Analysis of temporal and spatial changes of soil erosion under LULCC based on CSLE in the typical watershed on the Loess Plateau

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Abstract

Extreme meteorological events occur frequently, and changes in the spatial pattern of land use have greatly affected the soil erosion process in the hilly and gully region of the Loess Plateau. As a typical governance watershed in the hilly and gully area of the Loess Plateau, the Jiuyuangou watershed has experienced significant changes in land use and land cover (LULCC) in the past ten years due to the conversion of farmland to forests, economic construction, and abandonment of cultivated land. However, the evolution process of soil erosion under LULCC in the watershed is unclear. This study uses satellite images to extract information on LULCC in the watershed and the Chinese soil loss equation (CSLE) model to evaluate the temporal and spatial evolution of soil erosion in the watershed from 2010 to 2020. The main results showed that: (1) The continuous vegetation restoration project in the watershed reduced soil erosion from 2010 to 2015; however, the frequency of extreme rainfall events after 2015 reduced its impact. The annual average soil erosion modulus decreased from 10.85 t ha $^{-1}$ yr $^{-1}$ in 2010 to 8.03 t ha $^{-1}$ yr $^{-1}$ in 2015, but then increased to 10.57 t ha $^{-1}$ yr $^{-1}$in 2020; (2) The main LULC type in the Jiuyuangou watershed is grassland, accounting for 62.23% of the total area of the watershed, followed by forest land (28.41%), cropland (6.77%), building (2.49%), and water (0.09%). The multi-year average soil erosion modulus for land use type is cropland > grassland > building > forest land; (3) Significant spatial correlations between soil erosion change and LULCC for common ‘no change’ and common ‘gain’ occurred in the settlements, roads, valleys, and areas near the human influences with good soil and water conservation, but not other regions due to the influence of climatic factors (heavy rain events). This study provides a scientific reference for planning and managing water and soil conservation and ecological environment construction in the basin.

Introduction

Soil erosion, a serious environmental problem of global concern, leads to land degradation, which seriously affects sustainable agricultural development. The total area of the Loess Plateau suffers from serious soil erosion, with about 472,000 km^2 of its 640,000 km^2 erosion-prone and about 80% of the cropland area suffers from moderate to severe erosion (Meliho et al., 2019). The Loess Plateau is also a key area for soil and water conservation and ecological security construction in China (Huang, 2021; Zhang, 2016). Soil erosion restricts the sustainable development of the regional economy and society and determines the evolution of the Yellow River and its downstream safety (Fan et al., 2012). Soil erosion causes irreversible soil degradation, leading to topsoil losses and the migration of sediments (and associated nutrients) to water bodies, decreasing the available farmland area (Molina et al., 2012). Excessive sediments and pollutants lead to river siltation and ecosystem degradation, endangering regional food security and ecological environment quality. Thus, there is a need to understand the soil erosion status of the watershed through soil erosion assessments and mapping and determine the key areas for controlling soil erosion on the Loess Plateau. The general loss equation of soil erosion can calculate and analyze the distribution of soil erosion in watersheds. Various studies have used more than 30 soil erosion models to assess soil erosion rates on the Loess Plateau, with the common models usually divided into empirical models [MUSLE (Luo et al., 2015), RUSLE (Feng et al., 2010)] and physical models [WEPP (Han et al., 2016; Shen et al., 2009), SWAT (Shen et al., 2009), WATEM/SEDEM (Feng et al., 2010), Yang's model (Yang et al., 2011)].

The soil erosion models mentioned above are generally not suitable for the Loess Plateau because: (1) some are based on the revised general soil loss equation, RUSLE, which is not suitable for the unique terrain of the Loess Plateau with vertical and horizontal ravines and ignores the impact of important soil and water conservation engineering measures on erosion (MUSLE); (2) the function model obtained from experimental data in a certain area can not be used in other areas (Yang's model); (3) physical models require high-quality parameters and verification data, which is difficult to obtain in areas where little or poor quality data is available (WEPP, SWAT). Liu et al. (2002) considered the characteristics of soil erosion terrain on the Loess Plateau and proposed an LS(Slope length and slope factor) algorithm suitable for the region. Combined with the influence of human activities, they proposed incorporating biological measures (B factor), soil and water conservation engineering measures (E factor), and soil and water conservation tillage measures (T factor) to improve the applicability of the CSLE model on the Loess Plateau. This model is used widely in the region due to its relatively simple structure, high accuracy, and easy access to parameter factors, enabling rapid and comprehensive soil erosion assessments at different temporal and spatial scales. Shi et al. (2018) modified the CSLE model using runoff data from three different watersheds on the Loess Plateau over three different periods (1956–1959, 1973–1980, 2010–2013) to predict soil losses accurately at the farmland scale. Duan et al. (2020) used the CSLE model and 0.5 m Worldview satellite images, combined with soil and water conservation engineering practices to estimate soil looses in China and the erosion modulus and soil erosion intensity in Yunnan Province, a mountainous area in southwest China. Liu and Liu (2020) used satellite remote sensing image interpretation to understand land use changes in a small watershed in southern China from 1989 to 2015 and the CSLE model to calculate the contribution rate of soil erosion change and gully erosion to sediment yield.

Since the 1970s, numerous soil and water conservation projects have been undertaken on the Loess Plateau, such as the Converting Farmland to Forest Project (1999–2010), the construction of check dams, and improvements to sloping land (Fang et al., 1993). The continuous development of soil and water conservation and governance has significantly improved soil erosion and the ecological environment on the Loess Plateau, changing the spatial pattern of land use (Zhao et al., 2022). Land use and management affect runoff and sediment transport by changing the surface morphology, the dominant factor associated with soil erosion (Fu et al., 2020). The hilly and gully area of the Loess Plateau is the most severely eroded area. Extreme rainfall events and changes in land use patterns in recent years have setback the soil erosion improvements (Li et al., 2022). Using soil erosion models to assess soil erosion changes under the LULCC will help understand the governance effects of previous engineering measures and the evolution process of soil erosion to formulate future spatial pertinence and sustainable land management and restoration strategies. However, few studies have assessed soil erosion in the background of LULCC using CSLE in the hilly and gully area of the Loess Plateau. Therefore, considering the superiority of the CSLE model and changes in land use in the recent ten years (2010–2020), we evaluated: (1) temporal and spatial changes in soil erosion factors in the CSLE model for the Jiuyuangou watershed, a typical watershed in the hilly and gully region of the Loess Plateau, from 2010 to 2020; (2) temporal and spatial dynamic evolution of soil erosion under land use change in the study area from 2010 to 2020; (3) the spatial correlations between the soil erosion change and LULCC. our study will provide a scientific reference for land use management and ecological restoration projects in the basin.

