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RESEARCH ARTICLE
10.1029/2025EF008049

Replacement of Corn by Perennial Cellulosic Bioenergy Crops on Sloping Farmland: Implications for Water Quality and Economic Benefits

Xiaoyu Zhang[1], Baogui Li[2], Yingqi Zhang[1], Junyu Qi[3], Srinivasulu Ale[4], Yiwen Han[5], Raghavan Srinivasan[6], Xiaojie Liu[7], Ru Zhang[8], and Yong Chen[1]

[1]College of Land Science and Technology, State Key Laboratory of Efficient Utilization of Agricultural Water Resources, China Agricultural University, Beijing, China, [2]Department of Hydraulic Engineering, Tsinghua University, Beijing, China, [3]Earth System Science Interdisciplinary Center, University of Maryland, College Park, MD, USA, [4]Texas A&M AgriLife Research (Texas A&M University System), Vernon, TX, USA, [5]Beijing Water Science and Technology Institute, Beijing, China, [6]Department of Ecosystem Science and Management, Texas A&M University, College Station, TX, USA, [7]Key Laboratory of Natural Resource Coupling Process and Effects, Ministry of Natural Resources, Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, China, [8]Key Laboratory of Poyang Lake Environment and Resource Utilization, Ministry of Education, School of Resources and Environmental, Nanchang University, Nanchang, China

Abstract Perennial cellulosic bioenergy crops have the potential to control nutrient losses from agriculture while providing biomass for biofuel production. This study employed a rigorously calibrated Soil and Water Assessment Tool (SWAT) model to assess the effects of replacing conventional corn (*Zea mays* L.) with *Miscanthus* × *giganteus* and Alamo switchgrass (*Panicum virgatum* L.) on nitrogen (N) and phosphorus (P) losses across three slope categories (<2%, 2%–4%, and >4%) within the Upper Mississippi River Basin (UMRB), a typical Mollisol region with intensive agricultural production. Model results indicated that N and P losses were effectively reduced by replacing corn with two bioenergy crops in 1984–2018. Organic P loss, dissolved inorganic P loss, and nitrate N (NO_3-N) loss by runoff were reduced by an average of over 93%, with more significant reductions occurring at higher slopes. NO_3-N leaching was reduced in most zones. Notably, replacing corn with *Miscanthus* and switchgrass achieved economic benefits from biofuel production of 3,000–6,000 US$/ha and environmental benefits from savings in pollution-control costs of approximately 2,700 US$/ha. By a trade-off analysis between environmental and economic benefits, *Miscanthus* was suitably planted in the western and downstream zones of the basin with single and double harvesting, and switchgrass was suitably planted in the northeastern zones with single harvesting, achieving a total attainable economic benefit of 24.2 billion US$. These findings emphasize that replacing corn with perennial bioenergy crops on sloping farmland with high risk of nutrient loss and low productivity can provide a win-win situation for environmental protection and agricultural sustainability.

Plain Language Summary This study comprehensively assessed the implications of replacing corn with perennial cellulosic bioenergy crops of *Miscanthus* and switchgrass on sloping farmland for water quality, as well as the corresponding economic benefits in the macro-scale Upper Mississippi River Basin (UMRB). Using a rigorously calibrated SWAT model, researchers found that replacing corn with two bioenergy crops could effectively reduce various species of nitrogen and phosphorus losses on sloping farmland by different passways. Meanwhile, replacing corn with *Miscanthus* and switchgrass also achieved substantial economic benefits from biofuel production and environmental benefits from savings in pollution-control costs. By a trade-off analysis between environmental and economic benefits, *Miscanthus* was suitably planted in the western and downstream zones of the basin with single and double harvesting, and switchgrass was suitably planted in the northeastern zones with single harvesting, achieving a total attainable economic benefit of 24.2 billion US$. These findings highlight that replacing corn with bioenergy crops on sloping farmland with high risk of nutrient loss and low productivity can simultaneously protect water quality and support sustainable agriculture.

Key Points:

- Perennial crops reduced nutrient losses on sloping farmland based on model simulations, setting up for current land management and weather
- Biofuel production from bioenergy crops and savings in pollution-control costs generated considerable attainable economic benefits
- Double-harvest *Miscanthus* was suitable in the western and downstream, single-harvest switchgrass was suitable in the northeastern

Supporting Information:

Supporting Information may be found in the online version of this article.

Correspondence to:

Y. Chen,
yongchen@cau.edu.cn

Citation:

Zhang, X., Li, B., Zhang, Y., Qi, J., Ale, S., Han, Y., et al. (2026). Replacement of corn by perennial cellulosic bioenergy crops on sloping farmland: Implications for water quality and economic benefits. *Earth's Future*, *14*, e2025EF008049. https://doi.org/10.1029/2025EF008049

Received 2 JAN 2026
Accepted 23 MAY 2026

Author Contributions:

Conceptualization: Xiaoyu Zhang, Baogui Li, Yong Chen
Data curation: Xiaoyu Zhang, Baogui Li, Junyu Qi
Formal analysis: Xiaoyu Zhang, Yingqi Zhang, Yong Chen
Funding acquisition: Xiaojie Liu, Yong Chen
Investigation: Xiaoyu Zhang, Yong Chen
Methodology: Xiaoyu Zhang, Baogui Li, Yingqi Zhang, Junyu Qi, Yong Chen
Project administration: Yong Chen
Resources: Xiaoyu Zhang, Junyu Qi, Srinivasulu Ale, Yong Chen

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1. Introduction

Nitrogen (N) and phosphorus (P) losses from agriculture pose a growing threat to global water quality (Lee et al., 2024; McDowell & Haygarth, 2025; Zhou et al., 2023). Long-term intensive fertilizer application and

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Software: Xiaoyu Zhang, Baogui Li, Yingqi Zhang, Junyu Qi, Srinivasulu Ale, Raghavan Srinivasan, Yong Chen
Supervision: Yong Chen
Validation: Xiaoyu Zhang, Baogui Li, Junyu Qi, Yiwen Han
Visualization: Xiaoyu Zhang, Yingqi Zhang
Writing – original draft: Xiaoyu Zhang, Yingqi Zhang
Writing – review & editing: Xiaoyu Zhang, Junyu Qi, Srinivasulu Ale, Yiwen Han, Raghavan Srinivasan, Xiaojie Liu, Ru Zhang, Yong Chen

irrational nutrient management have resulted in substantial residual and accumulation of N and P in soils (Feng et al., 2023; Yan et al., 2021). These nutrients are subsequently lost into water bodies through surface runoff, soil erosion, and leaching (Corrado et al., 2018), driving eutrophication of surface waters and degradation of groundwater quality (Liu et al., 2024; Usman et al., 2022). Characterized by their invisible, stochastic, and diffuse nature, agricultural N and P pollution affect an estimated 30%–50% of the global water bodies (Wang et al., 2020). This challenge is particularly acute in fertile and highly productive Mollisol regions, which are renowned as global granaries and primarily distributed across the Midwestern U.S., Northeast China, and Ukraine in the Northern Hemisphere (Li, Pi, et al., 2024; Yang et al., 2023). The U.S. Environmental Protection Agency (USEPA) reports that over 40% of nationally assessed waters exhibit elevated N and P (USEPA, 2024a, 2024b). Among these, excessive nutrient loss from intensively cultivated farmland in the Midwestern U.S. is a major contributor to the hypoxia zone in the Gulf of Mexico (Alexander et al., 2008; NRC, 2011; Robertson & Saad, 2021; Stackpoole et al., 2021). Therefore, implementing effective strategies to curb N and P losses from agriculture is an urgent priority.

The USEPA report indicated that N and P loads in the Mississippi River Basin must be reduced by at least 45% to shrink the Gulf of Mexico hypoxic zones to an acceptable size (USEPA, 2007). To this end, relevant U.S. departments and Midwestern states have implemented extensive conservation research and practices to monitor and control the amount of N and P pollutants entering water bodies (Kirk et al., 2024; Markland, 2023; Rabotyagov et al., 2014; USDA-NRCS, 2012). The 1972 Clean Water Act (CWA) emphasized the importance of scientific fertilization (Litke, 1999). Research showed that adjusting fertilizer application rates according to the crop requirement can reduce N loss in the U.S. Corn Belt, but only by approximately 20% (Zhang, Han, et al., 2024). In addition, a suite of Best Management Practices (BMPs) has been widely adopted in the Mississippi River Basin to control nutrient losses from farmlands, and their effectiveness has been evaluated by the Conservation Effects Assessment Project (CEAP) (USDA-NRCS, 2012). For example, the Conservation Reserve Program (CRP) implemented by the U.S. Department of Agriculture (USDA) has been proven to effectively reduce nutrient loading (Gleason et al., 2011; Johnson et al., 2016). Stackpoole et al. (2021) found that the no-till area in the Mississippi River Basin has greatly expanded to over 40% from 1980 to 2017, decreasing soil erosion and nutrient losses in the short term by reducing surface runoff. However, other studies have noted that long-term no-till might increase nitrate leaching and P accumulation in surface soils (Daryanto et al., 2017; McDowell & McGregor, 1984; Power & Schepers, 1989). Vegetated buffer strips and cover crops primarily intercept surface runoff, and constructed wetlands physically remove sediments and N transport (Christianson et al., 2018). Notably, the effectiveness of these BMPs is often limited in complex terrains, particularly on sloping farmland, which typically generates faster runoff velocities and higher erosion potential, thereby exacerbating the challenges of controlling nutrient losses (Ramos et al., 2019; Wang, Zhao, et al., 2019). Meanwhile, many of these BMPs, particularly engineering practices, involve relatively high investment costs without generating direct economic returns (Wen et al., 2025; Zygas et al., 2014).

