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Key Points:

- Increased extreme precipitation (EP) events have amplified soil erosion and sedimentation in the Mississippi River Basin since the 1990s
- A shift in the spatial pattern of EP events substantially intensified sediment yield in the Midwest in the 2010s
- The major driver of soil erosion and sediment yield shifted from land use change to climate change during the past century

Supporting Information:

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

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Understanding the Shift of Drivers of Soil Erosion and Sedimentation Based on Regional Process-Based Modeling in the Mississippi River Basin During the Past Century

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Abstract Soil erosion and sedimentation problems remain a major water quality concern for making watershed management policies in the Mississippi River Basin (MRB). It is unclear whether the observed decreasing trend of stream suspended sediment loading to the mouth of the MRB over the last eight decades truly reflects a decline in upland soil erosion in this large basin. Here, we improved a distributed regional land surface model, the Dynamic Land Ecosystem Model, to evaluate how climate and land use changes have impacted soil erosion and sediment yield over the entire MRB during the past century. Model results indicate that total sediment yield significantly increased during 1980–2018, despite no significant increase in annual precipitation and runoff. The increased soil erosion and sediment yield are mainly driven by intensified extreme precipitation (EP). Spatially, we found notable intensified EP events in the cropland-dominated Midwest region, resulting in a substantial increase in soil erosion and sediment yield. Land use change played a critical role in determining sediment yield from the 1910s to the 1930s, thereafter, climate variability increasingly became the dominant driver of soil erosion, which peaked in the 2010s. This study highlights the increasing influences of extreme climate in affecting soil erosion and sedimentation, thus, water quality. Therefore, existing forest and cropland Best Management Practices should be revisited to confront the impacts of climate change on water quality in the MRB.

Plain Language Summary Climate and human activities have the potential to aggravate soil erosion and sediment yield in rivers, causing water quality degradation in the Mississippi River Basin (MRB). This study evaluated the impacts of climate and land use changes on sediment yield across the entire MRB by using a regional computer simulation model. The simulated results show that the increased extreme precipitation (EP) has amplified soil erosion and sediment yield in cropland-dominated regions in the 2010s. Since the 1930s, climate variability has replaced land use change and become the dominant contributor to the changes in sediment yield. This study highlights the risks of EP on soil erosion and water quality in the MRB and emphasizes the need for appropriate management strategies to address these emerging challenges.

1. Introduction

Soil erosion and sediment delivery from land to aquatic systems have been substantially altered by human activities and remain a major environmental concern (Poesen, 2018). The removal of fertile soil has been recognized as a threat to healthy soil and food security (Borrelli et al., 2017; Kaiser, 2004), and the changing sediment supply may impose risks to aquatic habitats, dam lifespan, and channel regulation (Denic & Geist, 2015; Lane et al., 2007; Shalash, 1982). As soil carbon and nutrient pools are critical components in global carbon and nutrient cycles, soil erosion and sediment fluxes play an important role in controlling global carbon and nutrient exports from the terrestrial biosphere to coastal ecosystems (Bian et al., 2022; Galy et al., 2015). Soil erosion and sediment flux are controlled by climate, topography, soil properties, and vegetation in natural conditions. Human activities have significantly modified soil erosion and sedimentation processes across various scales, ranging from local watersheds to large regions, as a result of deforestation, urbanization, overgrazing, and cultivation (Syvitski et al., 2005; Zheng, 2006). Although global soil erosion is currently increasing (Borrelli et al., 2017; Wuepper et al., 2020), the trajectories of human impacts on sediment transport along the land-ocean continuum vary dramatically in different regions of the globe. Increasing sediment loads are mainly driven by deforestation

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and agricultural practices while declining sediment loads primarily result from sediment trapping by dams (Walling, 2006).

The Mississippi River Basin (MRB), the largest river system in North America, encompasses the major agricultural regions in the U.S. and delivers substantial amounts of water, nutrients, and sediment to the Gulf of Mexico (Turner & Rabalais, 2004). Soil erosion-induced nutrient export from the MRB is one of the major contributors to the expansion of the hypoxia zone in the Gulf of Mexico (Robertson & Saad, 2021; Wang et al., 2021). Over the past century, climate change and anthropogenic disturbance have significantly altered MRB hydrological and biogeochemical cycles, including the land-ocean fluxes of sediment and erosional carbon and nutrients (Raymond et al., 2008). Despite the intensive agricultural activities within the basin, a substantial decrease in suspended-sediment discharge has been observed over the last eight decades. This reduction has been attributed to the trapping characteristics of dams and other engineering practices that have effectively eliminated sediment sources, such as river-training structures, bank revetments, and soil erosion controls (T. Li et al., 2020; Meade & Moody, 2010). However, the decrease in suspended sediment within river channels might have masked the changes in soil erosion and sediment yield originating from upland areas. Climate changes, particularly extreme rainfall events, may have contrasting effects on sediment loading compared to dam construction and land management practices (Tan et al., 2021). Previous studies based on observed channel sediment fluxes data cannot directly evaluate how climate and land use change have altered the long-term dynamics of soil erosion and land sediment yields in the entire MRB (Hassan et al., 2017; Yin et al., 2023).

Physical- and empirical-based soil erosion models have the advantage of describing soil erosion over spatial and time scales in response to changes in land use and climate. Numerous models have been developed and applied to quantify soil erosion and sediment yields at field and watershed scales (Borrelli et al., 2021; Mao et al., 2010; Pandey et al., 2016). Nevertheless, large-scale (over millions of square kilometers) soil erosion modeling is still in its infancy. Combining soil erosion algorithms and land surface model provides a pathway to simulate soil erosion and sediment yield over large spatial scales and long-time scales. For example, the Morgan-Morgan-Finney model was implemented into the Energy Exascale Earth System Model (E3SM) land model (ELM) (Tan et al., 2018, 2022). In addition, the Adjusted Revised Universal Soil Loss Equation (Adj. RUSLE) model was coupled with the Organizing Carbon and Hydrology In Dynamic Ecosystems land surface model (Naipal et al., 2020). Similarly, we have integrated the Modified Universal Soil Loss Equation (MUSLE, Williams, 1975) into the Dynamic Land Ecosystem Model (DLEM), a process-based land surface model. Compared with commonly used RUSLE, which can only estimate the average annual soil erosion, the MUSLE is capable of estimating soil erosion at fine temporal scales (e.g., daily) and is more suitable for simulating soil erosion under extreme precipitation (EP) events (Djoukba et al., 2019; H. Zhang et al., 2020). Although the DLEM coupling with MUSLE has been used to estimate erosion-induced carbon and nutrient loading to coastal oceans (Bian et al., 2022; Tian, et al., 2015b), the performance of DLEM in simulating sediment flux was not comprehensively evaluated.