Material and Methods

Study area

Jiuyuangou watershed (37°33' to 37deg38' N, 110deg16' to 110deg26' E) is in the hilly and gully region of the Loess Plateau and a first-class tributary on the left bank of Wuding River in Yulin City, Shaanxi Province, China(Figure 1). The basin has a gully density of 5.34 km km^{-2}, area of 70.7 km^2, and altitude of 820 to 1180 m. The main soil type is Malan loess, which is loose, porous, and prone to erosion. The basin topography is representative of the hilly and gully region of the Loess Plateau. In 1953, the Yellow River Water Conservancy Commission established the Suide Test Station in Suide, and determined Jiuyuangou—the representative area of the first sub-area of the Loess Hills and Gully region—as the Yellow River soil and water conservation ecological construction demonstration area.

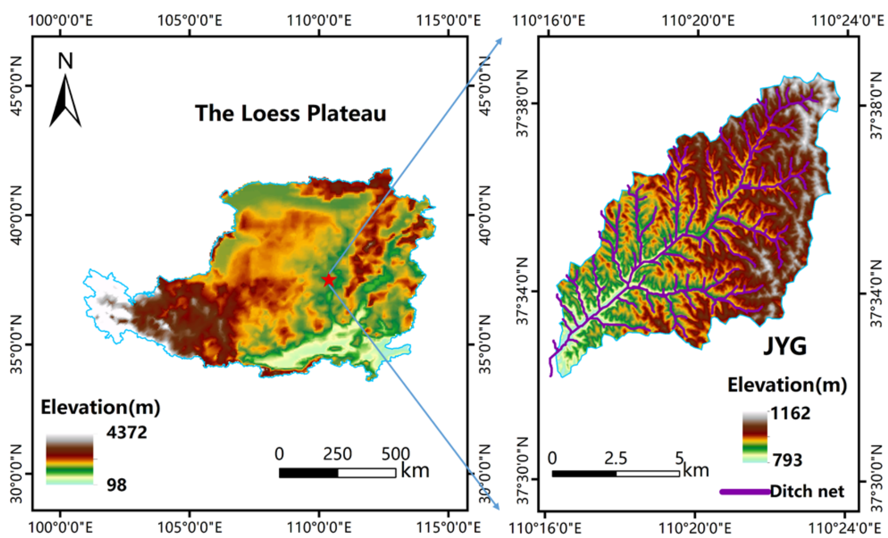

Figure 1. Location of the study area

Data collection

We used Sentinel 2A and Landsat 5–8 series satellite data downloaded by the United States Geological Survey USGS (https://www.usgs.gov/) to draw the 2010–2020 land use type map, divided into five categories: cropland, building, forestland, grassland, and water. Vegetation information was also extracted to obtain the time series of vegetation coverage in the Jiuyuangou watershed from 2010 to 2020. The 12.5 m resolution DEM data was downloaded through NASA (https://search.asf.alaska.edu/#/) to extract topographic parameters of the watershed and the slope length and slope factor. We downloaded the daily rainfall dataset from 1960 to 2020 from the National Meteorological Data Center (https://data.cma.cn/) and performed a spatial interpolation of meteorological data based on this data to obtain the 2010–2020 rainfall erosivity layer of the basin. The soil physicochemical properties of the watershed were obtained from the FAO 250 m resolution global soil texture survey data (https://soilgrids.org/). We used Google high-resolution historical imagery to identify soil and water conservation tillage measures in the watershed from 2010 to 2020.

Model implementation

Liu et al. (2002) innovatively proposed the vegetation measure (B factor), engineering measure (E factor), and tillage measure (T factor) according to the actual soil and water conservation situation on the Loess Plateau and combined them with the RUSLE equation to establish a Chinese soil erosion prediction model suitable for the Loess Plateau:

where A is the soil erosion modulus based on the CSLE model (1 t ha^{-1} yr^{-1}=100 t km^{-2} yr^{-1}), R is rainfall erosivity (MJ[?]mm·ha^{-1}[?]h^{-1}[?]yr^{-1}), K is soil erodibility factor (t[?]ha[?]h^{-1}*ha^{-1}[?]MJ^{-1}[?]mm^{-1}), L is slope length factor, S is slope factor, B is vegetation coverage measure factor, E is water and soil conservation engineering measure factor, and T is water and soil conservation tillage measure factor.

We obtained the rainfall erosivity grid layer using the rainfall erosivity model based on daily rainfall data from meteorological stations around the Jiuyuangou watershed. For soil erodibility factor (K factor) in the Loess Plateau region, most studies have adopted the soil erosion and productivity impact estimation model (EPIC; Williams et al., 1983), which uses soil organic matter and particle composition for estimation. Based on 12.5m ALOS DEM data (https://www.earthdata.nasa.gov/), the LS_TOOL slope length and slope factor calculation software developed by Zhang et al. (2017) was used to complete the terrain factor calculations, and ArcGIS 10.7 was used to generate a raster layer of slope length and slope factors. In this study, based on the 'Technical Regulations for Dynamic Monitoring of Regional Soil Erosion' from the Department of Soil and Water Conservation, Ministry of Water Resources, China, the vegetation coverage measure (B factor) was calculated using the vegetation coverage combined with land use type data and monthly rainfall erosion ratio with month as the time step. The E factor of the watershed was obtained by interpreting Google historical imagery within the study area. The raster calculator in ArcGIS was used to assign the T factor to the corresponding slope grading map and obtain the T factor map of soil and water conservation tillage measures.

Land cover and land use changes and soil erosion changes (2010–2020)

For soil erosion change and LULCC assessment, we used the transition matrix method, where diagonal values show the 2010–2020 stable area of LULC and soil erosion grades. The soil erosion modulus map and LULC map combined with the transition matrix help us understand the spatial and temporal evolution of land use patterns and soil erosion grades in the Jiuyuangou watershed. As per Gilani et al (2021), we stipulate soil erosion transformations from lower to higher erosion grades as 'loss' and higher to lower erosion grades as 'gain'. For changes in the spatial pattern of land use, we specify the conversion of other land use types to cropland as 'loss' and cropland to other land use types as 'gain'. On this basis, we conduct a binary variable spatial correlation analysis to determine how the two variables change simultaneously in the whole watershed space (Nandi and Shakoor, 2010). Finally, we produced a bivariate choropleth to understand the spatial pattern of soil erosion and LULCC and the association of gain, loss, and no change between 2010 and 2020.