Among various conservation practices, planting perennial bioenergy crops has proven to be a relatively economically viable solution. They not only effectively reduce nutrient losses and soil erosion (NRC, 2008), but they also replace corn (*Zea mays* L.) in producing cellulosic fuels to achieve the biofuel targets mandated by the U.S. Energy Independence and Security Act (EISA) with economic gains (Demissie et al., 2012; Wang et al., 2021; Xu et al., 2022). In the Plant Materials Program supported by the USDA-Natural Resources Conservation Service (USDA-NRCS), *Miscanthus* × *giganteus* and Alamo switchgrass (*Panicum virgatum* L.) occupy a prominent position (USDA-NRCS, 2009, 2011), and have been proven to be more suitable than traditional BMPs for controlling nutrient losses from sloping farmland due to their high adaptability, environmental friendliness, and biofuel production potential (Chen et al., 2017; Kane et al., 2023). Since the cultivation or introduction of *Miscanthus* and switchgrass to the Mississippi River Basin, they have been able to adapt rapidly to the local Mollisols and climate conditions (Heaton et al., 2004; McLaughlin & Adams Kszos, 2005), particularly suitable for planting on marginal lands such as sloping farmland (Feng et al., 2017; McIsaac et al., 2010). Compared to annual food crops, two perennial crops demonstrate agronomic, economic, and environmental advantages: (a) both have agronomic traits such as broad climatic tolerance, rapid growth rates, and resistance to periodic or seasonal soil moisture stress (Barney & DiTomaso, 2010; Zub & Brancourt-Hulmel, 2010); (b) both are regarded as core feedstocks for cellulosic biofuels, possessing high biomass yield potential and considerable economic value prospects (Chen et al., 2016; Iqbal et al., 2015); and (c) both significantly reduce soil erosion and nutrient losses in agricultural regions, thereby delivering substantial environmental benefits (Li, Wen, et al., 2025;

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McIsaac et al., 2010). Meanwhile, due to differences in biomass yields (Iqbal et al., 2015), regrowth rates suitable for various harvest frequencies (Li, Wen, et al., 2025), and regional adaptability (Feng et al., 2017), the two crops will generate varying economic and environmental benefits across different slopes and zones. Therefore, incorporating both into the study will enable a more comprehensive analysis to determine the appropriate planting placement of bioenergy crops in the Mississippi River Basin. However, there is currently a lack of systematic quantitative assessment of the effects of replacing traditional crops with perennial cellulosic bioenergy crops in sloping farmland on N and P losses to guide an appropriate land use placement under varying slope conditions.

Hydrological models are essential for simulating N and P losses in complex watersheds (Dechmi et al., 2012). Among various available hydrological models, the Soil and Water Assessment Tool (SWAT) has been employed in more than 6,800 peer-reviewed studies globally (https://litdb.swat.tamu.edu/), with a popularity far exceeding the use of other hydrological models in the U.S. and other countries over the past 20 years (Hu et al., 2026). This is mainly due to the wide applicability and easy usability of the SWAT model, making it the best choice for simulating hydrology, soil erosion, and N and P losses at a watershed scale. The SWAT has been extensively applied to evaluate N and P delivery throughout the Mississippi River Basin and the effectiveness of management practices under the CEAP (Duriancik et al., 2008; White et al., 2014). The Upper Mississippi River Basin (UMRB) is a vital component of the Mississippi River Basin, and as a typical Mollisol region with complex geographic conditions and intensive agriculture, it is severely affected by N and P losses from sloping farmland. In our previous study, we utilized the SWAT model to demonstrate that soil erosion could be effectively mitigated by planting *Miscanthus* and switchgrass in the UMRB, and determined the appropriate harvest frequency of those two crops based on their biomass yields under various slope categories (Li, Wen, et al., 2025). Building on that foundation, this study aims to: (a) evaluate the effects of replacing corn with *Miscanthus* and switchgrass on various forms of N and P losses across the slope categories (<2%, 2%–4%, >4%) within different hydrological zones of the UMRB; (b) quantify biofuel production and savings in pollution-control costs of this replacement, enabling a comprehensive trade-off analysis between environmental and economic benefits; and (c) determine appropriate bioenergy crop placements for each slope condition within every hydrological zone in the UMRB to achieve the dual objectives of pollution control and economic benefit enhancement. This study can provide a generalized methodology for realizing "reduce pollution and increase benefits" in Mollisol regions, and a scientific reference for sustainable agricultural transformation in similar regions worldwide.

2. Materials and Methods

2.1. Study Area

The UMRB is located in the Midwestern U.S. and covers 492,000 km^2 in five states of Minnesota, Wisconsin, Iowa, Illinois, and Missouri (Figure 1a). The elevation of the watershed ranges from 85 m in the south to 641 m in the north, and the topography of the watershed is dominated by plains and gently sloping hills (Figure 1b). The watershed has a semi-humid continental climate, with an average annual precipitation of 720–1,000 mm and an average annual temperature of 7.5–14.0°C (Figure 1c). The UMRB is one of the three Mollisol regions in the Northern Hemisphere, with soils dominated by organic matter-rich powdery loam and loam soils (66% of the watershed) (Mohammed & Hansen, 2024), and nearly half of the land is used for agricultural production (primarily continuous corn, corn-soybean rotation, and continuous soybean) (Risal et al., 2025). As a result, it is known as the Golden Corn Belt (Kimm et al., 2020). The N and P losses from farmland are a major water quality problem in the UMRB due to intensive agricultural activities. Although the UMRB covers only 18% of the entire MRB, it contributes over 60% of N and P loads downstream, resulting in "Dead Zones" in the Gulf of Mexico and localized eutrophication of lakes (Rabotyagov et al., 2014; Zhang, Han, et al., 2024). A large number of sloping farmlands in the UMRB are concentrated on both sides of the river, with farmlands of slope >2% accounting for 63% of the total area of continuous corn, located in the valley areas near the main stream of the Mississippi River (Figure 1e). These areas seriously threaten water quality and cause environmental problems in downstream rivers and estuaries (García et al., 2016; Ren et al., 2022).

2.2. SWAT Model Description and Simulations of N and P Losses in SWAT

The SWAT model is a widely used distributed hydrologic model that can divide complex watersheds into Hydrologic Response Units (HRUs) by regional land use, soil, and slope characteristics (Arnold et al., 1998). In addition, the hydrologic cycle, nutrient transport, and crop growth processes are simulated and calculated based