Therefore, this study improved and applied the DLEM to simulate soil erosion in the MRB where the spatially explicit estimate of soil erosion over the entire basin is still lacking, and the responses of soil erosion to climate and land use change over long-term scales have not been well investigated. Our guiding hypothesis was that land management contributes to mitigating runoff and soil erosion problems in croplands, but EP events are increasingly controlling sedimentation in the MRB. We also hypothesized that forests have disproportionately more runoff but less sediment yield compared to croplands. Specifically, our objectives were to (a) improve and evaluate the DLEM in simulating sediment yields; (b) estimate spatial and temporal dynamics of runoff and sediment yield over the MRB and quantify runoff and sediment sources from different land use types; (c) investigate the impact of climate, especially EP, on sediment yield; (d) comprehensively assess the contributions of climate and land use change on sediment yield over the last century.

2. Methods

2.1. Dynamic Land Ecosystem Model

The DLEM is a process-based land surface model integrating terrestrial biophysics, vegetation dynamics, plant physiology, and hydrological and biogeochemical cycles (Pan et al., 2015; Tian et al., 2010, 2011). The model estimates daily and spatial water, carbon, and nutrient dynamics across terrestrial and aquatic ecosystems. The DLEM uses a grid cell as its fundamental simulation unit and employs the concept of plant functional types

(PFTs) to characterize terrestrial biomes. Like other land surface models, in the DLEM, a cohort structure represents a subgrid hierarchy. Each grid may contain vegetation cover, impervious surfaces, bare ground, glaciers, and water bodies (Lawrence et al., 2019). The vegetation cover includes at most five PFTs, with one reserved for crops and four reserved for natural PFTs.

Each grid also represents a hydrologic unit (Tesfa et al., 2014). Key hydrological processes in the DLEM include canopy interception, soil evaporation and canopy evapotranspiration, infiltration, soil moisture movement, surface and subsurface runoff generation, and river flow routing (M. Liu et al., 2012, 2013). Canopy evaporation and transpiration are calculated based on the Penman-Monteith approach (Wigmosta et al., 1994), considering CO₂ fertilization effects on stomatal conductance. Vertical soil water flow in 10 soil layers is simulated using the Richards equation, and surface runoff is generated when rainfall exceeds the maximum soil infiltration capacity or the first soil layer (0.5 m) becomes saturated. Finally, the channel routing processes within a grid cell are separated into hillslope flow, subnetwork flow, and main-channel flow based on the Model of Scale Adaptive River Transport scheme (H. Li et al., 2013, 2015; Yao et al., 2021). The DLEM has successfully been used to simulate water (M. Liu et al., 2013), carbon (Tian, et al., 2015a), nitrogen (Tian et al., 2020), and phosphorus (Bian et al., 2022) loading from the MRB to the Gulf of Mexico.

2.2. Sediment Module

The daily sediment yield due to soil erosion is calculated based on the MUSLE (Williams, 1975, 1995).

$$\text{Sed} = a \cdot (Q \cdot q_{\text{peak}} \cdot \text{area})^b \cdot K \cdot C \cdot P \cdot \text{LS} \quad (1)$$

where Sed is sediment yield (t day⁻¹); Q is surface runoff (mm) and q_{peak} is daily peak runoff rate (m³ s⁻¹); area is the land area (ha) within a grid cell; K is the soil erodibility factor which is calculated based on soil texture (percents of clay, silt, and sand) and soil organic carbon content; C is the cover and management factor; P is the support practice factor and varies with land slope for cropland while it is set as 1 for other land use types; LS is the topography factor derived from slope; a and b are fitted coefficients in the equation. The MUSLE mainly covers rill and inter-rill (sheet) erosion processes, whereas gully erosion or landslides connected to the river network are not considered (Kale & Vadsola, 2012).

The DLEM estimates peak runoff and MUSLE factors (K , C , P , LS) following the methods in the SWAT model (Neitsch et al., 2011).

$$q_{\text{peak}} = \frac{\text{frc} \cdot Q \cdot \text{area}}{3.6 \cdot t_{\text{conc}}} \quad (2)$$

$$\text{frc} = 1 - \exp[2 \cdot t_{\text{conc}} \cdot \ln(1 - \text{frc}_{0.5})] \quad (3)$$

where t_{conc} is the time of concentration for the hydrological unit (hr) and is obtained based on Manning's equation; frc is the fraction of daily rainfall occurring during the time of concentration; $\text{frc}_{0.5}$ is the fraction of the half-hour highest rainfall in daily rainfall which can be generated according to precipitation data.

$$C = \exp([\ln(0.8) - \ln(C_{\text{mn}})] \cdot \exp(-0.00115 \cdot \text{rsd}) + \ln(C_{\text{mn}})) \quad (4)$$

where C_{mn} is the minimum value of C factor for the land cover and rsd is soil residue content simulated by the DLEM (kg ha⁻¹).

To overcome the lower performance of MUSLE in simulating sediment in regions where snow melting dominants runoff generation (Fagundes et al., 2021), in this study, we modify sediment yield by using the following equation (Neitsch et al., 2011):

$$\text{sed}_{\text{snow}} = \frac{\text{Sed}}{\exp\left(\frac{\text{SNP}}{8.47}\right)} \quad (5)$$

where sed_{snow} is sediment yield (t day⁻¹) when snow is present; SNP is snow package equivalent water (mm).

Sediment yield reaching aquatic systems is then delivered through river networks within and between grid cells. Hillslope overland flows carry sediment from land and converge with subsurface runoff forming subnetwork flows (Yao et al., 2021). Then local subnetwork flow combined with upstream water flows into the main channels

Table 1
A Summary of Model Input Data and Validation Data

Data variables	Original spatial resolution (period)	Reference/source
Model input data/Environmental drivers		
Climate (Temperature, Precipitation)	5 arc min (1979–2018) 0.5° (1901–1978)	GRIDMET (1979–2018) (http://www.climatologylab.org/gridmet.html) CRUNCEP (1901–1978) (https://doi.org/10.5065/PZ8F-F017)
Land Cover and Land Use (Crop density)	1 km (1901–2018)	Yu and Lu (2018)
Soil properties (%silt, % sand, %clay, pH)	5 arc min	ISRIC-WISE Batjes (2012)
River network and flow direction	1/16°	Wu et al. (2012)
DEM	30 arc s	HYDRO1K, Earth Resources Observation and Science Data Center, USGS
Model Calibration and Validation data		
Sediment yields	Catchment	Tan et al. (2017) USGS National Water Information System (https://waterdata.usgs.gov/nwis)

before draining into the downstream grid cell. The suspended sediment is deposited as water transports along the network. The net deposition velocity v_s (m day⁻¹) of suspended sediment is calculated according to Stokes' Law (Thomann & Mueller, 1987):

$$v_s = 0.033634 \alpha (\rho_s - \rho_w) d^2 \quad (6)$$

where α reflects the impact of the particle's shape on settling velocity (dimensionless, for a sphere it is 1.0); ρ_w and ρ_s are the density of water and suspended sediment (g cm⁻³), respectively, and d is the average diameter of the sediment particle (μm) (Chapra, 2008). The major parameters and local sensitivity analysis are presented in Supporting Information S1 (Tables S1 and S2).