Results

Analysis of soil erosion factors

Rainfall, vegetation, and soil and water conservation engineering measures are the three major factors affecting soil erosion in the Loess Plateau. We analyzed the characteristics of erosion conditions in the watershed through temporal and spatial changes of erosion factors in the CSLE model. For this purpose, various soil erosion factors in the model were calculated and presented as a 10 m resolution grid map. The soil erodibility factor (K), slope length and slope factor (LS), and tillage measure factor (T) remained unchanged from 2010 to 2020 (Figure 2a-c), while the rainfall erodibility factor (R), vegetation cover measure factor (B), and soil and water conservation engineering measure factor (E) varied with year.

Figure 2d-f is the rainfall erosivity map of Jiuyuangou watershed in 2010, 2015, and 2020 In general, average annual rainfall erosivity from 2010 to 2020 first decreased and then increased. Spatially, the rainfall erosivity increases from the northeast of the watershed to the southwest of the watershed.Basin rainfall is concentrated from June to September but extremely uneven during the year and prone to rainstorm erosion.

Vegetation cover impacts soil erosion development by affecting surface runoff processes in the watershed. Figure 2g–i shows three-year vegetation coverage factors from 2010 to 2020. At the same time, areas with low B values increased from 75% in 2010 to 84% in 2020. The low B value area gradually expands from the northeastern part of the watershed to the southern residential area and agricultural land, representing better vegetation cover and lower erosion risk than the high B value area. Figure 2j–l shows that terraces and check dams are the main soil and water conservation engineering measures in the basin, and unique to the Loess Plateau. The area of terraced fields continued to decrease from 2010 to 2020, and the area of check dams increased from 2010 to 2015 and then decreased from 2015 to 2020. Since the project of returning farmland to forest commenced in 1999, the construction of check dams on the Loess Plateau started and continued until 2015, when the layout of the dam system was completed. Due to problems such as sediment deposition and poor management, the check dam area in 2020 was significantly less than 2015. Terraces are an important soil and water conservation measure in the basin, mostly horizontal terraces on ridges. During the study period, the area of terraced fields in the basin decreased year on year due to scour damage caused by rainfall and farmland abandonment. In 2020, the area of terraced fields had declined by 12.3% compared with 2010.

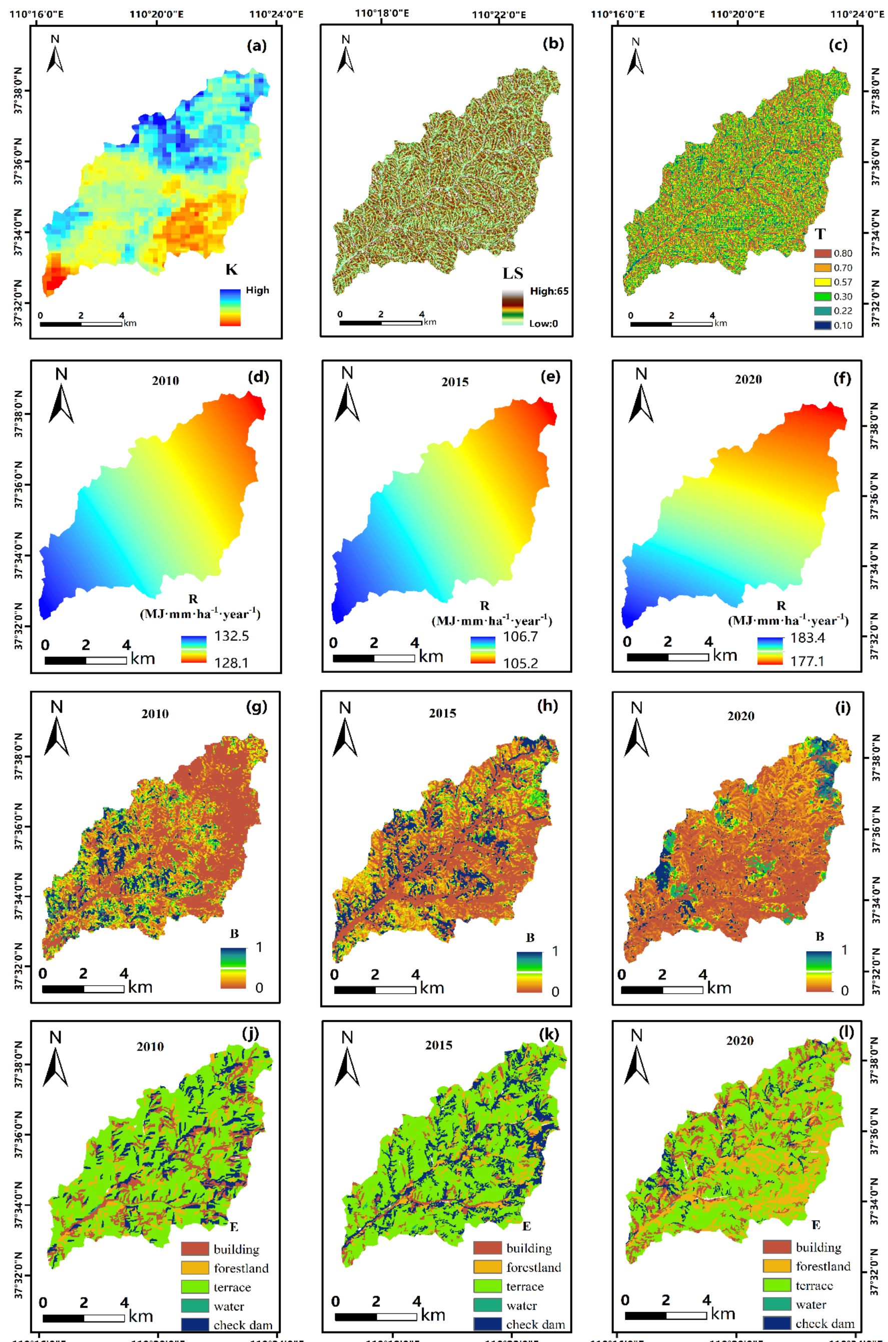

Figure 2. Distribution map of K factor(a), LS factor(b), and T factor (c) in the Jiuyuangou watershed,spatial distribution of R factors(d–f), B factors (g–i) and E factors(j–l) in 2010, 2015, and 2020

Temporal and spatial evolution of soil erosion (2010–2020)

We calculated the soil erosion modulus of the Jiuyuangou watershed in 2010, 2015, and 2020 using the CSLE model. According to the Soil Erosion Classification Standard (SL190-2007) issued by the Ministry of Water Resources of the People's Republic of China, the soil erosion modulus is divided into six grades: weak (0–10 t

$ha^{-1}yr^{-1}$), slight (10–25 t $ha^{-1}yr^{-1}$), moderate (25–50 t $ha^{-1}yr^{-1}$), intensive (50–80 t $ha^{-1}yr^{-1}$), very intensive (80–150 t ha^{-1} yr^{-1}), and severe (>150 t ha^{-1} yr^{-1}) (Figure 3). The average soil erosion modulus in the watershed was 10.85 t ha^{-1} yr^{-1} in 2010, 8.03 t ha^{-1} yr^{-1} in, and 10.57 t ha^{-1} yr^{-1} in 2020.