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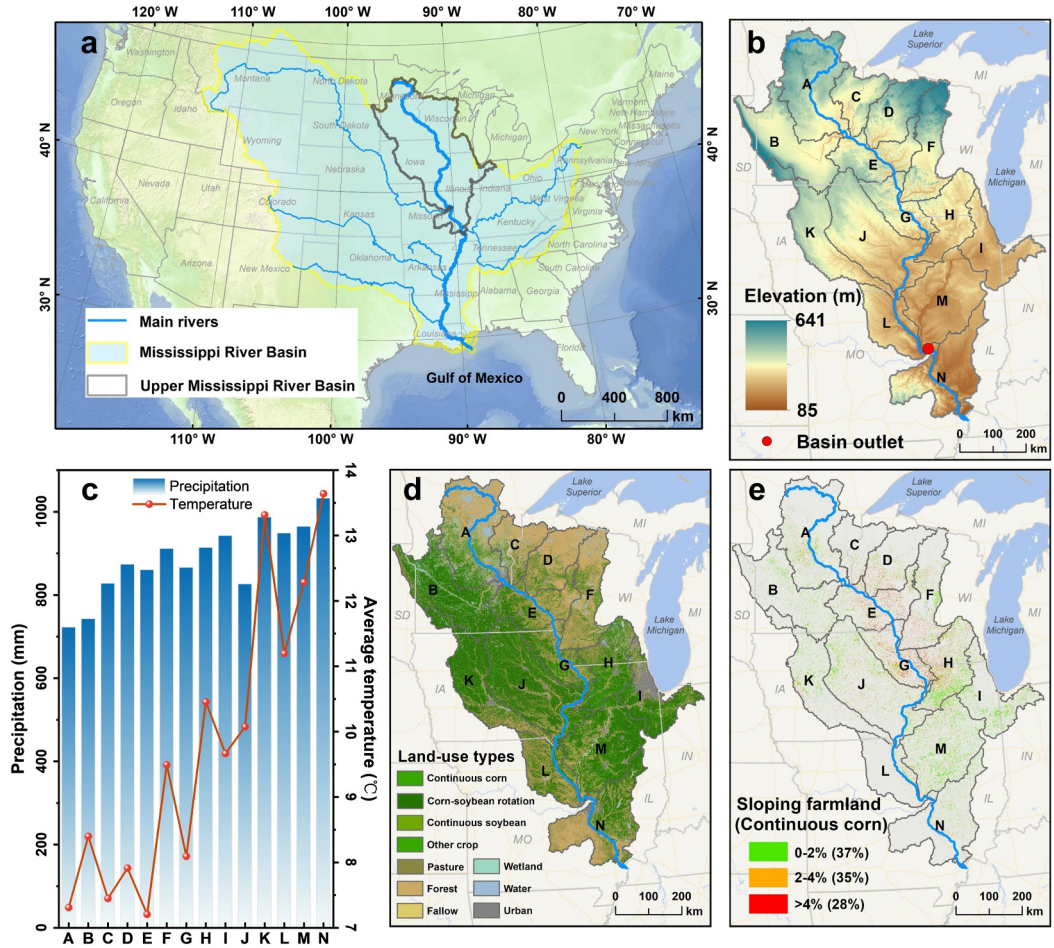

Figure 1. (a) Location of the Upper Mississippi River Basin (UMRB) in the U.S. and main rivers of the Mississippi River Basin, (b) Elevation and basin outlet, (c) Average temperature and precipitation (1984–2018) in 14 zones, (d) Spatial distribution of land-use types, and (e) Sloping farmland (continuous corn) of the UMRB.

on these HRUs. Therefore, the SWAT model can effectively quantify the impacts of changes in land uses on N and P losses (Neitsch et al., 2011; Zhang, Zhang, et al., 2024). Nitrogen and P in the soil are lost to other areas or streams by surface runoff, soil erosion, and leaching, further polluting the environment (Yuan & Koropeckyj-Cox, 2022). This study focused on simulating various forms of N and P losses by different pathways that were closely related to sloping farmland on continuous corn planting areas to compare changes under two different land uses of corn versus bioenergy crops. Three N pathways were considered in this study, which were organic nitrogen (ORGN) loss through soil erosion, nitrate nitrogen (NO_3-N) loss by surface runoff, and NO_3-N leaching into groundwater through percolation, and two P forms considered were organic phosphorus (ORGP) loss through soil erosion and dissolved inorganic phosphorus (DIP) loss by surface runoff (Figure 2). The specific descriptions and formulas used for simulating the above forms of N and P losses in SWAT are included in the Supporting Information S1.

2.3. Model Setup, Calibration, and Validation

In this study, the UMRB was divided into 131 subbasins based on the hydrogeological data, as well as 9,778 HRUs based on land use, soil type, and slope characteristics. Various forms of N and P losses, as well as crop yields, are calculated at the HRU scale. The subbasins were combined into 14 zones based on hydrological characteristics (Figure 1). Notably, during the SWAT model setup, various land-use types were considered for the UMRB based on local conditions and relevant literature (Srinivasan et al., 2010; USDA-NRCS, 2012), including row crops such as continuous corn, corn-soybean rotation, and continuous soybean, as well as pasture and other

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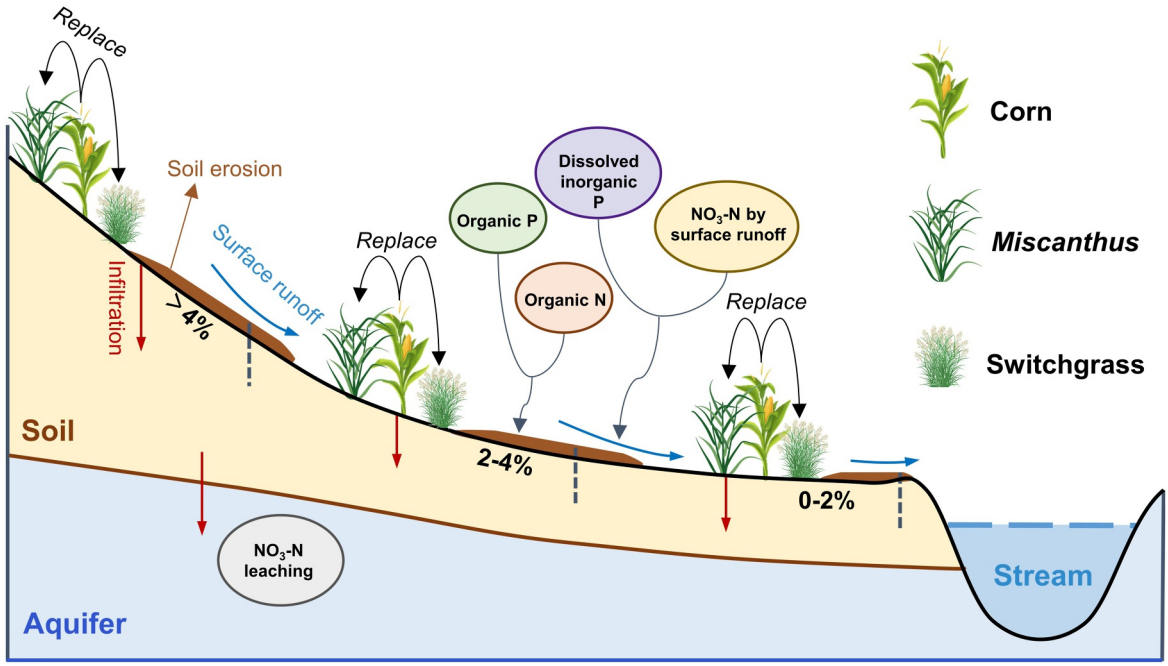

Figure 2. Schematic diagram showing various forms of nitrogen and phosphorus losses by different pathways in sloping farmland at a watershed scale.

land-use types. Research indicates that continuous corn systems in the Midwestern U.S. exhibited a more pronounced risk of nutrient losses than other crop types (Li, Guan, et al., 2025). Therefore, this study focused on the nutrient losses and control effects for the terrestrial processes in continuous corn planting areas in the UMRB. By comparing and analyzing changes in N and P losses under corn and bioenergy crops on continuous corn farmland with three slopes (<2%, 2%–4%, and >4%) in the 14 zones, this study ultimately determined the appropriate placement of bioenergy crops for each slope in each zone based on their environmental and economic trade-offs (Figure 3). The data sources and details required for the SWAT model setup are shown in Table S1 in Supporting Information S1.

This study used the Sequential Uncertainty Fitting Ver. 2 (SUFI-2) algorithm in the SWAT-Calibration and Uncertainty Procedures (SWAT-CUP) to calibrate and validate the model for crop yield, evapotranspiration (ET), streamflow, sediment yield, and various forms of N and P loads in the UMRB. Notably, calibrations and validations of streamflow, sediment yield, and various forms of N and P loads were done at the selected locations (Figure S1 in Supporting Information S1). But the spatial domain of the UMRB extends beyond the selected basin outlet location (Figure 1b). Specifically, observed crop yield data from National Agricultural Statistics Service (NASS, https://www.nass.usda.gov/) was first used to adjust crop-related parameters in 14 zones, then observed monthly streamflow and sediment yield data from U.S. Geological Survey (U.S. Geological Survey, 2024) were used to calibrate hydrologic parameters in a sequence from upstream to downstream, and finally various forms of N loads at five monitoring stations and P loads at three monitoring stations were calibrated in this study (Figure S1 in Supporting Information S1). ET data is sourced from the TerraClimate data set (Abatzoglou et al., 2018) provided by the Google Earth Engine, and the ET data was calibrated and validated in 14 zones. The calibration and validation periods for each variable are shown in Table S2 in Supporting Information S1. Three statistical measures were applied to assess the simulation performance of the SWAT model: percent bias (PBIAS), coefficient of determination (R^2), and Nash-Sutcliffe efficiency coefficient (NSE). And the calibration and validation targets for streamflow of this study were $R^2 \geq 0.50$, NSE ≥ 0.50, and $-25\% < \text{PBIAS} < 25\%$, which were considered to meet the suggested calibration and validation criteria for the SWAT model (Moriasi et al., 2007, 2015). For water quality, the targets were $R^2 \geq 0.50$, NSE ≥ 0.50, and $-40\% < \text{PBIAS} < 40\%$ (Moriasi et al., 2007, 2015).

