively small compared to their impact on soil loss; these results are supported by other modeling studies (Feng et al., 2015) and field plot observations (Nyakatawa, Mays, Tolbert, Green, & Bingham, 2006). In some situations, however, negligible water runoff impacts associated with perennial placement have been indicated (Thomas, Ahiablame, Engel, & Chaubey, 2014). Relationships between slope gradient and percent switchgrass coverage must be considered to understand when and where runoff impacts are likely. Increasing switchgrass coverage on slopes $\geq 10\%$ tended to reduce runoff in this study, however, the relationship between switchgrass coverage and reduced runoff was statistically significant only for row crop replacement on slopes $\geq 3\%$ and $\geq 6\%$. Lower water infiltration rates should be expected with increasing slope steepness (Fox, Bryan, & Pricec, 1997). Slope gradient influences total infiltration through changes in overland flow depth, surface storage, and overland flow velocity, which impacts runoff and surface water residence time for infiltration (Fox et al., 1997). While switchgrass coverage has the potential to impact water runoff through elevated infiltration rates, the importance of slope gradient seems to increase and becomes dominant as slope gradient increases, reducing or negating the switchgrass cover impact.

For each scenario across all MLRAs, a linear relationship existed between annual rainfall and annual runoff with reasonably good fit (R^2 values between .65 and .71 for all four scenarios; Figure 4). Somewhat surprising, these linear relationships did not differ between scenarios. Perhaps this should be expected as Ai et al. (2015) identified relative impacts of main factors which contribute to runoff generation as rainfall \geq soil \geq topography \geq vegetation, and field plot runoff observations relying on natural rainfall failed to detect significant annual runoff differences between switchgrass, no-till corn, and sweetgum trees (Nyakatawa et al., 2006). For the current study, rainfall seems to dominate over the scenario effect on runoff across all hillslope groups studied.

Scenario impact on soil erosion was more sensitive to annual rainfall than was water runoff. While the power function fit for annual rainfall versus soil loss (Figure 5) had lower R^2 values than the linear fit observed for rainfall versus runoff (Figure 4), scenario effects were statistically unique. Furthermore, as switchgrass coverage increased, that is more

slope groups were covered with switchgrass, and the data scatter about the regression line decreased. R^2 values progressively increased from .26 for the baseline to .57 for the scenario in which all slopes $\geq 3\%$ were covered. Additionally, the graphical interaction depicted in Figure 5 illustrates the increasing importance of switchgrass cover as precipitation increases. Intuitively, with little or no rainfall, soil loss rates should be very low or nonexistent and similar or equal for all scenarios; as rainfall increases and soil erosion potential increases, the switchgrass cover has increasing potential to impact soil loss. The current study indicates that this is indeed true and that as annual rainfall amounts increase the separation between best fit lines, or differences in soil erosion, increases (Figure 5).

4.2 | Large-scale modeling with site-specific dynamic inputs

Spatially and temporally specific applications of real-time data over large areas and across yearly time scales offer a unique and powerful approach for investigating environmental outcomes capable of informing policy and/or impacting management planning. This project, which combines a soil erosion model, database management, and programming is one of the largest modeling studies conducted on marginal lands using site-specific dynamic inputs including real time rainfall estimations across multiple years and across a spatial domain including multiple physiographic regions. While this study quantified regional soil erosion and water runoff impacts of strategically targeting perennial bioenergy crops to specific slopes, scenarios ranging from climate change to land management impacts on soil and water loss could be addressed. Furthermore, while this case study is applied to the Central United States, the opportunity to study scenario impacts in any region is limited only by availability of input data.

5 | CONCLUSIONS

The integration of databases, remote sensing, and computational models allows regional-scale assessments of the efficacy of soil conservation policy options. Here we show through using such an integrated system for the Midwest US that policies designed to incentivize the replacement of row crops with switchgrass, a perennial biomass crop, on slopes $>10\%$ would have a disproportionate positive impact on soil conservation. For this case study the DEP modeling system indicates that average water erosion could be reduced by 50% or more when row crops are replaced by switchgrass on slopes with gradients $\geq 10\%$, but the specific impacts are precipitation and site-specific. The soil conservation efficiency

associated with switchgrass replacement of row crops increases with slope gradient. The effect of switchgrass on hillslope soil loss was greater than it was for water runoff for all hillslope groups across multiple years.

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DATA AVAILABILITY STATEMENT

Data are available on request from the authors.

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