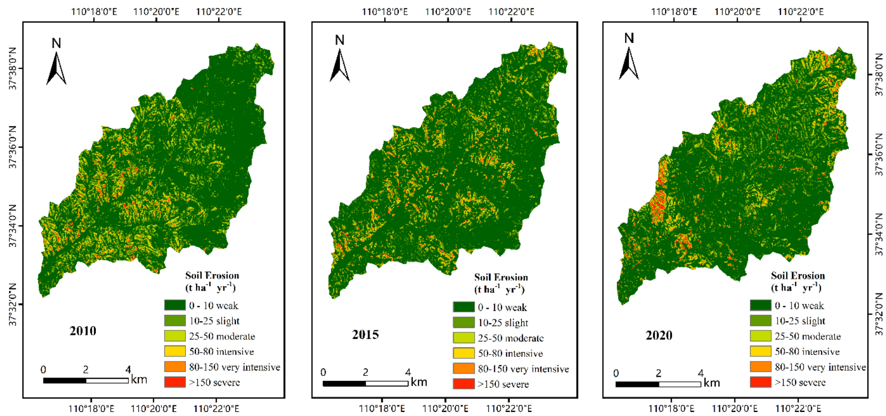

Figure 3. Soil erosion modulus estimated by the CSLE in Jiuyuangou watershed for 2010, 2015, and 2020

Table 1 shows that the soil erosion grades in the basin from 2010 to 2020 are mainly weak erosion and slight erosion, accounting for 88.17–90.28% of the total area of the watershed. Notably, the severe erosion area only accounts for 0.62–1.46% of the total area, with the erosion area below slight following an increasing then decreasing trend and the severe erosion area following a decreasing then increasing trend from 2010 to 2020. Using the soil erosion area transfer matrix (Table 2), the dark color marks the area that remained unchanged in different soil erosion grades from 2010 to 2020: 4407.47 ha below moderate erosion, with only 13.7 ha above intensive erosion. From 2010 to 2020, 38.04 ha of the watershed area changed from severe to below moderate erosion, while only 1.62 ha changed from severe to intensive erosion. In addition, 77.83 ha of the watershed area changed from below moderate to severe erosion, while only 19.2 ha changed from intensive and very intensive to severe erosion.

Table 1. Statistics of soil erosion grade area in different years in Jiuyuangou watershed from 2010 to 2020.

Soil erosion class (t ha^{-1} yr^{-1})	**Soil erosion class (t ha^{-1} yr^{-1})**	**2010**	**2010**	**2015**	**2015**	**2020**	**2020**
		Area (ha)	**%**	**Area (ha)**	**%**	**Area (ha)**	**%**
Weak	0–10	5162.25	74.31	5539.9	79.81	5304.44	76.39
Slight	10–25	962.94	13.86	726.52	10.47	873.4	12.58
Moderate	25–50	486.82	7.01	285.68	4.12	354.74	5.11
Intensive	50–80	157.11	2.26	160.18	2.31	168.69	2.43
Very intensive	80–150	132.5	1.91	186.52	2.69	141.48	2.04
Severe	>150	45.75	0.66	42.77	0.62	101.15	1.46

Table 2. 2010–2020 soil erosion grade area transfer matrix in Jiuyuangou watershed (ha).

Soil erosion class	**Weak**	**Slight**	**Moderate**	**Intensive**	**Very intensive**	**Severe**	**Total in 2010**
Weak	**4210.42**	537.32	222.10	92.62	60.09	27.59	5150.13
Slight	626.28	**160.78**	70.55	42.30	39.42	22.01	961.35
Moderate	281.73	92.93	**36.27**	22.95	24.08	28.23	486.21
Intensive	91.54	30.20	11.33	**4.57**	10.22	9.18	157.03
Very intensive	69.03	34.94	8.92	4.24	**5.24**	10.02	132.39
Severe	17.13	15.84	5.07	1.62	2.17	**3.89**	15.72
Total in 2020	5296.14	872.01	354.24	168.31	141.22	100.91	**6932.83**

Temporal and spatial evolution of LULC (2010-2020)

The main LULC types in the Jiuyuangou watershed are grassland (62.23%) and forest land (28.41%), followed by cropland (6.77%), building (2.49%), and water (0.09%). The spatial distribution of land use is affected by topography and human activities. Cropland is distributed throughout the Jiuyuangou watershed and close to residential areas. Settlement, roads, and other building areas are mainly distributed in flat terrain areas, while water bodies mainly include artificial lakes in the basin, with a small area close to construction land (Figure 4).

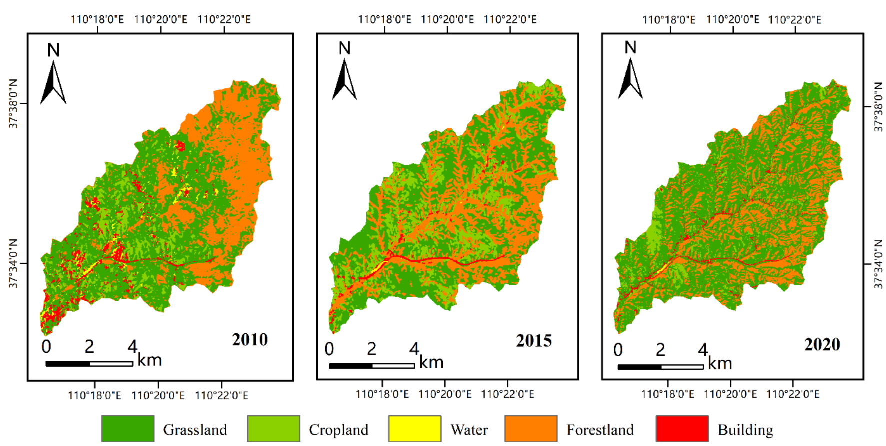

Figure 4. Spatial distribution map of land use and land cover (LULC) in Jiuyuangou watershed in 2010, 2015, and 2020.