A comparison between the observed and simulated values showed satisfactory agreement for each indicator during the calibration and validation periods. Specifically, the model effectively simulated continuous corn yields

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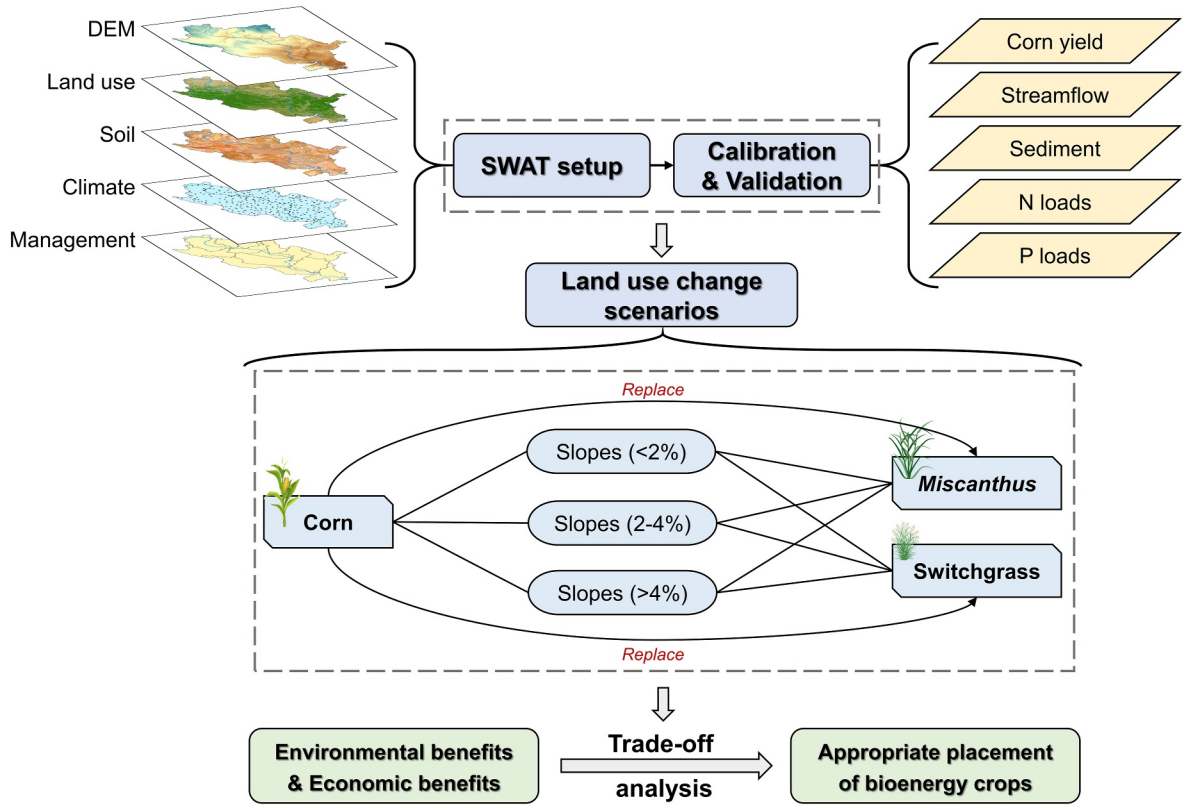

Figure 3. Flowchart of the SWAT model setup, calibration, and validation, and scenario design and data analysis for the land use change scenarios.

with PBIAS ranging from −1.9% to 11.5% in the UMRB (Table S4 in Supporting Information). Comparisons of the observed and simulated ET across 14 zones revealed R^2 ranging from 0.72 to 0.91, NSE ranging from 0.66 to 0.90, and PBIAS within ±25% (Figures S2 and S3 in Supporting Information S1). For hydrological variables of streamflow and sediment yield, the overall performance of the model was satisfactory with R^2 and NSE values for most of the outlets above 0.60 and PBIAS within ±25% (Table S5 in Supporting Information S1). In addition, the average R^2, NSE, and PBIAS values for all forms of P loads were 0.71%, 0.67%, and 5.5%, respectively, during the calibration period and 0.72%, 0.66%, and 16.9%, respectively, during the validation period. The average values of R^2, NSE, and PBIAS for all forms of N loads were 0.68%, 0.60%, and 5.9% during the calibration period and 0.67%, 0.59%, and 13.3% during the validation period, respectively (Table 1). More detailed information on calibration and validation is provided in Tables S1−S5 in Supporting Information S1.

2.4. Agricultural Management Practices for Planting Corn and Bioenergy Crops

For the macro-scale UMRB, crop management in the SWAT model was organized based on the accumulation of heat units (Neitsch et al., 2011). The formulas related to crop growth and harvesting in the model are detailed in the Supporting Information S1. To satisfy the nutrient demand for corn growth and to reduce N and P stress, the automatic fertilizer application function in the SWAT model was used in this study (Wielgat et al., 2021). Meanwhile, beef manure was applied before planting corn in the UMRB (Motew et al., 2018).

Based on our previous study, the appropriate harvest frequency was determined by the maximum biomass yield of *Miscanthus* and switchgrass in each zone of the UMRB (Li, Wen, et al., 2025). Switchgrass was harvested once in all 14 zones. *Miscanthus* was harvested once in Zones A-G and twice in Zones H-N. Moreover, to ensure adequate biomass yields of both bioenergy crops for biofuel production, this study applied 56 kg N/ha (Trybula et al., 2015) and 45 kg P/ha (Kering et al., 2012) to both crops before planting, and for the double-harvest of *Miscanthus*, N and P fertilizer was applied again after harvesting at two-thirds of the first application (Table S7 in Supporting Information S1). The details of the growth parameters and harvest time of the two bioenergy crops are included in Tables S6–S8 in Supporting Information S1.

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Table 1
Model Performance in Simulating Different Forms of N and P Loads in the Upper Mississippi River Basin

Indicator		Station no.	Calibration period			Validation period		
			R^2	NSE	PBIAS (%)	R^2	NSE	PBIAS (%)
N loads	Organic N	5331580	0.81	0.67	−17.9	0.73	0.57	25.0
		5587455	0.58	0.53	7.7	0.64	0.56	21.3
		5526000	0.68	0.66	10.0	0.64	0.59	−6.2
		5543500	0.82	0.52	37.9	0.64	0.50	8.8
		5552500	0.69	0.51	8.1	0.66	0.62	−5.7
	Nitrate N	5331580	0.55	0.55	−0.9	0.84	0.70	31.1
		5587455	0.62	0.58	−3.6	0.57	0.52	15.6
		5526000	0.58	0.52	20.0	0.61	0.58	14.0
		5543500	0.82	0.70	8.2	0.64	0.45	18.4
		5552500	0.53	0.51	12.4	0.57	0.53	17.6
	Total N	5331580	0.67	0.65	−14.0	0.88	0.83	23.9
		5587455	0.72	0.67	−11.5	0.66	0.64	3.0
		5526000	0.61	0.57	17.1	0.62	0.58	18.6
		5543500	0.85	0.77	11.8	0.66	0.50	10.7
		5552500	0.68	0.67	3.5	0.71	0.69	2.7
P loads	Organic P	5331580	0.72	0.70	−21.6	0.74	0.71	16.9
		5587455	0.60	0.60	−1.1	0.62	0.60	11.8
		5526000	0.59	0.54	31.2	0.54	0.52	21.7
	Dissolve inorganic P	5331580	0.76	0.70	7.9	0.79	0.64	11.5
		5587455	0.86	0.81	2.7	0.86	0.73	22.5
		5526000	0.64	0.60	10.6	0.69	0.61	18.4
	Total P	5331580	0.76	0.75	−6.8	0.79	0.77	14.3
		5587455	0.74	0.74	1.9	0.77	0.71	15.2
		5526000	0.68	0.59	24.9	0.66	0.61	19.9

2.5. Evaluation of Environmental and Economic Benefits

Both corn and bioenergy crops can provide considerable economic benefits, and replacing corn with environmentally friendly bioenergy crops can provide additional environmental benefits (Nazli et al., 2018). In this study, the attainable economic benefits are defined as the sum of the economic benefits of biofuel production and the environmental benefits resulting from savings in pollution-control costs generated by replacing corn with bioenergy crops, and then subtracting the economic benefits of corn.