In order to exclude the human disturbance within river channels, here, our analysis will focus on upland sediment yield, representing the amount of detached sediment reaching aquatic systems.

2.3. Data Sources

The input data sets to drive DLEM include climate, land cover/use change, atmospheric CO₂ concentration, soil properties, river network, atmospheric nutrient deposition, fertilizer and manure nutrient application, and topography (Table 1 and Figures 1 and 2). All input data sets were developed or resampled into a spatial resolution of 5 × 5 arc-min (around 9.2 × 9.2 km at the equator). Data on daily climate variables, such as precipitation and temperature, spanning from 1979 to 2018, were acquired from GRIDMET. To incorporate climate data before 1979, the CRUNCEP data set was downsampled and adjusted for bias to align with the GRIDMET data set. The soil properties (% sand, % silt, % clay, pH) were derived from a global soil data set ISRIC-WISE (Batjes, 2012). The land use inputs represented by the fractions of PFTs and non-vegetated cover were developed by combining multiple land use products, including the National Land Cover Database, potential vegetation map (Ramankutty & Foley, 1999), and crop density maps (Yu & Lu, 2018). The land use change during 1901–2018 was assumed to be primarily driven by cropland expansion and abandonment, and urbanization. The Digital Elevation Model (DEM) data was aggregated from a high-resolution (30 arc sec) digital elevation data HYDRO1K provided by U.S. Geological Survey (USGS). The river network data, including flow direction, channel slope, and channel length, were derived from a global river network database (Wu et al., 2012).

The observed sediment yield data from small catchments (Tan et al., 2017) were used for model validation at the grid cell scale. Observed sediment fluxes in these headwater catchments were less likely to be impacted by dam construction compared with large sub-basins. We selected 30 catchments with sediment yield data covering the period after 1979 when the high-resolution climate data was available. These catchments are distributed in all the major sub-basins (Ohio, Upper Mississippi, Missouri, Arkansas, Red, Tennessee, and Lower Mississippi) and major land use types (forest, cropland, shrubland, grassland) (Figure 1 and Table S3 in Supporting Information S1). The average area of these 30 catchments is 69 ± 51 km² which is close to the grid area in this study (56–78 km²). The sediment yields of these catchments were compared with the simulated results on the corresponding grid cells. The observed sediment yield data from 20 catchments were used to calibrate the model, and data from the left 10 catchments were used for validation. We used the coefficient of determination (R^2) and Nash-Sutcliffe efficiency (NSE) to evaluate the DLEM performance.

2.4. Simulation Experiments

The DLEM simulations involved three steps. The first step was an equilibrium run that utilizes the 40-year mean historical climate (1861–1900) to establish the initial state under the pre-1900 conditions. The second step was a spin-up simulation to remove noise from the transition from equilibrium to transient run. The final step was the transient run that utilizes 118 years (1901–2018) of input data sets to generate simulation results. In this study, we first selected the years 1980–2018 to analyze temporal and spatial changes in sediment yield and investigate the impacts of EP and land use types on sediment yield. Here, we defined EP as daily precipitation above the 95th percentile of all daily precipitations from 1980 to 2018 within each 5-arc-min grid. Second, we assessed the contributions of long-term climate and land use changes on sediment yield over the entire 1901–2018 period by comparing the historical simulation S0 (baseline) with two additional “without” simulation experiments S1 (“fixed climate”) and S2 (“fixed land-use”) (Table 2). In experiment S1, the climate

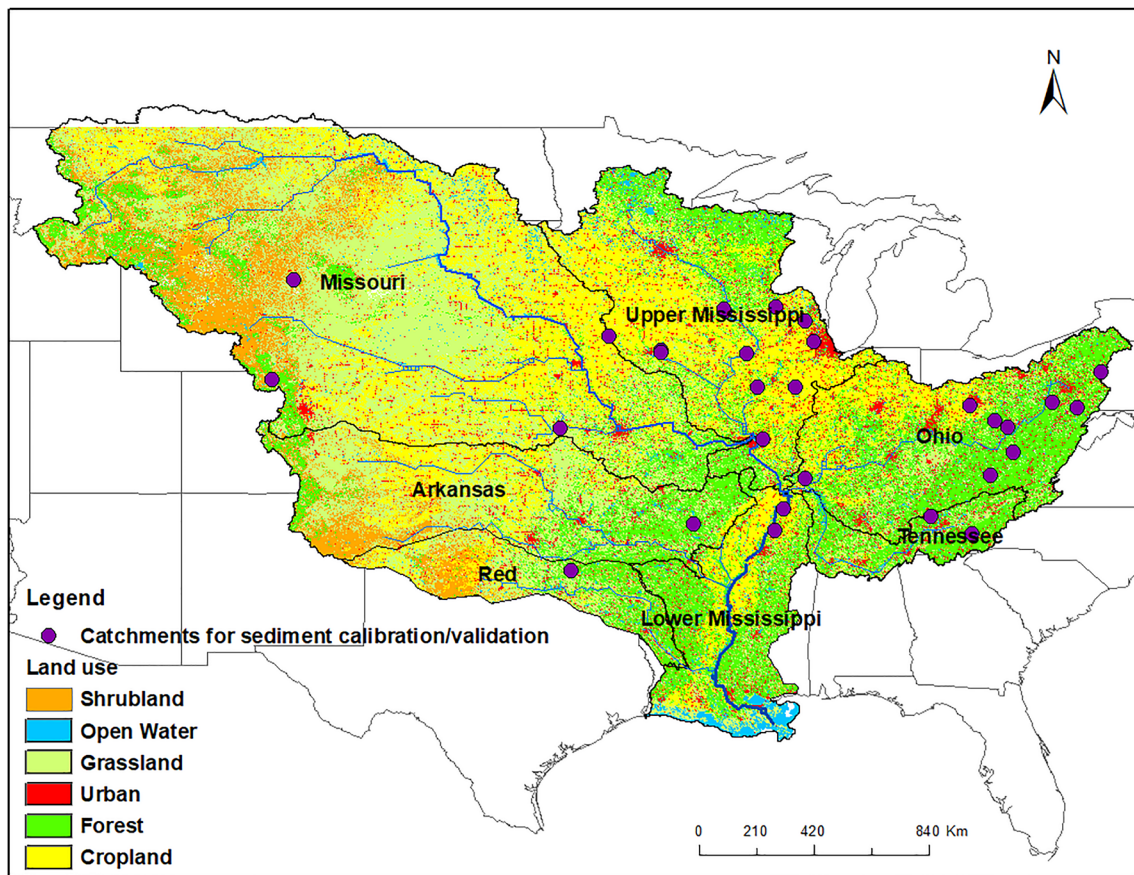


Figure 1. Land cover, river network, and catchments used for calibration and validation in the Mississippi River Basin.

variables were held constant at 1907 (annual precipitation is 766 mm and the average daily temperature is 9.85°C), which is most close to the annual averages of climate data (precipitation = 763 mm, temperate = 9.95°C) during 1901–1920. Using precipitation in a representative year has the advantage of maintaining EP signals compared to long-term averages. In experiment S2, land use was fixed to 1901, while the other forcings varied over time. The impacts of the corresponding factors were determined by comparing the differences between S0 and S1–S2.