Table 3 shows that grassland increased from 3613.33 ha in 2010 to 4349.05 hm^2 in 2020, and forest land decreased from 2191.53 ha in 2010 to 1985.54 ha in 2020. Forest and grass cover in 2020 increased by 10% compared to 2010. Land use types changed from 2010 to 2020 in the Jiuyuangou watershed: 877.04 ha converted from cropland and construction land to forest land and grassland, 447.48 ha converted from forest and grassland to cropland and construction land, and 3542.24 ha of forest and grassland area remained unchanged. Forest and grass coverage areas in the basin increased, with remarkable results from regional environmental governance and the project of returning farmland to forest.

Table 3. Transfer matrix of LULC area in Jiuyuangou from 2010 to 2020(ha).

Land use	Grassland	Cropland	Building	Forestland	Water	Total 2010
Grassland	**2464.97**	287.22	104.15	756.87	0.13	3613.33
Cropland	547.94	**94.94**	12.19	23.97	0	679.04
Building	237.67	43.08	**31.29**	68.16	0.74	380.93
Forestland	1058.13	37.08	19.03	**1077.27**	0.02	2191.53
Water	40.34	10.50	7.69	59.28	**5.52**	123.32
Total 2020	4349.05	472.81	174.35	1985.54	6.4	**6988.14**

Evolution of soil erosion based on LULCC (2010–2020)

Figure 5 shows the average soil erosion modulus for land use types in 2010, 2015, and 2020: cropland (55.1 t ha^{-1} yr^{-1}) > grassland (8.93 t ha^{-1} yr^{-1}) > building (1.6 t ha^{-1}yr^{-1})>forest land (1.65 t ha^{-1} yr^{-1}). The average soil erosion modulus of cropland is 4.5–7.4 times that of the grassland. Cropland experienced the most soil loss, ranging from 49.05 t ha^{-1} yr^{-1} in 2010 to 38.57 t ha^{-1} yr^{-1} in 2015, but increasing to 77.97 t ha^{-1} yr^{-1} in 2020. Grassland soil losses ranged from 10.87 t ha^{-1}yr^{-1} in 2010 to 5.72 t ha^{-1}yr^{-1} in 2015, but increased to10.36 t ha^{-1} yr^{-1} in 2020. Building and forest land followed a similar trend change to cropland from 2010 to 2020. Forest land had the lowest soil losses, decreasing from 1.07 t ha^{-1} yr^{-1} in 2010 to 0.97 t ha^{-1} yr^{-1} in 2015, and then increasing to 2.91 t ha^{-1} yr^{-1} in 2020.

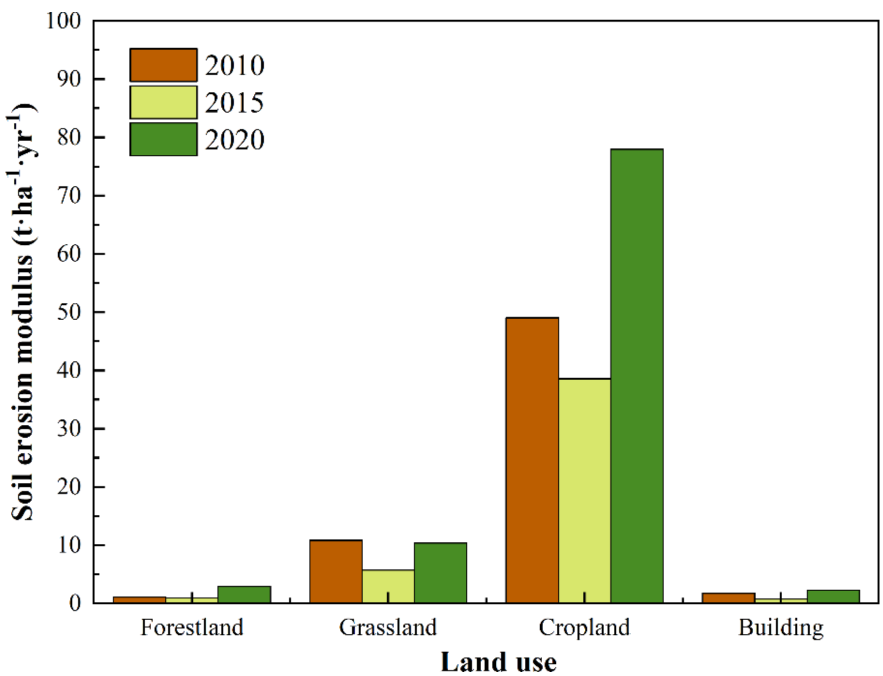

Figure 5. Soil erosion modulus of LULC in Jiuyuangou watershed in 2010, 2015, and 2020

Grassland composed of small vegetation such as different low canopy and grass and forest land composed of tall trees and shrubs have different contributions in protecting soil from root erosion and reducing the erosion of topsoil by rainfall through canopy coverage. At the same time, the dead plants also increased the content of soil organic matter and the water holding capacity of soil after falling to the ground. so, in the past 10 years (2010–2020), the soil loss of grassland decreased by 0.51 t ha^{-1} yr^{-1}, however, the soil loss of forestland increased by 1.84 t ha^{-1}yr^{-1}.

Figure 6 shows the area statistics for land use type and soil erosion grade in the Jiuyuangou watershed in 2010, 2015, and 2020. Changes in the building area due to human activities had little effect on serious soil erosion, with the predominantly weak erosion decreasing from 365.01 ha in 2010 to 161.89 ha in 2020. Similarly, forest land mainly had weak erosion (94.7%-98.8%), decreasing from 2144.43 ha in 2010 to 1863.68 ha in 2020. Cropland mostly had weak, slight, and moderate erosion. From 2010 to 2020, The area of three kinds of soil erosion in cropland decreased. Considering that grassland occupies the vast majority of the watershed area, it comprises all soil erosion grades, predominantly weak (65.4%-72.7%) and slight (16.9%-22.15%%) erosion. Different from cropland, weak erosion in grassland increased from 2355.68 ha to 3149.54 ha and slight erosion decreased from 797.92 ha to 733.60 ha.