Firstly, the economic revenues of biofuel production were calculated based on the market value of their conversion to ethanol in this study. Relevant literature suggested that 331 L of ethanol could be produced per ton of biomass yield from bioenergy crops (Humbird et al., 2011; Lin et al., 2023). And meta-analysis data since 2000 showed that the average market price of ethanol (produced by bioenergy crops) was 2.65 US$/gallon (Aui et al., 2021). Moreover, based on fertilizer use and price data from the Economic Research Service of the USDA (USDA, 2019), the average costs of fertilizer applied to the bioenergy crops were 651.7 US$/ton for N fertilizer and 745.6 US$/ton for P fertilizer. Therefore, the economic benefits of bioenergy crops after deducting fertilizer costs are calculated as follows:

$$\mathrm{EcB_{bio}} = \mathrm{Yield_{bio}} \times \partial - (\mathrm{Fert_N} \times 651.7 + Fert_P \times 745.6) \quad (1)$$

where $\mathrm{EcB_{bio}}$ represents the economic benefit of biofuel production (US$/ha); $\mathrm{Yield_{bio}}$ is the biomass yield of bioenergy crop (ton/ha); ∂ is the monetary value of ethanol produced per ton of bioenergy crop after unit

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conversion, which is 231.7 US$/ton; and $Fert_N$ and $Fert_P$ represent the amount of N fertilizer and P fertilizer applied to bioenergy crop (ton/ha).

Secondly, the environmental benefits in this study were defined as the cost savings associated with pollution-control, calculated by multiplying the reduction in N and P losses achieved by planting bioenergy crops (relative to corn) by the corresponding unit control costs. A study conducted in the U.S. Corn Belt demonstrated that N and P losses could be effectively mitigated through the implementation of buffer zones, cover crops, and land-use changes, with the combined application of these measures providing the best effect (Christianson et al., 2018). In this study, the total cost of implementing these practices was adopted as the control costs (average of Iowa and Illinois), which were 14.1 US$/kg N and 188.5 US$/kg P. Therefore, the environmental benefits of bioenergy crops are calculated as follows:

$$EnB_{bio} = \Delta N \times 14.1 + \Delta P \times 188.5 \quad (2)$$

where EnB_{bio} represents the environmental benefits of bioenergy crop (US$/ha); and ΔN and ΔP are changes in N and P losses, respectively, from planting bioenergy crops relative to corn (kg).

Thirdly, the economic revenues of corn were calculated as the multiplication of corn yield and its market price. Specifically, this study used the multi-year average market price of corn in 1984–2018, with 116.5 US$/ton from the statistical data set of the Food and Agriculture Organization of the United Nations (FAOSTAT) (http://www.fao.org/faostat/en/#data) for five major states in the UMRB (Illinois, Iowa, Minnesota, Missouri, and Wisconsin). This price represents the long-term average market price in the basin and effectively reflects the monetary value derived from corn production. Additionally, chemical fertilizer and manure were applied to corn. The average cost of fertilizer applied to the corn was 651.7 US$/ton for N fertilizer and 745.6 US$/ton for P fertilizer according to data from the USDA (USDA, 2019). The cost of manure was determined to be 5.6 US$/ton based on a report of the USDA-NRCS (USDA-NRCS, 2022). The economic benefits of corn after deducting fertilizer costs are calculated as:

$$EcB_{corn} = Yield_{corn} \times 116.5 - (Fert_N \times 651.7 + Fert_P \times 745.6 + Fert_{manure} \times 5.6) \quad (3)$$

where EcB_{corn} represents the economic benefits of corn (US$/ha); $Yield_{corn}$ is the yield of corn (ton/ha); and $Fert_{comp}$ and $Fert_{manure}$ represent the amount of compound fertilizer and manure applied to bioenergy crop (ton/ha).

Finally, the formula for calculating the attainable economic benefits (AEcB) was as follows:

$$AEcB = EcB_{bio} + EnB_{bio} - EcB_{corn} \quad (4)$$

Based on environmental effects and economic evaluation, and to maximize the attainable economic benefits, the selection of *Miscanthus* or switchgrass for each slope in each zone of the UMRB was further determined in this study.

2.6. Scenario Design and Data Statistics and Analysis

In this study, the simulation period was selected as 1984–2018. The first five years before the simulation period (1979–1983) were used as a warm-up period, during which the model was brought to a stable and equilibrium state by initializing key state variables. During the simulation period, three land use scenarios for corn, *Miscanthus*, and switchgrass were designed to compare the effects of planting bioenergy crops to replace corn on N and P losses. Furthermore, due to the large size of the UMRB, we have developed a series of Python codes for batch-changing the management practices for replacing corn with *Miscanthus* and switchgrass, selecting appropriate bioenergy crops of *Miscanthus* or switchgrass for each slope in each zone, and extracting and summarizing the massive output data. The statistical significance of differences in N and P losses from planting *Miscanthus* and switchgrass relative to planting corn was calculated using analysis of variance (ANOVA) and assigned to three levels of significance of $p < 0.05$, 0.01, and 0.001.

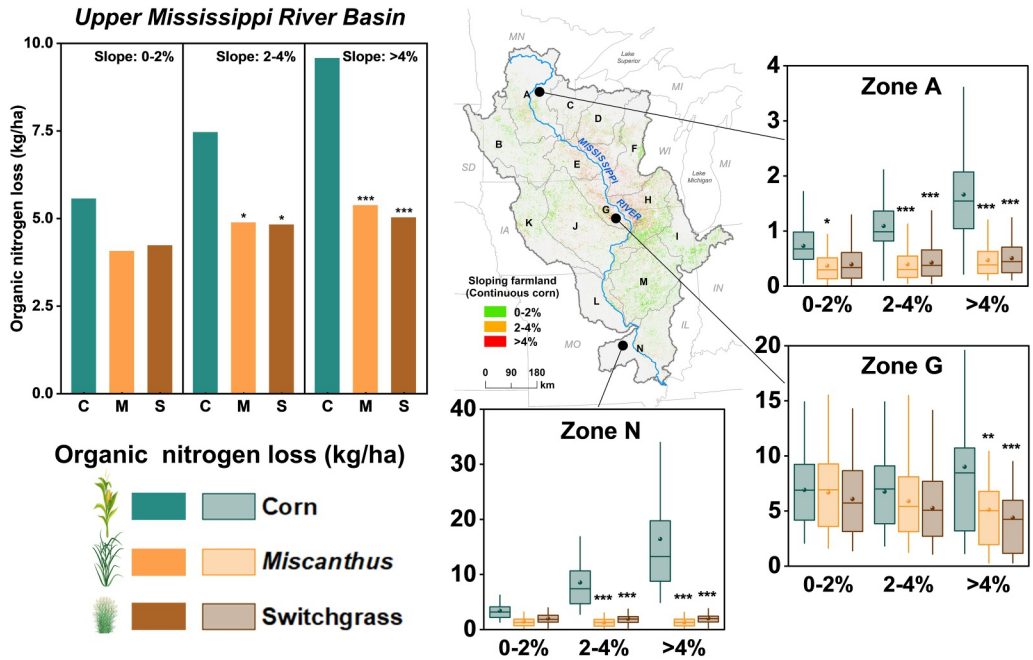

Figure 4. Comparison of the average (1984–2018) organic nitrogen loss by planting corn, *Miscanthus*, and switchgrass at different slopes in the UMRB and representative zones. C, M, and S represent the scenarios of planting corn, *Miscanthus*, and switchgrass, respectively. * represents the significance of *Miscanthus* or switchgrass compared to corn (*$p < 0.05$, **$p < 0.01$, and ***$p < 0.001$).

3. Results and Discussion

3.1. Evaluation of Changes in N Losses by Replacing Corn With Bioenergy Crops at Different Slopes of the UMRB

Under the current land use of planting corn in the UMRB, the risk of NO_3-N leaching was the greatest, followed by ORGN loss, and the risk of NO_3-N loss by surface runoff was relatively lower (Figures 4–6). Specifically, ORGN loss increased with slopes, approaching 10 kg/ha at >4% slopes, which was approximately 1.7 times the loss at <2% slopes (Figure 4). An opposite trend was found for NO_3-N leaching, with loss as high as 42 kg/ha at <2% slopes, approximately 2.2 times the loss at >4% slopes (Figure 6). This difference was attributed to the fact that in flat areas, more N was leached into groundwater with the vertical infiltration process of water (Hoogendoorn et al., 2016), while in areas with higher slopes, N was more likely to be carried away by surface runoff and sediment into streams or other regions (Wang, Feng, et al., 2019). By replacing corn with *Miscanthus* and switchgrass, NO_3-N loss by surface runoff was highly significantly reduced ($p < 0.001$) at all slopes, ORGN loss was highly significantly reduced at higher slopes (>4%). And NO_3-N leaching was also reduced to varying extents at all slopes. These results suggested that, despite there being some differences, both bioenergy crops were effective in reducing the loss of each N form, and this finding was confirmed by previous studies of the Mississippi River Basin (Ferin et al., 2023; Gu et al., 2015; VanLoocke et al., 2017).