3. Results

3.1. Model Performance Evaluation

Generally, the DLEM can reasonably estimate sediment yields at headwater catchments. The R^2 between annual simulated and observed sediment yields in 30 catchments was 0.63 (0.65 in calibration and 0.68 in validation),

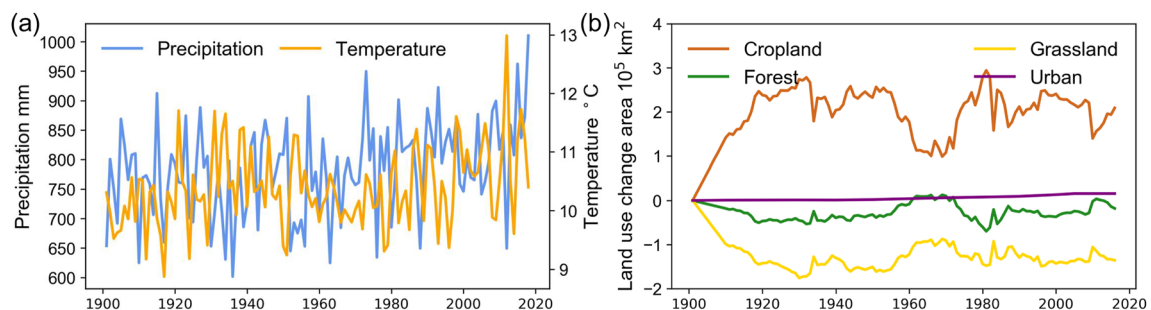


Figure 2. Interannual variations of (a) climate and (b) land cover/use change in the Mississippi River Basin during 1901–2018.

Table 2
Factorial Simulation Experiments With the Dynamic Land Ecosystem Model

Experiments	Climate	Landuse
S0 (Baseline)	1901–2018	1901–2018
S1 (Fixed climate, dynamic land use)	1907	1901–2018
S2 (Fixed landuse, dynamic climate)	1901–2018	1901

and the NSE was 0.61 (0.64 in calibration and 0.51 in validation) (Figure 3b), indicating the DLEM simulated sediment yields were overall comparable with USGS observation. The DLEM performed better in capturing high sediment yields ($>100 \text{ t km}^{-2}$) compared with simulating low sediment yields ($<10 \text{ t km}^{-2}$), which were overestimated by the model. The overestimation of low sediment yield may be related to the overestimation of low water yield (Figure 3a). Although significant biases can occur when modeling low sediment yields, their effect on the overall estimation error of the total annual sediment yield for the entire basin may be relatively minor.

3.2. Temporal and Spatial Changes in Sediment Yield

The interannual variation in simulated total sediment yield in the MRB was dominated by precipitation and runoff changes. The simulated annual total sediment yield significantly increased (p -value < 0.01) from 1980 to 2018 (Figure 4b). Meanwhile, the increases in annual precipitation and total runoff were not significant (p -value > 0.05) (Figure 4). The annual average total sediment yields increased by 27% from $1.89 \times 10^8 \text{ t yr}^{-1}$ in the 1980s to $2.39 \times 10^8 \text{ t yr}^{-1}$ in the 2010s (2010–2018), with the rapid increase primarily occurring after the 2000s. Simulated sediment yield was extremely high in 2018 when precipitation and runoff peaked.

The spatial variability of simulated sediment yield differed from that of runoff (Figure 5). Simulated runoff decreased along a gradient from the southeastern basin to the northwestern basin (Figure 5a). Sediment yield was high in the Ohio sub-basin, where precipitation and runoff were high, as were the Upper Mississippi, Lower Mississippi, and eastern Missouri sub-basins, where croplands dominated (Figure 5b). The high sediment yield in northwestern Missouri was associated with the steep slope and precipitation in mountain areas. From 1980 to 2018, the major sub-basins contributing to the most runoff were Ohio (25%), Lower Mississippi (18%), and Missouri (17%), while the major contributors for sediment yield were Missouri (33%), Ohio (26%), and Upper Mississippi (22%). The forests and croplands occupied a similar proportion (around 30%) of the entire MRB. Nevertheless, the forests contributed a higher proportion (57%) of water yield and a lower proportion (20%) of total sediment yield compared with croplands which contributed 25% of water yield and 61% of total sediment yield (Figure 5c). As forests dominate in the wet areas of the MRB, water yield from forested lands is much higher than that from other land use types despite the relatively high evapotranspiration of forests. Forest soils covered with litter and understories in wet areas have high infiltration capacity and less overland flow, playing a crucial role in mitigating soil erosion during intense rainfall events.

3.3. Impact of Extreme Precipitation on Sediment Yield

Across the MRB, the proportion of EP amount and the number of EP days (EP days) increased from 1980 to 2018, especially after 1990 (Figure 6a). The average share of EP in annual total precipitation increased from 22% in

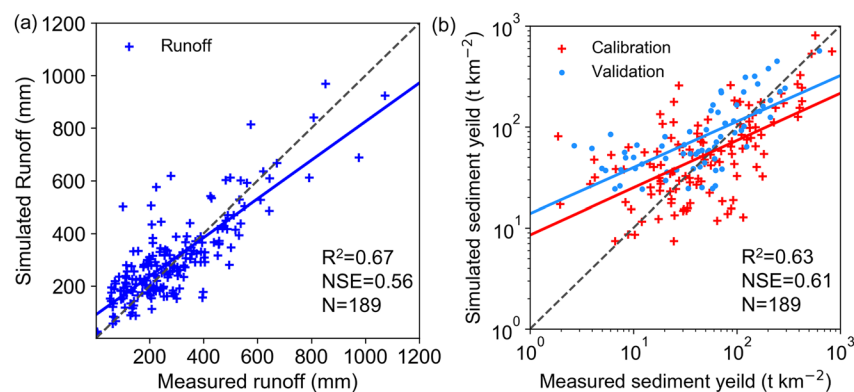


Figure 3. A comparison of DLEM-simulated and USGS-observed annual (a) runoff and (b) sediment yields in 30 catchments within the Mississippi River Basin. The coefficient of determination (R^2) and Nash-Sutcliffe efficiency reflected the overall relationship between measured and simulated sediment yields in all the catchments used for calibration and validation. The log scale is used in (b).