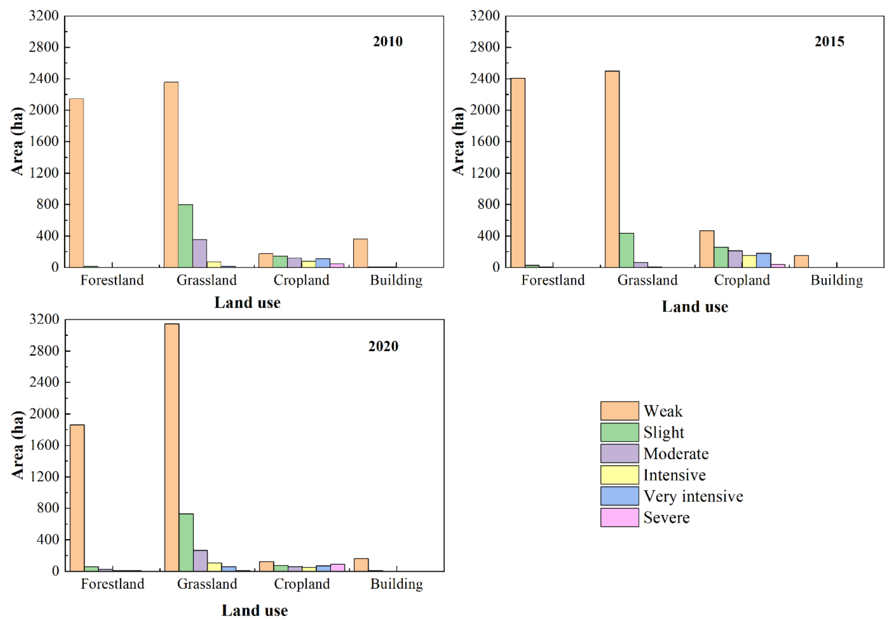

Figure 6. Classification statistics of soil erosion area of LULC in Jiuyuangou watershed in 2010, 2015, and 2020.

We considered the conversion of cropland to other land use types in the land use space transfer as 'gain', and the conversion of other land use types to cropland as 'loss'. For changes in the spatial pattern of soil erosion, we considered the increase in soil erosion grade as 'loss', and the decrease in soil erosion grade as 'gain'. Therefore, we plotted a bivariate choropleth map (Figure 7) to understand spatial patterns and the association between gain, loss, and no change in soil erosion and LULCC. During the study period, some areas of the watershed were covered by 'no change' between LULCC and soil erosion change, mainly concentrated near roads, residential areas, cultivated land, and perennial forest land in the eastern part of the watershed. Significantly, the northeast of the watershed showed a common 'loss' between soil erosion change and LULCC, and cropland near residential areas in the central and southwest of the watershed showed a common 'gain' between soil erosion change and LULCC. At the same time, we also observed a 'gain' in soil erosion change with 'no change' in LULCC in the central and southwestern watersheds. In addition, the soil erosion level in the central and southwest part of the watershed declined, and the land use pattern followed a trend of transforming cropland into forest and grassland. Therefore, 'gain' was detected for both LULCC and soil erosion change in the central and southwest part of the watershed, with a high spatial correlation between LULCC and soil erosion change.

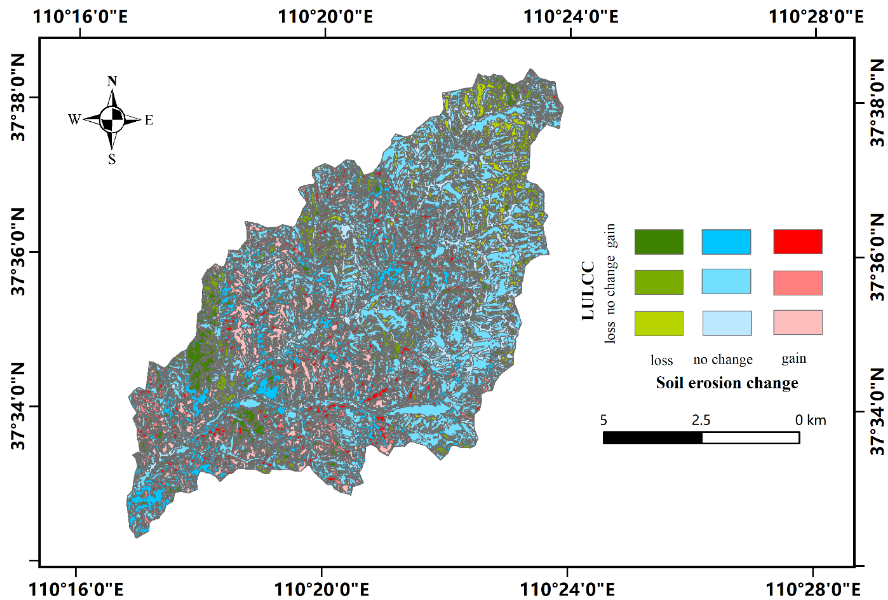

Figure 7. Bivariate spatial analysis map of soil erosion change and LULCC from 2010 to 2020.

Discussion

Validation of model results

The CSLE model has been used widely on the Loess Plateau (Kou et al., 2020; Wei et al., 2021; Wu et al., 2016; Zhang et al., 2020), and advances in remote sensing data resolution and geographic information system technology have vastly improved model applicability and accuracy.

Current assessments of soil erosion models typically use measurements based on field monitoring and isotope tracer techniques, often relying on depleted radionuclide inventories to simulate medium/long-term soil redistribution rates. Other remote sensing means use high-resolution aerial imagery to assess erosion severity in a qualitative/semi-quantitative manner (Fischer et al., 2018). Due to the lack of detailed historical field observation data in this study, we collated the results of published papers in the study area and compared them to our model results. Huang et al. (2020) used the CSLE model to assess soil losses in the Jiuyuangou watershed from 1970 to 2015, drew soil erosion modulus grading maps (1977, 2004, and 2015), and analyzed the effects of land use and slope on soil erosion. We compared the soil erosion modulus in 2015 with our results for the slope classification statistics (Figure 8a), carried out a correlation analysis based on this comparison, and calculated the correlation coefficient (R^2) and Nash coefficient (NSE) using the previous data as the verification value. The results of both studies differed for slopes less than 15° (MRE=68.13%) but were more consistent for slopes greater than 15° (MRE=10.84%). The difference is acceptable due to the different calculation methods used for the T factor. In Figure 8b, the R^2 (0.93) and NSE (>0.8) indicate credible model results. We also compared our results with the soil erosion assessment conducted by Wang (2018) in the Wuding River Basin from 2000 to 2014, which reported that weak erosion dominated the watershed (88.35% of the total watershed area), consistent with this study.

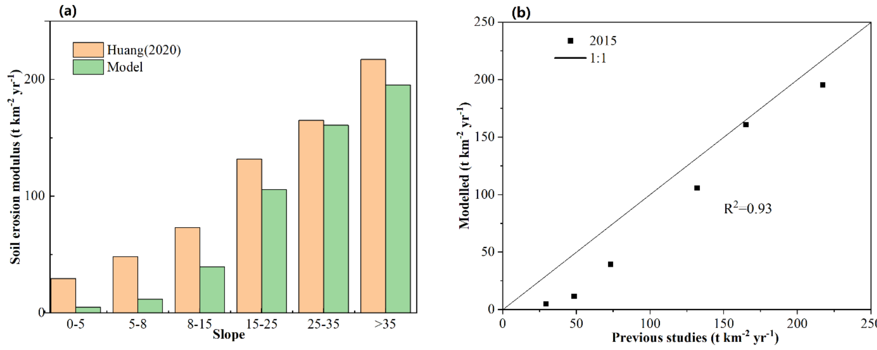

Figure 8. Statistical comparison of soil erosion by slope between previous study(Huang,2020) and our study in 2015(a) Statistical correlation analysis of soil erosion modulus by slope between the previous study(Huang,2020) and our study in 2015(b).