Specific to each zone of the UMRB, replacing corn with *Miscanthus* and switchgrass significantly reduced ORGN loss in the upstream Zones A and B, the downstream Zones M and N, and at high slopes (>4%) in some midstream zones (Figure S4 in Supporting Information S1). NO_3-N loss by surface runoff showed highly significant reductions ($p < 0.001$) at all slopes in all zones, with reductions exceeding 90% (Figure S5 in Supporting Information S1). For NO_3-N leaching, planting both bioenergy crops on all slopes in the upstream Zones A and B and the downstream Zones L-N significantly reduced it, with an average reduction of 62.7%. However, planting *Miscanthus* in some midstream zones increased NO_3-N leaching compared to corn (Figure S6 in Supporting Information S1). After replacing corn with bioenergy crops of *Miscanthus* and switchgrass, their perennial characteristics enable them to maintain ground cover all year, reduce soil disturbance, and have a high water use efficiency (Hodgson et al., 2024), thereby significantly inhibiting NO_3-N leaching. However, in the midstream zones, the increase in NO_3-N leaching for planting *Miscanthus* was probably related to its lower N uptake during

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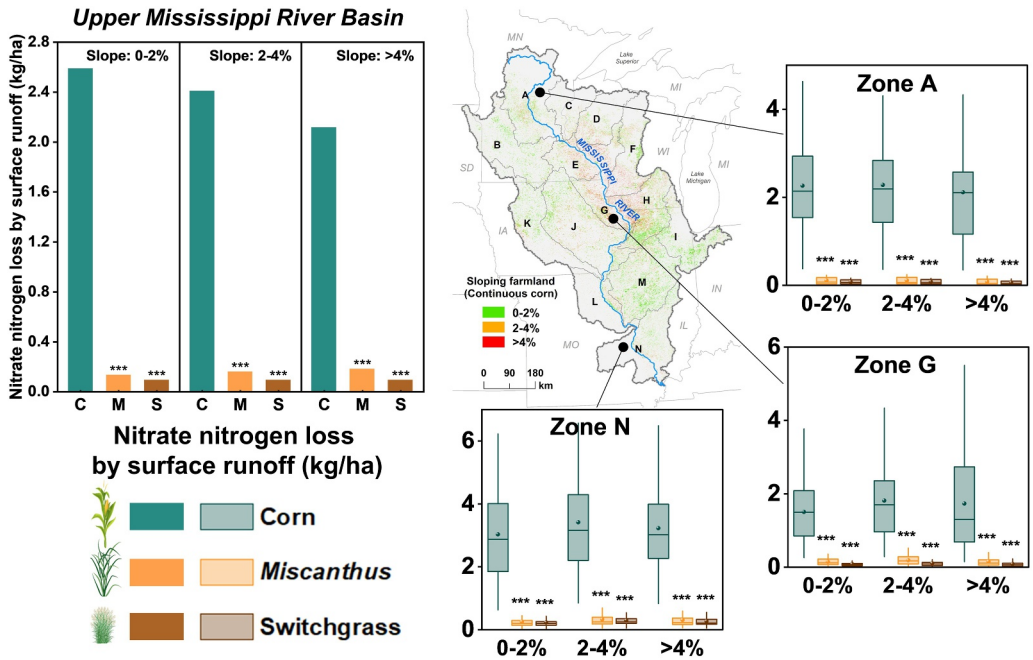

Figure 5. Comparison of the average (1984–2018) nitrate nitrogen loss by surface runoff by planting corn, *Miscanthus*, and switchgrass at different slopes in the UMRB and representative zones in 1984–2018. C, M, and S represent the scenarios of planting corn, *Miscanthus*, and switchgrass, respectively. * represents the significance of *Miscanthus* or switchgrass compared to corn (*$p < 0.05$, **$p < 0.01$, and ***$p < 0.001$).

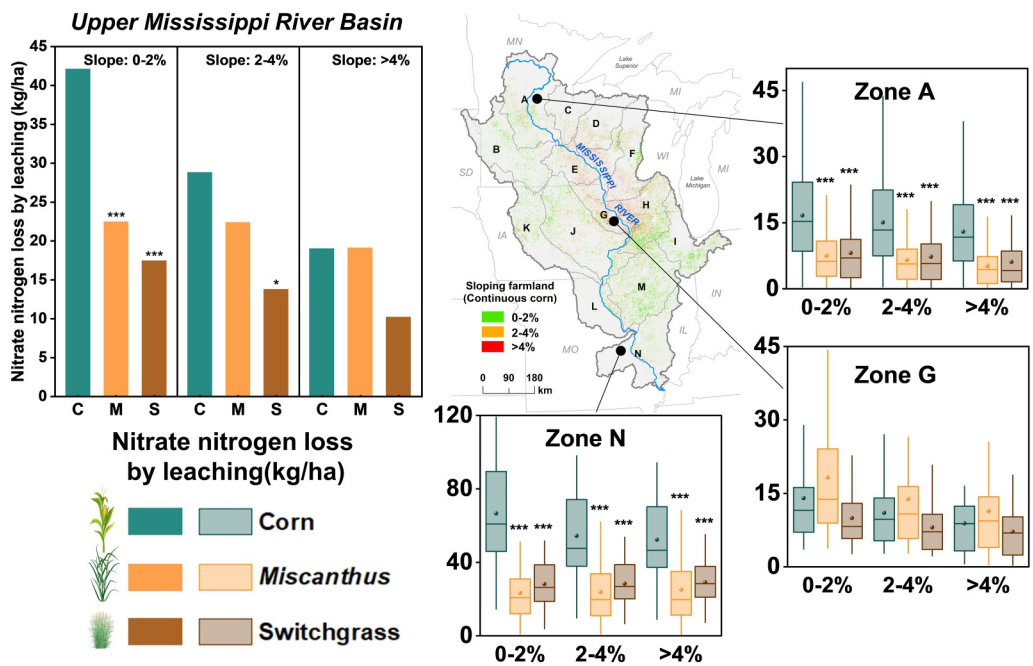

Figure 6. Comparison of the average (1984–2018) nitrate nitrogen leaching by planting corn, *Miscanthus*, and switchgrass at different slopes in the UMRB and representative zones. C, M, and S represent the scenarios of planting corn, *Miscanthus*, and switchgrass, respectively. * represents the significance of *Miscanthus* or switchgrass compared to corn (*$p < 0.05$, **$p < 0.01$, and ***$p < 0.001$).

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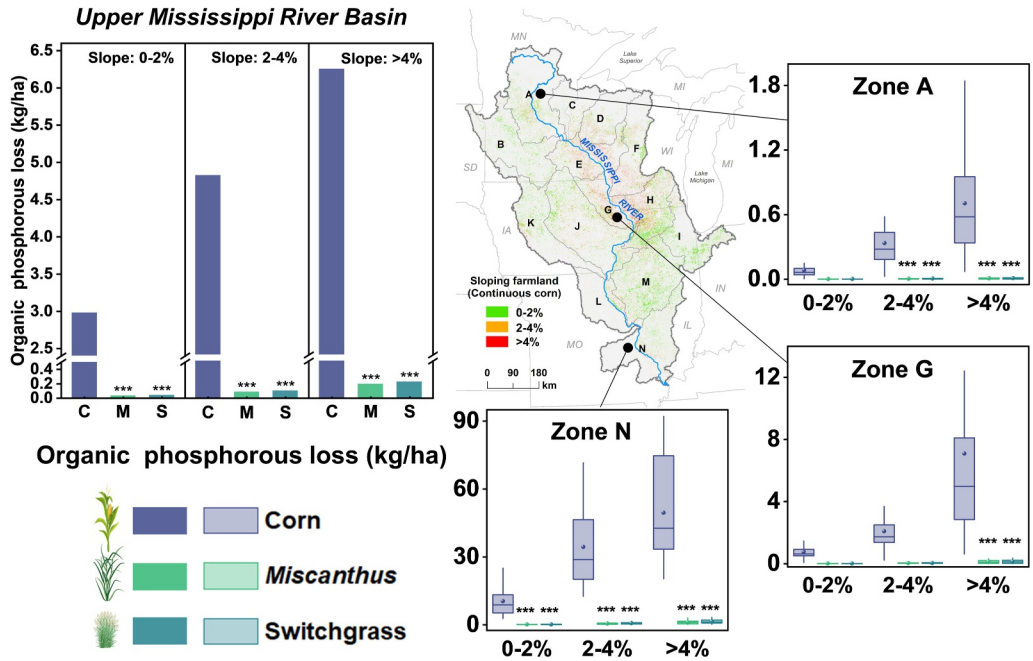

Figure 7. Comparison of the average (1984–2018) organic phosphorus loss by planting corn, *Miscanthus*, and switchgrass at different slopes in the UMRB and representative zones. C, M, and S represent the scenarios of planting corn, *Miscanthus*, and switchgrass, respectively. * represents the significance of *Miscanthus* or switchgrass compared to corn (*$p < 0.05$, **$p < 0.01$, and ***$p < 0.001$).

the growing season and smaller removal during harvest compared to those of switchgrass and corn (Table S6 in Supporting Information S1), which would leave more residual N in the soil (Trybula et al., 2015). Meanwhile, the harvest coefficient of 0.7 used for *Miscanthus* (compared to 0.9 for switchgrass) also determined that only 70% of the total biomass was taken away during harvesting under the same planting conditions, also resulting in more N remaining in the soil and accumulating for a long time, which exacerbated the risk of NO_3-N leaching. In addition, to ensure a large quantity of biomass, this study adopted a double-harvest strategy for *Miscanthus* in the downstream zones and supplemented N with fertilizer after the first harvest (Table S7 in Supporting Information S1), which further exacerbated the accumulation of NO_3-N in the soil, and consequently, higher levels of NO_3-N leaching were found in Zones H and I.