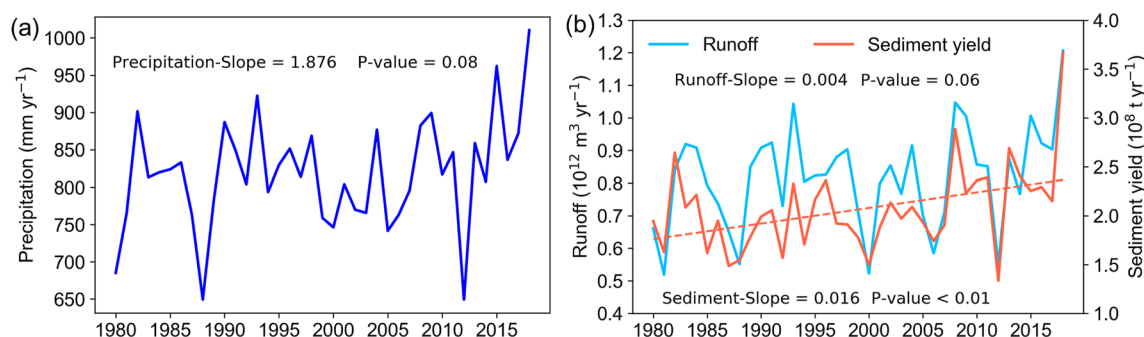


Figure 4. Interannual variations and trends in (a) precipitation and (b) total runoff and sediment yield in the (Mississippi River Basin) MRB during 1980–2018.

the 1980s to 36% in the 2010s. The impacts of EP on runoff and sediment yield have substantially amplified in recent decades (Figure 6b). The percentage of annual runoff attributed to EP was estimated to increase from 13% in the 1980s to 25% in the 1980s. The percentage of annual sediment yield that occurred on EP days increased from 27% to approximately 45%.

The simulated runoff on EP days was high in the lower Mississippi and decreased along the gradient toward all other sub-basins, which also reflected the spatial pattern of EP (Figure 7a). The runoff on EP days intensified across the central and eastern parts of the basin from the 1980s to the 2010s. Different from the spatial pattern of runoff on EP days, the sediment yield on EP days was also high ($>10 \text{ t km}^{-2} \text{ yr}^{-1}$) in the Midwest, the agricultural core zone in the U.S. (Figure 7b). Although sediment yield on EP days increased in both forests and croplands, soil erosion in croplands was more vulnerable to enhanced EP compared to forests (Figures 7c and 7d). From the 1980s to the 2010s, the increase in sediment yield on EP days was over three times higher in croplands compared to forests, despite the increase in the water yield on EP days being lower in croplands than in forests.

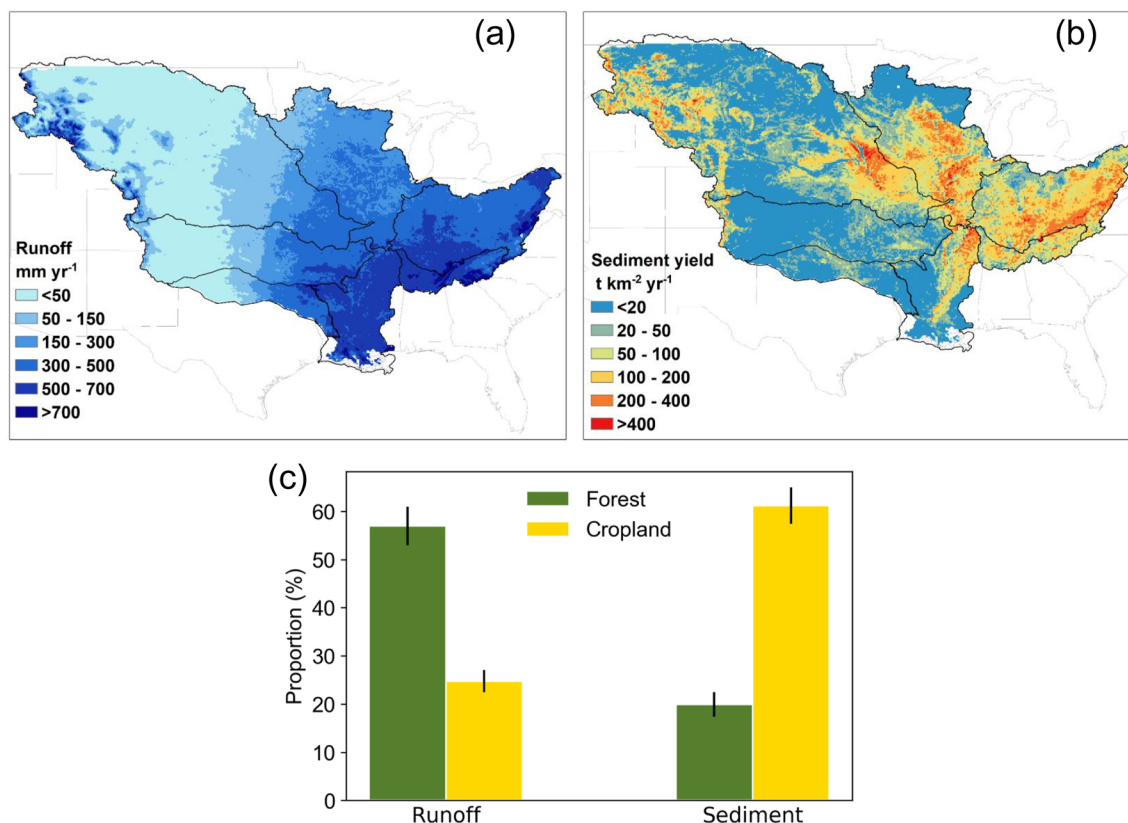


Figure 5. The spatial patterns of annual average (a) runoff and (b) sediment yield, and (c) the contributions of forests and croplands to total runoff and sediment yield in the Mississippi River Basin from 1980 to 2018. The error bars in (c) represent the standard deviation of annual values during 1980–2018.