Relationship between land use and soil erosion

Our results showed that for the 2010–2020 LULCC, the multi-year average soil erosion rate for different land uses significantly differed, with cropland (55.1 t ha^{-1} yr^{-1}) > grassland (8.93 t ha^{-1}yr^{-1}) > building (1.6 t ha^{-1} yr^{-1}) > forest land (1.65 t ha^{-1} yr^{-1}), similar to the findings of Zhao et al. (2022) and Han et al. (2020). The 'Returning Farmland to Forest Project' program implemented in 1999 significantly increased the vegetation coverage rate, increasing the grassland and forestland area from 83.1% in 2010 to 90.7% in 2020. The Loess Plateau has recently experienced large-scale cropland abandonment due to rural population movements, cropland quality, and economic benefits. At the end of 2016, a survey of 235 villages in China revealed that 78.3% had abandoned up to 14.32% of their cultivated land. Soils on plots with lower vegetation cover were being disturbed more frequently and intensely by tillage, accelerating erosion (García-Ruiz, 2010; Zuazo and Pleguezuelo, 2009). The abandoned cultivated land resulted in increased biocrust and vegetation cover in interplant patches, increasing soil infiltration and reducing the generation of erosive runoff (Chirino et al., 2006; Yuan et al., 2020), and the vegetation root systems reduced soil erodibility, protecting the soil from raindrop erosion and runoff transport (Chen et al., 2021; Chuenchum et al., 2020). Therefore, soil erosion was curbed in the Jiuyuangou watershed from 2010 to 2015.

However, the increase in forest/grassland area and vegetation coverage from 2015 to 2020 increased the soil erosion rate in the watershed from 2015 to 2020, primarily due to more frequent extreme rainfall events after 2015. The Loess Plateau has an extremely uneven distribution of annual rainfall. The rainfall erosivity in the basin from June to September in 2010, 2015, and 2020 accounted for 85%, 50%, and 88% of annual rainfall erosivity, respectively. At the same time, frequent heavy rainfall events occurred in the basin after 2015 (e.g., July 26, 2017 (212.2 mm), August 7, 2018 (151.3 mm), August 7, 2019 (150 mm), and August 4–6, 2020 (80.3 mm)). Flooding season precipitation in the Jiuyuangou watershed has become the main precipitation for the year, with the erosion and sediment production caused by rainstorm erosion an important feature of this area. It is far sufficient to rely on surface micromorphological changes from vegetation restoration to manage rainstorm erosion (Han et al., 2020; Yang et al., 2011). The current land use distribution pattern in the hilly and gully region of the Loess Plateau in northern Shaanxi cannot prevent soil erosion under extreme rainstorm conditions. Optimizing the distribution of land use types in the catchment area should be the focus of soil erosion control (Wang et al., 2020). The frequent occurrence of extreme rainfall has affected the consistency of soil erosion changes and LULCC, evidenced by large-scale soil erosion losses in areas with no change in land use patterns. In the northern part of the basin, far from human settlements and construction land, land use and soil erosion followed a common 'loss' trend, 'no change' occurred in settlements and construction land. The frequent occurrence of extreme rainfall has affected the consistency of soil erosion changes and LULCC, evidenced by large-scale soil erosion losses in areas with no change in land use patterns. In the northern part of the basin, far from human settlements and construction land, land use and soil erosion followed a common 'loss' trend, 'no change' occurred in settlements and construction land. Therefore, the LULCC and soil erosion changes are spatially correlated in areas near the human activities or settlements, roads, cropland, and valleys with good soil and water conservation.

Conclusion

We quantitatively assessed soil erosion changes from 2010 to 2020 in the Jiuyuangou watershed, a typical watershed in the hilly and gully region of the Loess Plateau, using remote sensing, soil, climate, and topographic data, and the CSLE model from the background of LULCC . From 2010 to 2020, forest and grass coverage increased, as did vegetation coverage, with grassland (62.23%) and forestland (28.41%) becoming the main land use types in the watershed. From 2010 to 2015, soil erosion in the Jiuyuangou watershed weakened. However, with the frequent occurrence of extreme rainfall events, soil erosion has increased in recent years. Using bivariate spatial analysis to understand the spatial correlation between LULCC and soil erosion changes, a common 'no change' was detected between LULCC and soil erosion changes in settlements, roads, and valleys, with a common 'gain' detected in the areas near the influence of human activities in central and southwest the part of the watershed. Soil erosion is affected by numerous factors such as human activities, land use, and natural conditions. The research results showed that returning farmland to forests and ecological restoration played a positive role in alleviating regional soil erosion and reducing soil erosion. However, this is insufficient in the face of frequent extreme rainfall events. Therefore, we must continue to improve water and soil conservation engineering measures within the region, such as constructing terraces and repairing check dams.

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References

Chen J, Li Z, Xiao H, Ning K, Tang C. 2021. Effects of land use and land cover on soil erosion control in southern China: Implications from a systematic quantitative review. J Environ Manage. 282: 111924.

Chirino E, Bonet A, Bellot J, Sánchez J. 2006.Effects of 30-year-old Aleppo pine plantations on runoff, soil erosion, and plant diversity in a semi-arid landscape in south eastern Spain. Catena 65: 19-29.

Chuenchum P, Xu M, Tang W. 2020. Predicted trends of soil erosion and sediment yield from future land use and climate change scenarios in the Lancang–Mekong River by using the modified RUSLE model. International Soil and Water Conservation Research 8: 213-227.

Duan X, Bai Z, Rong L, Li Y, Ding J, Tao Y, et al. 2020. Investigation method for regional soil erosion based on the Chinese Soil Loss Equation and high-resolution spatial data: Case study on the mountainous Yunnan Province, China. Catena 184.

Fan X, Pedroli B, Liu G, Liu Q, Liu H, Shu L. 2012. Soil salinity development in the yellow river delta in relation to groundwater dynamics. Land Degradation & Development 23: 175-189.

Fang X, Zeng M, Zuo Z. 1993. Analysis of Sediment Retention by Warping Dam System in the Channel Basin of the Middle Reaches of the Yellow River——Taking Wangmaogou Basin as an Example. Soil and Water Conservation Bulletin .24-28.