3.2. Assessment of Changes in P Losses by Replacing Corn With Bioenergy Crops at Different Slopes of the UMRB

Compared to corn, both *Miscanthus* and switchgrass planted at different slopes in the UMRB significantly reduced ORGP and DIP losses (Figures 7 and 8). Under the current land use of planting corn in the UMRB, the P loss risk increased with increasing slope, especially at >4% slopes, with an average of more than 6 kg/ha. This indicated that planting corn, an annual crop, was prone to cause more water and soil losses in high slope areas due to insufficient ground cover and high soil disturbance (Li, Wen, et al., 2025), which further led to massive losses of ORGP and DIP that migrated with soil and water (Li, Zhang, et al., 2024; Mbonimpa et al., 2014). However, after replacing corn with *Miscanthus* and switchgrass, *P* losses were significantly reduced ($p < 0.001$) on all slopes, especially ORGP loss was reduced by more than 98% (Figure 7). Changes in *P* losses in all zones of the UMRB also reflected similar trends. Differences in ORGP loss were not significant at <2% slopes in some upstream and midstream zones, but gradually increased with increasing slopes (2%–4% and >4%), reaching an extremely significant value at >4% slopes (Figure S7 in Supporting Information S1). In the downstream Zones K, M, and N, where P losses were high under corn land use, planting *Miscanthus* and switchgrass significantly reduced P losses at all slopes. The effect of planting *Miscanthus* and switchgrass on DIP loss reduction was statistically significant at all slopes in most zones, and the significance levels increased progressively with increasing slopes (Figure S8 in Supporting Information S1). These results suggested that planting perennial *Miscanthus* and switchgrass in the UMRB was effective in reducing P losses, especially on sloping farmland with

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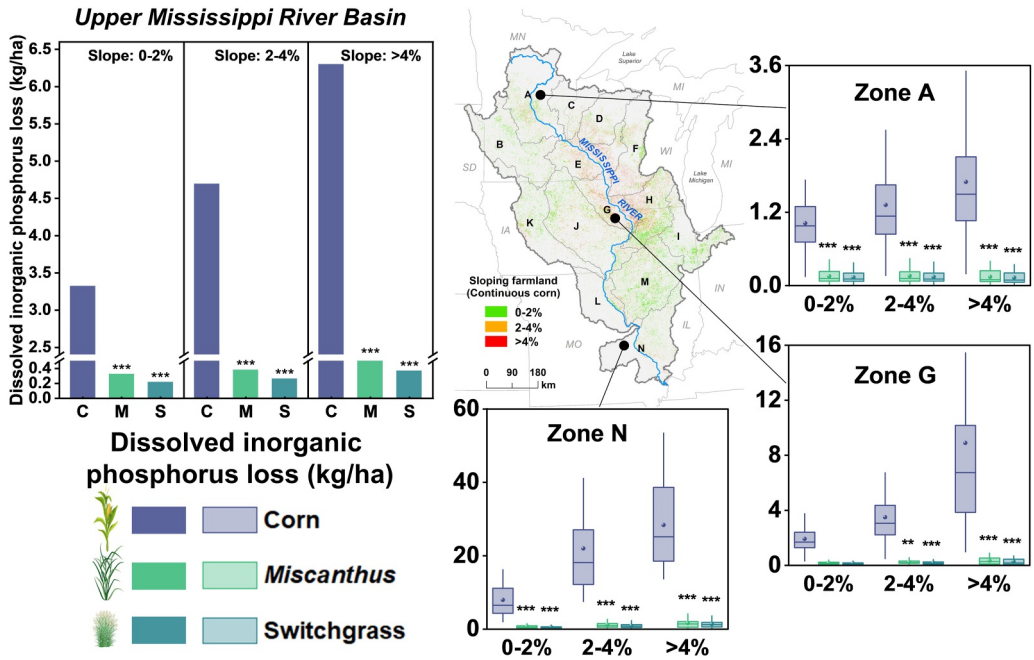

Figure 8. Comparison of the average (1984–2018) dissolved inorganic phosphorus loss by planting corn, *Miscanthus*, and switchgrass at different slopes in the UMRB and representative zones. C, M, and S represent the scenarios of planting corn, *Miscanthus*, and switchgrass, respectively. * represents the significance of *Miscanthus* or switchgrass compared to corn (*$p < 0.05$, **$p < 0.01$, and ***$p < 0.001$).

a slope >2%. Previous research had similarly confirmed that planting bioenergy crops in the Midwestern U.S. agricultural region could reduce P in the soil to limiting levels, even if large amounts of P fertilizer had been applied (Hussain et al., 2023). This was mainly due to the higher ground cover of these perennial crops, which could effectively reduce soil disturbance to prevent water loss, soil erosion, and P losses (Bredemeier et al., 2015; Mi et al., 2018).

3.3. Determining the Attainable Economic Benefits of Replacing Corn With Bioenergy Crops at Different Slopes and With the Appropriate Placement of Bioenergy Crops in the UMRB

The economic benefits of corn production in the UMRB were approximately 850 US$/ha from 1984 to 2018 (Table S9 in Supporting Information S1). Compared to corn, biomass yields and market prices for biofuel production of *Miscanthus* and switchgrass were higher, resulting in greater economic benefits than corn, reaching 6,000 US$/ha and 3,000 US$/ha, respectively. In addition, the two bioenergy crops created substantial environmental benefits worth approximately 2,700 US$/ha. To avoid the negative environmental impacts from planting bioenergy crops, this study excluded land use scenarios of bioenergy crops that increased NO_3-N leaching, and with the goal of maximizing the attainable economic benefits, finally determined the appropriate placement for planting of bioenergy crops at each slope in each zone of the UMRB. Overall, the suitable planting zones for *Miscanthus* were concentrated in the western and downstream zones of the UMRB, while the suitable planting zones for switchgrass were concentrated in the northeastern zones (Figures 9a–9c). The attainable economic benefits per unit area in space showed a distribution pattern of low in the east to high in the west, low in the north to high in the south. This was mainly because the biomass yield of *Miscanthus* far exceeded that of switchgrass (Feng et al., 2017; Gautam et al., 2023), which produced approximately twice the economic benefits of switchgrass for biofuels, and the double-harvest system was implemented for *Miscanthus* in the downstream zones (Li, Wen, et al., 2025), resulting in higher economic benefits. Meanwhile, N and P losses in downstream zones with high pollution were also significantly reduced by planting these two bioenergy crops, producing noticeable environmental benefits. In addition, the attainable economic benefits per unit area increased with the increasing slope, with the benefits at high slopes (>4%) being 1.5 times greater than those at low slopes (<2%), and averaging as high as 7,689 US$/ha. Von Cossel et al. (2020) also confirmed that using bioenergy crops to