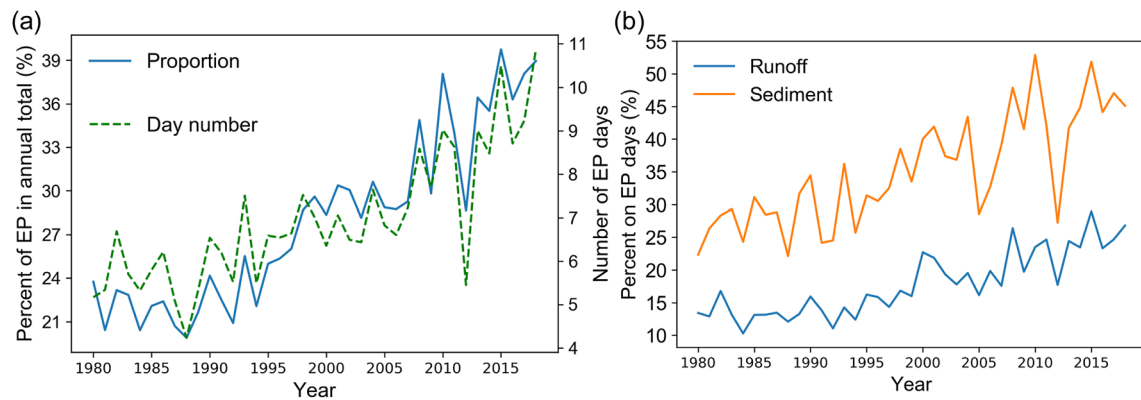


Figure 6. (a) The percentage of extreme precipitation (EP) amount in annual total precipitation and annual average numbers of EP days across grids within the basin from 1980 to 2018. EP was defined as daily precipitation above the 95th percentile of all daily precipitations from 1980 to 2018 for each 5-arc-min grid. (b) The percentages of simulated runoff and sediment yield occurred on days with EP relative to annual totals in the Mississippi River Basin.

Changes in the spatial distribution of EP altered sediment yield patterns across the whole basin (Figure 8). From the 1990s to the 2000s, the intensified EP and runoff on EP days mainly occurred in the Lower Mississippi and Ohio sub-basins, where forests covered most of the area except for the Mississippi River Valley. Meanwhile, sediment yield on EP days increased significantly in the river valley region but not extensively increased in other forest areas. In contrast, the 2010s witnessed further intensifying EP and runoff on EP days in the Midwest relative to the previous decade. The convergence of enhanced EP and extensive cropland areas resulted in a substantial increase in sediment yield in the Midwest compared to previous decades.

3.4. Long-Term Sediment Yield Change in Response to Climate and Land Use Change

The contributions of climate and land use change to alterations in runoff and sediment yield varied over the past century (1901–2018) (Figure 9). Climate variability, characterized by the range of precipitation and temperature changes, has primarily dominated the long-term changes in runoff and sediment yield. Since the 1940s, sediment yield in S0 (baseline simulation) was 10–64% higher than S1 (“fixed climate” simulation), indicating climate variability has increased sediment yield relative to the early 20th century. In contrast to sediment yield, the runoff in S0 was lower than in S1 during the 1950s and 1960s because climate variability reduced subsurface runoff even as it increased surface runoff. The climate-induced increase in sediment yield in the 2010s was over twice

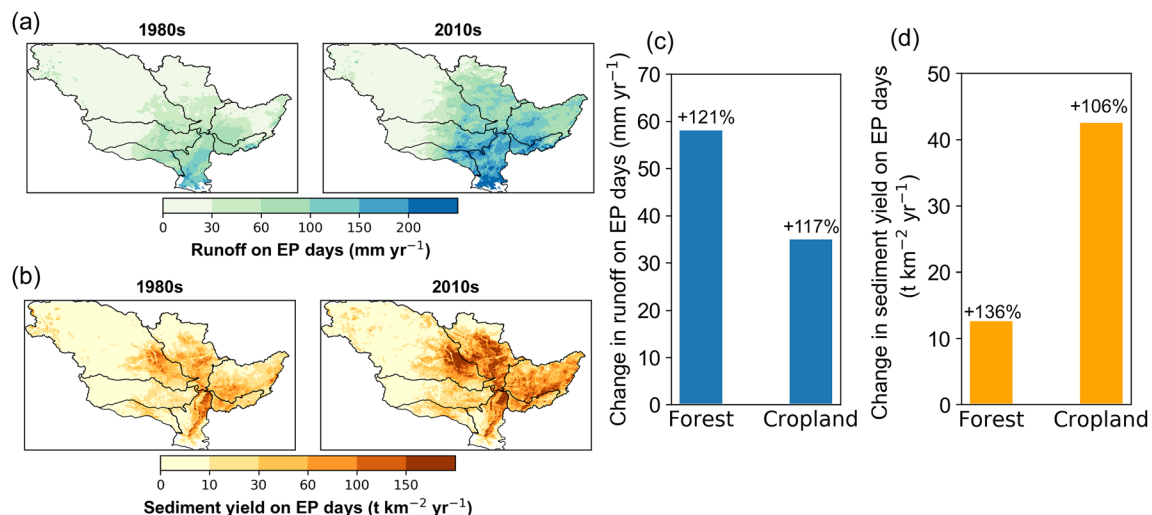


Figure 7. Spatial distributions of (a) runoff and (b) sediment yield occurred on extreme precipitation (EP) days in the 1980s (1980–1989) and the 2010s (2010–2018). The changes in (c) runoff and (d) sediment yield on EP days between the 1980s and the 2010s on croplands and forests. The bars and the numbers above represent absolute and percent changes, respectively.

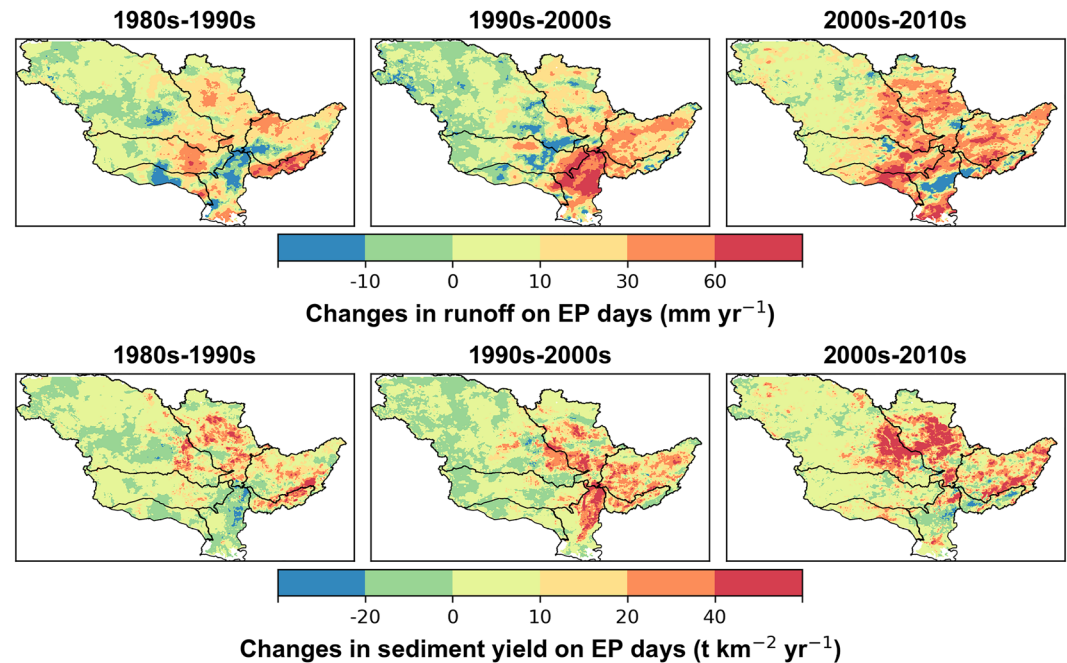


Figure 8. Spatial changes in runoff (top) and sediment yield (bottom) on extreme precipitation days from the 1980s (1980–1989) to the 1990s (1990–1999), from the 1990s to the 2000s (2000–2009), and from the 2000s to the 2010s (2010–2018).