Fischer FK, Kistler M, Brandhuber R, Maier H, Treisch M, Auerswald K. 2018. Validation of official erosion modelling based on high-resolution radar rain data by aerial photo erosion classification. Earth Surface Processes and Landforms .43: 187-194.

Fu S, Yang Y, Liu B, Liu H, Liu J, Liu L, et al. 2020. Peak flow rate response to vegetation and terraces under extreme rainstorms. Agriculture, Ecosystems & Environment .288.

Garcia-Ruiz JM. 2010. The effects of land use on soil erosion in Spain: A review. Catena. 81: 1-11.

Gilani H, Ahmad A, Younes I, Abbas S. 2021. Impact assessment of land cover and land use changes on soil erosion changes (2005–2015) in Pakistan. Land Degradation & Development. 33: 204-217.

Han F, Ren L, Zhang X, Li Z. 2016. The WEPP Model Application in a Small Watershed in the Loess Plateau. PLoS One .11: e0148445.

Han J, Ge W, Hei Z, Cong C, Ma C, Xie M, et al. 2020. Agricultural land use and management weaken the soil erosion induced by extreme rainstorms. Agriculture, Ecosystems & Environment. 301.

Huang C. 2021.Temporal and spatial variation of soil erosion in the Loess Plateau and its main controlling factors in the past 40 years. Northwest University.

Huang C, Yang Q, Cao X, Li Y. 2020. Assessment of the Soil Erosion Response to Land Use and Slope in the Loess Plateau—A Case Study of Jiuyuangou. Water .12.

Kou P, Xu Q, Yunus AP, Liu J, Xu Y, Wang C, et al. 2020. Landslide-controlled soil erosion rate in the largest tableland on the Loess Plateau, China. Human and Ecological Risk Assessment: An International Journal. 26: 2478-2499.

Li P, Chen J, Zhao G, Holden J, Liu B, Chan FKS, et al. 2022. Determining the drivers and rates of soil erosion on the Loess Plateau since 1901. Sci Total Environ. 823: 153674.

Liu J, Liu H. 2020. Soil erosion changes during the last 30 years and contributions of gully erosion to sediment yield in a small catchment, southern China. Geomorphology. 368.

Liu B, Zhang K, Xie Y. An empirical soil loss equation. 2002. Proc. 12th ISCO Conf. 2. pp. 21-25.

Luo Y, Yang S, Liu X, Liu C, Zhang Y, Zhou Q, et al. 2015. Suitability of revision to MUSLE for estimating sediment yield in the Loess Plateau of China. Stochastic Environmental Research and Risk Assessment. 30: 379-394.

Meliho M, Nouira A, Benmansour M, Boulmane M, Khattabi A, Mhammdi N, et al. 2019. Assessment of soil erosion rates in a Mediterranean cultivated and uncultivated soils using fallout 137Cs. Journal of Environmental Radioactivity. 208: 106021.

Molina A, Vanacker V, Balthazar V, Mora D, Govers G. 2012. Complex land cover change, water and sediment yield in a degraded Andean environment. Journal of Hydrology. 472: 25-35.

Nandi A, Shakoor A. 2010. A GIS-based landslide susceptibility evaluation using bivariate and multivariate statistical analyses. Engineering Geology. 110: 11-20.

Shen ZY, Gong YW, Li YH, Hong Q, Xu L, Liu RM. 2009. A comparison of WEPP and SWAT for modeling soil erosion of the Zhangjiachong Watershed in the Three Gorges Reservoir Area. Agricultural Water Management. 96: 1435-1442.

Shi W, Huang M, Barbour SL. 2018. Storm-based CSLE that incorporates the estimated runoff for soil loss prediction on the Chinese Loess Plateau. Soil and Tillage Research. 180: 137-147.

Wang N, Jiao J, Bai L, Zhang Y, Chen Y, Tang B, et al. 2020. Magnitude of soil erosion in small catchments with different land use patterns under an extreme rainstorm event over the Northern Loess Plateau, China. Catena. 195.

Wang T. 2018. Impacts of the Grain for Green Project on Soil Erosion: A Case Study in the Wuding River and Luohe River Basins in the Shaanxi Province of China. Applied Ecology and Environmental Research. 16: 4165-4181.

Wei H, Zhao W, Wang H. 2021. Effects of Vegetation Restoration on Soil Erosion on the Loess Plateau: A Case Study in the Ansai Watershed. Int J Environ Res Public Health. 18.

Williams JR, Dyke PT, Jones CA. Epic - a Model for Assessing the Effects of Erosion on Soil Productivity1 1Paper presented at the Third International Conference on State-of-the-Art in Ecological Modelling, Colorado State University, May 24–28, 1982. In: Lauenroth WK, Skogerboe GV, Flug M, editors. Developments in Environmental Modelling. 5. Elsevier, 1983. pp. 553-572.

Wu L, Liu X, Ma X. 2016. Application of a modified distributed-dynamic erosion and sediment yield model in a typical watershed of a hilly and gully region, Chinese Loess Plateau. Solid Earth .7: 1577-1590.

Yang T, Xu C-y, Zhang Q, Yu Z, Baron A, Wang X, et al. 2011. DEM-based numerical modelling of runoff and soil erosion processes in the hilly–gully loess regions. Stochastic Environmental Research and Risk Assessment. 26: 581-597.

Yuan J, Ye C, Luo L, Pei X, Yang Q, Chen J, et al. 2020. Sand fixation property and erosion control through new cellulose-based curing agent on sandy slopes under rainfall. Bulletin of Engineering Geology and the Environment .79: 4051-4061.

Zhang H, Wei J, Yang Q, Baartman JEM, Gai L, Yang X, et al. 2017. An improved method for calculating slope length (λ) and the LS parameters of the Revised Universal Soil Loss Equation for large watersheds. Geoderma. 308: 36-45.

Zhang Q. 2016. Evaluation and Analysis of Soil Erosion in the Loess Plateau. Northwest University.

Zhang W, Wang Z, Zhu X, Li W, Gao B, Yu H. 2020. A risk assessment of a water-sand inrush during coal mining under a loose aquifer based on a factor analysis and the fisher model. Journal of Hydrologic Engineering. 25: 04020033.

Zhao J, Wang Z, Dong Y, Yang Z, Govers G. 2022. How soil erosion and runoff are related to land use, topography and annual precipitation: Insights from a meta-analysis of erosion plots in China. Sci Total Environ. 802: 149665.

Zuazo VcHD, Pleguezuelo CRoR. 2009. Soil-erosion and runoff prevention by plant covers: a review. Sustainable agriculture. 785-811.