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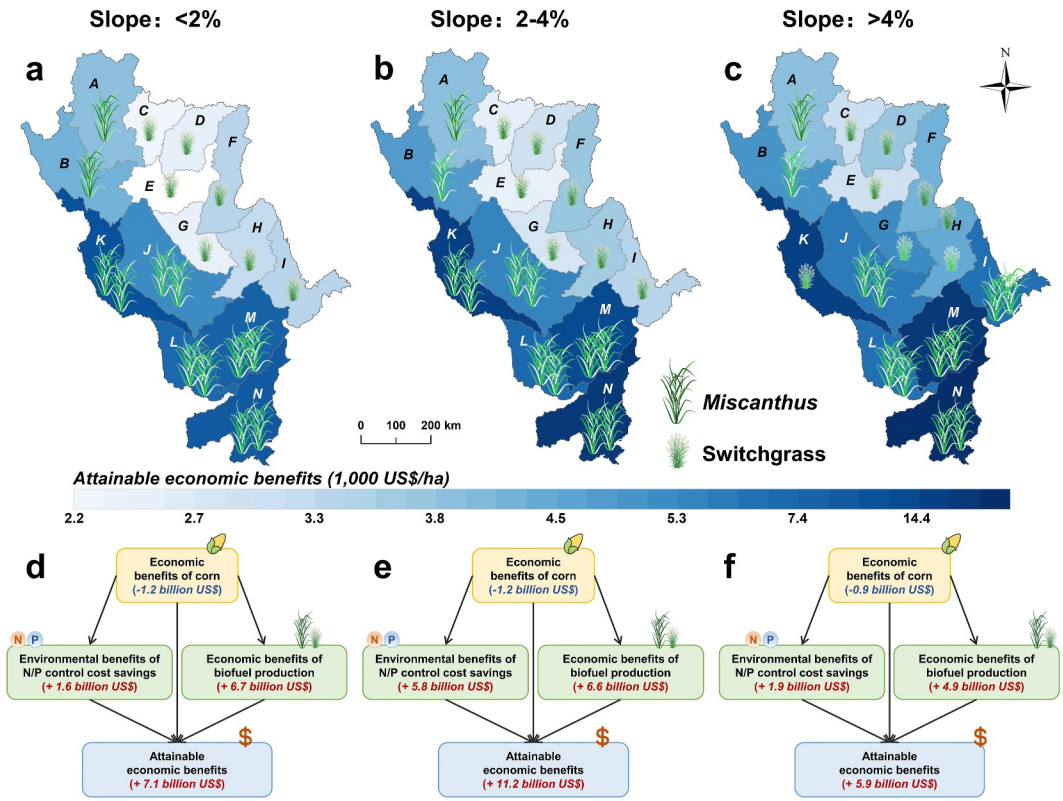

Figure 9. (a–c) Spatial distribution of average (1984–2018) attainable economic benefits per unit area and appropriate placement of bioenergy crops, and (d–f) the benefits by appropriate placement of bioenergy crops at different slopes and zones in the UMRB. A single crop symbol in the figure represents single-harvest management, and two crops symbol represents double-harvest management.

replace corn could result in greater cost savings per unit area for reducing pollutant losses and higher environmental benefits in higher pollution load areas.

Under the appropriate placement of bioenergy crops, the combined planting of *Miscanthus* and switchgrass jointly contributed a total attainable economic benefit of 24.2 billion US$ to the UMRB and resulted in reductions of ORGP, DIP, ORGN, NO_3-N loss by surface runoff, and NO_3-N leaching by 98.7%, 90.3%, 45.0%, 95.0%, and 41.9%, respectively (Figures 9d–9f, Table 2). Specifically, the economic benefits of biofuels were as high as 6.7 billion US$ at <2% slopes, coupled with environmental benefits of 1.6 billion US$ from controlling N and P losses, yielding an attainable economic benefit of 7.1 billion US$ after subtracting the economic benefits from corn (Figure 9d). At the 2%–4% slopes, the attainable economic benefits were 11.2 billion US$, the largest among all slopes. High economic benefits of 6.6 billion US$ at the 2%–4% slopes were accompanied by high environmental benefits of 5.8 billion US$, due to much higher reductions in N and P losses than at the low slopes and a much larger area of farmland with 2%–4% slope than at the high slopes (Figures 9f, Table 2). Due to the relatively

Table 2
Percentage Changes in Nitrogen and Phosphorus Reductions for the Appropriate Placement of Bioenergy Crops Compared to Corn Land Use in the Upper Mississippi River Basin

Slope (%)	Organic *N* (%)	NO_3-N loss by surface runoff (%)	NO_3-N leaching (%)	Organic P (%)	Dissolved inorganic *P* (%)
<2	−33.3	−95.5	−50.2	−98.7	−90.3
2–4	−58.5	−95.2	−52.3	−98.3	−92.8
>4	−43.2	−94.4	−23.3	−98.2	−91.1
Total	−45.0	−95.0	−41.9	−98.4	−91.4

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small area of farmland at >4% slopes, the attainable economic benefits were relatively low (5.9 billion US$), but still considerable (Figure 9f). Weik et al. (2022) suggested that planting bioenergy crops to replace food crops, although reducing food production, could maintain or increase regional incomes and improve the environmental quality in some regions. Furthermore, another study indicates that replacing traditional crops with bioenergy crops on generally low-productivity sloping farmland represents a strategic approach for gradual bioenergy deployment with reduced risks for food security and the environment (Næss et al., 2021). Therefore, although replacing corn with bioenergy crops on farmland with slopes <2% could also generate substantial attainable economic benefits, this study recommended prioritizing the replacement of corn with bioenergy crops on sloping farmland with high risk of nutrient loss and low productivity in the UMRB, which can effectively control *N* and *P* pollution and achieve substantial economic benefits while minimizing potential impacts on the main food production system and feed supply, achieving a trade-off among multiple objectives.

3.4. Limitations and Future Work

Although this study identified potential value in replacing corn with perennial bioenergy crops for pollution control and economic benefits on sloping farmland, several limitations should be considered when referencing these findings. First, this study estimated the economic benefits of bioenergy crops based on historical average market prices, yielding results that reflect potential benefits under stable conditions. In actual large-scale cultivation, factors such as market supply and demand fluctuations, supply chain costs, and technological advancements may trigger non-linear scale effects or diminishing returns. Second, the SWAT model in this study has undergone systematic calibration at multiple locations and zones for various variables across the watershed and can reflect macro-scale hydrological and nutrient cycling processes. Based on this, the study focuses on the long-term non-point pollution processes and management scenario responses on sloping farmland. However, at finer scales, it may fail to capture local details such as subsurface (tile) drainage in flat, poorly drained farmland and point source pollution from wastewater treatment facilities. These factors may have weaker impacts on long-term nutrient losses and control on sloping farmland, but they may affect nutrient loss pathways on farmland with <2% slope in the short term and thus introduce uncertainty in findings for such areas.

Future work will further determine the appropriate proportion of replacement of corn on sloping farmland by bioenergy crops based on the major risk. On this basis, more sophisticated economic models and systematic economic analysis are necessary to accurately capture the dynamic changes in the economic benefits as bioenergy crops expand in the UMRB, thereby comprehensively assessing the economic feasibility and broader applicability and acceptability of replacing corn with bioenergy crops. Furthermore, during the SWAT model setup, tile drainage data from the cropland data layer of the USDA and point source pollution data from the U.S. Geological Survey will be integrated into the model, which enables a more refined assessment of water quality pollution control effectiveness, ultimately providing more actionable control strategies.

4. Conclusions

This study utilized a well-calibrated SWAT model to investigate the changes in *N* and *P* losses and the environmental and economic benefits of replacing corn with two perennial bioenergy crops (*Miscanthus* and switchgrass) at three slopes in 14 zones of the macro-scale UMRB. The findings showed a substantial reduction in *N* and *P* losses by surface runoff and soil erosion by replacing corn with two bioenergy crops, with ORGP loss, DIP loss, and NO_3-N loss by surface runoff reduced by 98%, 93%, and 94%, respectively, and the significance levels increased progressively with increasing slopes. NO_3-N leaching showed a significant reduction in most zones, but replacing corn with *Miscanthus* in some midstream zones led to an increase in NO_3-N leaching, which was related to double-harvest management with fertilizer supplementation and crop characteristics of *Miscanthus*. Overall, replacing corn with two bioenergy crops of *Miscanthus* and switchgrass could effectively control *N* and *P* losses on sloping farmland with high risk of nutrient loss and low productivity, and also generate substantial environmental and economic benefits, which were higher at the downstream zones and higher slopes. Specifically, the economic benefits of biofuel production of *Miscanthus* and switchgrass were as high as 6,000 US$/ha and 3,000 US$/ha, and the environmental benefits generated by savings in pollution-control costs were both approximately 2,700 US$/ha. The total benefit of the bioenergy crop was higher than the economic benefit of corn. As a result, an appropriate placement of bioenergy crops in the UMRB was established by a comprehensive trade-off analysis between environmental and economic benefits, with *Miscanthus* being identified as suitable for planting in the western and downstream zones, and switchgrass suitable for planting in the northeastern zones. An

appropriate placement of *Miscanthus* and switchgrass created a total attainable economic benefit of 24.2 billion US$ for the UMRB and resulted in a dramatic reduction in various forms of *N* and *P* losses. These findings underscore the broader implications of replacing corn with perennial cellulosic bioenergy crops on sloping farmland, which effectively control *N* and *P* losses, improve water quality, and achieve significant attainable economic benefits, thereby creating a win-win situation for both the environment and the economy.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

The SWAT model (Zhang, 2025) was used for the full simulation results in this study.

Acknowledgments
This research was supported by the National Key Research and Development Program of China under award number 2024YFD1500900. This research was also supported by the National Natural Science Foundation of China under award number 42471294, the Chinese Universities Scientific Fund under award numbers 2024RC018 and 2025RC021, and the National Institute of Food and Agriculture, U.S. Department of Agriculture under award number NIFA-2021-67019-33684. We greatly appreciate the editors and anonymous reviewers for their valuable comments for improving this paper.

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