that of other decades, reflecting a risen risk of soil erosion during this period. In comparison, land use change had a more complex and time-varying effect on sediment yield. Compared with S2 (“fixed land use” simulation), land use change in S0 increased total sediment yield by 1%–10% before the 1940s as cropland expanded, but it shifted to reduce sediment yield in the 1960s and 1970s when cropland abandonment occurred. Overall, land use change played a more important role in contributing to sediment yields from the 1910s to the 1930s. Thereafter, climate became the major contributor and even outweighed the decrease caused by land use change. By the 1980s, land use change only had a marginal effect on sediment yield, as land use conditions remained relatively stable.

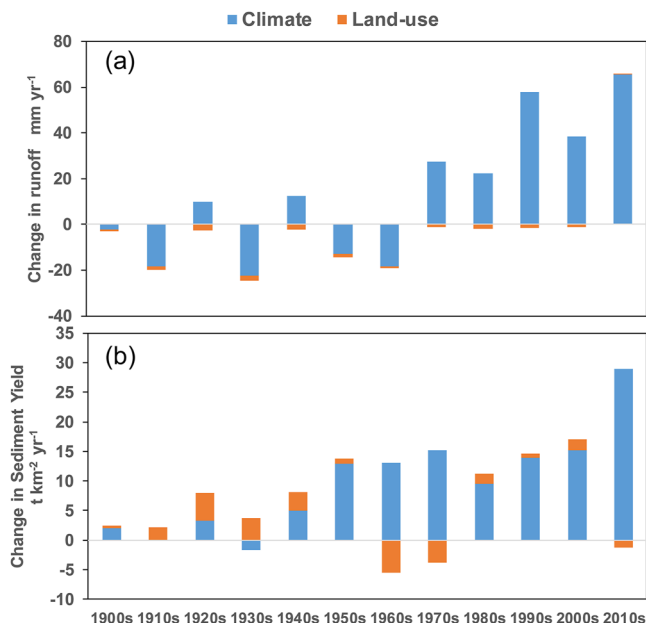


Figure 9. Changes in decadal average (a) annual runoff and (b) annual sediment yield in response to climate and land use changes. Decadal changes were the accumulative difference between baseline S0 and the other two scenarios S1 and S2 (Section 2.4).

4. Discussion

4.1. Impacts of Climate and Land Use Changes on Soil Erosion and Sediment Yield

Land use is widely recognized as the primary anthropogenic driver of soil erosion, and climate change may also aggravate soil erosion problems by intensifying rainfall and runoff (Borrelli et al., 2020). Land use is critical in determining cover vegetation, roughness, infiltration capacity, and overland flow in a landscape, which strongly influences soil erosion (Simonneau et al., 2015). As physical erosion rates in agricultural soils are considerably higher than in forested soils, deforestation and cropland expansion can amplify soil erosion and sediment yield (Montgomery, 2007; Reusser et al., 2015). In the MRB, cropland expansion before the 1940s contributed to the increase in the total sediment yield. In comparison, extensive cropland abandonment in the 1950s and the 1960s led to a decrease in the total sediment yield (Yu & Lu, 2018). As land use has become relatively stable since the 1980s, land use change was no longer the major contributor to sediment yield change.

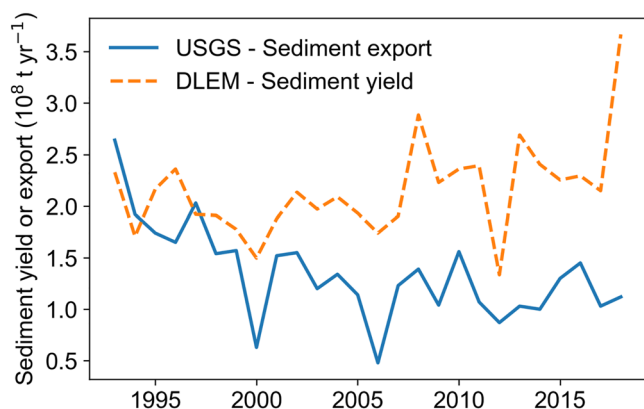


Figure 10. Comparison of USGS-observed annual riverine suspended-sediment export and DLEM-simulated land sediment yields from the Mississippi River Basin during 1993–2018. The USGS suspended-sediment loads were obtained from <https://nrtwq.usgs.gov/nwqn/#/GULF>.

Climate, especially precipitation, dominates in controlling interannual and long-term changes in soil erosion and sediment yields. Increasing rainfall amount or intensity can intensify soil erosion rates, particularly on unprotected soil surfaces (Nearing et al., 2005; Simonneaux et al., 2015). Numerous studies have indicated that soil erosion from extreme rainfall is significantly higher than that caused by average rainfall (Coppus & Imeson, 2002; Wei et al., 2009; Zhao et al., 2019). More frequent and intense EP in the MRB can exacerbate soil degradation and erosional nutrient loss, which poses a high risk to soil healthy, weakens ecosystem resilience, and threatens food and water security (Eekhout et al., 2018; Guerra et al., 2020; Morán-Ordóñez et al., 2020). This study suggests that soil erosion in croplands is more vulnerable to EP than in forests. Fortunately, the increased occurrence of extreme rainfall from the 1980s to the 2000s has predominantly been concentrated in the MRB's southern region, primarily characterized by forested areas, except the Mississippi Alluvial Plain. However, as climate changes toward a more vigorous hydrological cycle (Allan & Soden, 2008), more frequent EP events are projected to occur in the Upper Mississippi sub-basin, where cropland is the dominant land use type (J. Zhang et al., 2022). The intensified EP in the future may amplify soil erosion, as has already been exhibited in the 2010s

(Segura et al., 2014). The enhanced erosion of cropland soil and subsequent loss of organic matter and nutrients can pose threats to agricultural productivity and challenge water quality management in the Gulf of Mexico (Eekhout et al., 2018; Lu et al., 2020; Pimentel et al., 1995; Tan et al., 2021).

Therefore, risk assessment of potential soil erosion under future climate change holds importance for land managers and water and dam managers to regulate sediment exports from watersheds and silt accumulation in dams (Simonneaux et al., 2015). Existing Best Management Practices (BMPs), such as maintaining groundcovers, conservation or reduced tillage, riparian buffer strips, and crop rotation, need to be enhanced to prevent soil erosion under intensified EP events (Ahmad et al., 2020; Duan et al., 2020; O'Neal et al., 2005). Additionally, given the benefits of forests in controlling soil loss and providing clean water (N. Liu et al., 2022), keeping existing forests or restoring forests through reforestation in previously croplands areas will become important in regions where EP is projected to intensify in the future (Morán-Ordóñez et al., 2020).

4.2. Dam-Induced Discrepancy Between Sediment Yield and Riverine Sediment Export in Large River Basins

Sediment yields from land to aquatic systems are transported through complex river networks and may enter lakes, reservoirs, or coastal ecosystems. Sediment deposition and delivery are mainly influenced by the size, shape, and density of sediment particles, as well as the presence of dams and reservoirs. Fine fluvial sediment such as silt and clay is often bound together with organic matter as aggregates and can move long distances, while sand and coarser particles are more likely to settle along river channels and in reservoirs (Droppo et al., 2015). The land surface models coupled with erosion modules have been used to simulate sediment and erosion-induced carbon and nutrient loading to coastal ecosystems at continental or global scales (Naipal et al., 2020; Tan et al., 2022; H. Zhang et al., 2020). Nevertheless, most of these land surface models, including DLEM, do not account for the influences of dam construction on sediment transport along the river networks. Despite the DLEM can reasonably capture the variation of sediment yield in the MRB, the simulated change trend in sediment yield showed a discrepancy with the observed riverine export of suspended sediment to the Gulf of Mexico at the mouth of the MRB (Figure 10). It was estimated that about 46% of mobilized sediment was trapped in reservoirs over the entire MRB (Hassan et al., 2017). Sediment trapping by dams and reservoirs overwhelmed the influence of increased EP, causing a decreasing trend in suspended sediment loads in the MRB (T. Li et al., 2020; Meade & Moody, 2010).

Similarly, the trapping of sediment by dams and other soil conservation and sediment control measures has decreased sediment loads in around 50% of the world's rivers in recent decades (Walling & Fang, 2003). Long-term changes in soil erosion and land sediment yield were mainly controlled by precipitation and water yield capacity. However, long-term changes in global suspended sediment loads to coastal oceans were more

likely to be influenced by dam constructions than climate change (Syvitski et al., 2005; Walling, 2006; Walling & Fang, 2003). Additionally, given the close relationship between riverine exports of suspended sediment and particulate form carbon, sediment trapping by dams may substantially alter global carbon export from the terrestrial biosphere (Galy et al., 2015; Maavara et al., 2017). Modeling sediment trapping by dams is critical for accurately simulating large-scale exports of suspended sediment and carbon from land to coastal oceans. However, due to complex reservoir operation processes, there were limited efforts to incorporate dam and reservoir siltation processes into erosion models (Pandey et al., 2016). We call for more studies in understanding the mechanisms of dams and other hydraulic infrastructures in regulating land-ocean sediment transport in order to guide future land surface model development and accurately quantify large-scale sediment and carbon delivery.

4.3. Uncertainties and Limitations

Modeling large-scale soil erosion is challenging due to the complexity and high spatial heterogeneity. The simplified representation of several processes in the DLEM and the lack of long-term series and high-resolution input data sets might have contributed to simulation errors. First, soil erosion is sensitive to changes in peak overland flow and river flow, and the DLEM estimated flows using daily rather than hourly climate data. The absence of information regarding fluctuations in precipitation intensity throughout the day can introduce biases in simulated daily peak runoff and erosion. Meanwhile, peak runoff is also impacted by the time of concentration for each hydrological simulation unit. Catchment characteristics like shape and river network control the time of concentration. However, this study assumed each regular grid cell represents a hydrological unit, and missing accurate catchment information may also lead to biases in the simulation of peak runoff and sediment yield.

Second, the DLEM estimated landscape soil erosion resulting from overland flow while neglecting other erosion processes, such as gully erosion, landslide, floodplain erosion and deposition, and channel bank erosion. These limitations can be attributed to the utilization of the MUSLE model, which is primarily designed to operate at small-scale such as hillslopes without considering gully erosion. Moreover, due to historical soil erosion, the accumulation of sediments in the Mississippi River Valleys and floodplains has played a crucial role in providing the current sediment yields (Hassan et al., 2017). However, the DLEM-estimated sediment yields in river valleys and floodplain regions might be underestimated.

Third, the model may have underrepresented the complex spatiotemporal variations in the effects of soil conservation practices in croplands. For example, the sediment yields from uplands surrounding the Missouri-Mississippi River system diminished in recent decades due to soil conservation practices (Meade & Moody, 2010; Piess & Ziemnicki, 1979). Therefore, our simulated results may overestimate the sediment yield increases in the cropland areas within the Missouri and Upper Mississippi as the temporal and spatial changes in soil conservation practices were not considered in the model.

Fourth, the average soil properties and slope were used to represent the average condition of each grid cell, ignoring the spatial variability within each grid, and potentially introducing uncertainties to the simulated sediment yields. Furthermore, multiple input data sets, including soil, DEM, and land use, were resampled to arc 5-min resolution to align with other input data, which could have caused spatial biases.

Additionally, there might be data issues for direct model validations. The time series of suspended-sediment concentration and load data provided by USGS was computed by combining in-stream continuous turbidity and streamflow data (Rasmussen et al., 2009). However, it should be noted that turbidity measurements can be influenced by factors beyond suspended sediment alone. Particle size, shape, and color, for instance, significantly influence the amount of light scattered, which is a pivotal parameter in turbidity determination (Sutherland et al., 2000).

5. Conclusions

This study improved the erosion module in the ecosystem model, DLEM, for understanding the responses of upland soil erosion and sediment yield to climate and land use changes in the MRB. Simulations suggested that climate variations dominated the interannual and long-term changes in total sediment yield. Land use change, especially cropland expansion and abandonment, was the primary driver of total sediment yield change before the 1940s but played a less critical role thereafter. Despite the absence of a significant increase in runoff, simulated

soil erosion and total sediment yield increased significantly during 1980–2018, primarily due to the intensified and frequent EP, especially after 1990. Compared with forests, croplands contributed a more proportion of sediment yield and less proportion of water yield. Croplands were more vulnerable to EP than forests in terms of soil erosion. We found that the regions with highly intensified EP shifted from the Lower Mississippi to the Upper Mississippi and Missouri from the 2000s to the 2010s, exacerbating soil erosion and sediment yield from croplands in the Midwest in the 2010s. Given the predicted increase in EP in the Midwest, it is essential to revisit forest and agricultural BMPs to mitigate increasing soil erosion, sedimentation, and associated losses of carbon and nutrients to the Gulf of Mexico from the MRB.

Data Availability Statement

The model-simulated annual land sediment yield in the MRB is archived at <https://doi.org/10.5281/zenodo.8145754> (Bian et al., 2023).

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